

A thick white wavy line graphic that starts from the left edge, dips into a loop, and then rises in a series of smaller waves towards the right edge.

MURRAY **FUTURES**

Lower Lakes & Coorong Recovery

Specifying an environmental water requirement
for the Coorong and Lakes Alexandrina and
Albert: A first iteration
Summary of methods and findings to date

June 2011

Specifying an environmental water requirement for the Coorong and Lakes Alexandrina and Albert: A first iteration

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Foreword

The Coorong and Lakes Alexandrina and Albert wetland is one of Australia's most important wetland areas.

Designated as a Wetland of International Importance under the Ramsar Convention in 1985, the 142 500 ha site is a complex array of many bioregions and environments including permanent and seasonal freshwater lakes and marshes, streams, estuarine waters, coastal lagoons, intertidal mudflats and forested wetlands.

These provide habitat for more than 1000 species including many listed under the EPBC Act such as the southern emu wren (*Stipiturus malachurus*), migratory wader birds protected under international agreements, the orange-bellied parrot (*Neophema chrysogaster*), the southern bell frog (*Litoria raniformis*), and several threatened native fish species.

In addition to the conservation and environmental significance, the culture and wellbeing of the region's Traditional Owners, the Ngarrindjeri, are directly linked to the health of the Lakes and Coorong.

Central to the region's economy is a mix of primary industries (sheep and beef production, dairy, cereals, and wine production), as well as boat building, tourism, and a vibrant commercial and recreational fishing industry.

Everyone should be concerned with the state of the Murray-Darling Basin – and the Coorong, Lower Lakes and Murray Mouth (CLLMM). While the extent of the problems facing the CLLMM region may have only become apparent relatively recently, ecological degradation has been taking place for several decades. Over-allocation of water in the Murray-Darling Basin has been the main cause.

To ensure the region's economic, cultural and social future, it is critical to determine the environmental water requirements. Years of drought and over-use of water caused this internationally-significant wetland to dry, the lakes and aquatic biota to disconnect, the community and industries to suffer significant stress, and native species to be at risk of being lost. We must establish the needs of this system and then seek to meet them within the constraints imposed on a developed river system.

The long-term plan for the CLLMM region was prepared to ensure the region and its people have a healthy, viable and sustainable future in the context of variable climatic conditions and water resources. A key element of the overall strategy is the determination of the site's Environmental Water Requirements.

A healthy CLLMM region will depend on everyone accepting responsibility for its future. This document provides a foundation on which everyone can work together to build a sustainable and viable environment for the future.

The Australian and State Governments have allocated more than \$186 million in funding to support the projects and actions outlined in the long-term plan for the region. For it to be effective, we need to secure sufficient environmental flows through the Basin Plan. This report seeks to provide a useful input into that process.



Alan Holmes

Chief Executive

Department of Environment and Natural Resources

Acknowledgements

The development of this environmental water requirement for the CLLMM region has largely been a task of synthesis, and we would like to acknowledge the contribution and sincerely thank the following researchers, managers and institutions:

- those researchers who have contributed as authors to the individual reports that form the body of work that was used to develop this EWR and has been summarised within this report, particularly Ian Webster from the CSIRO for his ongoing willingness to provide access to his hydrodynamic model for the Coorong, and the numerous experts who reviewed the sections on the various sets of indicators (and have been cited explicitly in Lester *et al.*, 2011a);
- the researchers and managers who have contributed their expertise, understanding and data from the region to this process, particularly researchers associated with the CLLAMMEcology Research Cluster and/or the monitoring undertaken by the SA Murray-Darling Basin Natural Resource Management Board as a part of The Living Murray initiative;
- those researchers and managers who have contributed their time and expertise to comment on various aspects of this body of work, especially the government reference group who provided guidance throughout the process and those from the Department of Environment and Natural Resources and the Department for Water who provided helpful review comments on earlier drafts of this report; and
- Professor Ed Maltby from the University of Liverpool for his thoughtful review of this and the associated individual reports. His comments were particularly useful in improving the clarity and accessibility of this report, and led to two new sections including an extension of the investigation into the findings of less water and the investigation of the interaction with the USED scheme, which are now summarised here.

Finally, a special thank you to Rebecca Langley, Courtney Cummings and Ben Hamilton who provided excellent research assistance throughout this process and contributed to many aspects of the work, particularly the ecological modelling for the Coorong and the development of the indicator sets.

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Executive summary

An environmental water requirement for the Coorong, Lower, Lakes and Murray Mouth (CLLMM) region was developed based on ecological first principles. In line with the South Australian Department of Environment and Natural Resources (DENR)'s stated goal for the region that it be maintained as a healthy, productive and resilient wetland of international importance, we have described eight ecological objectives and 33 ecological outcomes that are associated with healthy, productive and resilient wetlands, based on ecological theory.

In a pristine wetland ecosystem, the ecological character of a wetland will be determined by the hydrology of that system. In a highly-modified system, where a return to without-development conditions is not practical, such as the CLLMM, the parts of the flow regime required to support the desired ecological character must be identified and preserved in order to maintain that ecological character. Therefore, we compiled a comprehensive list of taxa, assemblages and ecological processes that would occur in the CLLMM region under the Ramsar-nominated ecological character. This list was then linked to the ecological objectives and outcomes, and the flow-related requirements (including water quality, water level, connectivity and return frequencies for flooding and barrage flows) for each were assessed from the literature. Based on these requirements, we identified several possible salinity targets for Lake Alexandrina. Hydrological modelling showed that salinity in Lake Alexandrina was the variable that required the most flow to support in the long term, compared with the maintenance of lake levels or connectivity. Thus, if flows were sufficient to meet the salinity targets for Lake Alexandrina, other targets, such as those associated with water levels or barrage outflows, should also be met. Three qualitative targets for salinity in Lake Alexandrina were explored: an annual mean of $700 \mu\text{S cm}^{-1}$ electrical conductivity (EC); an annual maximum of $1000 \mu\text{S cm}^{-1}$ EC; and an annual maximum of $1500 \mu\text{S cm}^{-1}$ EC.

Flow sequences into Lake Alexandrina were explored using hydrological modelling to develop rules for the amount of additional flow needed to maintain salinities at or below the specified thresholds. In order to objectively compare between years in the modelled sequence, inflows needed to be adjusted so that the proportion of total flow over each year was standardised per month (i.e. to provide a fair comparison). This normalisation of inflows had a minimal effect on the predicted salinities of Lakes Alexandrina and Albert. An assessment of the effect of large inflows showed that the 'memory' of the system regarding flows was quite short; approximately three years. That is, large flows had the ability to lower the salinity of the system for up to three years, after which they began to rise again. Thus, rules were developed to specify the minimum volume of water needed to pass over the barrages (thus flushing salt from Lake Alexandrina) over a three-year period. In order to maintain salinities in Lake Alexandrina at less than an annual maximum of $1500 \mu\text{S cm}^{-1}$ EC, additional flow was required in 18 out of 117 years. The increase in average annual flow required was 790 GL per year under an historical climate. For the lower salinity targets of 1000 and $700 \mu\text{S cm}^{-1}$ EC, increases in average flows of 1455 and 2535 GL were required for 33 and 65 out of 117 years, respectively.

The hydrodynamic and ecological effects on the Coorong of these changed flow volumes, resulting from meeting the salinity targets in Lake Alexandrina, were also assessed. For this process, we used objectives that sufficient water be delivered to prevent degraded ecosystem states and that the Murray Mouth remained open naturally in 95% of years, and that an ecosystem state associated with high flows occurred at least as often as it had historically. We discovered that the alterations to the flow delivery regime had a substantial impact on both the hydrodynamics and ecosystem states of the Coorong, meaning that any improvements in ecological condition were likely to be dependent on the manner in which flows were delivered to the Coorong, as well as the volume that was delivered. The additional water specified to support salinity targets in Lake Alexandrina (i.e. from the hydrological modelling) affected the maximum salinity within the Coorong most

dramatically, with additional improvements in water level and depths throughout the system. The degree of improvement increased as more-severe climate change scenarios were considered (but the amount of additional water required to maintain the targets also increased). However, none of the scenarios investigated resulted in hydrodynamics or distributions of ecosystem states that approximated those predicted under natural (or 'without development') conditions. The predicted mix of ecosystem states was very similar under flows to maintain targets of either 1000 or 700 $\mu\text{S cm}^{-1}$ EC in Lake Alexandrina, although achieving the lower target (i.e. 700 $\mu\text{S cm}^{-1}$ EC) was required to prevent the appearance of any degraded marine-basin states in the Coorong. However, a more-detailed analysis of the effects of flow delivery timing is required to ensure that the desired ecological outcomes are achieved in the Coorong. Analysis using the ecosystem states model demonstrated that flows of this magnitude maintain the Murray Mouth sufficiently open to allow for ecologically-meaningful connectivity between the Coorong and the ocean.

An additional investigation of the low-flow requirements for the Coorong demonstrated that the volumes sufficient to meet the target of 1000 $\mu\text{S cm}^{-1}$ EC in Lake Alexandrina (or the lower target of 700 $\mu\text{S cm}^{-1}$ EC) were sufficient to limit ecological degradation in the Coorong. A similar analysis of high-flow requirements, however, showed that these were not satisfied by any of the proposed sets of minimum-flow delivery rules. Instead additional flows of 6000 and 10 000 GL year⁻¹ were required. In the absence of better data on which to recommend the frequency with which these flows are required, we recommend that they be maintained at their current frequency (of every 3 and 7 years, respectively).

Thus, we identified a set of flow-related objectives for the CLLMM region, in order to maintain the Ramsar-nominated ecological character as:

- A maximum salinity of 1000 $\mu\text{S cm}^{-1}$ EC in Lake Alexandrina should be maintained in 95% of years, never exceeding 1500 $\mu\text{S cm}^{-1}$ EC (with the additional caveat that the 5% of years where this is not met not be sequential).
- An average annual salinity of 700 $\mu\text{S cm}^{-1}$ EC in Lake Alexandrina is the long-term average for that Lake and should be the target for most years.
- High flows of 6000 and 10 000 GL year⁻¹ should be maintained at their current frequency of every 3 and 7 years in the Coorong.

In order to meet the target of 1000 $\mu\text{S cm}^{-1}$ EC in Lake Alexandrina, minimum flows over the barrages in any given year should be the maximum of:

- 650 GL
- 4000 GL - F_{X-1}
- 6000 GL - $F_{X-1} - F^*_{X-2}$

where F_{X-1} is the flow volume from the previous year and F^*_{X-2} is maximum of the flow volume from two years previous or 2000 GL. Similar sets of minimum flows are also given to meet the other two salinity targets.

In addition to the flow related objectives, the flora and fauna of Lake Alexandrina require a variable flow regime. A recommended water level regime varied seasonally between 0.35 and 0.75 m AHD. Every three years, lake levels were recommended to remain higher to induce flooding of surrounding riparian zones, such that they varied seasonally vary between 0.5 and 0.83 m AHD.

The implications for Lakes Alexandrina and Albert, and for the Coorong of delivering less water than has been recommended was demonstrated under predicted median and dry future climate conditions. Without provision of a secure entitlement, salinities were predicted to rise dramatically in both lakes and in the two lagoons of the Coorong. More degraded ecosystem states were predicted for the Coorong, rising as the proportion of water delivered declined from the recommended EWR. Under these scenarios, it is highly unlikely that the Ramsar-nominated ecological character would be supported in the region in the long term

without the provision of an environmental entitlement. It is also unlikely that healthy estuarine or even hypersaline ecosystems would replace freshwater systems in the Lakes, given the rapid and extreme fluctuations in salinity that were predicted for the region. In addition, the associated degraded conditions in the Coorong would be a departure from the stated goal for the region, even if a healthy estuarine or other ecosystem did colonise Lake Alexandrina and/or Lake Albert. Further investigation revealed thresholds in the trajectory of decline, which resulted in additional degradation in water levels, salinities and ecosystem states when crossed. These thresholds were either associated with the shortfall in water prescribed by the EWR and actual barrage flows in any one year, or when EWRs were not met for more than one year, in the cumulative shortfall (or 'discrepancy') in flow volumes compared with the recommended EWR across years. These trajectories of decline can be thought of as a measure of the risk of permanent ecological damage associated with delivering less water than recommended by the EWR described here. Increasing shortfalls in the delivery of water resulted in increasing levels of risk that the Ramsar-nominated ecological character could not be supported due to increasing salinities and lowered water levels.

Finally, we investigated the potential interaction between barrage flows and an existing proposal to expand the Upper South East Drainage (USED) scheme. The USED scheme delivers water to the Coorong's South Lagoon via Salt Creek and an expansion of this system has been proposed as a part of the Long-Term Plan for the Coorong, Lower Lakes and Murray Mouth. Historical rainfall patterns along the proposed flow path (i.e. used as a surrogate for potential future flows) showed that some additional water may be available for introduction to the South Lagoon in up to half of the years in which it is most needed. Assuming additional water was available in the lowest barrage flow years, and based on proposed intra-annual and historical inter-annual delivery profiles, average additions of 18, 36 or 63 GL year⁻¹ resulted in lower maximum salinities and some improvement in ecosystem states, although there was little effect on minimum water level. As barrage flows increased, the effect of USED flows was lower. Volumes in the order of 60 GL year⁻¹ would be required to have any ongoing impact in the South Lagoon, and even then very few effects in the North Lagoon were evident. Thus, additional water from the USED scheme resulted in equivocal benefits and, as such, the River Murray must continue to be the main source of fresh water for the Coorong if the desired ecological character of the region is to persist. Further investigations into a revised scheme and changes to delivery profiles would better characterise the benefits of the proposal and any refinement that could be made to the River Murray EWR as a result.

So, in summary, this has been the first attempt to develop an EWR for the CLLMM region by linking ecological and hydrological requirements. This EWR has not been constrained by practicalities associated with current delivery infrastructure, but has simply described what we have determined to be necessary in order to maintain the region as a healthy, productive and resilient wetland of international importance. This initial EWR has also been based on the assumption that the site will be managed to maintain the Ramsar-nominated ecological character, but a similar methodology could be used to determine an EWR to maintain a different ecological character, should that be necessary. While additional modelling would be required, the methodology, objectives and outcomes are robust and transferable and, as such, this method could be applied to develop EWRs for other regions as well.

It should be noted that, while we believe that the EWR defined here will support the Ramsar-described ecological character, there are limits to ecological resilience and any large transitions in environmental conditions should occur gradually. This is especially applicable to the recent degraded condition of the region, and thus any rehabilitation actions (including the addition of large volumes of fresh water) should proceed gradually, allowing time for the ecosystem to adapt. Recovery interventions that have the potential to result in rapid change should be carefully planned, managed and monitored in accordance with the adaptive management framework for the region in order to avoid unintended negative consequences.

