
# INDEPENDENT REVIEW OF LOWER LAKES SCIENCE INFORMING WATER MANAGEMENT

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## INDEPENDENT PANEL


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# PREAMBLE

## Background

The Lower Lakes in South Australia are an important environmental, social and economic national asset. The significance of the wetlands is internationally recognised as part of the Coorong and Lakes Alexandrina and Albert Ramsar listed wetland, supporting endangered migratory birds, threatened wildlife and rare plants. The Lower Lakes has economic significance and is a well-used recreation area, and the region has significant importance for the Ngarrindjeri People.

Over recent years, debate has emerged concerning the estuarine history of the Lower Lakes, specifically the extent to which maintaining them as freshwater systems is supported by scientific evidence and whether the associated water management arrangements are appropriate during periods of limited water availability. There is evidence that prior to large upstream human development, the Lower Lakes varied between freshwater and estuarine periods, depending on the prevailing hydroclimatic conditions. Development upstream reduced flows into the Lower Lakes, increasing the incursion of seawater into the Lower Lakes and the River Murray. The barrages were built in 1940 in response to these changes, and they now protect around 250 kilometres of the lower Murray River from the seawater, up to Lock 1 at Blanchetown.

The social, economic and environmental fabric of the Lower Lakes has adapted in response to river management over recent decades. Consistent with other parts of the Basin, the Lower Lakes comprise a human-modified riverine environment that contains important natural elements.

The Murray-Darling Basin is currently experiencing critical water shortages, and this has led to increased community interest regarding the management of the Lower Lakes. Although views about how water resources are utilised vary, most stakeholders agree that it is essential for the policies and management arrangements to be based on sound science. In response to the increased community interest, the Murray-Darling Basin Authority (MDBA) deemed it timely and prudent to initiate an independent review of the relevant science relating to the management of the Lower Lakes (including the connected lower Murray River and the Coorong).

The MDBA asked its Advisory Committee on Social, Economic and Environmental Sciences (ACSEES) to steer the review process by (i) advising appropriate Terms of Reference, (ii) advising on suitable experts to conduct the review, (iii) participating in a technical workshop to examine the preliminary findings of the review, and (iv) peer reviewing the draft final report.

## Terms of Reference

The review addressed the following key questions:

1. What are the various scientific perspectives on the past and current hydrology and salinity of the Lower Lakes and how have the lakes come to be managed in the way they are?
2. What would be the likely regional social, environmental and economic implications of removing the barrages, and would this result in significant water savings?
3. What knowledge needs are required to plan for the main social, environmental and economic vulnerabilities of the Lower Lakes to climate change?

## Panel Approach

The approach to this independent review includes the following:

- Briefing by the Murray-Darling Basin Authority.
- Meetings and discussions with key organisations involved in the planning and management of the Lower Lakes (Murray-Darling Basin Authority, South Australian Department of Environment and Water, Commonwealth Environmental Water Office).
- Review of knowledge and technical information in reports and scientific publications.
- Discussions with key researchers and technical experts.
- Preparation of draft report.
- Workshop with key researchers and technical experts to discuss draft report (the workshop agenda and list of participants are shown in Attachments A and B respectively).
- Further consultations.
- Preparation of final report, with review by the MDBA ACSEES (Advisory Committee on Social, Economic and Environmental Sciences).
- Submission of final report to the Murray-Darling Basin Authority.

## Report Outline

The report starts with a short summary, followed by one-page responses to each of the three terms of reference (Section 1). The reader is pointed to sections in the main body of the report where the summary responses are discussed in more detail.

Section 2 discusses the freshwater and estuarine history of the Coorong, Lower Lakes and Murray Mouth (CLLMM). Section 3 describes the hydrology and hydrodynamics of the CLLMM. Section 4 discusses the environmental, social and economic outcomes for the region.

A final section (Section 5) then summarises the CLLMM outcomes under the various scenarios (pre-development, pre-Basin Plan, post-Basin Plan, removal of barrages, climate change).

# SUMMARY

The Coorong, Lower Lakes and Murray Mouth (CLLMM) have been extensively studied over the past 20 years, with literally hundreds of research papers and reports on the geomorphology, hydrodynamics, hydroclimate, ecology, salinity regime, and water management of the CLLMM. The knowledge from these studies, together with ongoing monitoring of flow, salinity and water levels, and hydrological and hydrodynamic modelling have informed water management of the CLLMM.

The salinity regime of the Lower Lakes is driven by the relative influence of freshwater inflow from the Murray River and seawater input from the ocean. The pre-development long-term average annual Murray River inflow is more than 13,000 GL/yr, which would fill the lakes on average more than eight times in a year. The weight of evidence (from palaeoecological records, water balance estimates, hydrological and hydrodynamic modelling, and traditional knowledge of the Ngarrindjeri People and anecdotal accounts of early explorers and colonists) points to the Lower Lakes being largely fresh prior to European settlement, with moderate tidal influence and incursion of seawater during periods of low Murray River inflow.

Upstream development has reduced the river inflow by about half (about 6,000 GL/yr before the Basin Plan and about 7,500 GL/yr under the Basin Plan), resulting in more frequent incursion of seawater into the Lower Lakes. The barrages were built in 1940 in response to these changes, isolating the Coorong and the sea from the Lower Lakes.

The barrages keep the Lakes predominantly fresh and prevent seawater intrusions into the lower Murray River. Without the barrages, the Lower Lakes would be seasonally estuarine with prolonged periods of high salinity during droughts. Without the barrages, the freshwater values in the Lower Lakes cannot be maintained, significantly changing the ecological character of the Ramsar site, which would also impact traditional owner values and other socio-economic values that are reliant on a healthy CLLMM.

The CLLMM under current conditions can be considered as two systems separated by the barrages. The main water balance components of the Lower Lakes are freshwater inflow from the Murray River, net lake evaporation and outflow over the barrages. The Coorong is governed by complex hydrodynamics driven by the flow over the barrages (and from the south-east drainage system), tidal connection with the sea via the Murray Mouth channel, restriction between the North and South Lagoons, and wind and water set-up. The narrow and shallow channel between the North and South Lagoons restrict exchange of flows, and concentration of salt due to evaporation leads to hypersaline conditions in the South Lagoon. The Murray Mouth is a wave-dominated system that is clogging up with sand over time, and this would be exacerbated by barrage removal and/or climate change.

The additional inflow to the Lower Lakes secured under the Basin Plan significantly enhances the ecological outcomes of the CLLMM, through building resilience in the system and providing some inflow during dry years (like the Millennium drought and the recent drought). Environmental water is managed for multiple benefits, where water is reused as it flows down the river. As such, most of the environmental water delivered to the CLLMM has also been used for upstream environmental watering actions, including for the lower Murray River.

Under climate change, the management of the CLLMM would become increasingly challenging. Sea level rise would alter the hydrodynamics of the Coorong and Murray Mouth, as well as increase seawater ingression into the Lower Lakes. Evaporation from the Lakes would be higher under climate change. More freshwater inflow would therefore be needed to maintain lake water and

salinity levels and flow over the barrages. However, catchment runoff in the southern Murray-Darling Basin is projected to decline under climate change, and therefore future management of the CLLMM must be considered as part of whole-of-Basin planning and adaptation in response to climate change risk. Exploring adaptation of ecosystems and the services they provide under future climate scenarios would inform better management and identify values that can be maintained, those that can transition to some new state and those that cannot be sustained.

In summary, the water management of the CLLMM has been informed by an extensive body of knowledge, data and modelling. Nevertheless, there are gaps, particularly in the spatial and temporal details, and under different scenarios of hydroclimates and engineering and management interventions, and some of these are discussed in this report.

# 1. RESPONSES TO TERMS OF REFERENCE

## 1.1 RESPONSE TO FIRST TERM OF REFERENCE

What are the various scientific perspectives on the past and current hydrology and salinity of the Lower Lakes and how have the lakes come to be managed in the way there are?

The CLLMM are a wave-dominated estuary system. The geomorphic units within the system are a supra-tidal barrier (Younghusband and Sir Richard Peninsulas) separated by the narrow Murray Mouth, the Coorong Lagoon, a central Basin (Lakes Alexandrina and Albert), and a bay delta head (where the Murray River flows into Lake Alexandrina). [See cover page and Section 2.1].

Salinity conditions within the CLLMM are likely to have fluctuated during the Holocene (past 11.7 thousand years (ka)) due to changes affecting the relative influence of marine (sea level, barrier development) input from the south and fluvial (regional hydroclimate) input from the north. In combination, these changes are likely to have driven a decline in marine influence over the last 8 ka. [See Section 2.2].

Numerous palaeoecological sediment records have been analysed over the past 25 years. The records show clear spatial patterns, with highest salinity conditions in the South Lagoon of the Coorong, followed by the North Lagoon, the Goolwa Channel section of Lake Alexandrina, the mid-basins of Lakes Alexandrina and Albert, and finally the north end of Lake Alexandrina. In the Lower Lakes, the temporal trend is one of declining salinity, particularly during the last *ca* 2 ka, although there is some uncertainty due to hiatuses in several sediment records and uncertain dating.
[See Section 2.3].

A recent paper by Gell (2019) argues that a seminal study on the Holocene palaeoecology of the CLLMM (Fluin et al. 2007) has been misrepresented in a subsequent report (Fluin et al. 2009) and the broader literature to present the Lower Lakes as 'predominantly fresh' before European settlement. Our assessment is that Fluin et al. (2009) did not misrepresent conclusions of the original paper but downplayed marine influence in its interpretation. [See Section 2.5].

The weight of evidence points to the Lower Lakes being largely fresh prior to European settlement, with moderate tidal influence and incursion of seawater (with spatial variation in salinity described above) during periods of low river inflows. This is supported by the palaeoecological records, hydrological and hydrodynamic modelling, water balance estimates, traditional knowledge of the Ngarrindjeri People and anecdotal accounts of early explorers and colonists.
[See Sections 2.3 and 2.4].

Upstream development significantly reduced freshwater inflow, resulting in more frequent incursion of seawater into the Lower Lakes. The MDBA modelling indicates that the average annual inflow before development was more than 13,000 GL/yr, compared to long-term modelled average inflow of about 6,000 GL/yr before the Basin Plan, and about 7,500 GL/yr under the Basin Plan.
[See Figure 5.1]

The barrages were built in 1940 in response to these changes, isolating the Coorong and the sea from the Lower Lakes. The barrages keep the Lakes predominantly fresh and prevent seawater intrusion into the lower Murray River. The lakes are managed with the aim of maintaining Lake Alexandrina water level (0.40–0.85 m AHD) and salinity level (<1,000 EC in 95% of the years) and provide flow over the barrages to maintain connectivity for fish passage, reduce salinity in the Coorong and support the Murray Mouth openness.

## 1.2 RESPONSE TO SECOND TERM OF REFERENCE

### What would be the likely regional social, environmental and economic implications of removing the barrages, and would this result in significant water savings?

Without the barrages separating the Lower Lakes from the Coorong and the sea, Lake Alexandrina would become seasonally estuarine. From summer to autumn, rising sea level and low Murray River inflow and lake water level would result in salty seawater penetrating some distance into the lake. In late winter and spring, freshwater inflow during average flow years would push the saltwater out and reduce the salinity in Lake Alexandrina. During long droughts (like the Millennium drought and the recent drought) the Lower Lakes (and potentially upstream into the lower Murray River) would have high salinity for prolonged periods. Lake Albert could become a salt trap and have high salinity for long periods. The impact of barrage removal on the hydrodynamics and salinity of the Coorong is complex and difficult to ascertain but is likely to be smaller relative to the impact on the Lower Lakes. Barrage removal would increase tidal inflow and sand deposition, which would increase the propensity of the Mouth channel to be closed.
[See Section 3.4 and Figure 5.2].

Removing the barrages would result in an expansion of the estuarine habitat and a gradual (and changing, over seasons and years, depending on the Murray River inflow) freshwater gradient. The loss of freshwater values in the Lower Lakes would significantly alter the ecological character of the lakes and have implications for Australia's obligations under the Ramsar convention. Freshwater species like frogs and fish including small-bodied native fish would not survive, nor would freshwater submerged vegetation. Waterbirds would be impacted through disruptions in the food chain and loss of nesting habitat. Such ecological changes would have significant and ongoing consequences with respect to traditional owner values of the Ngarrindjeri Nation and other socio-economic values (e.g. tourism and fisheries) that are reliant on a healthy CLLMM system. Saltwater ingression upstream into the lower Murray River during long dry periods would impact water offtake for irrigation and for Adelaide and regional towns (although engineering solutions like the construction of Lock 0 at Wellington have been proposed to overcome this).
[See Section 4.4 and Figure 5.2].

Without the barrages, more Murray River inflow would be needed to keep the Lower Lakes fresh (<1,000 EC). The Murray River flow is also needed to achieve the Coorong salinity and ecological outcomes and to support the Murray Mouth openness. Therefore, removing the barrages would not result in any water savings if the targets informed by science and modelling and envisaged under the Basin Plan are to be met. Environmental water is managed for multiple benefits, where water is reused as it flows down the river, to sustain a healthy system across the entire Basin. Most of the environmental water delivered to the CLLMM by the Commonwealth Environmental Water Holder (CEWH) has also benefitted upstream assets. The MDBA modelling indicates that under the current settings of the Basin Plan, an additional 1,477 GL/yr flows into the Lower Lakes. However, in dry years, the environment, like all other water users, receives less water. In the past five years, the average annual environmental water managed by the CEWH that reached the Lower Lakes was less than 700 GL/yr, and this additional water has been critical in sustaining the CLLMM through the dry period and help the system bounce back when the drought ends.
[See Section 3.3].

## 1.3 RESPONSE TO THIRD TERM OF REFERENCE

### What knowledge needs are required to plan for the main social, environmental and economic vulnerabilities of the Lower Lakes to climate change?

Under climate change, the management of the CLLMM would become increasingly challenging. The Murray River inflow is projected to decline, and lake evaporation would be higher. Sea level rise would alter the hydrodynamics and geomorphology of the Coorong and Murray Mouth and increase seawater ingression into the Lower Lakes.

More freshwater inflow would be needed to maintain lake water and salinity levels and flow over the barrages, when runoff from upstream catchments is already projected to decline. The median projection for southern MDB under a high emission scenario for 2046–2075 (relative to 1976–2005) is a decline in mean annual runoff of about 20% (ranging from little change to a decline of 40%). [See Section 3.5.1 and Figure 5.2].

The sea level in the region is projected to rise by 52–98 cm by 2100 under the high emission climate change scenario, and this would impact the Coorong and Murray Mouth in several ways. The higher water level in the Coorong would have a negative impact on intertidal feeding habitat for shorebirds, while the less hypersaline condition in the South Lagoon may have a positive impact on ecological outcomes. The barrages and barrier islands would be overtopped more frequently increasing seawater input into the Lower Lakes.
[see Section 3.5.2, Section 4.5 and Figure 5.2].

The key knowledge needs required to plan for CLLMM outcomes under climate change include:

- <u>Predicting changes in Murray River inflow characteristics, and the impact on, and adaptation options for, the CLLMM</u>. The hotter and likely drier climate would be amplified in the hydrology, and this would impact all catchments in the southern MDB. As such, management and adaptation options for the CLLMM must be considered in the context of climate change risk to the entire MDB. The adaptation challenge is compounded by the large range or uncertainty in the future hydroclimate projections.
- <u>Predicting the impacts of sea level rise on the hydrodynamics and geomorphology of the CLLMM</u>. Knowledge needs include: How much would the Coorong water level rise? How much would the South Coorong salinity reduce? How often would the barrages and barrier islands be overtopped? Would the barrier islands be submerged? Would the Mouth channel be closed requiring permanent dredging? How much higher must the Lower Lake water level be maintained to allow Murray River flow to exit to the sea? These questions could be assessed through targeted research and undertaking hydrodynamic modelling and bottom-up sensitivity analysis of potential outcomes under climate change. With better knowledge, management options and infrastructure solutions can be more confidently developed and assessed.
- <u>Predicting social, environmental and economic vulnerabilities under climate change.</u> These would be closely linked to the biophysical impacts described above. There is a large body of literature on the vulnerabilities of Australian ecosystems and species to climate change and several studies specific to the CLLMM. Adaptive management of the CLLMM could be informed by a thorough review of the existing literature, matched to a monitoring program which can test the predicted changes over time. Ultimately, climate change, particularly if the extreme end of drying and sea level rise projections are realised, would have very significant and profound impact. Exploring adaptation of ecosystems and the services they provide under future climate scenarios would inform better management and identify values that can be maintained, those that can transition to some new state and those that cannot be sustained.

# 2. FRESHWATER AND ESTUARINE HISTORY OF THE LOWER LAKES AND COORONG

## 2.1 Geomorphology of the Coorong, Lower Lakes and Murray Mouth

- The Coorong, Lower Lakes and Murray Mouth (CLLMM) are a wave-dominated estuary system.
- The main geomorphic units within the system are a supra-tidal barrier, a central basin and a bay head delta.
- The structure of the system reflects the balance of fluvial, tidal and wave energy and the Quaternary history of glacial cycles and rising and falling sea levels.
- The current CLLMM was formed when global sea levels reached their approximate current level around 8 ka ago.

### 2.1.1 Background on the system

The Coorong, Lower Lakes and Murray Mouth (CLLMM) (or the Coorong and Murray Mouth after barrage development) form a large, wave dominated estuary where the River Murray debouches into the Southern Ocean (Ryan et al. 2003). Estuaries are transitional zones with a high degree of spatial and temporal variability in water quality, principally in relation to salinity, reflecting the relative influences of marine and freshwater inputs. In addition to the variation in water quality, estuaries are also subject to clear energy gradients that reflect the relative influences of fluvial and marine (via waves and tides) at different locations within the system. These gradients create complex hydrodynamics and serve to generate dynamic, spatially diverse physical habitats within the system. The CLLMM is a wave-dominated estuary, reflecting the high wave energy of the coastal environment, the micro tidal regime (<2m) and the relatively low volumes of water and sediment delivered by the River Murray (despite its large catchment). The CLLMM conforms to the typical wave-dominated estuaries in relation to both physical features and energy environment. In relation to physical structure, the CLLMM features a supra-tidal barrier at the mouth (Younghusband Peninsula) that encloses a central basin (Lakes Alexandrina and Albert, and the Coorong Lagoon) and limits exchange of water between the central basin and the sea (see cover page). The CLLMM also features a fluvial or bay head delta at the terrestrial end of the central basin (where the Murray River flows into Lake Alexandrina), formed by fluvial sediments deposited as they are transported from the channel into the lower energy central basin.

### 2.1.2 Geomorphological history of the system

The current structure and character of the CLLMM is the product of long geological and geomorphological history. Geological processes, operating over millions of years have determined the basic topography of the coastal fringe and the larger Murray and Darling Basins and the nature of the terrestrial and marine sediment available to be eroded, transported and deposited through geomorphological processes (Bourman et al. 2018a). The result is a low gradient drainage system that does not deliver large quantities of coarse sediment to the estuary and an estuary system that extends many kilometres inland due to the low gradient of the river valley (Helfensdorfer et al. 2019).

The geomorphology of the CLLMM reflects both the current balance of fluvial, tidal and wave energy and the longer-term history of fluctuating sea levels due to changing ice volumes through the Quaternary (the last 2.6 million years) associated with glacial climate cycles. The melting of continental ice that occurred after the most recent glacial maximum at around 20 ka (20,000 years before present) brought sea levels from more than 100 m lower than today to roughly the current level by around 8 ka (Lewis et al. 2013). This transgression brought the ocean margin to its approximate position and transported sediments from the broad continental shelf to the current near shore environment where they were thus available to contribute to the development, once sea-levels stabilised, of the large barrier system that largely encloses the estuary (Bourman et al. 2018b). This barrier system began as a series of barrier islands that coalesced to form a near complete barrier, broken only by the narrow Murray mouth to form the Sir Richard and Younghusband Peninsulas to the north and south of the mouth respectively (Bourman et al. 2018b). The much larger Younghusband Peninsula encloses the North and South Lagoons of the Coorong, the landward side of which corresponds to the last interglacial shoreline (~130 ka), during which time the regional sea-level is estimated to have been approximately 2 m higher than today (Bourman et al. 2018b).

The current salinity regime, incorporating temporal and spatial variation in salinity in the CLLMM is principally a function of the inputs of seawater through the mouth and freshwater inputs from the river, with internal hydrodynamics driven by wind and evaporation also acting to influence spatial and temporal patterns, especially in the Coorong (Bourman et al. 2018). Over the course of the Holocene (the last 11.7 ka) the balance of marine versus freshwater inputs is likely to have shifted at a range of scales. In the case of marine influence, this is likely to have varied according to the development of the barrier and relative sea level (Bourman et al. 2018b). In the case of freshwater inputs, these would have varied based on regional scale hydroclimatic variation (Fluin et al. 2007).

## 2.2 Drivers of salinity regimes during the Holocene

- Salinity conditions within the CLLMM are likely to have fluctuated during the Holocene due to changes affecting the relative influence of marine (relative sea level, barrier development) and fluvial (regional hydroclimate) inputs.
- In combination, these changes are likely to have driven a decline in marine influence over the last 8 ka, especially the last 1–2 ka, when the sea level reached its current position.

### 2.2.1 Barrier development

The barrier isolating the Coorong from the Southern Ocean formed after the marine transgression brought sea levels to their approximate position at around 8-7 ka. It is likely that the Barrier formed through the development of connections between a series of barrier islands rather than progressive lengthening of a spit by longshore drift (Bourman et al. 2018b). This process, along with the availability of abundant material entrained from the continental shelf during the marine transgression means that the isolation was probably fairly rapid. Establishing when the barrier became effective in isolating the Coorong as a lagoonal environment, however, is difficult, partly because of landward retreat of the barrier in the north (Sir Richard Peninsula) meaning that the oldest barrier sediment has been eroded (Bourman et al. 2018). Dating of sediments within the Coorong that contain *foraminifera*, *ostracoda* and molluscs and *charophyte oogonia* suggest partial isolation by around 6.8 ka, with full isolation occurring by around 5.5 ka (Cann and Lower 2018).

### 2.2.2 Holocene sea level

The late Pleistocene-Holocene marine transgression brought global sea levels to their approximate contemporary level by around 8-7 ka (Lewis et al. 2013). Coastal margins worldwide were subsequently subject to a complex array of isostatic adjustments, which resulted in relative sea levels in Australia around 7-6 ka being generally 0.5 to 3 m higher than today. As a result, this period is often referred to as the mid-Holocene sea level highstand. During the late-Holocene, relative sea-levels fell as post-glacial, hydro-isostatic adjustments of continental margins resulted in uplift of coastal areas and thus falls in relative sea levels. The heights of the mid-Holocene highstand and the timing of the falls to current levels vary globally and around the Australian coast based on variations in the directions, rates and magnitudes of post-glacial hydro-isostatic adjustments influenced by variables such as crustal thickness, composition and distance to the continental shelf (Lambeck 1993).

In the South Australia region, the best Holocene sea level records are from Spencer Gulf. These include a range of sedimentary indicators of sea level such as sedimentary remains of sea grass, sand flats, mangroves and chenier ridges (Belperio et al. 2013). These indicators show a distinct pattern of higher maximum mid-Holocene relative sea levels at greater distances from the continental shelf. In the region of Port Pirie, sea level appears to have been 2-3 m higher than present until around 1.5 ka ago (Belperio et al. 2013). Further south, around Port Lincoln, sea level averaged around 0.5 to 1 m higher during the mid-Holocene. This pattern reflects variation linked to distance from the margin of the continental shelf, whereby higher relative sea levels were experienced further from the shelf margin associated with hydro-isostatic adjustments. Indirect evidence of higher Holocene sea level also exists within the CLLMM itself in the form of higher levels in the Lower Lakes. This evidence includes lacustrine (lake) sediments extending to higher elevations on the periphery of the Lakes (Bourman et al. 2018a) and the presence of a valley-wide layer of laminated clays and muds that was deposited within the gorge section of the Murray channel between Wellington and Walker Flat during the mid-Holocene. This indicates an extensive central basin environment, effectively generating lacustrine conditions, which extended many kilometres upstream during the mid-Holocene sea level highstand (Helfensdorfer et al. 2019, 2020). These higher lake levels are interpreted to have arisen as a result of the combined effects of higher freshwater inputs from the river (see Section 2.2.3) and the damming effect of approximately 2 m higher relative sea level at this time (Bourman et al. 2018b, Hubble et al. 2020).

Sea level higher by up to 2 m would have potentially driven greater marine input through the Murray Mouth at times of low freshwater discharge, particularly during the early part of the highstand when the barrier system may not have been as complete as it is today (Cann and Lower 2018).

### 2.2.3 Regional hydroclimate

The Holocene climate was relatively stable compared to the dramatic changes that marked the Pleistocene-Holocene transition (Petherick et al. 2013). Nevertheless, significant fluctuations in climate did occur during the Holocene. The general pattern for Australia, and south-east Australia in particular, is that the climate was generally warmer and wetter during the early to mid-Holocene (12-6 ka) (Petherick et al. 2013). During this period, lake levels in closed catchment volcanic crater lakes in western Victoria were somewhat higher, suggesting greater effective moisture availability (Jones et al. 1998, Wilkins et al. 2013). Similarly, sediment cores taken from the ocean floor approximately 200 km south-west of the Murray Mouth suggest that discharge to the ocean was greatest between around 9.5-7.5 ka, based on the amount of fluvially-derived sediment in those records (Gingele et al. 2007). These findings are supported by the interpretation of fluvial sedimentation patterns in southeastern Australia by Cohen and Nanson (2007), which proposes that the period from 10 to 4.5 ka was one of enhanced water discharge, stable well-vegetated catchments and low sediment yields. Within the CLLMM system itself, as noted above, the higher lake levels between 7 and 5.4 ka provide further evidence of greater freshwater input at this time (Bourman et al. 2018b).

After around 6 ka, a general drying appears to have occurred in southeastern Australia. In the Victorian Western District lakes, this resulted in falling lake levels between 7 and 4.5 ka and the subsequent onset of a series of centennial-scale fluctuations in lake level of greater than 10m, the most recent of which was a drying phase that commenced around the time of European settlement of the region about 150 years ago (Tibby et al. 2018).

### 2.2.4 Summary of expected temporal patterns in salinity regime during the Holocene

Changes to barrier porosity, relative sea level and regional hydroclimate during the Holocene affect the balance of fluvial and marine influence in the CLLMM system. The history of change in these controlling factors can therefore be used to establish hypotheses regarding the salinity conditions within the CLLMM over the course of the Holocene, including the period immediately before substantial anthropogenic alteration of the system that began with irrigation diversions in the late 1800s (Mallen-Cooper and Zampatti 2018). Given the higher sea levels (Belperio et al. 2002, Lewis et al. 2013, Helfensdorfer et al. 2020) and presumed less complete barrier during the mid-Holocene (Bourman et al. 2018b), the CLLMM would have experienced more substantial marine incursions then. This pattern may have been counteracted somewhat by greater fluvial inputs during the mid-Holocene. However, as the fluvial inputs are subject to substantial inter-annual variation and event-based floods, there would have been the potential for more substantial sporadic marine incursions during low flow periods facilitated by higher sea level and a more open barrier system. Thus, while mean salinity measured over years or decades within the system during the mid- and late-Holocene may have been comparable to that of the late-Holocene, individual marine incursion events during the mid-Holocene have the potential to have been more extensive because of higher relative sea level and a more porous barrier system.

Over the course of the Holocene, the continued development of the barrier system and the fall in relative sea level is likely to have reduced the potential for substantial marine incursions. Opposing this pattern, the general drying of the climate and associated low river inflow likely created more frequent incursion events (Wilkins et al. 2013, Tibby et al. 2018). Thus, during the late-Holocene, there may have been longer periods of low river inputs, but the capacity of the ocean to penetrate the CLLMM system is likely to have been limited by lower sea levels and the restricted mouth, thus creating a variable salinity regime.

## 2.3 Palaeohistory of salinity in the Lower Lakes and Coorong

- Numerous sediment records from the Lower Lakes and Coorong have been analysed over the past 25 years.
- These records focus on preserved diatom remains, but also include forams, ostracods, molluscs and preserved aquatic plant remains.
- The records show clear spatial patterns in relation to salinity, with highest salinity conditions in the South Lagoon of the Coorong, followed by the North Lagoon, the Goolwa Channel section of Lake Alexandrina, the mid-basins of Lake Alexandrina and Lake Albert, and finally the north end of Lake Alexandrina.
- In the Lower Lakes the temporal trend is one of declining salinity over the past 8 ka.
- The palaeoecological records suggest that in the past 1–2 ka, the Lower Lakes were largely fresh, with moderate tidal influence of seawater during periods of low river inflows.

### 2.3.1 Estimating salinity conditions from process understanding, modelling and empirical palaeoecological evidence

The expected trends in salinity conditions summarised in Section 2.2 are based on independent evidence of regional hydroclimate, sea-level and geomorphology and conceptual understanding of estuary processes rather than empirical evidence of salinity conditions within the CLLMM. As such, they and the hydrodynamic modelling discussed in Section 3.2 provide a useful background for testing interpretations of the Holocene salinity history of the CLLMM based on empirical evidence, and for identifying areas of conflicting evidence or greater uncertainty.

The empirical evidence of salinity conditions within the CLLMM comes from palaeoecological analysis of sediment records. The CLLMM has been subject to extensive palaeoecological study over many years, reflecting the general and scientific interest in the ecological history of the system (Barnett 1994, Dick, et al. 2011, Fluin et al. 2007, Fluin et al. 2009, Gell 2019, Herczeg et al. 2001). To some degree the number of studies undertaken reflects a lack of definitive, reliably dated and contiguous high temporal resolution records from the system and the sometimes ambiguous signals presented in different cores from different locations. As is common to most palaeoecological studies, this uncertainty has provided impetus to continue sampling in an effort to produce a more definitive record and interpretation.

At this point it should be acknowledged that the interpretation of the palaeoecological records from the Coorong, and more particularly the Lower Lakes, has been the subject of dispute in the literature, particularly in relation to the degree to which the water quality in the Lower Lakes during the Holocene prior to the construction of the Barrages can be described as having been fresh, brackish or saline (Fluin et al. 2009, Gell 2019). The specific arguments made in relation to this topic by Fluin et al. (2009), Gell (2019) and Tibby et al. (2020) are discussed in Section 2.5. In this section, the focus is on summarising the palaeoecological records themselves, focussing on the records from the Coorong and Lower Lakes presented by Fluin et al (2007), augmented by more recent additional records from those lakes described by Fluin et al (2009) (Lake Alexandrina), Gell and Haynes (2005) and Dick et al. (2011) (Coorong), and Haynes et al. (2018) (Lake Albert and Coorong).

## 2.3.2 Palaeoecological history of the Lower Lakes

Published palaeoecological records from the Lower Lakes include four sediment cores taken from Lake Alexandrina and two from Lake Albert. These cores were taken over several decades beginning in 1986 and ending with the collection of the two Lake Albert cores in 2009 (Figure 2.1). The records vary in temporal coverage, but most have maximum ages of over 7 ka, with the longest records extending to 8.3 and 8.2 ka coming from Lake Albert (Haynes et al. 2018). The shortest record from Lake Alexandrina is RS1, reported in Fluin et al. (2009). This core was taken from the Goolwa Channel section of the Lake near to but upstream of the Barrage and covers only the last 720 years.

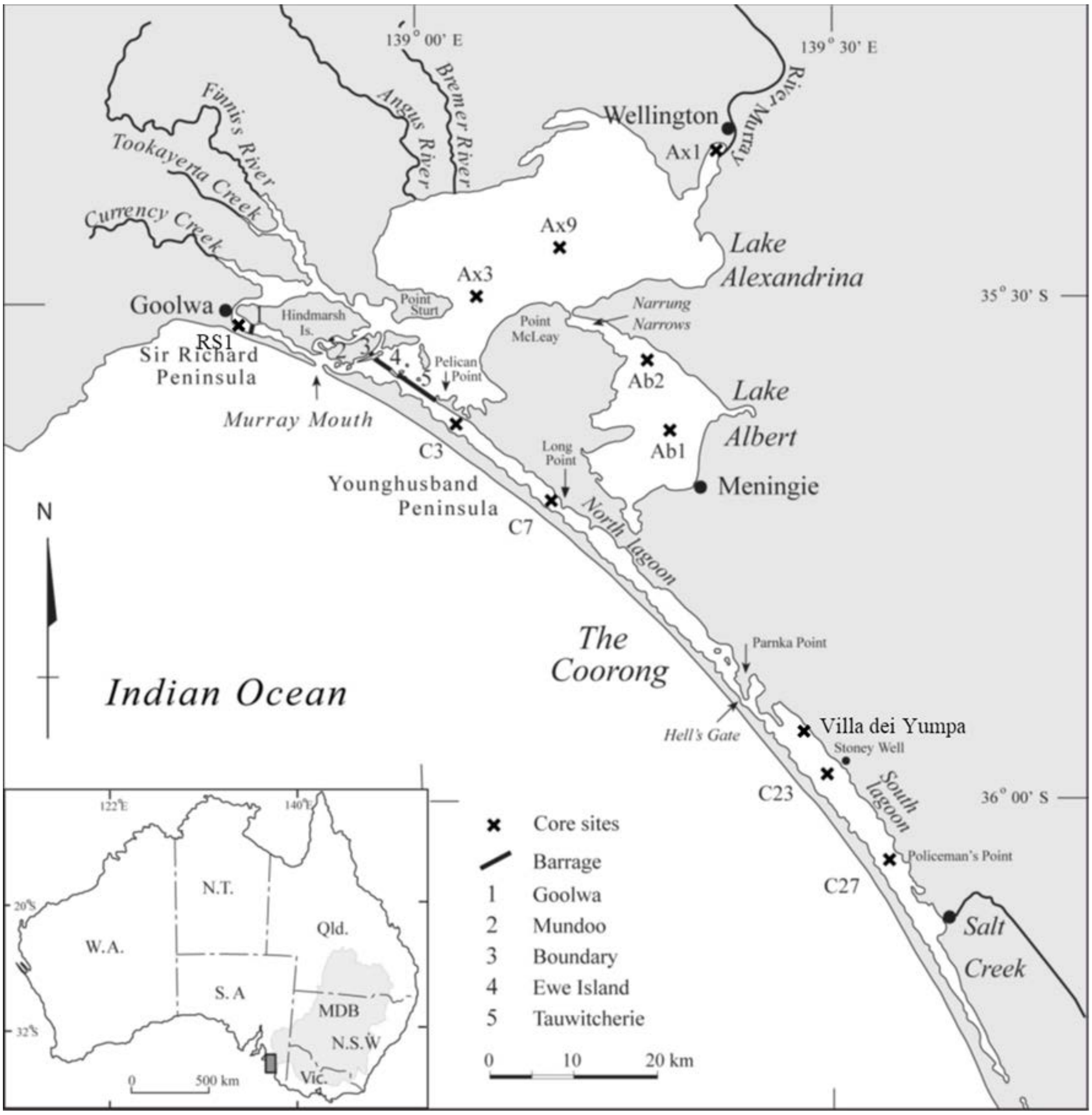


**Figure 2.1** Map showing the locations of cores in the Lower Lakes and Coorong referred to in the text (figure is taken from Haynes et al. 2018).

Importantly, although the basal ages of most of these cores extend to the early- to mid-Holocene, several records contain significant hiatuses. One Lake Alexandrina record (Ax9) is missing the period from around 6.8 ka until around 1930 AD and the two Lake Albert records are missing the periods from 4.2 ka to 1890 AD and from 2.1 ka until 1800 AD. Thus, critical periods of the late-Holocene record, including the immediate post-European settlement period and the period preceding barrage construction are missing from these records. The cause of these hiatuses is uncertain. One theory proposed by Job et al. (2020) is that the process of infilling ceased once sediment accumulation reduced the water depth to a threshold minimum, after which point wind-driven resuspension in the main basin was sufficient to prevent further accumulation until depth was increased again as a result of barrage construction. If this process is responsible, features such as depth, fetch and tidal currents at individual core locations should control whether or not continuous records exist. The apparently continuous records at Ax1 and Ax3 tend to support this theory, as these cores were taken from relatively deep water (3.5m in the case of Ax3) or from relatively sheltered locations (Ax3 and particularly Ax1). In contrast, the records with hiatuses were taken from a very central location subject to substantial fetch (Ax9) or shallow locations (Ab1 and Ab2). It should also be acknowledged that the dating on all cores incorporates some uncertainty, meaning that even the records that appear to provide a continuous record may, in fact, also have hiatuses.

Interpretation of the Lower Lakes records rely largely on preserved remains of diatoms to infer water quality conditions in the lakes. Diatoms are sensitive to both ionic concentration and composition and thus are effective indicators of salinity conditions (Gasse et al. 1995, 1997). Nevertheless, one of the key issues in interpreting the records from the Lower Lakes is the uncertainty regarding the salinity tolerances of some key taxa as well as established broad salinity tolerances in others (Fluin et al. 2007, Gell 2019).

The records from Lake Alexandrina are characterised by strong contrasts according to location within the Lake. Not surprisingly, the pattern is for species indicative of relatively high salinity (e.g. *Cocconeis peltoides*, Campylodiscus spp., *Paralia sulcata* and *Cyclotella striata*) to be more abundant closer to the Murray Mouth and for these species to be rare in the record collected from locations close to where the Murray River flows into the Lake (Fluin et al. 2007, 2009, Haynes et al. 2018). Thus, diatom assemblages in the core taken from the Goolwa Channel (RS1) contained an average of around 50% estuarine-marine diatoms (Fluin et al. 2009). In contrast, assemblages in cores taken from within the main basins of Lakes Alexandrina and Albert (two from each lake) were found to contain on average 20–25% estuarine-marine diatoms (Haynes et al. 2018). Finally, in the core taken from the northern end of Lake Alexandrina near where the Murray River enters the Lake, estuarine-marine diatoms are absent or less than 5% of the diatom assemblage except in one basal sample (Fluin et al. 2007, Haynes et al. 2018).

Temporal patterns are also evident, though clearly disrupted by the hiatuses in some cores. In most records this trend is for estuarine-marine diatoms to become less abundant over time. This trend is evident in two of the cores in Lake Alexandrina (Ax3 and Ax9 in Haynes et al. 2018, Figure 2.1) and the two Lake Albert cores, but best illustrated by the record from Ax3, which is the only record with complete temporal coverage (Haynes et al. 2018). In the Ax3 record, the three most abundant estuarine-marine taxa (*Cyclotella striata*, *Thalassiosira lacustris* and *Paralia sulcata*) are more abundant during the period from 7 ka to 2 ka than in the last 2 ka. At this point it should be noted that while *Thalassiosira lacustris* is often considered a brackish water indicator (Fluin et al 2007, Gell 2019) it is actually found in the lower reaches of the Murray River today around Morgan (Tibby and Reid 2004), and was estimated to have an optimum in relation to salinity of around 900 EC in the modern Murray River (Tibby and Reid 2004), so cannot be considered a particularly reliable indicator of significantly higher salinities. Of the remaining estuarine-marine taxa in Ax3, *Paralia sulcata* is absent from the record after 2.5 ka (Fluin et al. 2007), while *Cyclotella striata* is much less abundant after 2 ka. The one exception to this pattern is the appearance of *Cyclotella striata* at 8 cm, corresponding to approximately 1900 AD, at relatively high abundance. The abundance of *Cyclotella striata* subsequently falls to a level equivalent to the rest of the late-Holocene in the uppermost sample in this record (Fluin et al. 2007).

In contrast, no clear pattern is evident in the record from Core Ax1, situated near where the Murray River enters Lake Alexandrina, where estuarine-marine diatoms are rare throughout the record (Fluin et al. 2007, Haynes et al. 2018, Figure 2.1). The brief Core RS1 record only covers the last 700 years and shows a decline in marine-estuarine diatoms following the construction of the barrage in 1940 (Fluin et al. 2009). Clear barrage effects are difficult to discern in the remaining records from Lakes Alexandrina and Albert, given the relatively low temporal resolutions of these records. While the pattern is for the representation of estuarine-marine diatoms in the most recent sediments to be relatively low, this representation is not clearly lower than the sediments deposited in the last several hundred years.