There are a number of limitations to the current work that should be acknowledged. The amount of information available for relating the various indicators to our ecological outcomes varied substantially. Taxa and processes likely to be indirectly affected by flows (e.g. birds in particular) have not been included. Data relating to some groups (e.g. zooplankton) have not been collated for the site, and thus could not inform this EWR. Additional information regarding process indicators and their links to hydrological conditions is also currently required. In addition, we have based our assessment of the flow-related thresholds on previous studies. Information for many of the variables of interest (e.g. turbidity) was not available for many taxa, assemblages and processes. Most available studies considered the various hydrological conditions separately (e.g. salinity, flow, water levels), and few studies considered the effects of multiple factors simultaneously. Despite this, these factors will certainly interact in a wetland complex such as the CLLMM region, and tolerances to multiple stressors will almost certainly be lower than for single stressors. Thus, we took a cautionary approach, whereby the targets set were clearly within the tolerances of the majority of indicators for single stressors. Finally, in developing this EWR, we have made use of existing tools for the region. The use of modelling has meant that the various targets could be objectively compared against the same benchmark and the relative impacts of each assessed. In this way, the recommended EWR is defensible and relatively robust. However, additional work is needed by suitable local experts to qualitatively assess the EWR from the perspective of individual key taxa (or other criteria) that have not yet been considered. This will ensure that other requirements that may have been overlooked in this broad-scale assessment are captured for individual matters of national environmental significance.

This EWR represents a first attempt to define a flow regime that seeks to support the desired ecological character of the region. One of the first opportunities to implement this is via the Murray-Darling Basin Authority's (MDBA) Basin Planning process, which is currently underway. Thus, through the South Australian Government this information has been provided to the MDBA. We will continue to collaborate with the MDBA as the Basin Planning process progresses, as much as is possible, to assist them in understanding the consequences of their proposed water recovery targets and watering plans for the region.

To this end, we have also identified a list of future activities that should be undertaken, both immediately to improve the robustness of the EWR reported here, but also over time to incorporate this information into the management of the site. Some of these activities have commenced, and others will occur in the coming months. As a part of the adaptive management of the region, we anticipate that this EWR will continue to be refined through time, as we better understand the links between flow and ecological character of the CLLMM region.

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1. Introduction

Specification of environmental water requirements is a complex task that requires an objective assessment of the ecological benefits of competing environmental watering plans. In the past, attempts to develop environmental water requirements for wetlands have often been based on hydrology, where a particular aspect of an historic hydrograph is restored or specific conditions favouring one taxonomic group are achieved (e.g. for fish spawning; see examples within Arthington & Pusey 2003). While strategies have been proposed that take a whole-of-ecosystem approach (e.g. see Thoms & Sheldon 2002), to date many of these have tended to lack explicit links between hydrodynamic and ecological outcomes. We reviewed a number of methods that have been used in the past to develop environmental water requirements, but no one method suited the task at hand. Thus, we developed a composite method, using the most-applicable aspects of a range of existing methods, in order to take advantage of the tools at hand, but also operate within the resource constraints set.

The Coorong, Lower Lakes and Murray Mouth region is a Ramsar Convention-listed Wetland of International Importance, and is one of six identified Icon Sites in the Murray-Darling Basin as determined by the then Murray-Darling Basin Commission (DEH 2000). The CLLMM region meets eight of the nine criteria specified by the Ramsar Convention for determining Wetlands of International Importance (while its status against the ninth is unknown due to a lack of data but the region is likely to qualify; Phillips & Muller 2006). Over the last five years in particular, reduced freshwater inflows from the River Murray have had significant negative impacts on the region as a whole, with increasing salinities, decreasing water levels and the threat of large-scale acidification precluding the presence of healthy aquatic ecosystems. According to the most recent South Australian State of the Environment report (Mudge & Moss 2008), the current condition of the Coorong has been the worst ever recorded. The ecological effects of recent barrage flows have yet to be quantified although some recovery has been reported.

Despite the recent poor condition, investigations into the likely future of the region under climate change (based on current water-sharing arrangements) clearly indicate that the recent drought was highly unusual and will remain so, even under severe climate change scenarios (CSIRO 2008). Thus, the potential for the region to have a freshwater-driven future is good, as is the potential for recovery in the medium to long term, provided the current situation is managed with care. Therefore, we have started from the assumption that maintenance of the Ramsar-listed ecological character of the region (Phillips & Muller 2006) is, in fact, possible. This is consistent with the approach currently being taken by both State and Federal Governments for the region (e.g. see DEH 2010).

The Lower Lakes are the largest permanent lakes in South Australia, covering approximately 400 km² across Lakes Alexandrina and Albert (Figure 1). The majority of freshwater inflows to the region are from the River Murray (Phillips & Muller 2006). In addition, freshwater inputs come from several other tributaries (of which the largest are the Finnis River and Currency Creek), groundwater and rainfall (DEH 2000). Lake Alexandrina is the larger of the two lakes, and is connected to Lake Albert via a narrow channel. Lake Albert is a terminal system, with Lake Alexandrina supplying the majority of inflows. Lake Alexandrina is artificially separated from the Coorong, the estuary of the Murray Darling Basin, by a series of barrages that can be operated to control the flow of water between the Lakes and the Coorong.

The Coorong is a long, shallow, lagoonal system that stretches approximately 110 kilometres in a south-easterly direction (Figure 1). The Coorong has a single connection to the Southern Ocean near its northern end called the Murray Mouth and is separated from the ocean by two narrow sand peninsulas; Sir Richard and Younghusband Peninsulas. Having its major source freshwater inflows (i.e. through the barrages) located towards the same end as the Murray Mouth makes the Coorong an inverse estuary rather than the more-usual configuration of fresh inflows at one end and connection to the sea at the other. Therefore, environmental conditions result in a natural gradient from usually-estuarine conditions around

the Murray Mouth through to hypersaline conditions in the South Lagoon. A second, much smaller source of fresh water, Salt Creek, discharges diversions from the South East of South Australia (via the Upper South East Drainage [USED] scheme) into the southern end of the South Lagoon.

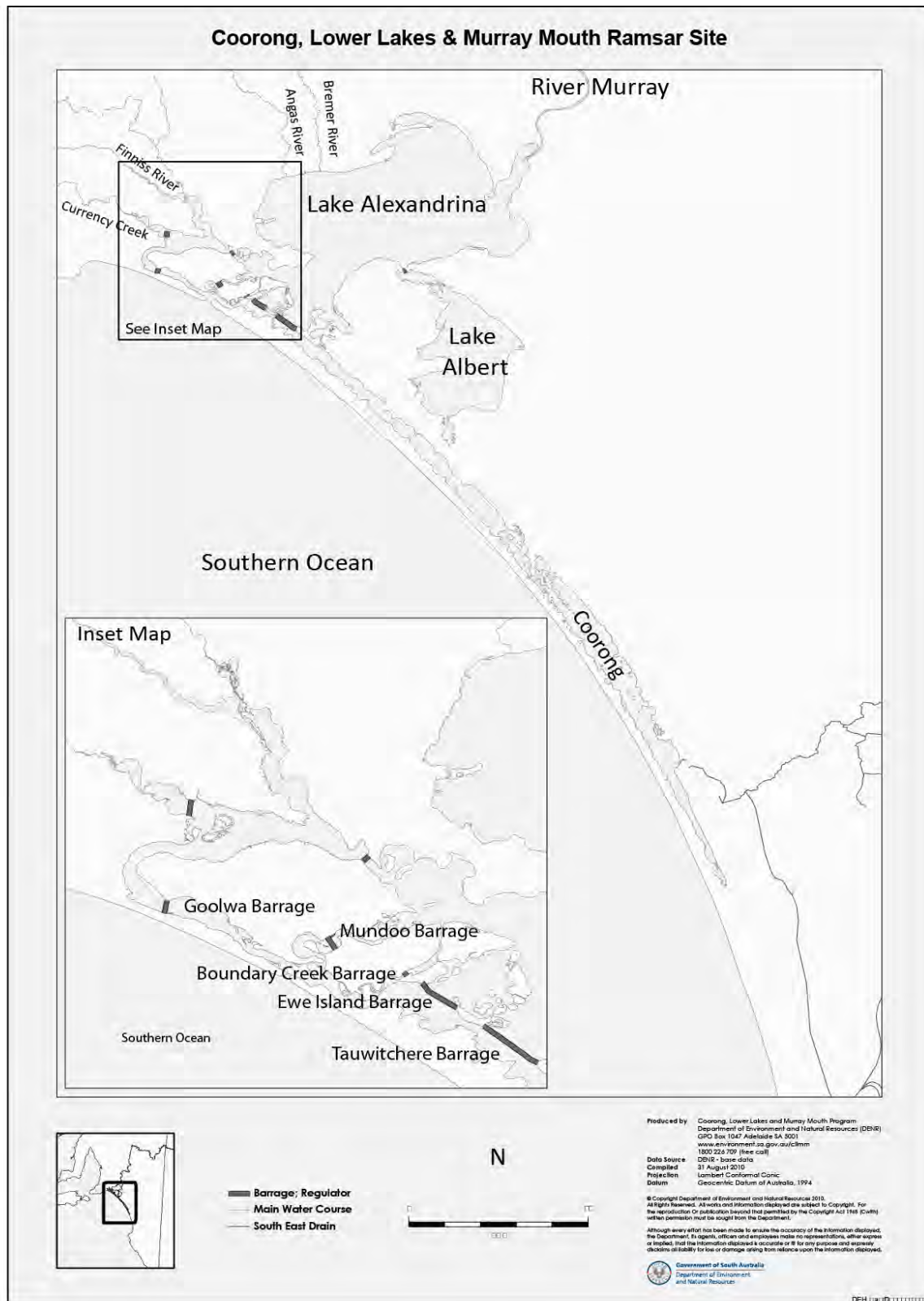


Figure 1: Map of the CLMM region illustrating primary water sources and permanent flow regulation structures (source: Felicity Smith, DENR)

This document summarises the work that has been done to date to develop an environmental water requirement (EWR) for the Lower Lakes and Coorong Ramsar site. Additional detail for each component of the work has been prepared separately, and these documents have been referenced where relevant herein. The document presents a summary of the methodology developed to determine an EWR for this region, the ecological objectives and outcomes that indicate that the region is a healthy, productive and resilient wetland of international significance, and the various indicators for each of these outcomes. A summary of how these indicators were then linked to hydrological parameters such as water levels, salinity and return frequencies of flows is then presented. Finally, the results of modelling to determine what volumes of environmental water are required from the River Murray to meet these hydrological conditions are presented. The implications of the work to date are discussed and synthesised, and a discussion of the limitations of the work is also presented. Terms that may be new to non-scientific readers are defined in Appendix A.

This work to determine an EWR for the Lower Lakes and Coorong does not attempt to address recovery from the recent degraded condition of the region, but rather focuses on longer-term water requirements in order to meet the current management vision for the site. It attempts to identify an EWR that will support and enhance the ecological character of the whole of the system. At present, the desired ecological character is described by the Ecological Character Description (ECD) for the region (Phillips & Muller 2006), but the method used and the data collated on various indicators are also applicable in the event that climate change or management within the Murray-Darling Basin (MDB) make the goal of restoring that ecological character impossible and another goal were selected (either now or in the future).

Additional work will be required in the future to continue to refine this environmental water requirement and to operationalise much of the information contained herein. For example, further work is needed to refine the indicator sets presented here and to set limits of acceptable change that will allow for an assessment of the success of the EWR in maintaining or enhancing the ecological character of the region. As new management actions are proposed (e.g. refinements to the proposed USED expansion), additional modelling may also be required to determine any interactions with the EWR described here. Finally, additional work is needed to determine how best to incorporate these findings into policy.

1.1 Summary

- **Robust environmental water requirements should be developed with explicit links between hydrodynamic and ecological outcomes.**
- **The Coorong, Lower Lakes and Murray Mouth region is a Ramsar-listed Wetland of International Importance and an environmental water requirement is needed to maintain its Ramsar-nominated ecological condition.**
- **This report summarises work done to develop an environmental water requirement for the CLLMM region that will support Ramsar-nominated ecological character in the long term.**

2. Methodology for developing a robust environmental water requirement for the CLLMM region

Previous attempts to determine environmental water requirements for the CLLMM region have been based on the best available knowledge at that time and have taken the form of a single value or combination of volumes (e.g. the volumes described to inform modelling undertaken for The Living Murray initiative; MDBA 2009a). These have been indirectly linked to ecological outcomes but have not been directly tested, so tradeoffs have not been fully articulated. Recommended volumes for barrage flows arising from those assessments have varied but include flows of between 1950 and 4000 GL of additional flows for the River Murray as a whole (Jones *et al.* 2002) and a mean annual target of 5365 GL as a barrage outflow to support the CLLMM region (Kingsford *et al.* 2011).

The methodology used here to determine a robust environmental watering regime attempted to address limitations associated with previous estimates by using tools and information garnered from recent research in the region (e.g. by the CLLAMMecology Research Cluster; Brookes *et al.* 2009). It was based on aspects of previous methods used to develop EWRs elsewhere, where they were most applicable (e.g. Ecological Limits of Hydrologic Alteration [Poff *et al.* 2010], Building Block method [King & Louw 1998]), and modified them to take advantage of the available tools for the CLLMM region.

The following tasks were used to identify an environmental water requirement for the CLLMM region:

1. Describing a healthy, productive and resilient wetland of international importance (Step 1; Figure 2)

Current planning for the CLLMM region sets a goal of maintaining the system as a “healthy productive and resilient wetland system that maintains its international importance” (DEH 2010; p. 84). Such a general statement requires additional definition before it can be used in the context of describing an environmental water requirement. Thus, a series of ecological objectives and associated outcomes were identified that would constitute a healthy, resilient wetland of international importance, based on ecological first principles.

2. Identification of indicator taxa and processes (Step 2; Figure 2)

The available literature for the region, along with expert opinion in some instances, was compiled to identify locally-relevant indicator taxa, assemblages and processes for each of the ecological outcomes identified in Task 1. Where taxa and assemblages were selected, these focused on those that could be considered:

- key species or assemblages in the region;
- ‘canary’ species or assemblages (i.e. sensitive species that are likely to be early indicators of change); or
- threatened species or assemblages as matters of National Environmental Significance (as defined by the Commonwealth Environment Protection and Biodiversity Conservation Act, 1999 [EPBC Act]).

3. Identification of critical thresholds for indicator processes and taxa (Step 2; Figure 2)

The literature utilised in Step 2 was also used to identify the critical thresholds of each of the indicator taxa and processes identified in that step. Critical thresholds were identified, where possible, for:

- water quality;
- flow regime;
- connectivity; and
- water levels (including links to water quality and connectivity).