In summary, the palaeoecological records from Lakes Alexandrina and Albert all show a pattern of declining abundance of estuarine-marine diatoms during the mid to late Holocene, suggesting salinity in the CLLMM was higher during the mid-Holocene when sea level was also higher, but that marine influence had declined, especially after 2,000 years ago. This contrasts with the pattern from Core RS1 closer to the Murray Mouth and hence marine influence, where estuarine-marine diatoms were relatively common even in the late-Holocene. This suggests that the main body of Lakes Alexandrina and Albert experienced, as noted by Fluin et al. (2007), "…relatively freshwater conditions… particularly after ca. 2,000 years b.p…" and that the lakes were "only moderately influenced by tidal inflow of seawater". This interpretation is also consistent with long-term hydrological modelling (see Section 3.3 and Section 5) that suggest that prior to upstream water extraction and barrage construction, salinity in the Lower Lakes remained below 1000 EC about 85% of the time. By contrast, the Goolwa Channel is likely to have been subject to substantially more marine influence, and thus more saline conditions, throughout the Holocene up until the construction of the barrages in 1940.

### 2.3.3 Palaeoecological history of the Coorong

Published palaeoecological records from the Coorong include two from the North Lagoon described in Fluin et al. (2007) and Haynes et al. (2018), one from the North Lagoon described by Reeves et al. (2015), two from the South Lagoon described in Haynes et al. (2018) and Reeves et al. (2015), and a further core from the South Lagoon described by Dick et al. (2011). There is also an unpublished report prepared for the South Australian Department of Land, Water and Biodiversity Conservation that reported on multiple records, including several listed above (Gell and Haynes 2005). The three North Lagoon cores provide the longest records, with basal ages ranging from around 4 ka to 7 ka (Gell and Haynes 2005, Reeves et al. 2015, Haynes et al. 2018). The South Lagoon records are shorter, ranging from around 3.7 ka for the Villa dei Yumpa core described by Dick et al. (2011) to just 0.85 ka and 0.55 ka for the two South Lagoon cores described by Haynes et al. (2018) and Reeves et al. (2015). Palaeoecological interpretations of the Fluin et al. (2007) and Haynes et al. (2018) are based on diatom records and mollusc remains, the Reeves et al. (2015) interpretation is based on diatoms, ostracods, forams and charophyte remains, while the Dick et al. (2011) interpretation is based on diatoms, forams, ostracods and macrophyte remains.

As is the case for the Lower Lakes, the records show an apparent spatial gradient in salinity conditions in the Coorong, though here the gradient is of increasing salinity away from the Murray Mouth. This gradient reflects the input of the brackish water created by the mixing of freshwater from Lake Alexandrina with seawater entering from the Mouth in the northern part of the North Lagoon. This brackish water is subsequently transported down through the North Lagoon into the South Lagoon when water level in the South Lagoon falls below that in the North Lagoon. The water in the lagoon can then become progressively more saline through evaporative concentration of salts contained in the original brackish source water. This concentration effect is mediated by freshwater inputs from Lake Alexandrina as well as some input of freshwater surface runoff from the south-east catchment via Salt Creek (Reeves et al. 2015).

In contrast to the records from the Lower Lakes, the six Coorong records show estuarine-marine conditions predominated throughout the pre-European settlement Holocene. In the North Lagoon, sediments deposited during the pre-European settlement period of the Holocene suggest a mostly open estuarine-marine environment, particularly during the mid-Holocene when higher sea level, a less developed barrier system and wetter regional climate would have facilitated greater exchange with the ocean (Reeves et al. 2015). Post European settlement, the system appears to have shifted to a more closed, lagoonal environment, with diatom and ostracod assemblages typical of lower energy environments subject to fluctuating salinities (Reeves et al. 2015). This shift likely reflects reduced freshwater inputs from the Murray River facilitating tidal ingress of seawater (Haynes et al. 2018).

Not surprisingly, given its distance from the mouth, the records from South Lagoon present a picture of a more closed lagoonal system, though the records mostly span the last 1,000 years. These records suggest that even prior to European settlement, much of the South Lagoon experienced hypersaline conditions, especially after around 500 years ago (Reeves et al. 2015). After European settlement, hypersaline indicator taxa among the ostracods increase, and forams indicative of lower salinities decrease. In the Villa dei Yumpa core from the north of the South Lagoon, the mesohaline macrophyte *Ruppia megacarpa* disappears, replaced by the more salinity tolerant *R. tuberosa* (Dick et al. 2011). These changes are thought to reflect the combined effects of reduced inputs of brackish water from the North Lagoon driven by reduced marine exchange and reduced Murray River inflows and reduced freshwater inputs from Salt Creek following the drainage of wetlands in the south-east and the redirection of surface water to the sea that had previously had entered the lake through the creek (Reeves et al. 2015).

## 2.4 Traditional knowledge and European anecdotal history of Lower Lakes salinity

- The traditional custodians of the CLLMM and the surrounding region, the Ngarrindjeri People, considered the Lower Lakes as a largely freshwater system, with occasional marine incursions during times of low freshwater inflows.
- Early explorer and settler accounts report the Lower Lakes as largely fresh.
- High salinity periods during the early European settlement were of sufficient intensity and duration to result in stock losses and abandonment of grazing leases.
- Reports of high salinity in the Lower Lakes increased around 1900, and both the Federation drought and upstream irrigation diversions were blamed for this.

### 2.4.1 Traditional knowledge and early accounts from European explorers and colonists

The traditional custodians of the CLLMM and the surrounding region, the Ngarrindjeri People, consider the Lower Lakes to have been a largely freshwater system (G Rigney, pers. comm.). This view is supported by teaching stories of ancestors catching freshwater fish (bony bream, *Nematalosa erebi* and silver perch, *Bidyanus bidyanus*) in large numbers in Lake Alexandrina (Ngarrindjeri Nation 2018, Sim and Muller 2004) and drinking the water from Lake Alexandrina. Importantly, the Ngarrindjeri do acknowledge that periods occurred when saltwater penetrated into the lake and even into the channel of the River Murray (Ngarrindjeri Nation 2018).

The understanding of the Ngarrindjeri is largely supported by the accounts of explorers and early settlers. The earliest European accounts of conditions in the Lakes were from sealers from the schooner Prince of Denmark. The captain of the Schooner, Captain Forbes wrote that in 1829 members of his crew had ‘discovered a very large lake of fresh water’ (Gill 1904-1906, cited in Sitters 2018). The explorer Charles Sturt reached and named Lake Alexandrina in 1830 and though he did not comment on its freshness, described the lake as “…a beautiful lake, which appeared to be a fitting reservoir for the noble stream that had led us to it.” (Sturt 1834, cited in Sitters 2018). Later explorers Strangways and Hutchison did report in 1837 ‘…water so pure that we filled our kegs’, while Robert Cock and his party reported in 1838 water ‘…being sweet and fresh.’ (Sim and Muller 2004).

Early settlers’ accounts also reported on the freshness of the lake. Charles Bonney overlanded cattle from the Glenelg river to the region and recorded that his cattle found and drank the freshwater of Lake Albert in 1839 (Sitters 2018) and that the water in Lake Alexandrina was ‘perfectly fresh’ (Sim and Muller 2004). A similar account is made by George Hamilton shortly after (Sitters 2018, Sim and Muller 2004).

Yet, there were accounts that attested to the variable nature of salinity conditions in the lakes. In 1840, Surveyor General Frome reported the water in Lake Albert as being good in parts, but in others slightly brackish (though still fit for use) (Sim and Muller 2004). Sturt describes that in 1830 (Sturt 1834, cited in Aldridge et al. 2018) the waters in the lake were fresh, but when they approached what is today Point Sturt near the Coorong, the water was “quite unpalatable” and further on he remarked that “the transition from fresh to salt water was almost immediate”. Later, he remarks that the water seven miles from the mouth of the river into Lake Alexandrina the water was brackish and 21 miles on (at Port Sturt) it was salty. This might be interpreted as a freshwater plume from the river inflow meeting the seawater at Point Sturt having some mixing zones at the inflow region.

Further reports (Sim and Muller 2004) hint at the inter-annual variability of fresh versus brackish or salty water in Lakes Alexandrina and Albert in the 19th century. Surveyor General Freeling and Collector of Customs Torrens noted that the water in Lake Alexandrina near the Goolwa Channel was occasionally brackish (Sim and Muller 2004). These periods of brackish water in the vicinity of the Goolwa channel were of sufficient intensity and duration in the 1850s to result in significant loss of cattle (Sitter 2018). This can be attributed to variable freshwater inflows into the Lakes as well as variability in the exchange of flows between the two lakes leading to increased salinity in Lake Albert at times.

### 2.4.2 Impacts of water resource development

Concern about the potential impact of upstream water diversions on the salinity of the Lower Lakes were voiced in the late 1880s, when the prospect of water extractions in New South Wales and Victoria led to predictions in the South Australian Parliament that such extractions would result in the lakes becoming salty. Reports of increasing salinity grew through the 1890s and the problem was exacerbated by the onset of the Federation Drought (Sim and Muller 2004). By 1902, the lake water was considered not fit for stock and fishermen were reporting catches of estuarine mullet in place of freshwater cod (Sim and Muller 2004).

The coincidence of the Federation Drought with a period of increasing upstream diversion make it difficult to disentangle their respective effects on the salinity environment in the lakes. At first thought, the amount extracted in 1901 (~600 GL/yr, Mallen-Cooper and Zampatti 2018) would seem insufficient to have a significant impact on a system with a mean annual outflow more than 10,000 GL/yr. However, as noted by Mallen-Cooper and Zampatti (2018), the irrigation diversions were concentrated during low flow periods, thus magnifying their potential to impact the water balance in the Lower Lakes.

## 2.5 The Holocene salinity debate

- A recent opinion paper by Gell (2019) argues that a seminal study on the Holocene palaeoecology of the CLLMM (Fluin et al. 2007) has been misrepresented in a subsequent report (Fluin et al. 2009) and the broader literature to present the Lower Lakes as 'predominantly fresh' before European settlement.
- Our assessment is that Fluin et al. (2009) did not misrepresent conclusions of the original paper, but downplayed marine influence in its interpretations.
- Fluin et al. (2009) could have also described spatial and temporal patterns in salinity indicators within the Lower Lakes more explicitly to present a clearer picture of the salinity history in the system.
- As discussed in Sections 2.3 and 2.4, the weight of evidence points towards the Lower Lakes being largely fresh prior to European settlement, with moderate tidal influence and incursion of seawater during periods of low river inflows.

### 2.5.1 Background

In 2019, Gell published a perspective paper in Pacific Conservation Biology that presented a series of arguments regarding the interpretation of palaeoecological records and historical and anecdotal accounts of the Lower Lakes with particular reference to the pre-barrage salinity conditions. Gell (2019) proposed that a report on the palaeoecology of the Coorong and Lower Lakes (Fluin et al. 2009) had, in arguing that the Lower Lakes were predominantly fresh during the Holocene, misrepresented the conclusions of an earlier published paper by Fluin et al. (2007) and a thesis by Fluin (2002). According to Gell (2019), these earlier works had concluded that the Lower Lakes were tidal and not predominantly fresh. Gell (2019) further argued that several other subsequent published studies, including a report on Indigenous knowledge and anecdotal history of the lakes by Sim and Muller (2004), had also misrepresented the Fluin (2002) conclusions in arguing that the lakes were predominantly fresh prior to water diversions and barrage construction. Gell (2019) was also critical of the Sim and Muller (2004) for, in Gell's view, not reporting on the findings of the Interstate Royal Commission on the River Murray by Davis et al. (1902) that were contrary to the view of a predominantly freshwater Holocene history for the Lower Lakes. Finally, Gell (2019) argued that flawed interpretations of Fluin et al. (2009) and Sim and Muller (2004) form the basis of the environmental watering strategy for the Lower Lakes under the Murray-Darling Basin Plan and thus undermine the science that is the basis of the Plan. Recently a response to Gell (2019) has been accepted for publication in Pacific Conservation Biology (Tibby et al. 2020) that challenges each of these arguments in support of Fluin et al. (2009) and Sim and Muller (2004) and further argues that the environmental watering strategy for the Coorong and Lower Lakes is not based on the findings of those reports.

### 2.5.2 The interpretations of Fluin et al. (2007) and Fluin et al. (2009)

Gell's (2019) arguments rest heavily on the contention that the Fluin et al. (2009) conclusion that Lake Alexandrina was predominantly fresh significantly misrepresents the conclusion of Fluin et al (2007). Our judgement is that this is not the case based on the following passages from Fluin et al. (2007): "*The Holocene diatom assemblages of Lake Alexandrina reflect relatively freshwater conditions with longstanding and major inputs from the River Murray, particularly after ca. 2,000 years b.p. at site LA2*"; and "*marine water indicators were never dominant in Lake Alexandrina*". While Fluin et al. (2007) do not use the phrase '*predominantly fresh*', the above statements clearly suggest that the Lake was more fresh than saline and do not contrast strongly with assertions that the lake was predominantly fresh, especially during the late-Holocene.

Nevertheless, there was intent in Fluin et al. (2009) to emphasise the largely freshwater condition in the lake over and above what was done in the Fluin et al. (2007) paper. This is illustrated by the different wording used in almost identical descriptions of the patterns of change in the diatom records in Fluin et al. (2007) and Fluin et al. (2009) that were highlighted by Gell (2019). While Fluin et al. (2007) refers to diatom assemblages indicating '*marine influence*', the later report refers to the same assemblages indicating '*minor marine influence*'. Similarly, while Fluin et al. (2007) suggest the diatom assemblages suggest '*increased penetration of seawater*', Fluin et al. (2009) suggest '*increased penetration of more brackish water*'.

The statements in the executive summary of Fluin et al. (2009) that "*there is no evidence in the 7000 year record of substantial marine incursions into Lake Alexandrina*" and conclusion of the report that "*the majority of the Lake has been fresh for its entire history*" also do not fully acknowledge the degree of spatial and temporal variation in the Lower Lakes records. For example, there are clear contrasts between the Goolwa Channel core indicative of higher salinity, the core from the north of Lake Alexandrina showing very low salinity, and the mid-basin cores indicative of intermediate salinity. Thus, marine or brackish incursions were sufficient throughout the Holocene at the mid-basin sites to create surface sediment assemblages that were distinct from those which developed in the north of the lake. Conversely, saline incursions were also not sufficient in the Holocene to create surface sediment assemblages in the mid basin that match those in the Goolwa Channel. Similarly, there are clear trends over time in most of the records. These trends for declining marine influence over the course of the Holocene, especially after around 2,000 years ago, were highlighted by Fluin et al. (2007) and were also emphasised in the more recent study of Haynes et al. (2018) that included the cores from Lake Albert. Downplaying this temporal trend, as Fluin et al. (2009) do in their conclusion, only serves to weaken the argument that the pre-European settlement Lower Lakes were 'predominantly fresh' because it considers the system stable with abundances of estuarine-marine indicator taxa of 30-50+% (as observed in the mid-Holocene in the mid-basin records, and equally likely in the late-Holocene), when in fact these estuarine-marine taxa are not found in the last 2,000 years in abundances greater than 20%.

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# 3. HYDROLOGY AND HYDRODYNAMICS OF THE LOWER LAKES, COORONG AND MURRAY MOUTH

## 3.1 Lower Lakes

- The knowledge about the Lower Lakes hydrology and hydrodynamics come from long-term measurements and extensive modelling of the Murray River system including the Lower Lakes (particularly the MDBA BIGMOD river system hydrological model). This knowledge informed the development of the Basin Plan and the water management of the Lower Lakes.
- The main water balance components of the Lower Lakes are freshwater inflow from the Murray River, net evaporative loss and outflow over the barrages. The Lower Lakes are managed to maintain lake level between 0.4 and 0.85 m AHD. Lake Alexandrina is predominantly fresh (median salinity of 742 EC), whereas the terminal Lake Albert has a higher salinity (median salinity of 1,734 EC).

### 3.1.1 Hydrology and lake water balance

The CLLMM under current conditions can be considered as two systems separated by the barrages: the Lower Lakes (Alexandrina and Albert); and the Coorong and Murray Mouth. The two systems behave differently with respect to their main driving forces.

Lake Alexandrina receives inflow mainly from the Murray River and to much a lesser extent through the Eastern Mount Lofty Ranges and groundwater. Lake Alexandrina and Lake Albert are connected via a narrow and shallow channel (Narrung Narrows) allowing for restricted water exchange. Depending on the Lake water level and barrage opening, water flows from the Lower Lakes into the North Lagoon of the Coorong and the Goolwa channel, but (largely) not in the reverse direction.

Prior to European settlement, the average annual Murray River inflow into the Lower Lakes was greater than 13,000 GL (MDBA (2012) and CSIRO (2008) modelling), with significant inter-annual and inter-decadal variation. The modelling (using 114 years of data from July 1895 to June 2009) estimates that, with current development and upstream water extraction, the long-term average annual inflow is 5,966 GL under pre-Basin Plan and 7,443 GL under the Basin Plan. The modelled long-term average annual flow over the barrages (also called "end of system flow") is 5,142 GL under pre-Basin Plan and 6,624 GL under the Basin Plan (MDBA 2012). These flows can vary significantly from year to year depending on rainfall and runoff in the southern Murray-Darling Basin and water management practice. The Eastern Mount Lofty Ranges contributes on average 85 GL/yr to the Lower Lakes (Gibbs et al. 2018), which is a very small volume compared to the Murray River inflow. Groundwater inflow is low but because of its very high salinity contributes significant salt loads into the Lower Lakes (see Section 3.1.3).

The flow over the barrages is not measured, but can be estimated from water balance, head differences across the barrages and barrage lock openings. The flow over the barrages is smaller than the freshwater inflow into Lake Alexandrina due to evaporation losses of lake water. The average net loss (evaporation minus rainfall) of the Lower Lakes is about 800 GL/yr (Heneker 2010). The flow over the barrages can cease under drought conditions when barrages are closed to maintain lake water level to avoid exposure of acid sulfate soils.

### 3.1.2 Water levels

The water level in Lake Alexandrina varies depending on inflow from the Murray River, lake evaporation and barrage operation (flow over the barrages). During long periods with very little inflow, the lake level can fall below sea level, for example it fell below -1 m AHD towards the end of the Millennium drought. The water level in Lake Albert shows a similar pattern, but with slightly lower level than Lake Alexandrina from November to March which can be partly attributed to the general wind pattern over these periods. The Lower Lakes are currently managed to maintain the water level between 0.4 and 0.85 m AHD. The lake water level has been continuously monitored on Lake Alexandrina at Milang since 1975 and on Lake Albert at Meningie since 2004.

The changes in water level associated with inflow, evaporation and wind induced seiching drive the exchange of flows across the Narrung Narrows between Lake Alexandrina and Lake Albert. Wind stress on the surface water leads to set-up of water in the downwind direction (Noye and Walsh 1976), causing surface seiches in the order of tens of centimetres height. The resulting flow exchange leads to a net transport of salt from Lake Albert to Alexandrina, and without this exchange, salt would accumulate in Lake Albert by evaporating water.

The very low water level towards the end of the Millennium drought (below -1 m AHD) exposed large areas of the lake bed to air, which led to pyrite oxidation and an increase in sediment acidity after rewetting. Consequently, pH levels at some locations were reduced to 2-3 (Mosley et al. 2014). The cost of management interventions for acidification events were estimated at $50m (Mosley et al. 2014). The maximum exposed sediment area for Lake Alexandrina and Lake Albert under the low water levels of April 2009 were 161 $km^2$ and 48 $km^2$, respectively with acidified areas of 20.23 $km^2$ and 1.5 $km^2$ (Mosley et al. 2014). The worst potential acid sulfate soil sites are in the marginal wetlands along the edges of the lakes which could be impacted even by small reductions in water level (DENR 2010). The dependence of acidity production on water levels was described by a modelling study (Hipsey et al. 2014) to identify critical water levels.

### 3.1.3 Salinity

Salt transport into the Lower Lakes is mainly via inflow from the Murray River and groundwater inflow. The salt inflow from the Murray River is in the order of 1 million tonnes per year, with significant interannual variability. Saline groundwater inflow (and the inflow from Eastern Mount Lofty Ranges tributaries) contributes a significant amount of about 200,000 tonnes of salt per year (Heneker 2010). Evapoconcentration is another influence on salinity, particularly over long periods of low inflows. Nevertheless, the evapoconcentration effect is usually offset through freshwater inflow resulting in salt transport over the barrages.

The median observed salinity level in Lake Alexandrina, recorded continuously since 1975 is 742 EC (with interquartile range of 558 to 1,154 EC). The median observed salinity level in the terminal Lake Albert is higher at 1,734 EC (with interquartile range 1,385 to 2,507 EC) (Gibbs et al. 2018). When water level in Lake Alexandrina is low, seawater intrusion/seepage occurs leading to increased salinity near the barrages (Aldridge et al. 2009). During storm surges, high water levels in the Coorong can also cause seawater to flow over the barrier islands and spill into Lake Alexandrina. In low flow years, salt would concentrate in the lakes and salinity increases. At the end of the Millennium drought, the salinity level exceeded 8,000 EC in Lake Alexandrina and 20,000 EC in Lake Albert. It took more than six years after the drought for sufficient water exchange between the two lakes to return the salinity level in Lake Albert to pre-drought condition.

Lake Alexandrina is generally well mixed vertically, but salt stratification can occur during saltwater intrusion, with fresh water floating on top of more brackish water (Aldridge et al. 2011). Strong winds across the lakes and night-time cooling generating convective mixing would usually break down such stratification.

### 3.1.4 River flow and salinity modelling with BIGMOD

The BIGMOD is a river system hydrological model, developed and enhanced by the MDBA over the last 40 years (MDBC 2002, MDBA 2012). The model simulates daily flow and salinity from the headwaters of the Murray River and Lower Darling (with tributary inflow inputs from states river system models) down to the barrages. The model has been calibrated to reproduce the observed streamflow at many locations. The BIGMOD is the key model used by MDBA for operational management and to simulate flow and salinity outcomes under different scenarios to inform planning including the development of the Basin Plan.

The BIGMOD model conceptually represents the barrages as a weir with Lake Alexandrina behind it. This representation assists with the modelling of salinity movement through the lake at a different rate compared to the flow. Lake Albert is modelled as a fully mixed lake adjacent to Lake Alexandrina, with exchange of water and salt between the two lakes to maintain the same water level in the two lakes. The BIGMOD model has been calibrated satisfactorily to reproduce the observed water level and average salinity in the Lower Lakes. The much faster computer run time for this simple representation (compared to complex hydrodynamic models) in BIGMOD lends itself to simulating long time series of Lake water and salinity levels, and flow and salt export over the barrages.

For simulation of pre-development condition with no barrages, BIGMOD simulates the flow exchange between the lake and the sea based on the flow required to maintain Lake Alexandrina at the same level as the sea. The model assumes instantaneous mixing of freshwater and seawater. More detailed and robust modelling, like the spatial and depth distribution of salinity through the Lower Lakes and the hydrodynamics of the Coorong, would require two-dimensional or three-dimensional hydrodynamic models (see Section 3.2.4).

## 3.2 The Coorong and Murray Mouth

- The hydrodynamic behaviour of the Coorong is governed by the flow over the barrages, tidal connection with the sea via the Murray Mouth channel, restriction between the North and South Lagoons, and wind and water set-up. The narrow and shallow channel between the North and South Lagoons restricts exchange flows, and evapoconcentration leads to hypersaline conditions in the South Lagoon.
- The salinity regime of the Coorong has been measured and understood through various measurements since 1963, by regular monitoring from 1998 onwards, and from hydrodynamic modelling.
- The salinity in the Coorong is comparable to seawater near the Murray Mouth, becomes fresher in the main body of the North Lagoon where the barrage flow comes in, and then gets gradually saltier towards the South Lagoon.
- The CHM and TUFLOW hydrodynamic models have been used to investigate salinity and flow outcomes in the Coorong under different flow, barrage operation, environmental watering and system configuration scenarios.

### 3.2.1 Geomorphology and hydrodynamics

The Coorong is a shallow lagoon that runs shore-parallel for approximately 110 km along the coast and is separated from the ocean by Holocene sand dunes and from Lake Alexandrina on its landward side by the line of five barrages constructed between the barrier islands. The key elements of the Coorong from a hydrodynamic perspective are the narrow Mouth channel connecting the main body of the Coorong to the sea, the North and South Lagoons, and the constricted channel at Parnka Point connecting the two lagoons. The average widths of the North and South Lagoons are 1.5 km and 2.5 km respectively, and the average water depths are 1.2 m and 1.4 m respectively.

The barrage flows empty into the Goolwa Channel (which is the old 7-km long main channel of the Murray) and the northern part of the North Lagoon. The flow through the barrages is determined by the flow from the Murray River into Lake Alexandrina and by the operation of the barrages (see Section 3.1). The South Lagoon also receives freshwater from the Upper South East Drainage (USED) scheme, but this flow is relatively small compared to the average flow through the barrages. With the South East Flow Restoration project, about 6 to 47 GL/yr of freshwater flowed into the South Lagoon near Salt Creek at its southern end in 2013–2016, and Mosley et al. (2017) suggest that the increased releases from the Morella Basin improved the South Coorong water quality by reducing nutrient levels. However, it is difficult to disentangle this benefit of increased flows from the effect of flow exchange through Parnka Point between the North and South Lagoons.

The Mouth connection to the sea allows both freshwater flow from the barrages to escape to the sea and mixing of seawater into the North Lagoon. The barrage flow serves to deepen the Mouth channel, with a greater scouring rate achieved with larger flows (Webster 2011). However, when the barrage flow subsides, the tidal currents through the Mouth together with sand resuspension by waves transport sand into the Mouth where it is deposited as a flood-tide delta (a delta landward of the Mouth) (Harvey 1996). This sand accumulation gradually causes the channel connecting the sea to the Goolwa Channel and North Coorong to block over time. The tendency of the entrances of similar lagoon systems to close has been observed in many seasonally open lagoons in Australia. The construction of the barrages and the reduction of flows from the Murray River have exacerbated this tendency over the last century (Harvey 1996). The Murray Mouth channel has always been relatively narrow, and also highly dynamic in terms of its position, depth, and width (Bourman et al. 2000). The Mouth has varied from being several hundred metres wide during flood flows (Walker 2003), to being nearly closed before barrage construction in 1940 (Bourman et al. 2018) and to being closed completely in 1981 during a protracted drought. In 2002, during the Millennium drought, dredging was needed to keep the Mouth channel open and continued until there were high flows in 2010. The dredges recommenced operating in 2015, with a short break during high flows in 2016/2017 (Thom et al. 2019). The dredging operations deposit sand into the beach zones where it can be transported back into the Mouth channel (Thom et al. 2019).

### 3.2.2 Water levels

Water levels in the Coorong are an important determinant of the habitats of flora and fauna along its shores and are indicators and drivers of the hydrodynamics that govern the distribution of salinity throughout the system. Water levels have been measured continuously since 1998 at several locations in the North and South Lagoons. Sea level measurements are available at Victor Harbor on Encounter Bay, 23 km from the Murray Mouth. The sea level varies seasonally over a range of about 0.2 m and peaks in winter (Webster 2010). The water level in the North Lagoon is generally highest in winter in response to the higher barrage flow and higher sea level, and typically lowest approaching 0 m AHD at the beginning of summer when barrage flow is low and sea level is near its lowest.

Superimposed on the seasonal water level cycle are the tidal variation and variations associated with short term wind events and longer period passage of weather systems. The tides along the coast of Encounter Bay are semi-diurnal (12-hour period) with a height range varying between ~1 m during spring tides to ~0.2 m during neap tides (Short and Hesp 1975). Wind events with periods of 1 to 30 days cause sea level variation off the Mouth, penetrate into the Coorong and also push water back and forth along it. How much of the sea level fluctuation penetrates into the body of the Coorong depends on the degree of Mouth openness and the frequency of the sea level fluctuation. Weather band fluctuations associated with the passage of fronts across southern Australia (recurring at intervals of 4–30 days) penetrate effectively, but high frequency tidal fluctuation (period of 12 hours) can be severely attenuated if the Mouth is partially closed. Harvey (1996) showed how the tidal fluctuation downstream of Tauwitchere gradually diminished following the cessation of barrage flows in 1980–1981 and in 1994–1995 due to the infilling of the Mouth channel. Tidal flows are important for mixing seawater and freshwater in and out of the Coorong and along its channel so partial or complete Mouth closure has significant consequences for the salinity dynamics. An open Mouth channel is also required for biological connectivity for species such as the mulloway which use the Coorong to breed.

The seasonal variation of water level commonly results in the separation of the North and South Lagoons in the summer months. For example, during the summers of 1992 and 1995, when the level in the North Lagoon reduced to about 0 m AHD, water level in the South Lagoon continued to decline to about -0.3 m AHD. During these summers, water level declined sufficiently to cause the disconnection between the two lagoons resulting in the South Lagoon level to fall further due to evaporation. The summertime depression of water levels in the South Lagoon occurs in most summers unless there are high summer barrage flows such as in the summer of 2016/17.

### 3.2.3 Salinity

The salinity regime of the Coorong has been measured and understood through various measurements since 1963, by regular monitoring from 1998 onwards, and from hydrodynamic modelling (Webster 2010, Joehnk and Webster 2014). The salinity in the Coorong is comparable to seawater near the Murray Mouth, becomes fresher in the main body of the North Lagoon where the barrage flow comes in, and then gets gradually saltier towards the South Lagoon. The salinity in the Coorong can vary considerably from year to year depending on the magnitude of the barrage flow, and also seasonally driven by the barrage flow and by net evaporation (evaporation minus rainfall).

The North Lagoon and the Goolwa Channel exhibit variations in salinity due to tidal exchange and fluctuations in freshwater input. Salinity in the North Lagoon varies between 20–80 g/L, and reached 100 g/L during the Millennium drought (Joehnk and Webster 2014). The salinity in the South Lagoon exhibits a clear seasonal cycle, with highest salinity in late March following high evaporation and reduced connection with the North Lagoon in summer. Salinity in the South Lagoon varies between 20–120 g/L, with salinity above 200 g/L recorded during the Millennium drought (Joehnk and Webster 2014).

The Coorong is relatively unusual in that the major freshwater input occurs through the barrages much closer to the estuary mouth than to its head (Webster 2010). Thus, the barrage flow only 'flushes' the Coorong between the barrages and the sea. However, large barrage flow releases can reduce salinities in the main body of the North Coorong as was observed in 2015 (Mosley 2016). Over most of its length, salt accumulating through evapoconcentration mixes back out of the system by fluctuating water motions caused by sea level variations propagating through the Mouth channel and by wind.

By scouring the Mouth channel on a seasonal basis, barrage flow facilitates the penetration of sea level variation into the Coorong leading to enhanced along-lagoon mixing. Further, barrage flow freshens the waters near the seaward end of the system at a time when this water is being pushed along the system towards its distal southern end by the rising water levels caused by elevated sea level and the barrage flow causing salinity to fall there.

### 3.2.4 Hydrodynamic modelling of the Coorong

Hydrodynamics in the elongated Coorong system is more complex than a river channel, being coupled to the Murray Mouth, having the North and South Lagoon connected via constricted channels and being subject to wind set-up driving water exchange. Nevertheless, its main dynamics can be still captured in a one-dimensional model. However, when dealing with coupling to the sea and thus morphodynamics of the Murray Mouth or coupling to the Lower Lakes under a no-barrage scenario, then two-dimensional or even three-dimensional hydrodynamic models are more suitable.

The main limitation of two-dimensional and three-dimensional hydrodynamic models is the long computer run time required to run multi-year and multi-decadal simulations, thereby limiting model calibration and validation activities, as well as scenario runs to very short simulation periods (although the use of high computing can help overcome some of these limitation). Because they simulate the complex multi-dimensional processes, hydrodynamic models have the potential to more reliably predict outcomes from changes in flow regime, sea level rise, and management and infrastructure interventions. A modelling strategy might include targeted studies applying the hydrodynamic model over longer salient time periods, further calibration and validation and model adaptation to improve key process representation. The more complex hydrodynamic models could also be combined with simpler one-dimensional model representations to provide insight into system responses over long time periods.

Several models have been used to inform the Coorong, Lower Lakes and Murray Mouth hydrodynamics and to investigate management strategies for water quality improvement in the last 15 years.

*Coorong Hydrodynamic Model (CHM)*

To simulate the water level and salinity response of the Coorong to its driving variables of barrage flow, inflow from the USED scheme, sea level, wind stress, evaporation and rainfall, a one-dimensional along-channel dynamic simulation model solving mass (water level), momentum (flow) and salt balance (salinity) was developed by Webster (2007). This model was calibrated against long-term datasets of barrage flow, sea level, and water level and salinity records in the Coorong. Flow over the barrages simulated by BIGMOD (see Section 3.1) is an input into this Coorong model. The Coorong Hydrodynamic Model (CHM) was developed from its parent model (Webster 2007), enhanced with further calibration and validation (Webster et al. 2009, Webster 2010, Webster 2012a, b) and transformed into an operational model system (Joehnk and Webster 2014) which is now used by the South Australia Department of Environment and Water (SADEW) and MDBA for long-term scenario simulations of the Coorong (e.g., Gibbs et al. 2018).

Model validation with datasets extending back to 1963 show that the model captures both qualitatively and quantitatively the major features of the water level and salinity regimes in the Coorong under different flow conditions, including drought periods (Webster 2012). The CHM has been run for hundreds of scenarios, often 100 years long, to investigate management strategies for the amelioration of the Coorong including Mouth dredging, environmental watering, manipulation of barrage flow timing, lagoon pumping, channel modification, and USED scheme development.

*TUFLOW*

The two-dimensional TUFLOW hydrodynamic model for the CLLMM was developed and calibrated by WBM Oceanics (2012). The TUFLOW modelling was improved over time, with further calibration against more data that cover periods of low and high Murray River inflows. The model was subsequently coupled to a sediment transport model (TUFLOW-MORPH, WBM Oceanics 2012) and a wave climate model (SWAN, Booji et al. 1999). The combined TUFLOW-MORPH-SWAN simulates sediment transport around the Mouth and can therefore be used to predict the degree of Mouth opening under different scenarios like barrage removal and higher sea level. However, model uncertainty would increase over longer simulation period (months to years) because it is difficult to properly model all the complex transport processes (wind and three-dimensional effects) over time. Nevertheless, a separate three-dimensional TUFLOW modelling application by Helfensdorfer et al. (2019) (which potentially better simulates the mixing and stratification processes) shows salinity simulations for the Lower Lakes and Coorong comparable to those obtained using the two-dimensional TUFLOW.

The two-dimensional TUFLOW hydrodynamic model was adopted by Gibbs (2020) for studies simulating drought conditions (2007–2010) for a range of scenarios including a no barrage scenario. The model validation confirmed that TUFLOW can reproduce satisfactorily the observed water levels, with larger uncertainty in the salinity simulation. The scenario run with estimated pre-development inflows indicated that the Lower Lakes were fresh. The scenario run with no barrages indicate that the Lower Lakes became salty very quickly under the low flow conditions during drought once the barrages were removed. Helfensdorfer et al. (2019) also used TUFLOW to simulate salinity regime focussing on the mid-Holocene (7-6 ka) sea level highstand.

*ELCOM*

ELCOM is a three-dimensional hydrodynamic model developed by the University of Western Australia, and set up for the Lower Lakes and the Murray downstream of Lock 1 by Hipsey et al. (2009). ELCOM is a coupled hydrodynamic-biogeochemical model, intended for detailed water quality simulations, such as assessing the risk of lake acidification due to acid sulfate soils (Hipsey et al. 2014).

## 3.3 Environmental watering of the CLLMM

- The environmental watering requirement for the CLLMM was informed by extensive research and modelling undertaken over the past 20 years.
- The additional inflow into the Lower Lakes under the Basin Plan significantly enhances the ecological outcomes of the CLLMM, through building resilience in the system and providing some inflow during dry years.
- Most of the environmental water managed by the Commonwealth Environmental Water Holder that is delivered to the Lower Lakes has also been used for upstream environmental watering actions.

### 3.3.1 Environmental water requirement for the CLLMM

The environmental water requirement for the Coorong, Lower Lakes and Murray Mouth (CLLMM) region are informed by the considerable research undertaken over the past 20 years, including the CLLMM ecology research cluster involving CSIRO, The University of Adelaide, Flinders University and the South Australian Research and Development Institute.

The scientific and technical details for environmental watering of the CLLMM are described in Lester et al. (2011), Heneker and Higham (2012) and MDBA (2014b) (see also Section 4.3). The aim of the environmental watering is for the region to be a healthy, productive and resilient wetland of international importance, and to maintain the Ramsar-listed ecological character. The determination of environmental watering required for the CLLMM considered eight ecological objectives to deliver 33 ecological outcomes. A total of ten vegetation taxa and assemblages, 17 fish species, 19 macroinvertebrate taxa and 12 ecological processes were identified as indicators for achieving the ecological objectives.

The ecology-salinity-flow studies and hydrological and hydrodynamic modelling (see Sections 3.1.4 and 3.2.4) indicated that salinity in Lake Alexandrina was the most flow-responsive variable affecting indicator taxa and processes. Based on literature review, analysis and synthesis of data and knowledge of the region, modelling studies and expert opinion, the scientific studies determined that maintaining the salinity in Lake Alexandrina at these levels should achieve most of the above ecological objectives: maximum of 700 EC in 100% of years; maximum of 1,000 EC in 95% of years; and maximum of 1,500 EC in 100% of years. Achieving the above targets should also deliver Lake Albert and Coorong salinity outcomes. In addition to the above targets, salinity levels in the South and North Lagoons of the Coorong should also not exceed 117 g/L and 50 g/L respectively at all times (Lester et al. 2011).

The ability to achieve the above targets can be related to the flow over the barrages (Lester et al. 2011, Heneker 2010). A rolling average barrage outflow of 4,000 GL/yr over a three-year period (i.e. no less than 12,000 GL over three years) with no less than 3,150 GL in any one of the three years is needed to ensure that a mean annual salinity of 700 EC is not exceeded in Lake Alexandrina. A rolling average barrage outflow of 2,000 GL/yr over a three-year period (i.e. no less than 6,000 GL over three years) with no less than 650 GL in any one of the three years is needed to ensure that a mean annual salinity of 1000 EC is not exceeded. In addition to this, to ensure a healthy Coorong, there must be an annual barrage outflow of 6,000 GL once in every five (preferably three) years and 12,000 GL once in every 17 (preferably seven) years.

### 3.3.2 Determination of sustainable diversion limits (and environmental flows) in the Basin Plan

The Water Act 2007 established the Murray-Darling Basin Authority (MDBA) and tasked it with developing the Basin Plan to provide for integrated management of the Basin's water resources. A key component of the Basin Plan is to establish and enforce environmentally sustainable level of take (ESLT) or long-term average sustainable diversion limit (SDL). The SDLs are long-term average volumes of surface water and groundwater that can be taken for human uses (domestic, urban and irrigation) and are set at a catchment and Basin scale (MDBA 2011). This report only considers surface water.

Extensive hydrological modelling (see Section 3.1.4) and analyses of flow-ecology relationships, and assessment of environmental and socio-economic outcomes were progressively carried out in 2010, 2011 and 2012, to develop the SDLs. Detailed hydrological modelling was carried out by the MDBA (2011, 2012) using 114 years of historical data (July 1895 to June 2009) to determine ecologically significant components of flow regimes required to support key environmental assets, key ecosystem functions, productive base and key environmental outcomes at 122 hydrological indicator sites (and in more detail for 27 sites). The modelling assessed potential environmental outcomes for three SDL options representing the recovery of 2,400, 2,800 and 3,200 GL/yr of water across the entire Basin.