This allowed the identified indicators of ecological condition to be directly related to the hydrodynamics and flow regime of the Lower Lakes and Coorong and explicit trade-offs to be explored regarding the effect of different values of each parameter. Based on this process, and the historical condition of Lake Alexandrina and other similar freshwater lakes, targets were set for use in hydrological modelling in the Lakes and Coorong.

4. Exploration of flow regimes to meet water quality, quantity and flow targets (Step 3; Figure 2)

Hydrological modelling used the historical flow record from the River Murray and existing models for the Lakes and Coorong to explore the various flow regimes and likelihood of meeting the targets identified in Step 3. Flow sequences required to maintain the salinity targets, and thus water levels, were also explored.

5. Exploration of the ecological implications of that flow regime for the CLLMM region (Step 4; Figure 2)

Outputs from the hydrological modelling were then used to assess the ecological implications of the recommended flow regime for the ecology of the CLLMM region. This assessment was qualitative for the Lakes, but quantitative for the Coorong, where an ecosystem states model (Lester & Fairweather 2011) was available for use. This modelling, in conjunction with the modelling undertaken in Step 3, was used to develop rules for the minimum delivery of water to the Lakes and Coorong, and of flooding flows for the Coorong.

6. Identifying the implications of smaller flow volumes (Step 5; Figure 2)

The results of the hydrological modelling were also used to identify the implications of smaller flow volumes or longer annual return frequencies than the recommended flow regime identified in Step 4 (Figure 2). Thresholds in the trajectory of decline were identified that could be used to approximate the level of risk associated with setting lower EWRs than recommended. These were based on salinities, water levels and ecosystem states. For other ecological implications, a similar approach to that identified in Step 5 was followed, explicitly highlighting the likely differences in ecological character arising from smaller flow volumes.

7. Identifying the likely effects of climate change (Step 5; Figure 2)

The likelihood of delivering the recommended flow regime, and several smaller volumes, under a number of future climate scenarios was explored. The implications of these climate scenarios on the desired ecological character were explored as well as implications for management options for the region, in the manner identified in Step 5 (Figure 2).

8. Identifying the likely interaction with USED flows (Step 5; Figure 2)

Interactions with the proposed expansion to the USED scheme were explored. This involved assessing the likelihood that additional water from the South East would be available in years when barrage flows were low and the impact of a range of average volumes on salinities, water levels and ecosystems states in low, medium and high barrage flow years.

9. Synthesis of findings

This summary and synthesis report has been produced to synthesise the findings of this investigation, and to highlight the implications and limitations of the work. Explicit links between the methodology used here and other ongoing approaches elsewhere in the Basin (e.g. the Aquatic Ecosystem Taskgroup and the Basin Plan requirements) have yet to be drawn, although these linkages are currently being explored. Future steps to improve the recommended environmental water requirement have also been identified.

Figure 2 summarises the methodology used to determine an EWR for the CLLMM region of each step, each of which is described in more detail in the following sections.

Throughout this process, regular meetings were held with a project reference panel comprising representatives from several relevant South Australian Government departments. Members of the reference panel included: Di Favier (DfW); Lisa Mensforth (DfW); Paul Harvey (Leda Consulting); Theresa Heneker (DfW); Piers Brissenden (DENR); Louisa Halliday (DENR); Russell Seaman (DENR); Judy Goode (DfW); and Heather Hill (DfW) or designated representatives where necessary. Through these meetings and regular reviews of the interim outputs, this SA Government project reference panel provided feedback and assistance with the development of the rationale and review of the project team's findings.

Additional detail regarding the methodology used for the determination of an environmental water requirement for the CLLMM region can be found in the associated report by Lester *et al.* (2011a).

2.1 Summary

- The method applied to develop an EWR for the CLLMM region attempted to explicitly link flow volumes to ecological outcomes in the region and was based on a range of previously used methods.
- This method used ecological first principles to describe the ecological objectives and outcomes associated with the goal of sustaining a 'healthy, productive and resilient wetland of international importance' and then linked these to the flow-related requirements of indicator taxa, assemblages and processes.
- Thresholds for salinity in Lake Alexandrina were modelled to determine rules to meet the desired conditions in the region.
- These rules were then modelled for the Coorong to assess their effects for those management units and the effects of climate change, lower flow volumes and interactions with the USED scheme were explored.

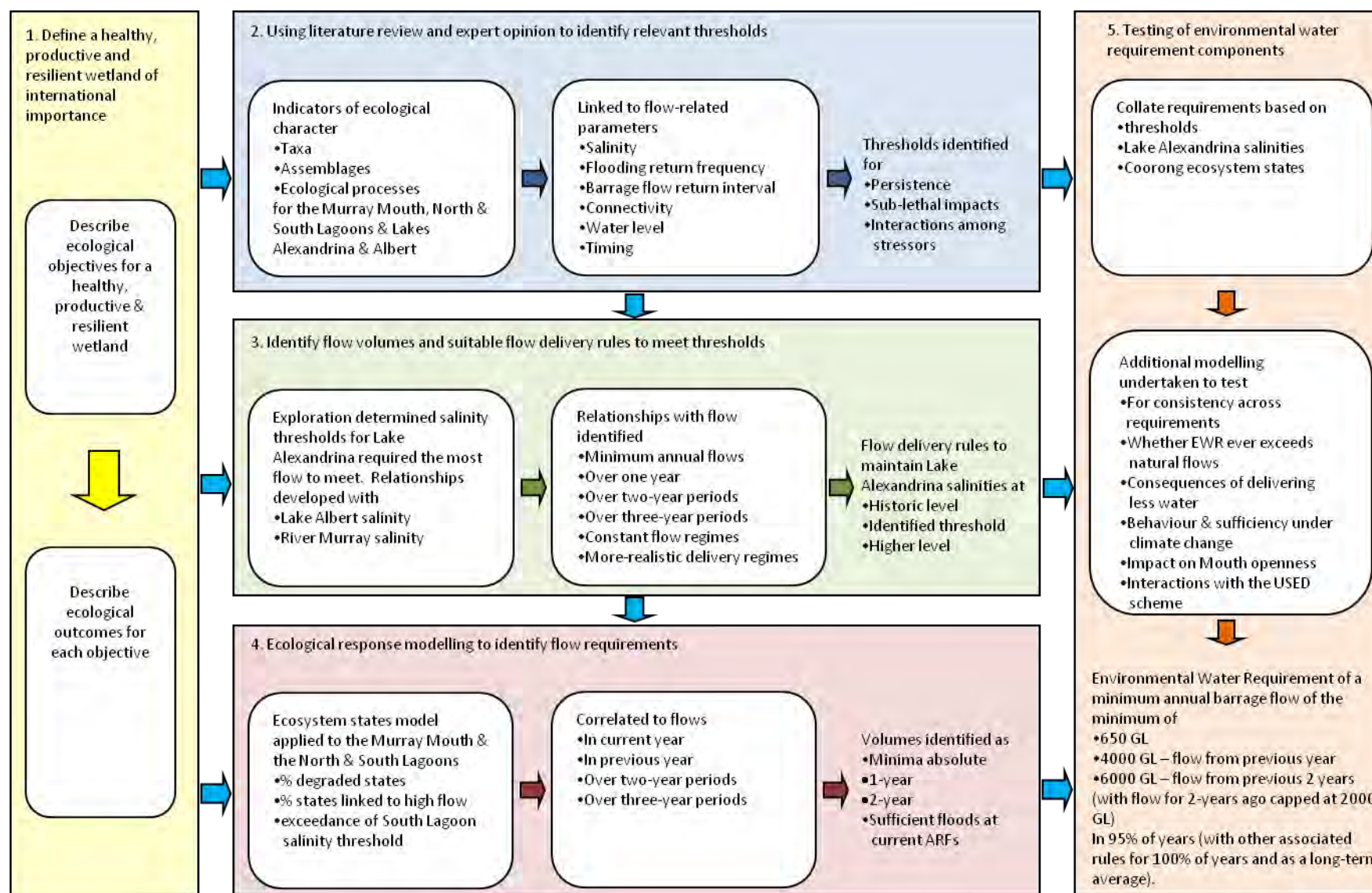


Figure 2: Summary of the methodology used to determine an environmental water requirement for the CLMM region

3. Ecological objectives and outcomes associated with a “healthy, resilient wetland of international importance”

In order to evaluate the water needed to meet the goal of maintaining a healthy, productive and resilient wetland of international importance, this goal needed to be converted into more-specific ecological objectives for the CLLMM region. Given that the broad management strategy for the site was based on maintaining the Ramsar-nominated ecological character (Phillips & Muller 2006), these objectives were based on the ecological first principles of what would constitute such a wetland. These were initially discussed and developed from a workshop in May 2009 involving local researchers and refined further by the project team. Each identified objective was then associated with several outcomes, which represented conditions within the region that would signify that the associated objective had been achieved and could be measured based on links between the physical, chemical and biological conditions in the region.

In developing these objectives and outcomes, we deliberately focused on the ecological processes and attributes that should occur within a site, rather than specifying particular taxa or wetland types (ecological components) that should be present. Specifying particular taxa or wetland types limits the utility of this method to the current ecological character. By focusing on ecological processes and attributes more generally, the site could potentially be managed based on these objectives regardless of the desired ecological character, in the event that that changed through time. Given the uncertainties regarding climate change and the management of the Murray-Darling Basin, the current target of restoring Ramsar-listed ecological character may not be possible in the long term, so a mechanism was needed by which a healthy, productive and resilient wetland could be defined even if that were not the same healthy, productive and resilient wetland (i.e. with the same ecological components) that was originally described. This decision was taken in light of the need to develop management plans for the region that would be applicable in the long term (DEH 2010).

3.1 Ecological objectives and associated outcomes

A description of, and rationale for, each of the eight identified objectives can be found in Lester *et al.* (2011a). Also in that document are the formal scientific definitions of each of the objectives. Much of the ecological theory that has been drawn on in developing these objectives (and their associated outcomes) is summarised in Boulton & Brock (1999), Edgar (2001) and Closs *et al.* (2004), but additional references are also given in Lester *et al.* (2011a). The following list is presented with a non-scientific audience in mind, and while many of the concepts are linked, each objective focuses on a unique aspect of what we believe constitutes a healthy, productive and resilient wetland of international importance. The definitions include references to ‘management units’ within the CLLMM region. These are: the Lower River Murray; Lake Alexandrina; Lake Albert; the Goolwa Channel; the Murray Mouth region; the North Lagoon; and the South Lagoon (Figure 1).

Simply put, the ecological objectives for the CLLMM region are that:

1. the region supports a range of taxa that persist without major and/or ongoing management intervention;

This objective specifies that a range of taxa should have the conditions and resources (e.g. habitat and food) that they require to survive naturally in the region in the long term.

2. a range of taxa are able to successfully breed and recruit in the region without interruption;

Successful reproduction and recruitment (i.e. breeding but also the successful growth of new individuals) in a region can be prevented by physical barriers (e.g. closed barrages can prevent fish passage necessary to complete their life cycle) but also by temporal barriers (e.g. droughts that extend beyond the lifespan of individuals or seed banks) or seasonal barriers (e.g. changes to the pattern of water delivery may mean that flooding occurs outside of the breeding season for floodplain biota). Thus timing and connectivity are important to ensure that successful recruitment occurs.

3. water links the various habitats and management units at the site;

A key feature of a healthy wetland is that all parts of the system receive water periodically and that water passes through, carrying nutrients, carbon and pollutants including salt. This objective focuses on the link between the River Murray, the CLLMM region, its tributaries, the South East of South Australia and the ocean.

4. a range of habitats exist within the region;

This objective seeks to maintain the range and variability of different habitats that exist in the CLLMM region and are largely responsible for the variety of biota found there.

5. a suitable salinity gradient is maintained across the site;

Another factor in the diversity of biota found in the CLLMM region is the range of conditions, from freshwater to estuarine to hypersaline in different management units at the same time. This objective seeks to maintain that range.

6. both flows and water levels vary through time;

The River Murray traditionally has extremely variable levels of flow and the biota of the CLLMM region (and elsewhere) is adapted to this variability. Therefore, a healthy wetland requires sufficient variability in water level and flows to maintain biotic diversity.

7. a variety of ecological functions are supported at appropriate levels; and

Healthy wetlands typically have more than one taxon that performs any one function (e.g. more than one taxa that breaks down organic matter) and are not dominated by a small number of very abundant taxa (e.g. invasive taxa or very tolerant and weedy taxa). This objective seeks to ensure that an appropriate mixture is maintained.

8. links exist between aquatic and terrestrial ecosystems.

This final objective focuses on connections between aquatic and terrestrial ecosystems that provide a source of food, habitat and a pathway for dispersal for many taxa.

Between two and six ecological outcomes were identified for each of these eight objectives. As an example, the first objective, of having the region support a range of taxa that persist without major management intervention, was linked to the following outcomes:

- I. Locally-breeding taxa successfully complete their breeding cycle often enough to sustain the population;
- II. Suitable habitat exists for breeding, feeding, shelter and development of individuals to accommodate all life stages (e.g. both larvae and adults);

- III. Suitable food resources exist for a variety of taxa; and
- IV. Water quality is within the tolerance ranges of all life stages for a variety of taxa for the majority of time.

A total of 33 outcomes were identified across the eight objectives, providing a comprehensive and detailed description of a healthy, productive and resilient wetland of international importance. The remaining ecological outcomes can be found in Appendix B. In developing the set of objectives and their associated outcomes, a short description of each and the rationale behind their selection was developed. These are outlined in Lester *et al.* (2011a).

3.2 Summary

- **Eight ecological objectives were identified that should be met so that the CLLMM region could be considered a healthy, productive and resilient wetland of international importance.**
- **For each objective, a number of ecological outcomes were specified that would indicate that objective was being met. Thirty-three outcomes were specified in all, across the eight objectives.**

4. Taxa, assemblages and processes identified as indicators of ecological outcomes

The ecological objectives and outcomes described above define what is meant by a healthy, productive and resilient wetland of international importance from an ecological perspective. However, both the objectives and their associated outcomes are still quite general and by design, could apply equally well to almost any coastal lake or lagoon complex. Thus, they need to be linked to a suite of indicators specific to the CLLMM region in order to assess ecological condition locally.