The use of the long hydroclimate time series (114 years) is standard practice in water resources system planning to capture the large range of characteristics and variability in the hydroclimate over different time scales (e.g. multi-year droughts and wet periods) (Chiew et al. 2009a, 2012). The MDBA modelling, which used data up to June 2009, would no doubt be extended to the present in the next Basin-wide modelling exercise (the data have been progressively extended in modelling by MDBA and the states). Nevertheless, the past 30 years have seen considerably less rainfall in late autumn and winter, which is amplified in the decline in streamflow, particularly in the southern Basin (Hope et al. 2017, Whetton and Chiew 2020). The past three years (2017–2019) were also the driest three years in instrumental record across most of New South Wales (Bureau of Meteorology 2019). This has led to discussions about whether the 1895–2009 data is an appropriate hydroclimate baseline for Basin planning. There has been part attribution of the cool season rainfall decline to climate change (CSIRO 2012, Hope et al. 2017), but it is difficult to robustly attribute (or apportion) this decline to climate change because of the high inter-annual and multi-year variability in the rainfall. As such, the choice of hydroclimate baseline needs to be guided by both the current science knowledge (including interpretation in the context of future climate change (see Section 3.5.1)) and the modelling and planning objectives. Examples include southwest Western Australia which use data from mid-1970s for planning (because the downward shift in rainfall there has lasted for more than 40 years now) (Indian Ocean Climate Initiative 2002), and the Victorian guidelines which recommend the use of post-1975 data for water resources planning (because being further south, there has been considerable decline in catchment runoff) (DELWP 2016, Potter et al. 2016).

Based on the modelling (with 1895–2009 data) and socio-economic assessments, the MDBA proposed a long-term average SDL of 10,873 GL/yr, representing a recovery of 2,750 GL/yr of water for the environment (Basin Plan 2012, MDBA 2014a). The majority of the 2,750 GL/yr (about 80%) comes from the southern connected basin. Following additional considerations, the 2,750 GL/yr was adjusted to 2,680 GL/yr after amendments to the Basin Plan informed by the northern basin review (MDBA 2016). Further, under the operation of the SDL adjustment mechanism, the recovery amount was reduced by a further 605 GL/yr due to the effect of "supply measures" to be implemented by 2024 (MDBA 2019a). The Plan also anticipates the recovery of an additional 450 GL/yr if this can be recovered while providing neutral or improved socio-economic outcomes.

The MDBA modelling shows that under the current settings of the Basin Plan (equivalent recovery of 2,750 GL/yr of water for the environment, i.e. purchased water entitlements plus SDL adjustments), the additional water that reaches the Lower Lakes, from return flows after environmental watering actions to deliver environmental water outcomes in the local catchments and in river channels and floodplains, is about 1,477 GL/yr (MDBA 2011 ,2012). The MDBA modelling and the modelling described in Section 3.3.1 indicate that the additional water reaching the Lower Lakes significantly improved the salinity outcomes in the CLLMM compared to the pre-Basin Plan baseline. The salinity targets for the Coorong (maximum salinity thresholds of 117 g/L in the South Lagoon and 50 g/L in the North Lagoon) were achieved throughout most of the 114 years of modelling. The modelling with 3,200 GL/yr water recovery option (similar/equivalent to the recovery of additional 450 GL/yr) achieved further improved outcomes for the CLLMM (as well as across the MDB), with the salinity targets for the Coorong achieved throughout the 114-year modelling sequence (MDBA 2011, 2012).

### 3.3.3 Environmental watering of the CLLMM

Environmental releases for the CLLMM is managed in partnership between the South Australian Department of Environment and Water (SADEW), MDBA and the Commonwealth Environmental Water Holder (CEWH). The environmental watering strategy for the CLLMM aims to maintain connectivity between the Lower Lakes and Coorong, achieve salinity targets in the Coorong, maintain an open Murray Mouth, and maintain the water level in the Lower Lakes with a seasonal profile between 0.4 and 0.85 m AHD (MDBA 2019). The CLLMM environmental water provides different outcomes in the different seasons, for example, winter pulse for fish migration, spring flows to inundate fringing wetland areas in the lakes and extend period of connection between the Coorong lagoons for fish and bird breeding, and summer flows for barrage release into the Coorong and lake level draw down for vegetation, bird habitat and fish spawning (CEWO 2019).

The CEWH (and MDBA) manages environmental water for multiple benefits, where return flows from upstream environmental watering action is used to benefit downstream, particularly in river channels and floodplains. As such, most of the environmental water delivered to the CLLMM has also benefitted upstream assets, including the lower Murray River (SCBEWC 2019, CEWO *pers. comm.* and catchment management plans). The direct order of CEWH environmental water at the South Australian border (i.e. water that was not delivered specifically for an upstream benefit) was less than 120 GL/yr averaged over the past five years (from MDBA environmental water accounting data).

During wet years, there is generally enough flow (from environmental water and unregulated flow) to achieve the environmental outcomes for the CLLMM as well as throughout the Basin. During dry years, the environment (just like other water users) receives less water (Interim Inspector-General 2020). The relatively smaller amount of environmental flow during the dry years is nevertheless critical to sustain the environment through the dry period and help the system bounce back when the drought ends. For example, in the past five years, the average environmental water reaching the Lower Lakes was less than 1,000 GL/yr (MDBA Basin Plan annual reports), of which 685 GL/yr was CEWH environmental water (MDBA Basin Plan annual reports), compared to the modelled long-term average annual inflow of 7,443 GL (which includes both environmental water and unregulated flow).

The monitoring and counterfactual water balance estimate for the CEWH (Stewardson and Guarino 2020) indicate that the lake water level was largely maintained at above 0.5 m AHD in the past five years, but without the CEWH environmental water (and assuming no change in barrage management), the lake level would have fallen below 0.4 m in 26% of the time. The flow over the barrages enabled by the CEWH environmental water also significantly improved the salinity outcomes for the Coorong. In the absence of the CEWH environmental water, and without management intervention, the barrage outflow would have been less than 100 GL/yr in three of the five years (Stewardson and Guarino 2020).

Towards the end of the 1997–2009 Millennium drought, very low inflow resulted in the lake water level falling to below -1 m AHD and salinity level above 8,000 EC, and prolonged hypersaline condition in the Coorong (Muller et al. 2019). The low lake water level exposed acid sulfate soils, and the high salinity level led to a deterioration of ecological condition (see Section 4.1.5). The MDBA modelling indicates that had the Basin Plan been in place at that time, the salinity level would have exceeded 1,000 EC for only a few months towards the end of the Millennium drought (peaking at 1,200 EC) and the lake water level would have not fallen below 0.2 m AHD (MDBA 2017).

## 3.4 Expected hydrology and hydrodynamics with no barrages

Without the barrages separating the Lower Lakes from the Coorong and the sea:

- Lake Alexandrina would become seasonally estuarine. From summer to autumn, rising sea level and low Murray River inflow and lake water level would result in salty seawater penetrating some distance into the lake. In late winter and spring, freshwater inflow would push the saltwater out and reduce the salinity in Lake Alexandrina.
- During severe droughts, the Lower Lakes (and potentially upstream into the lower Murray River) would have high salinity for prolonged periods.
- Lake Albert would likely become a salt trap and have high salinity for prolonged periods.
- Tidal inflow and sand deposition would increase, enhancing the likelihood of Mouth closure.
- Salinity changes in the Coorong would be relatively small compared to the changes in the Lower Lakes.

Without the barrages, the relatively free exchange of water between the Coorong and Lake Alexandrina would mean that water levels in the two water bodies would follow one another. With no barrages, the seasonal cycle of water level variation in the Lakes would be governed by the seasonal cycle of sea level variation and the Murray River inflow, as they presently are in the Coorong (Webster 2005). Currently, the constriction of the Mouth channel due to the barrage flow causes water to back up in the Coorong often to a further 0.3 m in height. Thus, non-tidal water level in the North Coorong shows a seasonal variation from about 0.1 m to 0.6 m AHD, and the Lower Lakes would follow suit if the barrages were removed. The barrages are managed to maintain Lake Alexandrina water level between 0.4 and 0.85 m AHD, although the seasonal minimum water level has generally been greater than 0.5 m AHD. Thus, the removal of the barrages would result in a reduction in lake water level as well as a larger seasonal cycle in the water level. If the Mouth is relatively open, then there is potential for significant tidal water level changes to penetrate into the Coorong and then into Lake Alexandrina.

When the river flow is low, the Murray River between Lake Alexandrina and Lock 1 would behave like a long narrow arm of the Lake so the water level fluctuation in the Lake would tend to extend all the way to the lock (Webster et al. 1997). The reduction in average water level with the removal of the barrages would have implications for the wetting and drying of wetlands, not just those surrounding the two Lower Lakes, but also along the river as far as Lock 1 (Webster et al. 1997). Mosley et al. (2017) considered that a minimum water level of 0.5 m AHD would need to be maintained between Mannum and Wellington to enable the efficient operation of most of the Lower Murray Reclaimed Irrigation Area (LMRIA) infrastructure. This level is currently accepted by LMRIA irrigators and corresponds on average to a critical minimum water level of approximately 0.4 m AHD in the Lower Lakes compared to the seasonal minimum of 0.1 m AHD without the barrages.

Flows between Lake Alexandrina and the Coorong would occur to equalise the levels in the two water bodies as the water level in the Coorong rises and falls at tidal, weather band (4–30 day periods) and seasonal frequencies. One might expect the maximum penetration of salty water into Lake Alexandrina when river flows are low, and the sea level is rising from summer through to autumn. The seasonal sea level variation of 0.2 m coupled to a weather band water level fluctuation of 0.2 m could cause a water level rise in Lake Alexandrina of 0.4 m which represents about 14% of the lake's volume. If horizontal mixing processes due to the wind are sufficiently vigorous to mix the introduced seawater throughout the lake in the time before any significant inflow, a salinity of about 5 g/L would occur. It should be noted that with a modelled average annual Murray River inflow of 7,443 GL under the Basin Plan, and an average annual net loss to the system from lake evaporation less precipitation of 800 GL, the inflow would be able to fill the lakes on average about four times in a year. One might therefore expect that this inflow is large enough to reduce the salinity of the Lower Lakes at the end of the main inflow period. It is therefore likely that the salinity in the main body of the lake would be seasonally variable ranging from fresh to brackish depending on the horizontal mixing processes.

However, during long droughts (like the Millennium drought and the recent/current drought), the salty water would not be flushed out of Lake Alexandrina on a seasonal basis allowing salt to accumulate from year to year. The modelling with TUFLOW from towards the end of the Millennium drought to about one year after the drought was broken (2007–2010) indicated that the Lower Lakes would quickly become saline if the barrages were removed. The inflows during this simulation period were not enough to flush the salty water out of Lake Alexandrina, and the salinity increased markedly from year to year approaching the salinity of seawater throughout the whole lake after less than three years of simulation (Gibbs 2020). During these extended periods of low river flow, it is likely that the saline water would mix up the river towards Lock 1 compromising water offtake for irrigated agriculture and water supply to Adelaide and towns in the region. Engineering solutions, such as Lock 0 at Wellington, have been proposed to overcome this problem.

Unlike Lake Alexandrina, Lake Albert does not have a direct flow-through of fresh water. The exchange between the two lakes occurs via wind-driven mixing through the Narrung Narrows and through the pumping of water in and out of the lake as its level rises and falls at seasonal and smaller time scales. With a potential increase in the variation in water levels at seasonal and weather band frequencies, the efficiency of water exchange between Lakes Alexandrina and Albert would tend to increase although this would be counterbalanced by a shallower Narrung channel tending to restrict the exchange. Much like the South Lagoon, Lake Albert would act as a salt trap with its water becoming more saline over time due to evaporation particularly if Lake Alexandrina became significantly more saline at times. The salinity in Lake Albert would be higher than that of Lake Alexandrina, as shown in the TUFLOW simulations for the no barrage scenario (Gibbs 2020). This tendency towards high salinity in Lakes Alexandrina and Albert would be exacerbated by any increases in evaporation rate due to climate change.

Under the no barrages scenario, water level in the Lower Lakes would not drop to the extremely low levels that were experienced during the Millennium drought when the barrages were closed, and therefore would reduce the risk associated with exposing acid sulfate soils (with the exception of fringing wetlands with acidic sulfate soil classification, Fitzpatrick et al. 2010).

The impact of barrage removal on the salinity regime of the Coorong would be relatively small compared to impacts in the Lower Lakes. The connection with Lake Alexandrina would mean that tidal and other longer period flows through the Mouth channel would increase (depending on the Mouth opening) to allow for the extra water flows into the lake. Since barrage construction the tidal prism for the CLLMM system has reduced by more than 87% (Harvey 1996). However, Thom et al. (2019) consider that enhanced frictional attenuation over the greatly expanded flood-tide delta since barrage construction would mean that the tidal prism after barrage removal would not return to what it was. During times of low or no water flow through the barrages, flows through the Mouth are dominated by tidal flows. The tidal water level and tidal current pattern is highly asymmetric through the Mouth and estuary region with the flood tide having higher current speed and shorter duration than the ebb tide. The strongly non-linear relationship between flow velocity and sand transport means that the flooding tide transports more sand than the ebbing tide even though its duration is less. Consequently, during periods of low barrage flow, there is a tendency for sand to be transported through the Mouth and to be deposited in the inside sand delta where current speeds are reduced. The modelling and measurements presented by WBM Oceanics (2003) show that this transport is likely to be particularly intensive under conditions of high waves and spring tides. One might conclude from this study that with increased tidal flows through the Mouth due to barrage removal that the rate of closing of the channel during periods of low inflow would increase. Unless rectified by dredging, the increased propensity of the Mouth channel to close would be expected to reduce the effectiveness of mixing processes along most of the length of the Coorong potentially leading to higher salinity in the South Lagoon.

The effective timing and duration of the flows from Lake Alexandrina into the Coorong without barrage control would certainly change. It has been demonstrated through modelling scenarios that smaller barrage flows delivered over a longer time are more beneficial in lowering the salinity in the South Lagoon than large barrage flows delivered over a shorter time (Webster et al. 2009). Removing the barrages would therefore have some impact on the salinity regime, but it is difficult to predict whether this would be beneficial or not. In any case, the changes are likely to be modest.

The above description of salinity outcomes if the barrages were removed is based on conceptual understanding of the hydrodynamics of the CLLMM and interpretations from limited hydrodynamic modelling of the system (Helfensdorfer et al. 2019, Gibbs 2020). Although it is certain that Lake Alexandrina would become estuarine if the barrages are removed, it is difficult to predict the extent and temporal (seasonal and multi-year) nature of significant seawater penetration into the lake. Two-dimensional and three-dimensional models like TUFLOW and ELCOM can provide some indication, but they need to be applied over a long period to predict salinity outcomes from long time series of freshwater inflow inputs. Such simulations are challenging to undertake because of the long run times of these models (see Section 3.2.4).

## 3.5 Expected hydrology and hydrodynamics under climate change

- The management of the CLLMM, as well as the whole Murray-Darling Basin, would become increasingly challenging under climate change.
- More freshwater inflow would be needed to maintain lake water and salinity levels and flow over the barrages because of higher lake evaporation and more seawater flowing into the Lakes.
- Runoff from upstream catchments is projected to decline under climate change.
- It is difficult to predict accurately the complex hydrodynamics and coastal processes of the Coorong and Murray Mouth under higher sea level. However, limited conceptual studies and hydrodynamic modelling indicate that (i) the Coorong water level would be higher, (ii) the Coorong South Lagoon would be less hypersaline, (iii) the barrages and barrier islands would be overtopped more frequently or possibly submerged, and (iv) the Mouth channel is likely to require permanent dredging to keep it open.

### 3.5.1 Expected hydroclimate conditions for the southern Murray-Darling Basin and Lower Lakes under climate change

Runoff across the southern Murray-Darling Basin (MDB) is likely to decline under climate change. This is mainly driven by the projected decline in winter-half rainfall when most of the runoff in this region occurs. Observed records show that winter-half rainfall over the past three decades is considerably lower than the long-term average (Hope et al. 2017, Whetton and Chiew 2020). The decline in winter-half rainfall has also been partly attributed to climate change, through the expanding Hadley cell under warmer condition pushing the winter storm tracks further south into the Southern Ocean (CSIRO 2012, Post et al. 2014, Timbal and Hendon 2011, Hope et al. 2017). Practically all global and regional climate models project a drier winter across southern Australia under climate change (Chiew et al. 2017, Chiew et al. 2009b). This decline in rainfall would be amplified as a two to three times greater percentage decline in the average annual runoff (Chiew 2006).

Hydrological modelling informed by climate projections from climate models indicate that, under RCP4.5 (Representative Concentration Pathway, low to medium greenhouse gas emission scenario), by 2046–2075 relative to the present, average annual runoff in southern MDB would decline by about 14% (median projection of -14%, with a $10^{th}$ to $90^{th}$ percentile range of -38% to +8%). Under RCP8.5 (high emission scenario), average annual runoff would decline by about 19% (median projection of -19%, with a range of -43% to +4%) (Whetton and Chiew 2020, Zheng et al. 2019, Chiew et al. 2017, CSIRO 2008, Reisinger et al. 2014). The decline in average annual runoff would be seen in reduced water availability and more frequent prolonged dry conditions. The large range in the future projections is because of the uncertainty in the future rainfall projections (CSIRO and BoM 2015, Chiew et al. 2017, Potter et al. 2018, Reisinger et al. 2014). The uncertainty in longer-term projections would also be enhanced as landscape hydrological models and river system models developed and calibrated against historical hydroclimates are extrapolated to predict a very different future under higher temperature, enhanced $CO_2$, changed precipitation pattern, and different dominant hydrological processes (Chiew et al. 2014, Bloschl et al. 2019, Fowler et al. 2016, Vaze et al. 2010). The higher temperature (~1.6°C under RCP4.5 and ~2.2°C under RCP8.5, by 2060 relative to 1986–2015) would increase potential evapotranspiration (Potter et al. 2011, Chiew et al. 2017), enhance the gap between water supply and demand (Chiew and Prosser 2011), and increase evaporation from the Lower Lakes (Thom et al. 2019).

Under climate change, the management of the Lower Lakes would become increasingly challenging because of higher lake evaporation and seawater ingression into the lakes (see Section 3.5.2). More freshwater inflow would therefore be needed to maintain the lake water and salinity levels. However, river flow from upstream catchments is likely to decline under climate change. For context, hydrological modelling indicates that under "median climate change", the inflow into the Lower Lakes under the Basin Plan would be approximately similar to the pre-Basin Plan inflow under present climate (Whetton and Chiew 2020, Reisinger et al. 2014). Planning and adapting to climate change are a complex whole-of-MDB challenge that require enhancing water supply and/or significantly enhancing water use efficiency through knowledge, technology, management and policy instruments.

The adaptation challenge is compounded by the considerable uncertainty in the future projections. Nevertheless, under the more extreme dry end of projections, significant adaptation is required including consideration of the types of desired and possible Basin futures under climate change and transitioning towards that future (Gross et al. 2012, Hart 2016, Alexandra 2017, Capon and Capon 2017). While the Basin Plan refers to several adaptation strategies to cope with climate change risks (Neave et al. 2014), it makes no specific adjustment for the anticipated reductions in water availability. Nevertheless, monitoring, new science and evaluation are at the core of adaptive management in the MDB, and the MDBA has recently initiated a research program to assess climate change risks to inform and develop adaptation mechanism through the 2026 Basin Plan review (MDBA 2019b).

### 3.5.2 Expected hydrodynamics and coastal processes in the Coorong and Murray Mouth under higher sea level

Since 1993, the sea level in the south-east coast of Australia has been rising by an average of 3.2 mm/year and the rate of rise has been gradually increasing. The sea level in this region is projected to increase by 52–98 cm by 2100 under the high RCP8.5 climate change scenario which is what the world is presently tracking (Church et al. 2013).

Rising sea level would impact the Coorong in several ways. The main channel along the length of the Coorong would deepen by the same amount of sea level rise assuming that sedimentation is insignificant. The deeper channel would result in tidal flows penetrating further towards the South Lagoon with a consequent increase in the long-channel mixing of salt.

The deepening of the shallow constriction between the North and South Lagoons near Parnka Point would have an even more profound effect on the salinity and water levels in the South Lagoon providing that the constriction does not fill in as the sea level rises. In some years, under low barrage flow and falling sea level through summer, water level has declined sufficiently to cause disconnection between the two lagoons, allowing the South Lagoon water level to fall further due to evaporation (Webster 2010) and increasing the salinity there. By deepening the constricting channel, even by as little as 0.1 m, it is likely that the summertime disconnection between the two lagoons would not occur, the water level in the South Lagoon would not drop over summer, and the South Lagoon would be less hypersaline due to maintenance of water exchange with the North Lagoon and the greater water depth. It should be noted though that despite a possible benefit to the South Lagoon from climate change due to a sea level rise, the higher temperature would increase evaporation rates, by about 8% for 1$^{o}$C higher temperature (assuming that other meteorological variable such as wind speed, cloudiness, and humidity remain similar) for a water depth of 1.5 m.