A comprehensive assessment of the ecological character of the CLLMM region was completed in 2006, approximately 20 years after its 1985 listing under the Ramsar Convention on Wetlands (Phillips & Muller 2006). The 142 454 ha site is renowned for providing habitat for more than 1000 species including Matters of National Environmental Significance (as defined by the EPBC Act) such as wetland-dependent plants, migratory wading birds, southern bell frog (*Litoria raniformis*), orange-bellied parrot (*Neophema chrysogaster*), southern emu wren (*Stipiturus malachurus*) and several threatened fish species (e.g. Murray cod, *Maccullochella peelii peelii* and Yarra pygmy perch, *Nannoperca obscura*). Across the site, 23 Ramsar wetland types were identified, ranging from permanent and seasonal freshwater lakes and marshes, streams, estuarine waters, coastal lagoons, intertidal mudflats and forested wetlands. From the combined assessment of scientific data and knowledge of Indigenous and other long-term stakeholders, it was apparent that the site had altered markedly over time (Phillips & Muller 2006), and the decline away from its nominated ecological character has been most rapid in the years since 2006, when discharges from the barrages, and thus flow-through, ceased until late 2010 (e.g. see Bice 2010, Gehrig & Nicol 2010 and Rolston & Dittmann 2009 for descriptions of the ecological decline). Changes following the return of flows in late 2010 had not been documented at the time of writing.

In 2006, the site was found to meet eight out of a possible nine criteria for Ramsar nomination and it is likely to still meet those same criteria even though it has been significantly and adversely affected in the intervening years (an update of the ecological character to include improved knowledge and understanding of the site compiled since preparation of Phillips & Muller [2006] is forthcoming). For example, the most recent surveys (in Feb 2010; SAMDBNRM, unpub. data) of Lakes communities showed that southern bell frogs still occur in three habitats around the former lake margin. Similarly, recent bird surveys recorded 9979 individuals from 41 species in the Lakes in 2008 and 7184 individuals from 37 species in 2009, despite its relatively-degraded state. This suggested that, although significant damage had occurred, the site remained an internationally-important wetland and should be managed as such.

Given the number of species recorded in the region (>1000), any attempt to characterise ecological character within the region needed to be based on a suite of indicators, rather than a comprehensive assessment of every species (e.g. see Kremen 1992). Many indicator suites are chosen without explicitly outlining the reason for their selection or detailing the alternatives that could have been chosen (Fairweather & Napier 1998). In developing a suite of indicators, a comprehensive approach was taken. Taxa and/or assemblages were selected that were considered to be representative of the range of life-histories present within the region, with special consideration given to taxa and assemblages that were:

- likely to be directly affected by hydrodynamic parameters (e.g. water levels, water quality);
- considered to be key species or assemblages within the region (primarily based on previous research in the region or expert opinion);

- listed as threatened species and thus considered to be a Matter of National Significance under the EPBC Act; or
- considered to be sensitive to environmental change (i.e. analogous to the canary in the coalmine).

Invasive taxa were also included in the list of indicators. This was in order to be able to predict potential negative impacts of environmental water regimes, as well as positive impacts, by investigating the potential for spread (or contraction) of known pests in the region. Consideration was also given to ensure that chosen indicators were specific, measurable, achievable, realistic, relevant, time-constrained and traceable (i.e. SMART; Wilkinson *et al.* 2007).

In this first iteration, indicator taxon and assemblage selections tended to focus upon lower trophic levels or taxa that tend to be directly affected by the hydrodynamic conditions. Other taxa not included (e.g. birds) are often affected largely indirectly (i.e. through the provision of specific habitat and food resources) so these have been excluded to date. The threatened southern bell frog has also been excluded from this first iteration, but the littoral and riparian vegetation upon which it depends have been included and thus inferences on habitat availability can be made. Similarly, the threatened orange-bellied parrot has not been included but its primary habitat and food resource at the site, samphire communities, have. Future work would seek to address these indirectly-affected taxa or assemblages.

In addition to including taxa or assemblages as indicators, ecological processes were also selected. These were included to address common problems associated with taxa-specific indicators (e.g. that choices are poorly-justified, research can be expensive, that the loss of a single taxon is not always a negative occurrence within a region; see Simberloff 1998). Process-based indicators tend to integrate responses across many taxa, to provide an understanding of ecosystem function and resilience. By using a combination of taxon- or assemblage-specific and process-based indicators, a balance can be achieved between conservation of particular taxa and the provision of a functional, productive and resilient wetland.

4.1 Linking indicators to hydrodynamic properties

In order to link this list of indicators to a recommended flow regime for the region, the response of each to flow-related variables was explored using literature reviews and expert opinion where no literature was available. The functional group, location and lifespan of each taxon or assemblage were identified. For all indicators (including processes), the relationship with the following variables were documented, wherever possible:

- salinity;
- turbidity;
- barrage flows or floodplain inundation (as an annual return frequency);
- connectivity;
- water levels; and
- timing of flows or water levels.

By identifying the thresholds and requirements of each indicator with respect to these hydrodynamic properties, the trade-offs associated with different flow regimes could be explicitly identified and recommendations made regarding the impact different targets for water levels and salinity thresholds for various components of the region.

Success in identifying the information varied widely across the different indicators. Some indicators were well-studied with very precise information regarding their tolerances. Others had detailed information for some tolerances but not others, and some were poorly understood and very little information was available. An important note is that some salinity tolerances, in particular, are based on salinities at which organisms or processes have occurred in the field, while others are based on

toxicological studies performed in the laboratory. In the latter case, values tend to be LC50 values (Lethal Concentration 50%) which is where 50% of the test population are dead. Clearly this represents a much higher risk to the population than would usually be considered acceptable in practice, so care needs to be used when setting targets based on those values.

4.2 Linking indicators to ecological outcomes

One of the assumptions of the work was that this suite of indicators would enable adequate evaluation that each of the 33 identified ecological outcomes (and thus the eight ecological objectives; Lester *et al.* 2011a) were met within the region. Published knowledge regarding the response of each set of indicators (i.e. vegetation, fish, invertebrate and process indicators) was compared with each of the outcomes. Detailed comparative tables and the rationale derived during this process can be found as appendices to Lester *et al.* (2011a). Findings for each set are summarised below.

Following this assessment, consolidation of the complete list of indicators is necessary, to give a shorter list of taxa, assemblages and processes that could be monitored within the site to identify ecological condition.

4.2.1 Vegetation indicators

Water regime (e.g. water levels, timing, duration) is a key driver of the occurrence of plant communities in wetland ecosystems, and the regulation and thus homogenisation of the water regime in the Lower Lakes region has led to the contraction and/or loss of plant taxa (Gehrig & Nicol 2010). Some of the selected vegetation taxa and assemblages currently occur at the site. Other vegetation taxa that no longer occur at the site or in their previous habitats are also considered as possible future indicators where they are likely to re-colonise (e.g. water milfoil, *Myriophyllum* spp. and sea tassel, *Ruppia* spp.) or regenerate from underground parts (e.g. reed beds), although the likelihood of this re-colonisation depends on the timing of recovery and the implementation of management interventions. Pest taxa (i.e. spiny rush, *Juncus acutus*) were also included as an indicator of decline in vegetation assemblages. The ten vegetation indicators covered a range of possible aquatic vegetation from the terrestrial edge of the floodplain to the lower edge of the euphotic zone (i.e. depth within which light penetrates the water column) in the CLLMM region. The usefulness of such taxa and assemblages as indicators were assessed for each of the 33 identified ecological outcomes, including temporal and spatial self-sustainability and connectivity, provision of ecosystem function and services, and responses to water regimes and quality.

The vegetation indicators as a group are potentially very useful for providing evidence for the achievement of long-term self-sustainability of populations, providing evidence that habitat and food sources were available. At least some indicators were also thought to provide excellent evidence that populations are connected (i.e. both temporally and spatially), a salinity gradient is maintained and that flow and water level variation is maintained, due to the general longevity and position of the vegetation taxa and assemblages (i.e. occasional recruitment and transition from aquatic to terrestrial habitats). For those outcomes for which the vegetation indicators were considered very or moderately useful, the most common metrics suggested were abundance (either as shoot density, propagule density or percent coverage), distribution, and recruitment events.

Finally, the vegetation indicators were considered least useful in providing evidence for individual outcomes such as whether a tidal signal was apparent and that regular oxidation of sulfidic material (which is a product of acid sulfate soils) occurs. The ecological objectives of hydraulic connectivity, habitat complexity and ecological function were unevenly indicated by the various vegetation indicator taxa and assemblages. Some indicators were able to provide evidence for these objectives,

but others were not. Where vegetation indicators were considered less useful, this was because: (a) they were not considered to indicate functions performed by multiple taxa on their own (i.e. a process or assemblage-wide indicator would be more useful); (b) they did not indicate the presence of invasive taxa (except where an indicator was invasive or tended to resist invasion); or (c) because their position at the site (i.e. usually at higher elevations) made it difficult for them to represent the site as a whole (e.g. the effects of long hydraulic residence times).

4.2.2 Fish indicators

Flow regime, physicochemical drivers (e.g. salinity) and connectivity are considered important drivers of the composition of fish assemblages in the region (Bice 2010). Fish species are highly mobile, often moving between habitats for feeding, shelter, at different reproductive stages and to avoid unfavourable conditions (Lucas & Baras 2001). The 17 identified indicator species cover the range of salinity gradient tolerances (i.e. freshwater, estuarine and marine) and site usage (i.e. migratory or resident). Pest species (e.g. European carp *Cyprinus carpio*) were also included in the fish species as an indicator of decline in site conditions and/or fish communities.

The fish indicators as a group are potentially useful for providing evidence for the achievement of the objectives of long-term self-sustainability, particularly in relation to successful recruitment, suitable habitats and food resources. This is primarily due to the mobile nature of fish species, whereby their presence and persistence indicates favourable conditions (e.g. salinity gradient, associated vegetation or habitats and food resources). Fish also tended to be useful indicators of outcomes relating to hydraulic connectivity, particularly in relation to longitudinal biological connectivity (i.e. exchange of energy, nutrient and carbon within and through the system). The indicator species were moderately useful for identifying where outcomes related to redundancy and appropriateness of ecological function (in relation to the complexity of food webs and presence of acid- and saline-tolerant species) and the maintenance of a persistent salinity gradient at the site. The most common metrics suggested where fish indicators were considered very or moderately useful were abundance, population demographics (e.g. size and age distributions of populations) and recruitment events (e.g. presence of young of year).

In contrast, the fish indicators were least useful in providing evidence for the achievement of outcomes relating to ecological function, in particular the functions performed by multiple species, efficiency of nutrient cycling and the control of invasive species. Variability in flow and water levels were also outcomes which the fish indicators as a set were least useful in providing evidence for. It is possible that this finding is because fish tend to be indirectly affected by changes in habitat diversity (partly as a result of their ability to move from adverse conditions), provided appropriate connectivity exists, as well as knowledge limitations in regards to behaviour responses to changes in flow for many of the species examined.

4.2.3 Invertebrate indicators

Invertebrates have long been used to detect change in water quality, quantity, flow, substrate quality, contamination (including via heavy metals) and management intervention (e.g. Rosenberg & Resh 1993, Wilson 1994, O'Sullivan 2005). The selection of a variety of marine, freshwater and estuarine indicator taxa within this section drew on knowledge derived from the literature and expert opinion, regarding details on the life-history characteristics and habitat preferences of each indicator, and provided an overview of the types of outcomes for which each of the various biota tended to be useful. One of the main limitations in using macroinvertebrates as indicators for the CLLMM region was the lack of specific knowledge and local data, particularly in the Lower Lakes. Thus, much of the rationale for this section was drawn from research and management undertaken elsewhere in comparable systems.

Macroinvertebrates were considered to be very good indicators of self-sustaining populations and for indicating that a range of suitable habitats (e.g. freshwater or estuarine) and food sources exist within the region. Numerous macroinvertebrate taxa were good indicators for water quality (due to often well-defined salinity tolerances) and so were also good indicators of a persistent salinity gradient.

Macroinvertebrate indicators were moderately useful for identifying where outcomes related to population connectivity (e.g. physical barriers to connectivity inhibiting distribution of taxa), hydraulic connectivity, flow and water level variability (e.g. some taxa are sensitive to variable flow speeds or are intolerant of flooding without refugia) and redundancy and appropriateness of ecological function (e.g. sheath-winged and sclerotised insects and taxa without an impermeable exoskeletons can be affected by increasing acidity) were achieved. Where macroinvertebrate indicators were considered very or moderately useful, the most common metrics suggested for measurement were distribution, abundance, evidence of recruitment, and composition of macroinvertebrate assemblages.

Macroinvertebrates were considered less useful for indicating temporal and spatial variability through a range of aquatic and terrestrial habitats (including habitat complexity), as well as being poor indicators of aquatic-terrestrial connectivity (including variability in water levels and mosaic of aquatic and terrestrial vegetation) because many of the selected indicators were predominantly aquatic, or little information was available related to their reliance on terrestrial systems.

4.2.4 Ecological process indicators

Ecological processes provide a mechanism for indicating the overall health and productivity of an ecosystem without the need to monitor every species that is present. This is because they tend to integrate effects across taxa. Using ecological processes as indicators can avoid common problems associated with species-specific indicators, in that monitoring tends to be less expensive, results can be easier to interpret and relationships with environmental variables are more straightforward (e.g. see Simberloff 1998). Ecological processes selected as indicators included basic ecological functions such as photosynthesis, decomposition and nutrient cycling, along with ecological responses to changing environments such as response to salinity and acid/base dynamics. In some instances, information was not available about the response of each ecological process to hydrological properties, particularly specifically for the CLLMM region. These knowledge gaps have been identified and should be the focus of research in the future.

Because of a current lack of detailed knowledge regarding how processes link to the various ecological outcomes, each process was allocated only to those outcomes for which we were sure a link existed. Based on this cautious assessment, ecological processes tended to be most useful as indicators of self-sustaining populations, and appropriateness and diversity in ecological function. Decomposition was identified as the single most useful process indicator, although all processes were indicative of at least one of the ecological outcomes. Where processes were identified as being useful indicators, the identified metrics included rates of change in the level of that process occurring through space and/or through time.

Ecological processes were moderately useful for identifying when outcomes related to population connectivity, a persistent salinity gradient across the region and aquatic-terrestrial connectivity were met. They were considered less useful as indicators of flow and water level variability across the region.

4.3 Synthesising indicators into sets for monitoring

In developing the indicator sets for use in this assessment of environmental water requirements, we took a comprehensive approach, whereby a range of key, sensitive and even invasive taxa and assemblages as well as ecological processes have been

used to develop links between the Ramsar-declared ecological character and hydrodynamics in the region.

This relatively comprehensive list (although see notes above regarding the inclusion of other taxonomic groups such as birds and amphibians) could be used as the basis for developing suites of indicators to be monitored within the region. This comprehensive list could thus be distilled to smaller suite(s) of indicators that spanned the ecological objectives and outcomes, along with any more-specific goals associated with a monitoring program (e.g. surveying EPBC-listed populations). This distillation process should focus not simply on the number of individual outcomes that a single taxon, assemblage or process was considered indicative of, but also the:

- uniqueness of the outcome set indicated (i.e. how many other possible indicators are there for each outcome?);
- relative strength of the association (i.e. how well does the indicator relate to the outcome and how many other similar indicators are needed to give a reliable assessment of that outcome?);
- reliability of the association (i.e. how well-described is the relationship between the indicator and the outcome?);
- precision of the indicator (i.e. how big a change in the indicator is necessary/significant in assessing changes in ecological character?);
- protocols that are in place for monitoring the indicator in question (i.e. is there a well-described, tested and repeatable method for measuring the indicator?); and
- practicality of measuring that indicator (i.e. how easily can the indicator be measured in the region?).