The sea level rise would impact the sediment dynamics of the Mouth channel, but it is unclear how and to what extent. For example, the mobile bed of the Mouth channel might rise in concert with the rise in sea level and therefore not affect how it opens and closes in response to barrage flows. On the other hand, Thom et al. (2019) argue that greater sand deposition from the higher sea level would permanently close the Mouth channel. Erosion from the Younghusband Peninsula would also provide a greater sand supply for deposition (Short and Cowell 2009). Likewise, dredging operations have deposited sand into beach zones where it can be transported back into the Mouth channel (Thom et al. 2019). Climate change may also introduce changes in wind conditions that would affect rates of Mouth closure due to changes in the wave regime and coastal currents which are the determinants of sediment transport in the coastal zone. Reduced Murray River inflows under climate change (see Section 3.5.1) would reduce the ability of the Mouth channel to clear itself. Therefore, it is quite likely that permanent dredging would be required to keep the Murray Mouth open under climate change.

Water level variations affect the suitability of shoreline mudflats for invertebrates with exposure for as little as one week being sufficient to eliminate them (Rolston and Dittmann 2009). Benger et al. (2009) suggest that the South Lagoon, which contains two thirds of the available mudflat habitat, would benefit from increased water level and reduced salinity. The mudflats and islands of the Coorong which are ecologically important for water birds and of cultural significance to the Ngarrindjeri may be drowned out and it is not clear that these would be replaced by the extension of the South Lagoon with the inundation of the currently ephemeral lakes to the south (Gross et al. 2012). Matthews (2005) suggested that changes in sea level would reduce mudflat extent, and that this loss can only be offset if there is sufficient supply of sediment to enable the tidal flats to grow upwards with sea level rise. In the absence of continued sedimentation, Matthews (2005) estimated that even a modest rise in sea level of 0.4 m would bring a permanent 49% reduction in mudflat habitat near Tauwitchere barrage. A systematic analysis of the extent of inundation and its impacts on bird nesting sites, mud flats, benthic habitat, and sacred sites due to sea level rise in the Coorong needs to be undertaken including the potential extension of the South Lagoon into the ephemeral wetlands to its south.

It has been speculated that the sand barrier separating the Coorong from the sea would be subject to increased erosion and possible breaching. Short and Cowell (2009) undertook geomorphological modelling of the seaward barrier face in response to hypothetical sea level rises of 1 m and 1.5 m. Shoreline recession would be driven by sea level rise together with sand loss to the dunes, the Murray Mouth flood tide delta and periodically to storm demand. They found that the maximum probable shoreline recession (with a probability of 1 %) for a 1 m sea level rise ranges from 189 to 215 m depending on position along the length of the sand barrier. As the narrowest section of barrier is 350–400 m wide along the Sir Richard Peninsula, even at the maximum rate of shoreline recession the barrier would remain at least 100 m wide and not be breached before 2109. Therefore, it is highly unlikely that the sand barrier would be breached by 2100 considering the maximum projection for sea level rise by the end of the century.

The higher sea level would also increase the frequency of overtopping the barrages and barrier islands between the Coorong and Lake Alexandrina, allowing the ingress of seawater into the lake. The overtopping occurs when high tides are superimposed on background high sea level fluctuations associated with large scale wind systems or storm surges. Based on the analysis of measured levels at Victor Harbor for 1976-2005, Webster (2009) calculated the likely water level exceedance for specified sea level rises based on the assumption that the statistics of future water level fluctuations would be similar to those of today. Possible increases in storminess associated with changing climate were not considered in that study. As an example of a result, a 1 m AHD elevation (the approximate level of overtopping) has been exceeded at Goolwa Barrage for an average of 11 hours per year during the measurement period, but if the sea level had been 0.2 or 0.5 m higher, then the exceedance durations would have been 97 and 1228 hours per year, respectively. A corresponding analysis with water level measurements from Tauwitchere barrage for the period 1981-2005 showed similar results.

Matthews (2005) has suggested that the greatest danger to the CLLMM region under sea level rise is the potential destruction of the barrage system. The barrages are comprised of constructed barrages and natural sections, with Ewe and Tauwitchere Islands as integral natural parts. These islands already flood when water levels on either side of the barrages reach 0.83 m AHD and may therefore be eroded and permanently inundated towards the end of the century. The barrier islands would be threatened by a sea level rise of 0.3 m and completely submerged by a rise of 1.0 m. The entire barrage system may therefore need to be replaced by a single barrier (possibly up to 13 km long from the Mundoo Barrage on Hindmarsh Island to Pelican Point) that would need to be one metre higher than today's barrages to accommodate sea level rise by the end of the century.

There would also be challenges in operating the barrages. To maintain flows through the barrages the water level in Lake Alexandrina would need to be some height above the Coorong water level. Therefore, with sea level rise, the water level in Lake Alexandrina would also need to be raised to allow river inflow to exit to the sea (BMT WBM 2014). Solutions to some of these challenges are discussed in Thom et al. (2019).

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# 4. ENVIRONMENTAL, SOCIAL AND ECONOMIC OUTCOMES FOR THE REGION

## 4.1 Ecological character of the Coorong and Lakes Alexandrina and Albert Wetland Ramsar Site

- The Coorong and Lakes Alexandrina and Albert Wetland was designated as a Wetland of International Importance under the Ramsar Convention in 1985 and Australia has an obligation to maintain the ecological character at this time point in time (regardless of previous historical states).
- There is a large body of knowledge, on the ecological character of the Coorong and Lower Lakes, collected from scientifically robust monitoring and evaluation projects over the past two decades, and most systematically since 2009.
- There is good evidence to indicate a decline in ecological condition of the Coorong and Lower Lakes during the latter part of the Millennium Drought.
- Recent monitoring has indicated with some certainty that parts of the system have recovered post drought and in response to changes mandated by the Basin Plan. The long-term sustainability of this recovery is uncertain and there are several parts of the system that have not yet recovered fully.

### 4.1.1 What is ecological character?

In November 1985, the Coorong and Lakes Alexandrina and Albert Wetland was designated as a Wetland of International Importance under the *Convention on Wetlands of International Importance Especially as Waterfowl Habitat* (Ramsar (Iran), 2 February 1971 (more commonly known as the Ramsar Convention). As a Contracting Party to the Ramsar Convention, Australia has obligations related to listed sites including to:

- '*formulate and implement their planning so as to promote the conservation of the wetlands included in the List, and as far as possible the wise use of wetlands in their territory*' (Ramsar Convention 1987, Article 3.1)
- '*arrange to be informed at the earliest possible time if the ecological character of any wetland in its territory and included in the List has changed, is changing or is likely to change as the result of technological development, pollution or other human interference*' (Ramsar Convention 1987, Article 3.2).

The Ramsar Convention (Ramsar Convention 2005) has defined "ecological character" and "change in ecological character" as:

> *'Ecological character is the combination of the ecosystem components, processes and benefits/services that characterise the wetlands at a given point in time'* and
> *'…change in ecological character is the human induced adverse alteration of any ecosystem component, process and or ecosystem benefit/service.'*

Within the definition of ecological character, the term '*at a given point of time*' refers to Resolution VI.1 paragraph 2.1, which states that '*It is essential that the ecological character of a site be described by the Contracting Party concerned at the time of designation for the Ramsar List'*. This essentially benchmarks ecological character with respect to management of Ramsar sites at the time of listing, which for the Coorong and Lakes Alexandrina and Albert Wetland Ramsar Site is 1985. This is an important point as, notwithstanding the debate and evidence of long-term historical conditions in the Coorong and Lower Lakes (see section 2 of this report), Australia's obligations under the Convention are to maintain character at the time of listing, which was in 1985.

The requirements for managing Australian Ramsar sites and maintaining their ecological character are established through the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). The EPBC Act establishes a Commonwealth process for the referral, and possible assessment, of proposed actions that may have a significant detrimental impact on 'matters of national environmental significance', which includes Ramsar sites.

### 4.1.2 What is the Coorong and Lakes Alexandrina and Albert Wetland Ramsar Site and why is it a wetland of international importance?

As of February 2020, there were 2,388 designated Ramsar sites in 170 countries covering over 250 million hectares (Ramsar 2020). These wetlands form a network of sites with many vital for supporting migratory shorebirds, whose flyways comprise different countries for breeding, feeding and over wintering.

The Coorong and Lakes Alexandrina and Albert Wetland Ramsar Site covers an area of approximately 140,500 hectares. It covers Lake Alexandrina, Lake Albert, lower portions of the Finniss River and Currency Creek, The Goolwa Channel, as well as the land and waters of the Coorong National Park, including both the North and South Lagoons.

In order to be designated as a wetland of international importance, a site must meet one or more of nine criteria. Guidance on the correct application of these criteria is provided in the Ramsar Strategic Framework (Ramsar Convention 2009). The most recent assessment (Department of Environment, Water and Natural Resources 2013) indicates that the Coorong and Lakes Alexandrina and Albert Wetland Ramsar Site would have met at the time of listing and continues to meet eight of the nine criteria, largely on the basis of the diversity of wetland types, supporting threatened species, important fish communities and the diversity and abundance of waterbirds, including international migratory shorebirds. The justification of these criteria is supported by a large body of evidence, albeit most of it collected since the time of listing (Department of Environment, Water and Natural Resources 2013).

### 4.1.3 Critical components, processes and services of the Coorong and Lakes Alexandrina and Albert Wetland Ramsar Site

The national guidance for the development of ecological character description (ECD) provides four criteria for identifying critical components, processes and services of Ramsar sites (Department of the Environment, Water, Heritage and the Arts 2008). Critical components, processes and services are those:

- that are important determinants of the site's unique character;
- that are important for supporting the Ramsar criteria under which the site as listed;
- for which change is reasonably likely to occur over short or medium time scales (< 100 years); and
- that will cause significant negative consequences if change occurs.

A recent review has applied these criteria in a systematic way and identified six components, two processes and ten services that are critical to the ecological character of the Coorong and Lakes

Alexandrina and Albert Wetland Ramsar Site (Butcher and Cottingham 2016). These are listed in Table 4.1, together with an indication of the related values.

**Table 4.1** Critical components, processes and services of the Coorong and Lakes Alexandrina and Albert Wetland Ramsar Site (Butcher and Cottingham 2016)

| Critical component, process or service | Related values / physical characteristics |
|---|---|
| Component: hydrology, surface water | Hydrology |
| Component: water quality, salinity | Salinity |
| Component: vegetation, freshwater/saline aquatic species diversity and extent | Inundation dependent vegetation |
| Component, fish diversity | Native fish |
| Component: waterbird diversity | Waterbirds |
| Component: waterbird abundance | Waterbirds |
| Process: fish breeding | Native fish |
| Process: waterbird breeding | Waterbirds |
| Service: maintenance and regulation of hydrological cycles and regimes | Hydrology |
| Service: cultural heritage and identity | *Kungun Ngarrindjeri Yunnan* (listen to Ngarrindjeri people talking) |
| Service: spiritual and inspirational | *Kungun Ngarrindjeri Yunnan* (listen to Ngarrindjeri people talking) |
| Service: hydrological processes | Hydrology |
| Service: provides physical habitat for waterbird species | Waterbirds, vegetation, hydrology |
| Service: threatened species, habitats and ecosystems | Waterbirds, fish, frogs, coastal saltmarsh |
| Service: priority wetland species and ecosystems | Waterbirds – in particular listed species and international migrants |
| Service: biodiversity | All biota |
| Service: ecological connectivity | Waterbirds and native fish |
| Service: food webs | All biota |

### 4.1.4 Ecological values of the Coorong and Lakes Alexandrina and Albert Wetland Ramsar Site

The following provides a short review of the ecological values of the Coorong and Lakes Alexandrina and Albert Wetland Ramsar Site and the information that has been used to develop the current understanding of the ecological character of the site. Consistent with Ramsar requirements, where data exists, this portion of the review is for the benchmark "at the time of listing" which is 1985. Changes since listing are considered in Section 4.1.5.

*Inundation dependent vegetation*

Information about vegetation in the Lower Lakes around the time of listing is limited and has largely been inferred from isolated surveys and observations. A recent review indicated that pre 2007 was the closest time period to the "time of listing" benchmark for which vegetation in the Lower Lakes could be described (Nicol 2016). This is largely based on extensive surveys conducted from 2003 to 2005 as part of the River Murray Wetlands Baseline Survey and habitat mapping to inform the ECD for the site (Seaman 2003, Holt et al. 2005, SKM 2006).

There is general agreement that the open water areas of Lakes Alexandrina and Albert largely do not support extensive stands of freshwater submerged vegetation, most likely due to wave action and depth, with these communities restricted to sheltered areas, Goolwa Channel and the lower reaches of Currency Creek and the Finnis River (Nicol 2016). Examples of freshwater submerged vegetation include beds of *Vallisneria australis* and *Myriophyllum* spp. in the shallows around Clayton Bay, submerged aquatic herblands with species such as *Myriophyllum* sp. and *Potamogeton* sp. on the eastern shore of Lake Alexandrina near Milang, and areas of *Mimulus repens*, *Myriophyllum simulans*, *Potamogeton pectinatus* and *Ruppia tuberosa* on the south western shore of Lake Alexandrina near Raukkan (Holt et al. 2005, SKM 2006).

The fringing vegetation of the Lower Lakes was characterised by stands of emergent species, dominated by *Typha domingensis* and *Phragmites australis* with other species present, but less common including *Eleocharis acuta*, *Bolboschoenus caldwellii* and *Schoenoplectus* spp. (Holt et al. 2005, SKM 2006). Ghania sedgelands comprising *Gahnia trifida* in freshwater areas and *Gahnia filum* in more saline conditions occurred mainly along the northern shoreline of the Finniss River and the western shoreline of Lake Alexandrina (Seaman 2003, Phillips and Mueller 2006). There were also areas of saltmarsh, comprising *Sarcocoria* spp., *Tecticornia* spp. and *Juncus kraussii* in areas of higher salinity and some lignum (*Duma florulenta*) shrublands in wetlands along the eastern shoreline of Lake Alexandrina, near the barrages and around Lake Albert (Seaman 2003, Holt et al. 2005, SKM 2006). Inundation dependent trees are uncommon around most of the Lower Lakes, with the exception of small areas such as Hindmarsh Island, where South Australian swamp paperbark (*Melaleuca halmaturorum*) is the dominant tree (Holt et al. 2005).

The North and South Lagoons of the Coorong, at the time of listing, were dominated by submerged aquatic macrophyte beds. Nicols (2005) comprehensively reviewed the existing literature and clarified the taxonomic identifications of species present prior to the Millennium drought. It is now clear that large-fruit sea tassel (*Ruppia megacarpa*) dominated the North Lagoon, with other species' present including the seagrasses *Lepilaena cylindrica* and *Zostera muelleri* (Paton et al. 2015). Tuberous sea tassel (*Ruppia tuberosa*) was the dominant species in the South Lagoon (Nicol 2005), with the charophyte *Lamprothamnium papulosum* also recorded (Paton et al. 2015).

*Native fish*

Fish data for the Lower Lakes were limited at the time of listing, with the first comprehensive surveys occurring in 2001 to 2003, when a diverse mix of diadromous and obligate freshwater species was recorded (Wedderburn and Hammer 2003). Eighteen species were recorded across the Lower Lakes including three species of conservation significance: Murray hardyhead, southern pygmy perch (*Nannoperca australis*) and Yarra pygmy perch. These species were found almost exclusively in littoral vegetated habitats and highlighted the importance of the Lower Lakes in supporting populations of small bodied native fish (Bice et al. 2019).

Fish distribution in the Coorong and Murray Estuary reflects the increasing salinity gradient from the mouth to the South Lagoon, with the highest diversity in the areas of lowest salinity (Murray Estuary) and species richness declining to just the highly salt tolerant small-mouthed hardyhead in the South Lagoon (Bice et al. 2019). The Murray Estuary and North Lagoon supported a number of species that are commercially or recreationally important including mulloway (*Argyrosomus japonicus*), black bream (*Acanthopagrus butcheri*) and yelloweye mullet (*Aldrichetta forsteri*) (Earl 2018). There is some evidence to suggest that the Coorong is an important nursery ground for several species including the marine migrant sandy sprat (*Hyperlophus vittatus*) (Watt 2013).
The Ramsar site supports fish with a wide range of life history strategies including obligate freshwater species, estuarine and marine species. Seven diadromous species have been recorded from the system including pouched lamprey (*Geotria australis*), congoli (*Pseudaphritis urvillii*) and common galxias (*Galaxias maculatus*) (Bice et al. 2019).

*Waterbirds*

There was little data on waterbirds in the Coorong and Lakes Alexandrina and Albert Wetland Ramsar Site at the time of listing. Regular annual surveys were only conducted since 2000 in the Coorong and 2009 in the Lower Lakes. As such the benchmark proposed for the updated ecological character description is largely based on data collected post 2000 (O'Connor 2015).

Current data for waterbirds in the system are comprehensive and based on best available science with respect to both diversity, abundance and a range of other metrics important for understanding condition such as the percentage of time birds spend foraging (Paton et al. 2016, 2017a, 2018). While both the Coorong and the Lower Lakes support large numbers of waterbirds, the species and communities differ. The Coorong supports large numbers and a diversity of shorebirds, with 31 species commonly recorded, the most numerous of which are typically red-necked stints, banded stilts and sharp-tailed sandpipers. Median abundance of shorebirds in the Coorong was over 60,000 (2000 to 2015) while in the Lower Lakes it was less than 1000 (2013 to 2015). Both the Coorong and Lower Lakes support moderate to large numbers of waterfowl (median abundances of around 30,000), but the species present differ. In the Coorong, grey teal (*Anas gracilis*), Australian shelduck (*Tadorna tadornoides*), chestnut teal and black swan (*Cygnus atratus*) are common. In the Lower Lakes the most common waterfowl species are Australian shelduck, Pacific black duck (*Anas superciliosa*), grey teal, Eurasian coot (*Fulica atra*) and black swan (Paton et al. 2019).

On average, the Lower Lakes support twice as many fish-eating waterbird species with the median abundance of around 37,000 (2013 to 2015) compared to 17,000 in the Coorong (2000 to 2015). The species present differs between the freshwater and estuarine systems. In the Lower Lakes, great cormorants, pied cormorants (*Phalacrocorax varius*), and whickered terns (*Chlidonias hybrida*) are most abundant; while in the Coorong larger numbers of hoary-headed grebes (*Poliocephalus poliocephalus*) and great crested grebes (*Podiceps cristatus*) are common (Paton et al. 2018, 2019). The Lower Lakes also support significant numbers of large-bodied waders such as royal spoonbills (*Platalea regia*), Australian white ibis (*Threskiornis moluccus*) and straw-necked ibis (*Threskiornis spinicollis*). In addition, the Lower Lakes provide habitat for a variety of cryptic crakes and rails, including the EPBC listed Australasian bittern (O'Connor and Rogers 2014).

There are a number of waterbirds that regularly breed (or have previously bred) in the Ramsar site, but data is limited and breeding activity rarely monitored (O'Connor 2015). There are historical records of 23 colonial nesting species breeding in the Ramsar site (O'Connor and Rogers 2014) although the regularity of breeding and the size of colonies is not well understood. At the time of listing colonial nesting species such as pied cormorants, little black cormorants, little pied cormorants and great cormorants all bred in the Lower Lakes. In the Coorong, significant breeding of Australian fairy terns, Australian pelicans, great crested terns (*Thallasius bergii*) and Caspian terns was supported on the islands of the South Lagoon (Paton et al. 2019).

*Frogs*

The freshwater environments of the Lower Lakes support a diversity of frog species. As with other biota, the most comprehensive data come from regular annual monitoring (spring and summer) from 2009 (Mason and Turner 2019), with historical information from isolated studies an opportunistic records. Twelve species of frog occur in the Ramsar Site including the EPBC listed threatened species southern bell frog (Mason and Turner 2019).

*Food webs*

The interdependent and complex relationships between biota within the Coorong have been studied through trophic relationship or food webs (Deegan et al. 2009, e.g. Bice et al. 2016, Lamontagne et al. 2016, Giatas et al. 2019) and this information used to inform management and important water regimes (Lester et al. 2011, O'Connor et al. 2015). Of note is the importance of tuberous sea tassel as a primary producer in the South Lagoon of the Coorong together with sandy sprat and small-mouthed hardyhead which are important for maintaining fish eating birds, particularly the EPBC listed Australian fairy tern (Rogers and Paton 2009, Giatas et al. 2019).