Thus, the smallest list of potential indicators (chosen based on the number of outcomes they are associated with) may not be the most useful and practical set for assessing the success of the environmental water requirements described here (or other management goals) and additional research is needed to develop a reliable set. It is envisaged that this work will commence in 2011/12, subject to funding. It is expected that the work would include the refinement of the selected set of indicators in addition to the inclusion of additional groups as a part of updating the Ecological Character Description for the site.

4.4 Summary

- **Current ecological character was represented by a comprehensive list of taxa, assemblage and process indicators including vegetation, macroinvertebrates, fish and ecological processes.**
- **The flow-related requirements (focused on water quality, levels, connectivity, barrage flows, flooding and timing) were assessed for each indicator.**
- **Links were drawn between each indicator and each ecological outcome, with rationale and knowledge gaps recorded.**
- **These indicators could be distilled into a subset that could be used to monitor the effectiveness of the EWR in achieving the stated goal for the region.**

5. Setting targets for salinities in the CLLMM region

Known tolerances of the suite of component indicators described above and historical salinity levels for the Lakes (as well as for other freshwater to brackish wetlands) were compiled to enable salinity targets to be identified for Lakes Alexandrina and Albert to form the basis of hydrological modelling to set an environmental water regime for the CLLMM region.

Salinity was identified as the water quality component that was most likely to affect the ecological character of the CLLMM region and to be best described both for the region and for the taxa, assemblages and processes identified as potential indicators. Acid/base dynamics were also likely to be important, but less information regarding tolerances to acidity was available for the region. Thus, salinity was a more conservative tracer than pH for the region. Also, salinity was relatively straightforward to model with existing hydrological tools for the region over quite long model runs (up to many decades), while acid/base dynamics are far more difficult to model accurately, and model runs would have only be possible for up to a few years at a time. Finally, the hydrology of the CLLMM region and the Lakes in particular, mean that salinity is the hydrological parameter that requires the most water to support (Section 7, Heneker 2010). Therefore, by meeting targets for salinity, it is likely that other targets (e.g. such as water level) would also be achieved, making separate targets for those parameters redundant. Thus, targets for water quality in Lakes Alexandrina and Albert were set based on salinity levels.

Once salinities reach an average of $1000 \mu\text{S cm}^{-1}$ EC for Lake Alexandrina, they approach known tolerances for some of the more salt-sensitive biota in the CLLMM region. Note that measures of electrical conductivity (EC) are not a direct measure of salinity *per se*, but are a more useful measure of the salts dissolved in water which is often used as a surrogate in fresh and brackish waters. Within the Lakes, water ribbons (*Triglochin procerum*), a key aquatic macrophyte, is likely to have an upper preferred salinity tolerance of $1000 \mu\text{S cm}^{-1}$ EC (although it is known to tolerate short periods of higher salinities; Goodman *et al.* 2010). The threatened Yarra pygmy perch (*Nannoperca obscura*) is another species for which $1000 \mu\text{S cm}^{-1}$ EC represents the likely maximum salinity for preferred habitat (although again, lethal tolerances would be higher; McNeil & Hammer 2007). When setting management targets for salinity, it is important to maintain a reasonable buffer below known upper tolerances, because of sub-lethal effects.

As salinities approach the species' upper tolerance limits, sub-lethal impacts begin to appear. These are changes that occur due to stress before that stress reaches a level that will kill an organism outright. Such changes can include increased incidence of disease, slower growth and failure to reproduce successfully (Hassell *et al.* 2006). Thus, while organisms may be able to survive conditions in the short term, in the long term it is likely that species would be lost (particularly where reproduction is affected) and the region would cease to function as a healthy, productive and resilient wetland. For many organisms, we have a poor understanding of the salinities at which sub-lethal impacts manifest. However, Hart *et al.* (1991) found that a salinity of 1 g L^{-1} (which is $\sim 1500 \mu\text{S cm}^{-1}$ EC) was the point at which Australia freshwater biota would be significantly adversely affected, with sub-lethal impacts increasingly common. Nielsen *et al.* (2003) found the same threshold for aquatic plants and stated that this was a likely threshold for Australian freshwater communities more generally. Thus, adopting a salinity target of $1500 \mu\text{S cm}^{-1}$ EC or higher for Lake Alexandrina is likely to compromise the ecological character of that region.

The lack of detailed understanding of sub-lethal impacts of salinity for the chosen indicators (and the prevalence of laboratory-based LC50 values as a measure of salinity tolerance) meant that we were unable to rely solely on tolerances from the

literature as a basis for setting salinity targets in the CLLMM region and that a conservative approach was warranted. Salinity tolerances for the ecological indicators, along with known thresholds for the appearance of sub-lethal impacts, indicated that a target of an average annual salinity of $700 \mu\text{S cm}^{-1}$ EC over the long term would be appropriate. This target is consistent with the salinity target identified in the Ramsar Ecological Character Description for Lake Alexandrina ($700 \mu\text{S cm}^{-1}$; Phillips & Muller 2006) and previous research and historical accounts that indicate Lake Alexandrina has been predominantly fresh ($>90\%$ of the time; Fluinet *et al.* 2009). One of the primary reasons for aiming for a conservative salinity target in Lake Alexandrina is the relationship between salinity in Lakes Alexandrina with that in Lake Albert (Heneker 2010). When Lake Alexandrina has an average salinity of $700 \mu\text{S cm}^{-1}$ EC, the average salinity in Lake Albert tends to be around $1000 \mu\text{S cm}^{-1}$ EC (Heneker 2010). Small-scale variability means that at that point at least some areas will exceed $1500 \mu\text{S cm}^{-1}$ EC for some of the time, making sub-lethal effects possible.

However, given the reliance of the region on flow from the River Murray and uncertainties about the effects of the Murray-Darling Basin Authority's forthcoming Basin Plan and the effects of climate change on flow volumes, salinity thresholds of a maximum of $1000 \mu\text{S cm}^{-1}$ and $1500 \mu\text{S cm}^{-1}$ were also selected for inclusion within the hydrological modelling in order to explore the trade-offs that would be associated with each of these higher salinity targets. This is not to suggest that either of these targets would be ecologically acceptable, but simply to provide managers with the tools to make that judgement. The ecological implications of each level are outlined below (see Section 9 and Lester *et al.* 2011a).

In the development of these salinity targets, practical constraints regarding water delivery and climate change (amongst others) have not been considered. That there are significant constraints regarding the timing and volumes able to be delivered to the system is acknowledged. However the aim of this research was to determine what the ideal environmental water requirement for the site was, from an ecological point of view. Thus, we have not altered the recommendations based on operational constraints. Instead, we have aimed to provide information that will allow managers to understand what the ecological optimum is, and what the trade-offs are that are associated with not meeting that optimum (see Sections 12 & 13). This will allow managers to take informed decisions, in light of those trade-offs, but also considering current and future operational constraints.

Specific salinity targets were not set for the Coorong. The development of an ecological response model for the Coorong suggested that salinity on its own is not a good predictor of the ecosystem states present in the system (Lester & Fairweather 2011). Instead, the existing ecosystem states model was used explicitly to determine the effect that the flow regimes proposed to maintain salinity targets within Lake Alexandrina would have on the Coorong ecosystem states.

5.1 Summary

- **Average annual salinity targets of 700, 1000 and 1500 $\mu\text{S cm}^{-1}$ EC were selected for Lake Alexandrina based on indicator tolerances (including the appearance of sub-lethal impacts), historical salinity levels and salinities commonly recorded for fresh versus brackish wetlands.**
- Salinity was selected as the basis for the targets, as it was most closely related to flow volumes and was likely to require the largest flow volumes to maintain (thus incorporating other flow-related requirements). It was also the variable for which we had the most understanding of ecological effects.
- Practical constraints were not considered in setting these targets which were based solely on ecological requirements, and individual targets were not set independently for the Coorong or Lake Albert.

6. Identifying a target water level envelope for Lake Alexandrina

In identifying a target water level envelope for the region, the focus was placed on Lake Alexandrina. This was because water levels in Lake Albert are usually entirely dependent on those in Lake Alexandrina. The implementation of short-term emergency management actions in 2008 saw a temporary disconnection between the two via the construction of an earthen bank at Narrung Narrows to allow pumping of water from Lake Alexandrina in order to maintain minimum level in Lake Albert. The temporary regulator has since been breached and is in the process of being completely removed, restoring connectivity between the two lakes. Coorong water levels are related to the openness of the Murray Mouth (either naturally or via dredging in the absence of barrage flows), barrage outflows and relative sea levels, hence are more difficult to manipulate artificially. Thus, identifying targets for water levels in Lake Alexandrina should drive water levels in Lake Albert as well, while Coorong water levels will be most influenced by barrage flows that affect Mouth openness (and are thus linked to flows to flush salt from Lake Alexandrina).

Under natural conditions, water levels in Lake Alexandrina are closely linked to River Murray flows, with substantial season and annual variability (see Muller 2010 presented as an appendix to Lester *et al.* 2011a for additional detail). Increasing regulation within the MDB has enabled water levels to be held relatively constant for approximately the last 50 years to allow for local irrigation (with lake levels usually between 0.50 and 0.83 m AHD), leading to a simplification of riparian ecosystems and the accumulation of acid sulfate soils over time as a result of this loss of variability in lake levels.

The identification of a target water level envelope for Lake Alexandrina was largely based on the requirements of vegetation indicator taxa and assemblages. Fish and macroinvertebrates tend to respond to water levels indirectly via associated changes in water quality or in the availability of suitable habitat (which is often vegetation-related), thus it is more difficult to link these biota to water levels directly. The relationship between ecological processes and water levels (other than flooding flows) is often not well-understood.

Increased variability was identified as a key requirement of a target water level envelope for Lake Alexandrina. Muller (2010) outlined the objectives of the variable lake level regime as seeking to:

- support self-sustaining littoral, riparian and floodplain vegetation communities that are wide and diverse that, in turn, will support productive and diverse ecological communities;
- promote temporal and spatial variation in habitat availability, ecological processes and the biota supported by those habitats; and
- minimise lakeshore erosion, which is thought to be greatest at a level of 0.55 m AHD (which coincides with the vertical transition from clays to Polltollach Sands).

To achieve these objectives, envelopes were developed to specify a target envelope for water levels on an annual return frequency (ARF) of 1 (i.e. minimum water levels to be achieved each year; Figure 3) and also at an ARF of 3 (i.e. levels to be achieved every 3 years on average [which are over and above those levels specified with the ARF of 1]; Figure 4) in recognition of varied requirements for the range of taxa present. The water levels that have been specified are monthly averages across the site. Topography, wind seiching and other factors mean that there will be small-scale variability in water levels across the Lake and at shorter temporal scales (e.g. daily), and this is recognised as a desirable outcome.

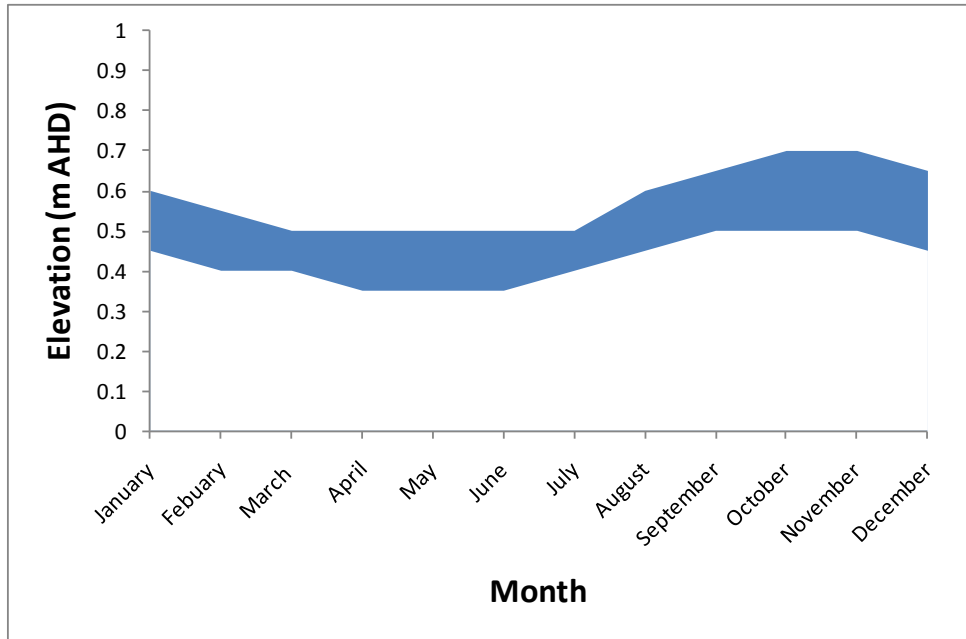


Figure 3: Proposed target envelope for water level in Lake Alexandrina at an Annual Return Frequency of 1 showing upper and lower limits (adapted from Muller 2010)

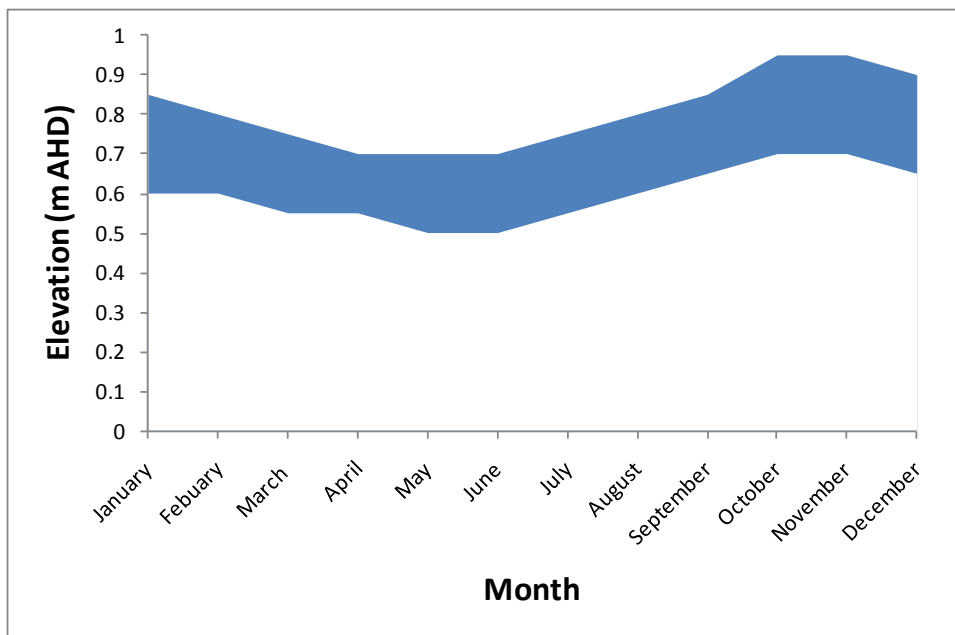


Figure 4: Proposed target envelope for water level in Lake Alexandrina at an Annual Return Frequency of 3 showing upper and lower limits (adapted from Muller 2010)

By identifying water level envelopes for ARFs of both 1 and 3, regular seasonal variability in water levels, as well as occasional inter-annual flooding requirements were both specified. For the envelope with an ARF of 1, lower limits for these water levels were set with physical disconnection points between habitats within the region in mind (e.g. Hindmarsh Island channels and Lake Alexandrina), as well as seasonal requirements for water and connectivity (e.g. fish passage through the Coorong to coincide with migration events). The upper limit for the ARF of 1 water-level envelope was determined based on the water requirements of the riparian zone and its position relative to the floodplain. Differences between the water-level envelopes for ARFs of 1 and 3 are largely focused on achieving occasional flooding of the surrounding floodplains.

As for the targets set for salinity, operational constraints were not included in the determination of these optimal water-level envelopes. A set of operational guidelines was provided to assist in the modelling and management decisions that would need to be taken to apply this recommendation (Muller 2010).

Additional information regarding the setting of lake level targets is presented in Muller (2010) which is appended to Lester *et al.* (2011a). This includes information on the historical condition of the lakes, the basis for setting targets and a discussion of the relevant operational constraints.

6.1 Summary

- **Target water-level envelopes were developed for Lake Alexandrina based on historical levels of connectivity and flooding requirements of riparian and floodplain vegetation.**
- **Separate targets have been set for yearly variability in water levels (i.e. return frequency of 1 year) and the higher levels associated with occasional flooding (i.e. return frequency of 3 years).**

7. Determining environmental water regimes to meet targets in Lake Alexandrina

In order to develop an environmental water requirement for Lakes Alexandrina and Albert, salinity and water level targets were used as the basis for hydrological modelling of the Lakes (see Section 8 for similar work for the Coorong). Given that hydrological models use flow as an input and water level or salinity as an output, this involved an iterative approach to understand how flow affected water levels and salinities.

The hydrological modelling that was undertaken in determining an environmental flow requirement for the CLLMM region is described in detail in Heneker (2010). The hydrological model of the Lakes that was used relied on input data from the MDBA model BigMod. This produces daily flow sequences that can be considered inflows to Lake Alexandrina. Scenarios included in the modelling were based on the Murray-Darling Basin Sustainable Yields project (SY; CSIRO 2008) and included an historical climate with current extraction levels (SY Scenario A), historical climate with no extractions (SY Scenario P) and two climate change projections; one describing a median 2030 climate (SY Scenario C_{mid}) and the other a dry 2030 climate (SY Scenario C_{dry}). Each scenario was modelled across the period of 1891 to 2008.

Briefly, the process used to determine flow regimes to maintain salinities in Lake Alexandrina below the relevant threshold involved:

- an examination of the historical record to understand the relationship between flow;
- modification of the input data (including inflow volumes) to standardise flow delivery patterns between years and allow for objective comparison between model runs and years; and
- the determination of the inflow and outflow combinations that would result in salinities below each target.

This last step involved using shorter model runs to coincide with the best salinity data for the system. In addition, the effect of inter-annual flow variability was explored using annual inflow sequences with varying magnitude of total flows and identifying the 'memory' of the system by exploring the effects of large flows one, two and three years later. These analyses assisted in the determination of a set of operational rules. Salinity responses based on these inflows were then compared with the salinities as a result of historical inflows and inflows predicted under median and dry future climates (C_{mid} and C_{dry} scenarios; CSIRO 2008).

Preliminary work (examining the volumes necessary to maintain water levels in the Lakes as opposed to water quality) indicated that meeting the salinity targets for Lake Alexandrina was likely to be the parameter that required the most flow to support, so modelling focussed on meeting these targets (Heneker 2010), with a later assessment exploring how the flow regimes identified by this process would affect water levels. Salinity in Lake Alexandrina was found to be largely determined by barrage outflows, which may initially seem counter-intuitive. However, salinity levels of River Murray inflows are relatively stable and barrage outflows provide a mechanism for flushing salt from Lake Alexandrina (i.e. including that transported from upstream) which would otherwise accumulate through evaporation. Salinity in Lake Albert is dependent on that of Lake Alexandrina via inflows, as a result of its terminal nature, and cannot be effectively managed independently.

The hydrological modelling that was undertaken aimed to determine flow regimes that would maintain average salinities in Lake Alexandrina below the 700, 1000 and 1500 $\mu\text{S cm}^{-1}$ EC targets (hereafter abbreviated to 700, 1000 and 1500 EC, respectively).

In order to develop sets of operational rules to deliver sufficient water to meet each of the three salinity targets, input data needed to be modified to allow for objective comparison between individual years within the model run. This involved modifying the historical model so that an average value was used continuously to represent system losses, diversions from the lake and groundwater salt inflows. A salt-inflow relationship was developed based on verified historical data so that the salinity of inflows varied consistently with the magnitude of flows. Finally, an averaged intra-annual inflow sequence was used to redistribute total annual inflows. This means that, while the total volume of inflows varies from year to year, the pattern in which they are distributed remains constant (i.e. a set proportion of the inflow occurs in each month each year).

Salinity within Lake Alexandrina and barrage outflows as a result of this modification were compared to with those for the historical record. The modified historical sequence did a good job of capturing trends in both salinity and barrage outflows compared with the historical record. However, the modified historical record did tend to under-estimate peaks in both salinity and barrage flows, resulting in somewhat less variability in the range of values observed in any given year. This was not found to have significant implications for the determination of an environmental water regime for the Lakes (Heneker 2010), but did have implications for the Coorong (see Sections 8 & 9). Salinity in Lake Alexandrina varied substantially across the historical record. Barrage outflows across three-year windows were found to have significant impacts on the salinity of Lake Alexandrina, indicating that a flow regime would need to be specified across at least three years. A threshold was identified when three-year cumulative barrage outflows fell below 6000 GL, where salinities tended to increase dramatically.

In order to meet the average salinity targets of 700, 1000 and 1500 EC in Lake Alexandrina, constant flow volumes (i.e. evenly distributed delivery across the year) of 4850, 2850 and 1850 GL year⁻¹ past Wellington were required, respectively. This resulted in maximum salinities of around 1400, 1800 and 2550 EC, respectively, in Lake Albert. This analysis, while involving a flow regime that would be unrealistic to deliver (i.e. constant flow), but provided an understanding of the magnitudes of flow volumes required to meet salinity targets in Lake Alexandrina and the corresponding impact of those flow volumes on Lake Albert salinities.

Further analysis allowed these constant flow volumes to be developed into a set of rules determining minimum inflows and outflows into the region in a more practical manner. Analysis of flow regimes highlighted the importance of considering one-, two- and three-year flow sequences in order to effectively manage salinities (Heneker 2010). Thus a set of rules was developed that require cumulative barrage outflow parameters to be determined for each salinity threshold as follows:

- B_1 being the minimum barrage outflow in any given year;
- B_2 being the minimum cumulative barrage outflow over two years; and
- B_3 being the minimum cumulative barrage outflow over three years.

The actual minimum barrage outflow required in any year (F_x) to maintain the salinity in Lake Alexandrina below the desired threshold, given the annual barrage outflows for the previous two years (F_{x-1} and F_{x-2} , respectively), was then the greater of:

1. B_1
2. $B_2 - F_{x-1}$
3. $B_3 - F_{x-1} - F_{x-2}$ (where F_{x-2}^* is equal to the minimum of F_{x-2} or B_{AVE}) (Heneker 2010).

As an example, for the 1000 EC threshold in Lake Alexandrina, the cumulative barrage outflow parameters were found to be: $B_1 = 650$ GL, $B_2 = 4000$ GL and $B_3 = 6000$ GL. The final parameter, B_{AVE} , was equal to 2000 GL. This means that the

minimum barrage outflow required in a given year to maintain Lake Alexandrina salinities below 1000 EC is equal to the greater of:

1. 650 GL
2. $4000 \text{ GL} - F_{x-1}$ (i.e. the flow from the previous year)
3. $6000 \text{ GL} - F_{x-1} - F_{x-2}^*$ (where F_{x-2}^* is $\min(F_{x-2}, 2000 \text{ GL})$)

So, while dry periods can result in flows that are much lower than the desired average (i.e. the minimum of 650 GL in a single year is much lower than the average of 2000 GL), flows in the next two years would need to be larger to compensate if salinities were to remain below the threshold.

When these rules were applied to the modified historical sequence, additional water was required in 33 of the 117 years in the model run (Table 1).

Statistics	
Length of Record	117 years
Additional Inflows Required	33 years
Average Annual Inflow Increase	1455 GL
Minimum Annual Inflow Increase	90 GL
Maximum Annual Inflow Increase	3280 GL
Additional Volume (GL)	Number of Years
Minimum Increase – 500	5
500 – 1000	7
1000 – 2000	9
2000 – 3000	9
3000 – Maximum Increase	3

Table 1: Additional flows required for historical inflow sequence to meet the 1000 EC threshold for Lake Alexandrina (source: Heneker 2010)

As a result of these adjustments, flows through the barrages were slightly increased from an average of 4925 to an average of 5320 GL per annum (Table 2). The majority of this change was in increasing the minimum flows within the system.

Statistics	Annual Barrage Outflow (GL)	
	Historical	Adjusted (1000 EC Threshold)
Mean	4925	5320
Median	3020	3220
Minimum	0	780
Maximum	44850	44725
10 th Percentile	260	1180
90 th Percentile	11215	11235

Table 2: Barrage outflow statistics for the historical and adjusted 1000 EC threshold sequences (1891 to 2008) (source: Heneker 2010)

Note: These statistics include barrage flows of 6000 and 10 000 GL at the recommended return frequencies (as described in Section 9) because those return frequencies mimic the occurrence of flows of that magnitude under the baseline scenario (when current extraction levels are considered).

Using these rules for the addition of environmental water to the system also has substantial benefits for Lake Albert. As a result of maintaining salinities below 1000 EC in Lake Alexandrina, salinity in Lake Albert was maintained below 1700 EC (a significant improvement on the peaks of greater than 2600 EC observed in the historical record; Heneker 2010).

Similar rules were also developed for the 700 and 1500 EC salinity thresholds in Lake Alexandrina. The rules associated with the 700 EC threshold were that the minimum barrage outflow required in a given year is equal to the greater of:

1. 3150 GL
2. 8000 GL - F_{X-1}
3. 12 000 GL - $F_{X-1} - F_{X-2}^*$ (where F_{X-2}^* is $\min(F_{X-2}, 4000 \text{ GL})$).

For the 1500 EC threshold, the minimum barrage outflow required in a given year to maintain Lake Alexandrina salinities below 1000 EC is equal to the greater of:

1. 0 GL but with inflows delivered to replace actual losses
2. 2000 GL - F_{X-1}
3. 3000 GL - $F_{X-1} - F_{X-2}^*$ (where F_{X-2}^* is $\min(F_{X-2}, 1000 \text{ GL})$).

Detailed results regarding the amount of additional water required the frequency and the effects on salinities in both Lakes Alexandrina and Albert are presented in Heneker (2010).

An analysis of the implications of these flows under climate change was also undertaken. Without additional environmental water, salinities were predicted to be significantly higher and water levels at very low levels much more frequently, particularly under a dry future climate. In fact, under the dry future climate, average salinity in Lake Alexandrina (1570 EC) approached the maximum observed under the historical scenario (1765 EC). Water levels under this historical scenario never fell below 0.1 m AHD, but were below 0 m AHD for more than 20 of 117 years in the dry future climate scenario. Similar changes were observed in Lake Albert.

In order to maintain the target salinities in Lake Alexandrina under a median future climate, additional water (above that which was needed under an historical climate; Table 2) was required (Table 3). As the salinity target became lower, the volume of water required increased, as expected. The middle threshold, of 1000 EC, required an average of 1430 GL of additional water to be source in 44 of 117 years.

Statistics	Salinity Threshold		
	700 EC	1000 EC	1500 EC
Length of Record	117 years	117 years	117 years
Additional Inflows Required	78 years	44 years	25 years
Average Annual Inflow Increase	2622 GL	1430 GL	860 GL
Minimum Annual Inflow Increase	281 GL	15 GL	15 GL
Maximum Annual Inflow Increase	4820 GL	4015 GL	2015 GL
Additional Volume (GL)		Number of Years	
Min Increase – 500	5	9	10
500 – 1000	5	8	5
1000 – 2000	14	14	9
2000 – 3000	20	9	1
3000 – 4000	24	3	0
4000 – Maximum Increase	10	1	0

Table 3: Additional flows required for the C_{mid} inflow sequence to meet the three salinity targets for Lake Alexandrina (source: Heneker 2010)

In interpreting all the results presented here, it is important to note that losses within the system have been set at 850 GL year⁻¹. Thus, in practice, to achieve target barrage outflows, inflows will need to be adjusted based on the actual losses (e.g. evaporation, seepage) within the system for that year.

It is also important to understand that barrage outflows higher than those specified here provide benefits in addition to lowering salinity in Lake Alexandrina across the CLLMM region. Also, larger flow volumes tend to be unregulated, meaning that it is impractical to attempt to divert the water elsewhere. Thus, while minimum flow volumes are specified here, these should not be taken as sufficient in themselves to

support the current ecological character of the region. Further consideration is given to larger flow volumes for the Coorong (see Section 10).

7.1 Summary

- Flows to maintain salinity targets in Lake Alexandrina were determined using hydrological modelling.
- Inflow sequences needed to be adjusted to allow for objective comparison between years.
- Operational rules were developed for each salinity target (of 700, 1000 and 1500 $\mu\text{S cm}^{-1}$ EC) over 3-year intervals. These rules specified the minimum flow volumes over the barrages needed to achieve these target salinities.
- Large flows were not found to be effective at reducing salinity in Lake Alexandrina for more than three years, due to a short 'memory' in the system. It was not practical to manage salinities in Lake Albert independently of Lake Alexandrina.
- To maintain the **target salinity of 1500 $\mu\text{S cm}^{-1}$ EC** in Lake Alexandrina, additional flow was required in 25 years of an average 860 GL under a median future climate change scenario. **For the lower targets of 1000 and 700 $\mu\text{S cm}^{-1}$ EC** in Lake Alexandrina, additional flow was required in 44 years (of 1430 GL on average) and 78 years (of 2622 GL on average), respectively, over the same 117-year median future climate change sequence.