In addition to the importance of food webs within the Ramsar site, is the effect of the Murray River discharge, through the CLLMM on productivity of coastal ecosystems. Recent investigations have illustrated the effect of river flow, and the nutrient loads carried in that flow, on productivity in the coastal ecosystems, with effects evident up to 60 km from the Murray Mouth (Auricht et al. 2018). This same study predicted, with a level of uncertainty, that reduced flows down the Murray River would have a significant effect on coastal productivity.

### 4.1.5 Has the ecological character of the Coorong and Lakes Alexandrina and Albert Wetland Ramsar Site changed since listing?

The ecological character description for the Ramsar Site indicated the system had been in ecological decline at the time of listing in 1985 and that "the ecological character of this site has been altered significantly over the past 20–30 years" (Phillips and Mueller 2006). In accordance with Article 3.2 of the Convention, the Secretariat was formally notified of potential changes in the ecological character of the site in December 2006. There is a very large body of evidence supporting an acceleration of the change in character during the Millennium Drought, particularly from 2007 to 2010 when water levels in the Lower Lakes fell. Monitoring and investigations were systematically implemented over the 2000s and have continued through to today. At the 11th Meeting of the Conference of the Contracting Parties, in 2012, Australia provided an update indicating that the ecological character of the site was stabilising and beginning to recover since 2010 when rainfall improved across the Basin. The major changes since listing are summarised in Tables 4.2 and 4.3.

**Table 4.2** Changes in ecological values in the Lower Lakes

| Ecological value | Benchmark (time of listing) | Millennium drought | Current (post 2012) |
|---|---|---|---|
| Inundation dependent vegetation | Earliest comprehensive data from 2003–2005 (Seaman 2003, Holt et al. 2005, SKM 2006) and time of listing information has been inferred from then. Extensive stands of emergent freshwater macrophytes (*Typha* sp. and *Phragmites australis*) with more localised areas of submerged aquatic plants. Some areas of saltmarsh and lignum shrublands, with isolated areas of inundation | Loss of freshwater submerged species and while emergent macrophytes persisted, there was no recruitment and condition was poor (Nicol 2016, Nicol et al. 2019b). Terrestrial plant species colonised areas of the lake bed (Nicol et al. 2019a). | There has been an increase in submerged and emergent vegetation in both Lake Alexandrina and Lake Albert, although these are still recovering to post-drought conditions. While the proportion of vegetation community targets (based on pre-drought benchmark conditions) has improved, typically only 50–60% of targets have been achieved (Nicol et al. 2019a). |

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| | dependent trees comprising South Australian swamp paperbark (Nicol et al. 2019b). | | |
| Native fish | Eighteen species of native fish recorded, important for small-bodied native fish and for three species of conservation concern: Murray hardyhead, southern pygmy perch, Yarra pygmy perch (Wedderburn and Hammer 2003). | A general decrease in species diversity and increase in the abundance of introduced species (Ye et al. 2016). The populations of all three species of conservation significance declined and estuarine species increased (Bice et al. 2019). | Populations of Murray hardyhead and southern pygmy perch have recovered to 2003 baseline conditions (Wedderburn et al. 2014). Yarra pygmy perch have not recovered and were not recorded in annual surveys to 2018 (Wedderburn and Barnes 2018). |
| Waterbirds | Moderate to large numbers of waterfowl and fish-eating species were regularly supported by the Lower Lakes. In addition, small to moderate numbers of large-bodied waders and several cryptic species of conservation significance (e.g. Australasian bittern) inhabit the littoral zones (O'Connor and Rogers 2014). Regular breeding of a number of colonial nesting fish eating species. | By 2009 there had been a decline in a number of species. Of note was the decline from many thousands of birds annually to very low numbers of Eurasian coot as well as significant declines in black swan, Pacific black duck and hardhead (data presented in O'Connor 2015). In terms of breeding, there was an absence of pied cormorants and other colonial nesting species in the late 2000s (Paton et al. 2019). | Abundance and diversity of waterbirds in the Lower Lakes appears to have recovered. In 2018 total counts for the Lower Lakes were over 90,000 with 53 species recorded (Paton et al. 2018). Pied cormorants continue to breed regularly in the reed beds of the Lower Lakes, but other fish-eating colonial nesting species have not been detected (Paton et al. 2019). Australian white ibis and straw-necked ibis continue to breed in moderate to large colonies (O'Connor and Rogers 2014). |
| Frogs | Good evidence for supporting a diversity of frogs and important population of the threatened southern bell frog (Mason and Turner 2019). | Decline in the diversity and abundance of frogs which are reliant on freshwater habitat. Of concern was the decline in the threatened southern bell frog (Mason and Turner 2019). | Recovery of many species, and although there have been improvements in the populations of southern bell frogs, they have yet to return to previous pre-drought states (Mason and Turner 2019). |

**Table 4.3** Changes in ecological values in the Coorong

| **Ecological value** | **Benchmark (time of listing)** | **Millennium drought** | **Current (post 2011)** |
|---|---|---|---|
| Inundation dependent vegetation | Large-fruit sea tassel dominated the North Lagoon and tuberous sea tassel was the dominant species in the South Lagoon (Nicol 2005). | Large-fruit sea tassel was last reported in the North Lagoon in 1995 and by 2007, there were no plants present and only very low amounts of viable seed (Nicol 2016, Nicol et al. 2019b). Similarly, since 2002 there has been a decline in tuberous sea tassel in the South Lagoon and by 2008 there were no plants | In 2011 there was colonisation of tuberous sea tassel in the South Lagoon and the southern end of the North Lagoon (Frahn et al. 2012). By 2017 there was tuberous sea tassel detected over 43 kilometres of the Coorong predominantly in the South Lagoon, but also in |

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|---|---|---|---|
| | | detected (Nicol 2016, Nicol et al. 2019b). Between 2006 and 2010 tuberous sea tassel established in the North Lagoon, but declined soon after (Paton et al. 2017b). | the south of the North Lagoon. High algal loads, however, are affecting the growth and reproduction of the species (Paton et al. 2017b) as are rapid falls in water level during spring preventing seed set (Paton et al. 2018). |
| Native fish | A diversity of fish across life history strategies. Several important commercial and recreational fisheries species. Nursery grounds for several fish species. At least seven diadromous species (Bice et al. 2019). | A decrease in fish abundance and diversity. Recruitment failures and declines in abundance of diadromous fish with two species of lamprey not detected during surveys (Ye et al. 2016). Loss of small-mouthed hardyhead from the South Lagoon (Ye et al. 2016). | Enhanced recruitment, and abundance of many species (Ye et al. 2016). Species such as mulloway have increased to former population levels, but others, including black bream have remained low (Earl 2018). |
| Waterbirds | Large numbers of shorebirds (both Australian resident and international migratory species) supported annually. Moderate to large numbers of waterfowl and fish-eating species. Regular breeding of several fish-eating species including the listed Australian fairy tern, Australian pelican and great-crested terns. | A decline in diversity and abundance of waterbirds from the mid to late 2000s. Prolonged decline in the abundance of shorebirds (O'Connor 2015). A decline in the breeding of several species including Australian pelican and Australian fairy tern (Paton et al. 2019). | Some increases in abundance of waterbirds, including waterfowl and fish-eating species. Resident and migratory shorebirds, however continue to decline in abundance (Paton et al. 2018). Breeding of Australian pelican and crested terns continues to be supported, but the numbers of nesting Australian fairy tern have not recovered (Paton et al. 2019). |
| Food webs | Tuberous sea tassel has been identified as a key primary producer and this, together with the high productivity of invertebrates and small bodied native fish provided high levels of food and good quality foraging for waterbirds and predatory fish. | Disruption of food webs and a restriction or loss of the brackish-marine components. Loss of tuberous sea tassel and small-mouthed hardyhead from the South Lagoon. Corresponding decline in productivity and food for shorebirds and fish eating species, particularly Australian fairy tern (Rogers and Paton 2009, Ye et al. 2016, Paton et al. 2019). | Some improvement in productivity and restoration of food webs. Increases (in some years) in the key species tuberous sea tassel and small-mouthed hardyhead. Improvement in the abundance and diversity of some waterbirds, but not the Australian fairy tern or migratory shorebirds 2016; Paton *et al.* 2019). |

## 4.2 Socio-economic values of the region

- The lower Murray River, Lower Lakes, Coorong and adjacent marine and land areas are important to the Ngarrindjeri Nation who have a long and continuing association with Country.
- Several studies have shown that maintaining the ecology of the CLLMM is important for providing a wide range of important socio-economic values including recreation, tourism, commercial fishing and water for agriculture.

### 4.2.1 Kungun Ngarrindjeri Yunnan (Listen to Ngarrindjeri People Talking)

In 2009 the Ngarrindjeri Nation in South Australia (SA) negotiated a formal Kungun Ngarrindjeri Yunnan Agreement (KNY — Listen to what Ngarrindjeri have to say) with the State Government that recognised traditional ownership of Ngarrindjeri lands and waters and established a process for negotiating and supporting Ngarrindjeri rights and responsibilities for Country (Rigney et al. 2015). In 2007 the Ngarrindjeri leaders prepared the Ngarrindjeri Nation Yarluwar-Ruwe Plan (Ngarrindjeri Nation 2007). The Ngarrindjeri Sea Country Plan was prepared by Ngarrindjeri people to help government agencies, natural resource managers, researchers, industry and the wider Australian community to better understand and recognise rights and responsibilities to our *Yarluwar-Ruwe* (Sea Country), including the lower Murray River, Lakes, Coorong and adjacent marine and land areas.

*Ngarrindjeri Concern for Country: Our Lands, Our Waters, Our People, All Living Things are connected. We implore people to respect our Ruwe (Country) as it was created in the Kaldowinyeri (the Creation). We long for sparkling, clean waters, healthy land and people and all living things. We long for the Yarluwar-Ruwe (Sea Country) of our ancestors. Our vision is all people Caring, Sharing, Knowing and Respecting the lands, the waters and all living things. Ngarrindjeri Vision for Country Kungun Ngarrindjeri Yunnan (Listen to what Ngarrindjeri people have to say).*

*Our goals are:*

- *For our people, children and descendants to be healthy and to enjoy our healthy lands and waters.*
- *To see our lands and waters healthy and spiritually alive.*
- *For all our people to benefit from our equity in our lands and waters.*
- *To see our closest friends — our Ngartjis (special animals) — healthy and spiritually alive.*
- *For our people to continue to occupy and benefit from our lands and waters.*
- *To see all people respecting our laws and living in harmony with our lands and waters.*

The Ngarrindjeri Vision for Country contains long-standing principles of ‘wise use’ of their ‘Country’, supporting healthy rivers, lakes, estuaries and coastlines. Fundamental to this vision is an understanding that everything is connected and that both cultural and natural wellbeing require healthy lands, waters and all living things (Ngarrindjeri Nation 2007). Like other Indigenous Peoples, the Ngarrindjeri understand their humanity and their Indigenous sovereignty as being constituted in inextricable relations with the non-human world. For Ngarrindjeri, this philosophy is embodied in the concept and practice of Yannarumi, or ‘Speaking as Country’. This philosophy expresses the interconnectivity between the lands, waters and all living things. As part of the living body of their Country, Ngarrindjeri believe they have an abiding right and responsibility to sustain what Western science understands as ‘ecological health’ (Hemming et al. 2019).

Further information on the Ngarrindjeri perspective on the Coorong and Lower Lakes and the maintenance of ecological character can be found in Ngarrindjeri Nation Yarluwar-Ruwe Plan

(Ngarrindjeri Nation 2007) and chapters 1.1 and 4.4 of the Natural History of the Coorong, Lower Lakes and Murray Mouth Region (Yarluwar-Ruwe) (Mosley et al. 2019).

### 4.2.2 What other socio-economic values does the Coorong and Lakes Alexandrina and Albert Wetland provide?

There have been several descriptions of ecosystem services (benefits that people derive from the natural environmental) for the Coorong and Lower Lakes (Phillips and Mueller 2006, Vandeleur Environmental 2013, Colloff et al. 2015, Butcher and Cottingham 2016). While all these assessments have used slightly different language, similar services have been identified and provide a basis for identifying the socio-economic values provided by the wetlands and the biota they support and are summarised in Table 4.5.

**Table 4.5** Provisioning and cultural ecosystem services provided by the Coorong and Lower Lakes (all information from Colloff et al. 2015 unless otherwise specified)

| Ecosystem service | Description |
|---|---|
| Irrigation, stock and domestic water supply | Water from Lakes Alexandrina and Albert is used to supply irrigation in areas directly adjacent to the Lakes as well as for the Angus Bremer system. There are around 133 GL of irrigation entitlements in the region, although the importance of the Lower Lakes for water supply has diminished since the Millennium drought when alternative water supplies were developed in response to falling lake levels. |
| Commercial fisheries | The Coorong and Lower Lakes support a commercial fishery that is worth over $6 million annually (PIRSA Fisheries and Aquaculture 2015). Major native species in the Lower Lakes include golden perch and bony bream and in the Murray estuary species include mulloway, black bream and greenback flounder. It has been estimated that the economic contribution of the CLLMM fishing industry in South Australia is substantial. In 2017/2018, for example, the direct and indirect contribution of commercial fishing was over $30 million and contributed over 160 full time equivalent jobs directly and through flow on effects such as transport and manufacturing (BDO EconSearch 2019). |
| Grazing | Grazing is the dominant land use in the areas immediately surrounding the Lower Lakes. Although grazing on freshwater vegetation in the littoral zone of the lakes can occur, some areas have now been fenced to maintain ecological values. |
| Genetic biodiversity resources | The Coorong and Lower Lakes support genetically variable fin fish, crustaceans and molluscs that have current and future value in aquaculture industries as well as a variety of plants that have value for native bush foods, medicines and ornamental gardens. |
| Boating, camping, four-wheel driving | The Lower Lakes and Coorong are important recreational boat and four wheel drive locations. In 2004, recreational boating was estimated to have a gross economic value of about $14 million per year, employing 140 full-time jobs. |
| Recreational fishing | The Lower Lakes and Coorong support a significant recreational fishery targeting species such as mulloway, yellow-eye mullet and golden perch (PIRSA Fisheries and Aquaculture 2015). Recreational harvest comprises a significant proportion of the total catch for certain species, for example around one third of the total catch for golden perch and up to 80% of the harvest of black bream (Ferguson et al. 2019). Annual recreational fishing experienced a substantial decline during the Millennium drought (Ferguson et al. 2019) illustrating the links with water regime and salinity. |
| Bird watching and wildlife enjoyment | Eco-tourism continues to be a focus for a proportion of visitors to the CLLMM region. |
| Tourism and recreation | The CLLMM region is an important centre for tourism in South Australia, estimated to be worth over $30 million annually. Visitation rates for the Lakes site |

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|---|---|
| | declined during the Millennium Drought because of public perception of poor ecosystem health. |
| Education and research | The CLLMM region has been subject to extensive scientific research and has advanced our knowledge and understanding of aquatic ecosystems. |

## 4.3 Flow and salinity requirements to maintain ecological, social and economic values

- The hydrology and salinity regimes of the CLLMM do not have intrinsic value, but are managed to maintain the ecology of the system and the socio-economic values that are reliant on them.
- There is a comprehensive body of evidence that identifies hydrology and salinity as the two most important characteristics for maintaining ecological and associated socio-economic values.
- There remains some uncertainty about other influencing factors (e.g. nutrients, pest plants and animals) and their influence on restoring ecological character.

A large and comprehensive assessment of the environmental water requirements for the CLLMM was completed in 2011 (Lester et al. 2011). The project involved leading scientists from several universities and research organisations and summarised the available knowledge on the water regime and salinity requirements of the ecological values of the Coorong and Lower Lakes. The study was internationally peer reviewed (Maltby and Black 2011). The peer review concluded (page 2) that "*By any standards the body of the work represented by the report is exceptional and covers a wide range of studies / reviews at least comparable in quality and comprehensiveness to high profile assessments carried out elsewhere in the world*". The authors of the peer review made recommendations related largely to improving understanding with further monitoring and assessment and that this monitoring be used to refine environmental water requirements over time.

Another body of evidence that demonstrates the importance of hydrology and salinity on the ecological, social and economic values of the CLLMM region is provided from monitoring since the middle to late 2000s. The changes in ecological character described in Tables 4.3 and 4.4 illustrate the direct effects of decreased freshwater inflows and increasing salinity during the Millennium Drought and the improvements following increased freshwater inflows from 2010/2011 onward. What is less clear is the effect of non-flow related variables (e.g. increased nutrients, pest plants and animals) on recovery of ecological character, and the long-term sustainability of ecological, social and economic values under future climates (Leterme et al. 2015).

These ecology-salinity-flow studies, together with hydrological and hydrodynamic modelling, inform the environmental watering requirements and strategies for the CLLMM, and are summarised in Section 3.3.

## 4.4 Impact of barrage removal on environmental and socioeconomic conditions in the CLLMM region

- The removal of the barrages would result in a loss of freshwater values in the Lower Lakes, which would significantly change the ecological character of the Ramsar site.
- These ecological changes would have significant and ongoing consequences with respect to traditional owner values and other socio-economic values that are reliant on a healthy CLLMM system.

The review of the hydrology and hydrodynamics with no barrages (Section 3.4) concludes that there would be increased periods of saline and stratified conditions in the Lower Lakes, and more pronounced in Lake Albert which may become a salt trap. Increases in salinity would likely extend up the river to Lock 1 (in the absence of a new "Lock 0" at Wellington) during droughts. The water regime is predicted to be more seasonally variable, and the water depths in the Lower Lakes would decrease.

The combined effects of changes in water and salinity regime would result in the loss of freshwater values in the Lower Lakes. Scientific knowledge of flow-ecology relationships and the water regime and salinity tolerance of the biota of the CLLMM (e.g. Lester et al. 2011), together with the evidence from monitoring during the latter part of the Millennium Drought, provide very clear evidence of the likely impacts of removing the barrages on the values of the CLLMM region. We can predict with some confidence that:

- freshwater species such as frogs and the threatened southern bell frog would no longer be supported by the Lower Lakes;
- freshwater fish, including threatened small-bodied native fish, would also not survive;
- freshwater submerged vegetation that is currently present in the Lower Lakes would not survive increased salinity and while the fringing emergent vegetation can tolerate estuarine salinities for some period of time it would probably not survive the combined effects of reduced water level and increased salinity;
- impacts to waterbirds would be related to effects through the food chain and/or loss of nesting habitat. It is possible that the water regime on the Lower Lakes would no longer support significant colonial nesting breeding, with the prolonged inundation through the breeding season required being absent. Similarly, cryptic species like bitterns and snipes that rely on emergent vegetation as habitat may be affected;
- there is likely to be less risk of exposure to acid sulfate soil and acidification in the Lower Lakes (except for fringing wetlands with seasonally lower water levels);
- there would be likely impacts to commercial and recreational fishing, especially with respect to species that rely on freshwater or specific salinity gradients;
- based on past experience, declining health of the CLLMM would negatively impact tourism and recreation values; and
- increased salinity and altered water regime that extend upstream the Murray River during long droughts would affect the condition and community composition of riverine freshwater biota and fringing wetlands along the Murray River.

Any decline in condition and loss of values in the CLLMM region would have implications for Australia's obligations under the Ramsar Convention. It would also have implications for the Ngarrindjeri Nation with a loss of traditional owner values associated with healthy waters including *Ngartjis* (special animals) and Indigenous fisheries. There would also be potential implications with respect to water offtake from the lower Murray River for irrigated agriculture and water supply to Adelaide and regional towns.

## 4.5 Potential impact of climate change on environmental and socioeconomic condition in the CLLMM region

- Under climate change, it is likely to be increasingly difficult to maintain freshwater values in the Lower Lakes.
- Increased water levels in the Coorong lagoons would diminish intertidal feeding habitat for shorebirds.
- Warmer conditions may favour different species, including invasive species.
- These ecological changes would have significant and ongoing consequences with respect to traditional owner values and other socio-economic values that are reliant on a healthy CLLMM system.
- Exploring adaptation strategies for ecosystems and the services they provide under future climate scenarios would inform better management and identify values that can be maintained, those that can transition to some new state and those that cannot be sustained.