8. Identifying the effect of the EWR on the hydrodynamics of the Coorong

In this section, we examine the impact of the proposed environmental water allocations on the hydrodynamics of the Coorong. Flows into the Lower Lakes were altered to achieve various salinity targets for Lake Alexandrina and the effects of the various resultant barrage flows on the Coorong's physical responses are explored here. Further detail is given in Lester *et al.* (2011a).

8.1 Introduction to the hydrodynamics of the Coorong

In order to understand the effect of environmental water regimes on the Coorong, it is helpful to have a basic understanding of the relatively unusual hydrodynamics of the Coorong. The information presented here is based on Webster (2005, 2007, 2010).

Water level and salinity are two of the major determinants of suitable habitat in the Coorong. Water levels are a key to determining the physical habitat and food resources for birds, in particular, but also other aquatic biota. Salinity levels and the amount of variability in salinity (i.e. the maximum and minimum salinities, but also rates of change) also affect the aquatic biota that are able to utilise Coorong habitats, and the relative 'health' of those biota.

In the Coorong, the concentration of salinity is determined by inflows to the region (both freshwater and marine) and the mixing processes that occur within the system. A number of factors combine to influence the amount of mixing that occurs within the system;

- wind and tidal flows occurring near the Murray Mouth create exchange along the length of the system;
- natural, seasonal sea-level changes in Encounter Bay play an important role in mediating water levels along the length of the Coorong;
- freshwater flows over the barrages are a major driver of the degree of Mouth 'openness' (i.e. the degree of connection with Encounter Bay that determines the level of tidal exchange and the influence of sea-level changes); and
- evaporation, which tends to concentrate salt through time, but the evaporative loss of water also stimulates replacement flow along the Coorong, which carries water from near the Murray Mouth with it. In times of low barrage flows, this water is likely to be about the salinity of seawater, but in times of higher flows, this water may be estuarine, or near fresh.

At the same time, long-Coorong mixing processes tend to transport salt towards the Murray Mouth. The Murray Mouth has always been relatively narrow and extremely dynamic. The width of the Murray Mouth has varied from being several hundred metres during flood flows (Walker 2002), to being completely closed in 1981 and almost closed in 2002. Exchange through the Mouth is influenced by a natural delta inside the Mouth that restricts water movement and salt exchange.

Barrage outflows influence the salinity dynamics in the Coorong in three important ways. As is listed above, freshwater flows affect the degree of Mouth openness. This occurs because periods of high barrage flows tend to deepen the Mouth channel, which allows more active mixing along the Coorong's length. Secondly, by freshening the water at the northern end of the Coorong (compared to seawater), freshwater flows tend to lower salinity as water that replaces evaporative losses has a lower salinity than it otherwise would (despite ongoing evaporation). Thirdly, periods of high barrage flows tend to increase water levels throughout the Coorong and push water further south into the system. This dampens the effect of seasonal changes in sea level in Encounter Bay and, so increases the connectivity and mixing within the

system. Variations in discharge have a similar effect, as they cause water to move back and forth along the Coorong, enhancing longitudinal mixing.

The Coorong naturally splits into North and South Lagoons at Parnka Point. There are several channel sections on either side of Parnka Point that are very narrow (approximately 100 m wide) and relatively shallow. These channels are the main restriction for water exchange between the two Coorong lagoons. The volumes of the North and South Lagoons are 86 and 140 GL, respectively (i.e. the South Lagoon is larger).

Ultimately, the salinity levels throughout the system are determined by the balance of 'forward' transport in the system (i.e. towards the southeast) of flows to replace evaporative losses and the salt that accompanies those flows, with 'backward' mixing of salt by currents induced by winds, barrage flows and seasonal changes in sea level. Thus, inputs of fresh water to the North Lagoon (from the River Murray via the barrages) reduce salinity and affect water levels both directly and indirectly in the South Lagoon.

The effect of barrage flows on South Lagoon salinities and water levels is still currently much larger than the effect of inflows from Salt Creek (i.e. despite being largely indirect; Figure 1). Flows via Salt Creek are comparatively small and the effects on salinity are much smaller than those of the River Murray (approximately 5% of the effect of River Murray flows; I. Webster, pers. comm.). While this may not have always been the case (as there are no data available for historical flow volumes prior to the construction of drains in the South East), it is likely that the River Murray has always been the primary determinant of salinity and water level in the Coorong, simply because of the larger volumes that regularly flow into the Coorong. Also, surface water inflows from the South East to the Coorong are currently capped as a part of its approval under the EPBC Act and there are physical limitations to the amount of water that can currently be transported using this existing scheme. These facts will continue to limit the amount of water that can potentially enter the Coorong via Salt Creek, current proposed extensions notwithstanding. Thus, for the foreseeable future, the River Murray will continue to be the primary determinant of salinity and water level for the Coorong, including in the South Lagoon (but see Section 13 for an analysis of interactions between barrage and USED flows).

These natural hydrodynamics of the Coorong can be altered through human manipulation. Historically, these 'levers' have included:

- dredging the Mouth when it is threatened by closure;
- altering the timing and magnitude of flows past the barrages; and
- additional releases from the Upper South East Drainage scheme (USED) into the southern end of the South Lagoon at Salt Creek.

Other management actions (e.g. pumping of hypersaline water from the South Lagoon of the Coorong to Encounter Bay) are also possible, and some of these are currently under consideration through the Long term plan for the Coorong, Lower Lakes and Murray Mouth (DEH 2010). However, the majority of other actions are in response to the recent drought situation, and so are not relevant to the determination of a long-term environmental water requirement for the Coorong.

8.2 The effect of the EWR on Coorong hydrodynamics

The effect of environmental water allocations on the hydrodynamics of the Coorong was investigated using a one-dimensional hydrodynamic model (Webster 2010). This model simulates water levels and salinities along the length of the Coorong, allowing the effect of varying barrage flows to be assessed and compared between scenarios. The model structure, calibration and validation have been described in more detail by Webster (2010).

The domain of the model extends from the Murray Mouth to the south end of the South Lagoon (~5 km past Salt Creek). The model simulates water movement and levels along the entire domain, as these respond to the driving forces associated with water-level variations in Encounter Bay (including tidal, weather band and seasonal variations), winds, barrage inflows, flows in Salt Creek (USED) and evaporation.

Overall, the model does a credible job of simulating the response of the system in both salinity and in water level, explaining ~90% of salinity changes in the system. It should be recognised that an individual modelled salinity value is expected to differ from a measurement due to a number of reasons, including small-scale variability. Additional calibration detail is provided in Webster (2010) and Lester *et al.* (2011b).

The hydrodynamic model was run for 19 scenarios. The 19 scenarios contained combinations of flows to support different salinity targets in Lake Alexandrina, in combination with different climate change scenarios. Current water allocations were modelled under an historical climate, plus median and dry future climate scenarios, as was natural flow (i.e. with no extractions in the Murray-Darling Basin) under historical climate conditions.

There were high levels of variability in the distribution of barrage flows in the historical record over the period of 1975 to 2007. Between 2007 and late 2010, annual average flows over the barrages were zero, which was longer than any other dry spell in the modelled sequence. Salinities have been estuarine in the North Lagoon for several extended periods but have tended to oscillate in the estuarine to marine range on a mostly-seasonal basis for the majority of the time sequence.

In the North Lagoon, the historical record shows large inter-annual variability in salinities, with some short periods of unusually low salinities and two notable periods of unusually high salinity. In the South Lagoon, simulated salinities under the modified flow scenario (using the historical climate & consistent with that used by Heneker 2010) were consistently lower than those predicted for the standard flow-delivery scenario (using the same climate & again consistent with the scenario used by Heneker 2010). The pattern of seasonal variability was similar, but the modified flow scenario did not show the same peaks of high salinity as were evident under the standard flow delivery scenario.

Four hydrodynamic variables have been shown to drive the mix of ecosystem states that are present in the Coorong, including average water level, maximum salinity, average depth from two years previous and the annual range in water level (see Lester & Fairweather 2011 for additional detail). For each of these variables, the effects of environmental water allocations have been explored in additional detail (Lester *et al.* 2011a).

Adjusting the timing of flow delivery to facilitate comparison between years for the Lakes affected the simulated hydrodynamics of the Coorong. When flows were adjusted, there were higher overall water levels and water depths in the North Lagoon. It also had a positive effect on the simulated water levels and salinities in the South Lagoon. These differences were not improvements as a result of changes in water allocation and should be considered with caution when the effects of other environmental water allocation scenarios are investigated.

The median climate change projection had a relatively small impact on the hydrodynamic drivers of ecosystem states in the Coorong, while the dry future climate change projection had a larger negative impact, particularly on water levels and maximum salinities. Current extraction levels within the Murray-Darling Basin were affecting all the hydrodynamic drivers of ecosystems states within the Coorong to a large degree.

Constant flow delivery to maintain a particular salinity target in Lake Alexandrina had very little impact on the annual range in water level or the depth of water in the

Coorong. However, it did affect both the water levels and maximum salinities simulated. Lake Alexandrina salinities have historically been lower than $1000 \mu\text{S cm}^{-1}$ EC, and thus less water is delivered to maintain salinities of either 1000 or $1500 \mu\text{S cm}^{-1}$ EC (when delivered at a constant rate) than has historically occurred. So, under these scenarios, water levels were lower and salinities higher than under historic conditions.

Results from the constant delivery of water did not change consistently with increasing volumes of water. These non-linear patterns of change in water levels and depths are most likely due to the dual effects of barrage flows to elevate water levels in the Coorong and to scour the Murray Mouth, changing the relative depth and thus the connectivity with Encounter Bay. The non-linearity from different constant flow scenarios was not evident in the South Lagoon.

When additional environmental water was allocated to the Coorong (using the environmental watering rules), the largest impact was seen on the maximum salinity for each scenario. Rules-based addition of environmental flows had little effect on median average or annual range in water levels, but resulted in less variability in water levels across the model run.

Scenarios assessing the impact of additional barrage flow (using the rules identified above) resulted in an improvement in both the water levels and depths in the North Lagoon for all three salinity targets. Increased volumes of additional water resulted in larger improvements in North Lagoon hydrodynamics. This pattern was also evident in the South Lagoon, where a correlation between additional environmental water and improvements in water levels and salinities was evident. In both North and South Lagoons, however, the volumes of additional water to meet any of the three Lake Alexandrina salinity targets were insufficient to approximate the effect of natural flows (i.e. with no extractions in the Murray-Darling Basin).

When the effect of rules-based environmental flow delivery was explored under a median climate change projection, the results were very similar to those under the historical climate scenario. The addition of environmental water resulted in improvements in both water levels and depths in the North Lagoon, for all three Lake Alexandrina salinity targets, compared to the historical condition or a median future climate change projection. Additional water also resulted in improvements in South Lagoon water levels and salinities compared to both the standard or modified flow delivery scenarios under a median future climate. Similar results were observed under the dry future climate scenarios. Under a dry future climate, all four hydrodynamic drivers of ecosystem states showed substantial change as a result of the additional water. Water levels were much higher when additional environmental water was added and were also less variable.

A key finding of this work was that adjusting the timing of flow delivery (i.e. so that a set proportion of flow was allocated to each month, where the proportions did not vary between years) had an unexpectedly large impact on the hydrodynamics of the Coorong. Thus, the results of this modelling need to be interpreted with care. This does not mean that the simulated improvements in water levels, depths, and salinities resulting from additional environmental water allocations cannot be relied upon. Instead, the trends that emerge with additional environmental flows are consistent across different climate scenarios and tend to increase with larger volumes as would be expected, giving confidence in their reliability. However, the absolute values that are predicted should be thought of as indicative only, and it is likely that peaks (i.e. both high and low) are underestimated.

In the Coorong, pattern of flow delivery clearly had a large impact, in some instances as much as the volumes of additional water explored here, at least under historical climate conditions. Thus, the efficacy of environmental flow allocations will vary depending on how that flow is added, particularly in times of low barrage flows, and thus additional modelling is required to determine when environmental flows should

be added, and how. This unexpectedly-large effect of adjusting the timing of flow delivery highlights the importance of investigating the method of flow delivery (in terms of timing and duration) as well as simply considering the volume of water added. Therefore, optimising flow delivery could mean that relatively small volumes of water could have a comparable effect to larger flow volumes with sub-optimal flow delivery and this should be understood to ensure that the maximum benefit is achieved for the amount of additional water added.

Another key finding was that none of the scenarios investigated here resulted in hydrodynamics that approximated the effect of natural flows under any climate projection. But time series analysis did show that the volumes of water added to maintain salinities in Lake Alexandrina were sufficient to arrest the high salinities associated with drought conditions in both the North and South Lagoons. This suggests that these salinity targets were potentially sufficient to limit the ecological decline associated with droughts in the region although not to reverse the effects of current extraction levels.

The modelling undertaken here suggested that the hydrodynamics of the Coorong would not be dramatically affected by median levels of climate change, should climate change manifest in the simulated manner. The hydrodynamics under the standard and adjusted flow-delivery scenarios for the median future climate were very similar to those under the historical climate. This was also true of the scenarios investigating the rules-based addition of environmental water. A simulated dry future climate, on the other hand, had a dramatic effect on the hydrodynamics of the Coorong, with lower water levels, much higher salinities and much more variable conditions than occurred for either the historical or median future climate. The additional environmental water resulted in complete reversal of the effects of the both future climates. But, it should be remembered that the larger amounts of water would be required to maintain salinities below the target levels in Lake Alexandrina than under historical or median future climate conditions (see Section 7). So, while these targets may be appropriate, they would also be harder to achieve with increasing severity of climate change and so more water (both in absolute terms and as a proportion of inflows) would be needed to meet those targets.

8.3 Summary

- A hydrodynamic model was used to assess the effect of recommended barrage flow regimes on the water levels and salinity of the Coorong.
- Adjustments made to the flow sequence to allow for objective comparison between years in Lake Alexandrina had a large impact on the hydrodynamics of the Coorong, with substantially less variability associated with a more even flow distribution.
- Additional water delivered to the Coorong (to maintain salinities in Lake Alexandrina) had the largest effect on maximum salinity, with improvements also apparent for the water level and depths along the system.
- This improvement with additional water was more marked when median and dry future climates were considered. However, none of the scenarios investigated replicated the effects of natural flow volumes through the system.
- The pattern and timing of flow delivery had as much, or more, impact than the differences in flow volumes explored here, highlighting the importance of understanding how the timing of flows affects the hydrodynamics of the Coorong.