The review of the hydrology and hydrodynamics under climate change (Section 3.5) indicates increasing difficulty in maintaining the freshwater values of the Lower Lakes and concludes that there would be increased periods of saline and stratified conditions in the Lower Lakes and increases in marine water incursions. In addition, there is likely to be higher water levels in the Coorong lagoons, and increased air and water temperatures. Scientific knowledge of flow-ecology relationships and the water regime and salinity tolerance of the biota of the CLLMM (e.g. Lester et al. 2011), together with our understanding of climate change impacts on species distributions (e.g. Pecl et al. 2017) provide some evidence of the likely changes to the values of the CLLMM. Although there is a degree of uncertainty associated both with the future physical and chemical conditions in the CLLMM and the ecological responses to those conditions, it is likely that:

- reductions in freshwater inflow would affect conditions and biota supported by the lower Murray River channel and wetlands;
- freshwater species such as frogs and the threatened southern bell frog would no longer be supported by the Lower Lakes, due both to increases in salinity as well as the predicted increases in chytrid fungus under warmer air and water temperatures (Rodder et al. 2010);
- freshwater fish, including threatened small-bodied native fish, would be impacted by higher salinity levels;
- freshwater submerged vegetation that is currently present in the Lower Lakes would not survive increased salinity and while the fringing emergent vegetation can tolerate estuarine salinities for some period of time it cannot survive extended periods of dry conditions, high salinity and marine incursions;
- a reduction in extent and diversity of saltmarsh (Saintilan and Rogers 2013) and potential replacement with either invasive species such as Spartina which are favoured under warmer conditions (Crosby et al. 2017), or mangroves which are predicted to be favoured by increasing sea levels and temperatures in southern Australia (Saintilan et al. 2014);
- increased water levels in the Coorong Lagoons would have serious implications for shorebirds that feed in shallow intertidal waters;
- improved salinity in the South Lagoon could have some positive effects on benthic vegetation, fish and waterbirds;
- increased periods of Mouth closure would have serious implications for migratory fish and the recreational and commercial fisheries they support;
- reduction in freshwater outflow would likely impact the productivity of the coastal region outside the Murray Mouth;

- the declining health of the CLLMM would have impacts on tourism values with a reduction in visitor numbers and likely flow on effects to the local economy;
- recreation and commercial fisheries could decline, directly impacting species that rely on freshwater, as well as species like black bream that have specific salinity gradient requirements;
- declining water levels in the Lakes would reduce access for boats, further impacting on visitation, tourism and the local economy;
- sea level rise could result in impacts to low lying agricultural lands (cultivated and grazed) and water infrastructure that could become inundated and salt affected;
- changes to the ecology and condition of the lands and waters of the CLLMM would impact on the Ngarrindjeri Nation with a loss of traditional owner values associated with healthy waters; and
- impacts to ecological, social and cultural values could also result in increased pressure and stress in local communities.

These predicted changes would have implications for the management of the CLLMM in the future. There is a large body of literature on the vulnerabilities of Australian ecosystems and species to climate change (e.g. Boon et al. 2010, Garnett et al. 2013, Klemke and Arundel 2013, Saintilan and Rogers 2013, Garnett and Franklin 2014) and several studies specific to the CLLMM (Gross et al. 2012). There have also been developments in thinking about climate change adaptation such as the adaptation pathways concept (Wise et al. 2014). Adaptive management of the CLLMM could be informed by a thorough review of the existing literature with respect to species and communities the system supports, matched to a monitoring program which can test those predicted changes over time. In addition, exploring adaptation of ecosystems and the services they provide under future climate scenarios would inform better management and identify values that can be maintained, those that can transition to some new state and those that cannot be sustained.

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# 5. SUMMARY OF CLLMM OUTCOMES UNDER DIFFERENT SCENARIOS

- Under pre-Basin Plan, flow and salinity targets for the Lower Lakes and Coorong are not met during dry periods.
- Under the Basin Plan, flow and salinity targets are met most of the time.
- Under the 'no barrages' scenario, Lake Alexandrina would be seasonally estuarine, with prolonged periods of high salinity during droughts. Lake Albert could become a salt trap and have high salinity for long periods. The loss of freshwater value would threaten the Ramsar ecological character, and would negatively impact traditional owner values, socio-economic values, and potentially offtake for drinking water and irrigation.
- Under climate change, there is likely to be less freshwater inflow, and higher sea level would alter the geomorphology and hydrodynamics of the Coorong and Murray Mouth. However, there are significant knowledge gaps and future projections span a large range.

This report has explored a range of scenarios and how they would impact on the Coorong, Lower Lakes and Murray Mouth. They include conditions prior to development, post-development, pre-Basin Plan and post-Basin Plan. They also include scenarios involving the removal of barrages and under future climate change. These scenarios are described in Table 5.1 and their likely impacts are summarised in Figures 5.1 and 5.2.

The inflow into the Lower Lakes, water and salinity levels in Lake Alexandrina, and flow over the barrages for the pre-development, pre-Basin Plan and Basin Plan scenarios come from the MDBA Basin Plan modelling (Sections 3.1 and 3.3). The historical climate baseline used in the modelling spans 114 years from July 1895 to June 2009. Results for the median climate change scenario are inferred from the same MDBA modelling for pre-development and pre-Basin Plan using empirically scaled future climate series informed by the CSIRO Murray-Darling Basin Sustainable Yields project (see Section 3.5.1).

The hydrodynamics of the Coorong and Murray Mouth for all the scenarios are estimated from MDBA and SADEW modelling with the one-dimensional CHM and the two-dimensional TUFLOW models (see Sections 3.2, 3.4 and 3.5). The ecological and socio-economic outcomes are estimated based on their relationship with the flow and salinity characteristics (Sections 4.3, 4.4 and 4.5).

The flows presented in Figures 5.1 and 5.2 are long-term annual averages. They represent numbers that are generally used for reporting and discussion and provide useful context, although impacts and management challenges generally occur during dry periods. The freshwater inflow during non-dry years are nevertheless important as they enhance the CLLMM system resilience to better cope during dry periods.

There is considerable uncertainty in the prediction of outcomes under climate change, particularly in the large range of projected decline in runoff in the southern MDB and therefore inflow into the Lower Lakes, the uncertainty in the amount and timing of sea level rise, and the geomorphology and hydrodynamics of the Coorong and Murray Mouth under higher sea level. The median climate change outcome presented in Figure 5.2 is inferred from various sources (Section 3.5) and can be assumed to occur in about 50 years (~2070), but with significant uncertainty in the prediction.

**Table 5.1** Scenarios considered in this report and for which outcomes are summarised in Figure 5.1 and 5.2.

| Scenarios | Hydroclimate | Barrages | Development | Water use |
|---|---|---|---|---|
| **No Development** | Historical baseline | No | None | None |
| **Pre-Basin Plan** | Historical baseline | Yes | Present | Pre-Basin Plan |
| **Basin Plan*** | Historical baseline | Yes | Present | Basin Plan |
| **No barrages** | Historical baseline | No | Present | Basin Plan |
| **Median climate change** | Median climate change | Yes | Present | Basin Plan |

*Equivalent of 2,750 GL/yr recovered for the environment (purchased entitlement water plus SDL adjustments) (see Section 3.3.2).

In summary, the water management of the CLLMM has been informed by an extensive body of knowledge, data and modelling, which has been reviewed and synthesised in this report. There is a high level of agreement in the science and knowledge, although gaps remain in the details, particularly the spatial and temporal details, and outcomes under different scenarios of hydroclimates and engineering and management interventions. The management of the CLLMM will become increasingly challenging under climate change, and further research is needed to assess the likely impacts and plan adaptation options.

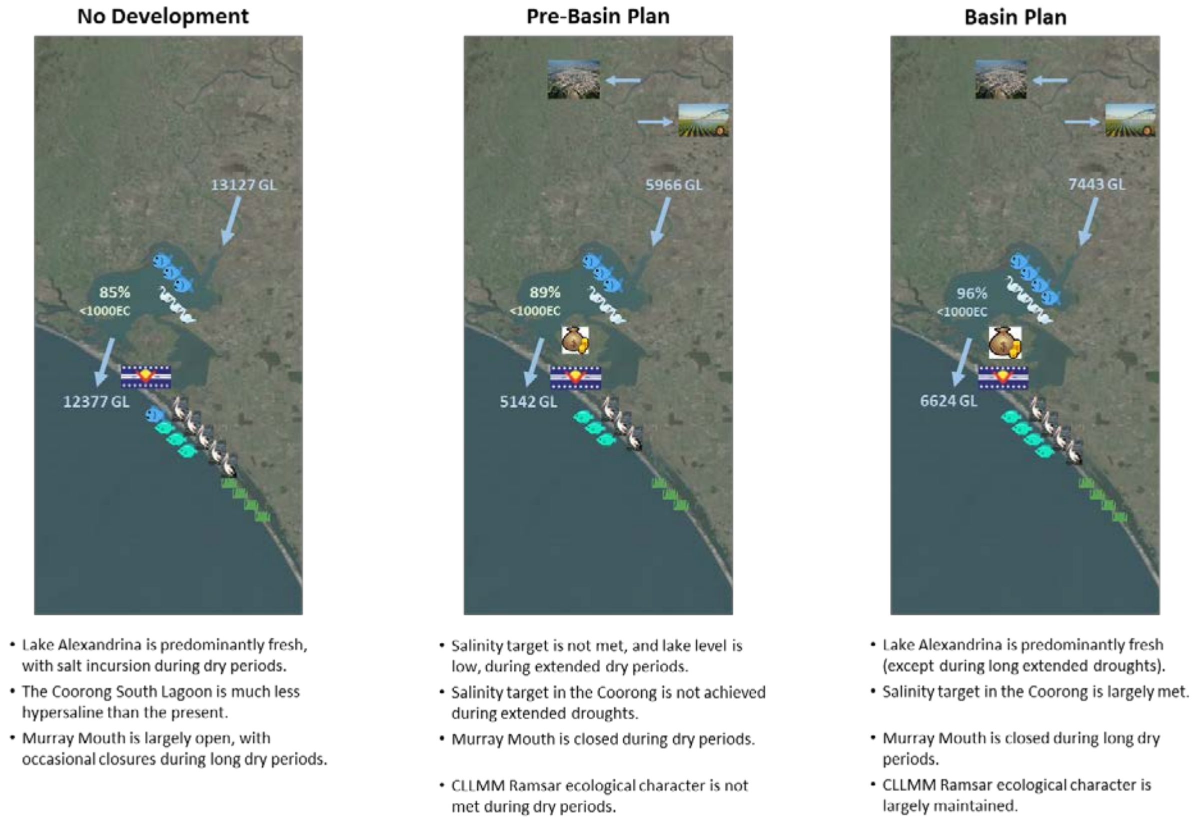


**Figure 5.1** Predicted outcomes for the CLLMM region under pre-Development, pre-Basin Plan and Basin Plan scenarios


**Basin Plan**

- Lake Alexandrina is predominantly fresh (except during long extended droughts).
- Salinity target in the Coorong is largely met.
- Murray Mouth is closed during long dry periods.
- CLLMM Ramsar ecological character is largely maintained.

**No Barrages**

- Lake Alexandrina is seasonally estuarine, with prolonged periods of high salinity during droughts. Lake Albert may become hypersaline.
- The Coorong is relatively similar to the present (under Basin Plan).
- Murray Mouth (further north) will be closed over long periods
- Lower Lakes Ramsar ecological character is not maintained.
- Negative impact on Ngarrindjeri people and socio-economy of the region.
- Potential salinity impact on water offtake for irrigation and for Adelaide and towns.

**Median Climate Change**

- Longer periods with high salinity in Lake Alexandrina (because of reduced inflow and seawater ingression).
- The Coorong has higher water level. The South Lagoon of the Coorong is less hypersaline.
- Murray Mouth would be closed frequently/permanently (requiring permanent dredging).
- Poorer Lower Lakes Ramsar character.
- More seawater ingression into Lower Lakes (from seepage and more frequent overtopping of barrages and barrier islands).

**Figure 5.2** Predicted outcomes for the CLLMM region under Basin Plan, No barrages and Median climate change scenarios

**<u>Attachment A – Lower Lakes science review workshop agenda</u>**

# Lower Lakes Science Review Workshop

**The Function**
**Level 3 The Beachhouse,**
**4 Colley Terrace,**
**Glenelg, Adelaide**

**27 February 2020**

**9.30 am to 3:30 pm**

## <u>Agenda</u>

<table>
<tr><td>9:30 – 9:45</td><td colspan="2">Welcome and Introduction<br>*[Rob Vertessy – Chair, MDBA ACSEES]*</td></tr>
<tr><td>9:45 – 10:15</td><td colspan="2">Terms of reference, processes and CLLMM outcomes scenarios<br>*[Francis Chiew – Chair, Independent Review of Lower Lakes science]*</td></tr>
<tr><td>10:15 – 10:45</td><td colspan="2">Rapid scan of the room – strengths and weaknesses of our interim review<br>*[Jennifer Hale]*</td></tr>
<tr><td>10:45 – 11:00</td><td colspan="2">Freshwater/Estuarine history of the Lower Lakes<br>*[Michael Reid]*</td></tr>
<tr><td>11:00 – 11:15</td><td colspan="2">Environmental and social and economic outcomes of the CLLMM<br>*[Jennifer Hale]*</td></tr>
<tr><td>11:15 – 12:30</td><td>Freshwater/Estuarine history of the Lower Lakes<br>[Discussion]<br>• Palaeohistory and salinity regime in the Holocene<br>• Lower Lakes during pre-European settlement (palaeoecological studies, anecdotal history, modelling)</td><td>Environmental and social and economic outcomes of the CLLMM<br>[Discussion]<br>• Environmental watering and outcomes under Basin Plan<br>• Implications of barrage removal<br>• Potential impacts (and knowledge gaps) under climate change</td></tr>
<tr><td>12:30 – 13:00</td><td colspan="2">LUNCH</td></tr>
<tr><td>13:00 – 13:15</td><td colspan="2">Hydrodynamics of the CLLMM<br>*[Ian Webster / Klaus Joehnk]*</td></tr>
<tr><td>13:15 – 13:30</td><td colspan="2">Environmental watering of the CLLMM<br>*[Francis Chiew]*</td></tr>
<tr><td>13:30 – 14:45</td><td>Hydrodynamics of the CLLMM<br>[Discussion]<br>• Under Basin Plan (current management)<br>• With no-barrages scenario<br>• Under climate change (and knowledge gaps)</td><td>Environmental watering of the CLLMM<br>[Discussion]<br>• Environmental flows for the Basin and Lower Lakes<br>• Would barrage removal result in significant water savings?</td></tr>
<tr><td>14:45 – 15:30</td><td colspan="2">Reflections on feedbacks and Next steps</td></tr>
<tr><td>15:30</td><td colspan="2">CLOSE</td></tr>
</table>

**Morning and afternoon tea will be available at 11:15 am and 2:15 pm – participants to serve themselves when they like.*

## Attachment B – List of workshop participants

### Independent expert panel

| | | |
|---|---|---|
| Chiew | Francis | CSIRO (Chair) |
| Hale | Jennifer | Environmental Consultant |
| Joehnk | Klaus | CSIRO |
| Reid | Michael | University of New England |
| Webster | Ian | Hydrodynamics Consultant |

### Workshop participants

| | | |
|---|---|---|
| Bond | Nick | MDBA ACSEES |
| Byron | Neil | MDBA ACSEES |
| Carlile | Lucy | Commonwealth Environmental Water Office |
| Campbell | Michelle | Commonwealth Environmental Water Office |
| Garland | Neville | Murray-Darling Basin Authority |
| Gibbs | Matthew | South Australia Department of Environment and Water |
| Harvey | Nick | University of Adelaide |
| Heneker | Theresa | South Australia Department of Environment and Water |
| Hipsey | Matthew | University of Western Australia |
| Hubble | Tom | University of Sydney |
| Hudson | Rohan | Royal HaskoningDHV |
| Job | Thomas | University of Sydney |
| Korn | Alistair | Murray-Darling Basin Authority |
| Lamontagne | Sebastien | CSIRO |
| Lucardie | Will | Murray-Darling Basin Authority |
| MacGregor | Angus | South Australia Department of Environment and Water |
| Marsland | Kelly | Murray-Darling Basin Authority |
| McLeod | Anthony | Murray-Darling Basin Authority |
| Moore | Anthony | Commonwealth Environmental Water Office |
| Morony | Chris | South Australia Department of Environment and Water |
| Mosley | Luke | University of Adelaide |
| Neave | Ian | Murray-Darling Basin Authority |
| Nicol | Jason | South Australia Research and Development Institute |
| Pittock | Jamie | Australian National University |
| Post | David | CSIRO |
| Quinn | Rebecca | South Australia Department of Environment and Water |
| Ramamurthy | Sharada | Victorian Department of Environment, Land, Water and Planning |
| Rumbelow | Adrienne | South Australia Department of Environment and Water |
| Sparrow | Ashley | Victorian Department of Environment, Land, Water and Planning |
| Tafts | Kathryn | Southern Cross University |
| Tibby | John | University of Adelaide |
| Vertessy | Robert | MDBA ACSEES |
| Wedderburn | Scotte | University of Adelaide |
| Wood | Alastair | Victor Harbor Resident |
| Ye | Qifeng | South Australia Research and Development Institute |

*The review also benefitted from discussions with and feedbacks from more than 20 other researchers and technical experts who did not attend the workshop.

## Attachment C – Profiles of panel members

**Dr Francis Chiew** has more than 25 years of experience in research, teaching and consulting, and in science leadership and management. Dr Chiew is globally recognised for his expertise in hydroclimate, hydrological modelling and integrated river basin management, and his research is widely adopted and cited. Dr Chiew and his team have led many major hydroclimate initiatives and water resources assessment projects, informing water resources planning and adaptation in Australia and globally. Dr Chiew and his team are also active in converting research outcomes into modelling tools and guidelines for the water industry. Dr Chiew is a member of several global and national water expert committees including lead author of two Assessment Reports for the United Nations Intergovernmental Panel on Climate Change.

**Ms Jennifer Hale** is an aquatic ecologist with expertise in wetland, riverine and estuarine systems with over 30 years of experience in the management of aquatic ecosystems. Ms Hale has extensive knowledge of the Ramsar Convention and its application to the management of wetlands in Australia. Ms Hale was one of three leaders of the technical review panel for Ramsar documentation and was involved in the development of guidance on implementation of the Convention including on the definition of Limits of Acceptable Change (LAC) and change in ecological character. Ms Hale has acted as an advisor on Ramsar wetlands for State and Australian governments and has recently completed a review of the effect of large-scale drivers on ecological character.

**Dr Klaus Joehnk** leads the Modelling Water Ecosystems team in CSIRO Land and Water. Dr Joehnk has over 20 years of experience in research and consultancy on hydrodynamic and water quality modelling of lakes and rivers. Dr Joehnk and his team conduct research into combining hydrodynamic and water quality modelling with satellite remote sensing of inland waters, developing operational short-term forecasting of water quality, and building integrated simulation tools for assessing ecological outcomes of inland water management. Dr Joehnk serves on the editorial board for Ecological Informatics Journal and is a committee member of the Australian Water Association.

**Associated Professor Michael Reid** works in Geography and Planning at the University of New England. Dr Reid has more than 20 years of experience in research focusing on understanding pattern and process in floodplain and river ecosystems across a range of spatial and temporal scales and on understanding how human activities impact river ecosystems. This focus requires interdisciplinary research and expertise in palaeoecology, food web ecology, floodplain and aquatic vegetation community ecology, geomorphology, hydrology and ecohydrology. Dr Reid is the current president of the Australian Freshwater Sciences Society.

**Dr Ian Webster** is an independent consultant. Dr Webster is an expert in physical oceanography, coastal lakes and processes, hydrodynamic modelling and biogeochemical modelling. Dr Webster was a senior principal research scientist in CSIRO until he retired in 2012. Dr Webster is well known in Australia and overseas for his scientific leadership of multidisciplinary projects that support the management of lakes, rivers and estuaries. Dr Webster has a deep knowledge of the Lower Lakes, having developed the hydrodynamic model for the Coorong for assessing the effectiveness of salinity amelioration measures.