9. Identifying the effect of the EWR on the ecosystem states of the Coorong

Assessing ecological condition at an ecosystem scale is a difficult task. Typically, there are some aspects of an ecosystem that are well-studied and understood (e.g. birds and fish) and others that are less well understood (e.g. groundwater inputs and microbes). In order to assess ecological condition in the Coorong, we used an existing ecosystem response model that is based on 'ecosystem states' (Lester & Fairweather 2011).

The work described here focused on identifying the likely mix of ecosystem states that would be supported by the flow regimes designed to meet salinity targets in Lake Alexandrina (see Section 7). Additional detail can be found in Lester *et al.* (2011a).

The ecosystem states model is a statistical model, where data for the region has been statistically analysed and modelled to identify associations and relationships between the biota that occur within the system at any one point in time, and the environmental conditions under which they occur. The ecosystem state model developed for the Coorong identified eight distinct ecosystem states. These can be divided into two 'basins of attraction'; a marine basin, and a hypersaline basin. Within each basin, there are four states, ranging from a relatively-healthy state to a more-degraded state. Thus, the four states within each basin can be considered to be a continuum of conditions from a healthy ecosystem to a more-degraded ecosystem, although it should be noted that a diverse range of conditions is the norm for the Coorong region. Additional information regarding development and testing of the model is given in Lester & Fairweather (2011).

As an example, the Estuarine/Marine state is characterised by tidal influences from the Murray Mouth, low average salinities, a short period since flow occurred over the barrages, and the highest average water depths and water levels of any of the identified states. In addition, low nutrient (e.g. ammonia and TKN) and chlorophyll (*a* and *b*) concentrations and low turbidity are characteristic of this state. The Estuarine/Marine state is also characterised by a unique assemblage of fish, birds, and invertebrates shown below in Figure 5.

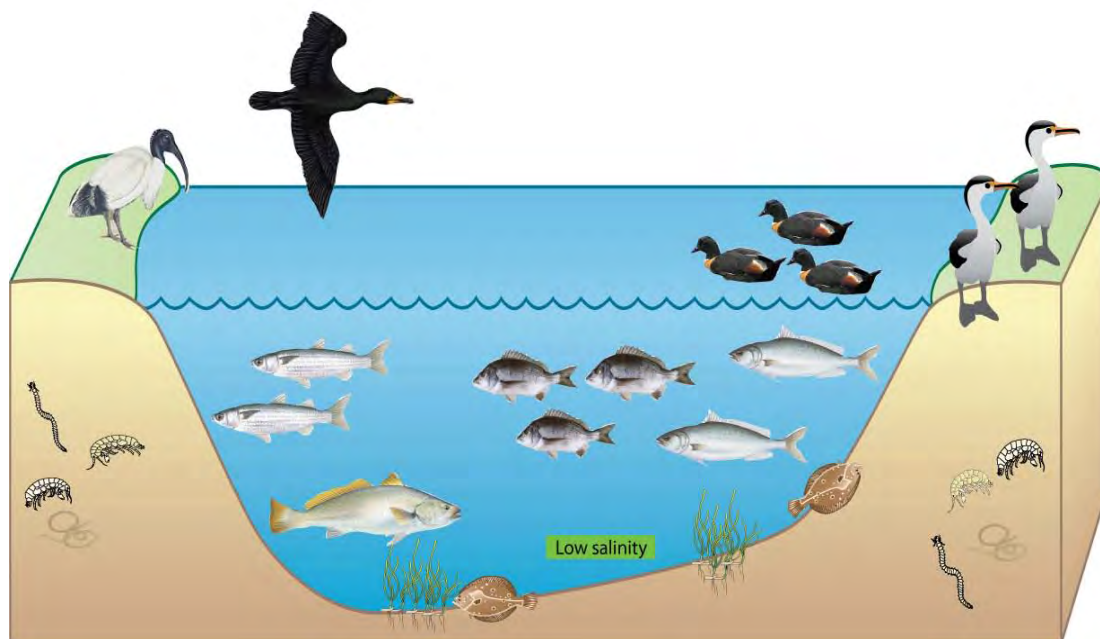


Figure 5: Conceptual diagram of the key biological and environmental characteristics associated with the Estuarine/Marine state (source: Lester & Fairweather 2011)

Note: This diagram is a conceptual characterisation designed to illustrate the suite of taxa characterising the Estuarine/Marine ecosystem state. It does not illustrate all taxa present nor the most abundant taxa necessarily. Instead, it shows those taxa that distinguish this state from the others. The number of organisms depicted and their relative size are not to scale and the geomorphic setting is not realistic. Key to taxa depicted can be found in Lester & Fairweather (2011), which is also the source of the diagram. Average salinity is indicated by a colour-coded bar in the water column, using a continuum from low to high.

One of the key limitations of the ecosystem model is its ability to correctly predict the recovery of the system. The model was developed using data from 1999 to 2007, which was a particularly dry period, when the ecological condition of all the Coorong was deteriorating. Another limitation stems from the model treating the trajectory of decline as the same as the trajectory of recovery, and assuming both occur over the same length of time. This is likely to be unrealistic and, until data describing the recovery of the system are available, there is no way to quantify this scale of uncertainty. For this reason, we have used this model in combination with other taxa- and assemblage-specific data (derived from the literature) to ensure that any bias does not adversely affect the setting of an EWR.

In assessing the effect of the flow regimes proposed to meet salinity targets in Lake Alexandrina, on the Coorong, the objective of avoiding ecological degradation through the appearance of unhealthy ecosystem states (i.e. specifically ecosystem states that are associated with no barrage flows for more than 339 days; see Lester *et al.* 2011b and Lester & Fairweather 2011 for additional detail) was used. The mix of ecosystem states predicted under each scenario was assessed relative to this objective.

The majority of 'site-years' (where a 'site-year' is one site in one of the modelled years, so here we refer to the majority of sites in the majority of years) under the scenario exploring the historical climate with current extraction levels were either in the Estuarine/Marine state or the Average Hypersaline state (both of which are considered healthy). There were departures from this typical condition, with North Lagoon sites changing to the Unhealthy Marine state for one or two years at a time and South Lagoon sites switching to the degraded hypersaline-basin states for up to eight-year stretches in times of drought.

Changes in the hydrodynamic parameters in the Coorong associated with adjusting the timing of flow delivery within the year also affected the mix of ecosystem states predicted under each scenario. The alterations to the pattern of flow delivery resulted in more site-years in the Estuarine/Marine and Average Hypersaline states than occurred in the standard flow-delivery scenario, with fewer site-years in the Unhealthy Marine and Degraded Hypersaline states, in particular. This difference does not represent real improvement in ecological conditions in this instance, but does highlight the importance of the timing and pattern of delivery for the Coorong.

Constant flow delivery to maintain a specified salinity in Lake Alexandrina (i.e. a mean of 700, or maxima of 1000 or 1500 $\mu\text{S cm}^{-1}$ EC) under an historical climate resulted in reduced diversity in the mix of ecosystem states present. Constant additional flow to maintain a maximum salinity of 1500 $\mu\text{S cm}^{-1}$ EC in Lake Alexandrina was insufficient to maintain a mix of healthy ecosystem states. Flow regimes to maintain salinities of either 700 or 1000 $\mu\text{S cm}^{-1}$ EC in Lake Alexandrina resulted in the vast majority of site-years being in either the Estuarine/Marine state in the North Lagoon or the Average Hypersaline state in the South Lagoon.

When additional environmental water was allocated to the Coorong using the environmental watering rules (see Section 7), there was less difference in the mix of ecosystem states for each scenario. Very similar mixes of ecosystem states were predicted, particularly between the flows to maintain either 700 or 1000 $\mu\text{S cm}^{-1}$ EC in Lake Alexandrina. This suggests that either should be sufficient to maintain the ecological character of the Coorong. However, flows designed to maintain the lowest salinity target (i.e. 700 $\mu\text{S cm}^{-1}$ EC) were required to prevent the occurrence of degraded marine states (predominantly the Unhealthy Marine state), although the incidence of these states was relatively low even for the scenarios maintaining higher salinity targets.

Providing sufficient environmental flows to meet the target of 1500 $\mu\text{S cm}^{-1}$ EC in Lake Alexandrina did not show the same improvements as the other two targets, suggesting that a target of no higher than 1000 $\mu\text{S cm}^{-1}$ EC should be adopted for Lake Alexandrina to ensure the ecological character of the Coorong. But there was little difference evident between the predicted mix of ecosystem states when water was delivered to meet the target of 1000 $\mu\text{S cm}^{-1}$ EC compared with that required to meet a mean of 700 $\mu\text{S cm}^{-1}$ EC in Lake Alexandrina. Based on this, it would be difficult to justify the lower target, and a moderate target of a maximum of 1000 $\mu\text{S cm}^{-1}$ EC would thus be recommended (but see Section 5).

None of the flow scenarios investigated that included additional environmental-water allocations resulted in a large increase in the proportion of Healthy Hypersaline states (which is associated with high flow conditions; Lester *et al.* 2011a), suggesting that the conditions provided by the rules-based flow addition were not yet optimal for South Lagoon ecosystems. In particular, it is likely that high flow requirements for the Coorong are not addressed by these flow delivery rules. This is further addressed in Section 10.

When the effects of climate change were explored, the major difference between the two climate change projections (other than the magnitude of change), in the absence of additional environmental water, was the incidence of the Degraded Marine and Degraded Hypersaline states in the dry future climate scenarios. Under a dry future climate, the majority of South Lagoon site-years were predicted to be in the least-healthy hypersaline state (i.e. the Degraded Hypersaline state) while approximately a quarter of site-years were predicted to be in the Degraded Marine state. When additional environmental water was added using the rules described above, there were dramatic improvements in the mix of ecosystem states in the Coorong under a median future climate. Under a dry future climate projection, no matter which salinity target was maintained in Lake Alexandrina, there was a large decline in the proportion of site-years in degraded ecosystem states, although none

were sufficient to completely eliminate degraded ecosystem states entirely. Additional environmental water required to meet a Lake Alexandrina target of $1500 \mu\text{S cm}^{-1}$ EC, in particular, still resulted in a substantial proportion of site-years predicted to be in the Degraded Hypersaline state, again indicating that this target would not be sufficient to maintain the ecological character of the Coorong.

A key finding of this work is that the timing and manner of flow delivery affects the ecology of the Coorong, as well as its hydrodynamics (see Section 8). Given that much of the ecology of the Coorong is linked to the hydrodynamics, this is not unexpected, but non-linearities in the response of the system may have complicated the ecological impacts. The addition of constant flows to the Coorong, in order to maintain one of three salinity targets in Lake Alexandrina, resulted in very little variability in the mix of ecosystem states in the Coorong, while the rules-based flow additions resulted in improvements in the mix of ecosystem states no matter which climate scenario was modelled.

This means that a more detailed exploration of the effects of the timing and mode of delivery of environmental flows is needed to gain an understanding of the implications for ecological character, and to ensure that any additional water provided has the maximum possible impact. Optimisation of the delivery for the flow volumes modelled here may result in substantial additional improvement. Similarly, delivery of these volumes in a less-optimal manner may result in less improvement in ecological condition than suggested here, making this assessment critical.

9.1 Summary

- An ecosystem states model was used to assess the effect of recommended barrage flow regimes on the ecology of the Coorong.
- Adjustments in the timing of flow delivery made to allow for objective comparison of years in Lake Alexandrina had a large impact on the predicted ecosystem states in the Coorong, highlighting the importance of delivery mode for this system.
- **Flows to maintain salinities of either 700 or 1000 or $\mu\text{S cm}^{-1}$ EC in Lake Alexandrina produced very similar mixes of predicted ecosystem states in the Coorong, with only flows to achieve the lower target (i.e. $700 \mu\text{S cm}^{-1}$) sufficient to prevent the appearance of degraded marine states.**
- Flows to maintain any salinity target in Lake Alexandrina resulted in improvements in the mix of ecosystem states under climate change, with the two lower targets showing the greatest improvements.
- A more detailed exploration of the effects of flow delivery timing is needed to ensure that ecological outcomes are achieved in the Coorong.

10. Additional environmental flow requirements for the Coorong

In addition to modelling the impact on the Coorong of the flow regimes proposed to maintain specified salinity targets in Lake Alexandrina, a separate analysis was also undertaken to identify whether there were any additional flow requirements for the Coorong (Lester *et al.* 2011a). As for the analyses undertaken above, this assessment has been based on the ecosystem states model of the Coorong and thus the recommendations made here are subject to the same caveats identified above.

In order to determine whether there were additional environmental flow requirements for the Coorong, two aims were considered:

- to avoid ecological degradation through the appearance of unhealthy ecosystem states in 95% of years, including consideration of whether sufficient water exists to maintain the Murray Mouth open without dredging; and
- to provide high-flow conditions such that the Healthy Hypersaline state (which is associated with high-flow events; Lester *et al.* 2011a) occurs as frequently in the South Lagoon as it has previously.

These two aims effectively divided the determination of additional environmental flow requirements for the Coorong into an assessment of minimum-flow requirements and one of high-flow requirements.

Minimum-flow requirements were determined using two methods. The first focused on flow volumes required to minimise the proportion of degraded ecosystem states present in Coorong. The second used a predictive model identifying likely future degraded ecosystem states in three years.

The first approach, which aimed to determine flow volumes to limit the proportion of degraded ecosystem states in the Coorong, used a similar analysis to that undertaken by Heneker (2010), where flow volumes were correlated with the proportion of degraded ecosystem states each year for the historic record and for the median and dry future climate change scenarios (Lester *et al.* 2011a). One- and two-year time lags were the most relevant in this analysis (compared with up to three years for Lakes salinity; Heneker 2010), indicating that minimum-flow volumes should be set across two-year sequences. This shorter lag is likely to be related to the role of the Murray Mouth in influencing hydrodynamic conditions within the Coorong and the amount of time that individual large flow events are capable of sustaining a relatively-open Mouth.

Substantially more variability was observed in the effect of flow volumes on ecosystem states in the Coorong than was apparent for salinities in Lake Alexandrina. Thus, widely different barrage flows were capable of producing either completely healthy ecosystem states, or completely degraded ecosystem states. This suggests that barrage flows are not the only factor influencing the ecosystem states in the Coorong. Bearing that in mind, based on these analyses, for an historical flow-delivery pattern, under any climate, Coorong flow requirements (when considering the proportion of degraded ecosystem states) can be summarised as:

- More than 1000 GL must be delivered across two consecutive years so as to maximise the likelihood that the Coorong supports at least some healthy ecosystem states;
- If the Coorong is have any chance of supporting healthy states, in any single year the total flow delivered cannot fall below 120 GL;
- To ensure that the occurrence of any degraded states would be prevented, more than 15 000 GL delivered over two years was needed (or 12 000 GL over one year); and

- More than 6000 GL was needed over two years before it was ensured that the Coorong would support at least some healthy ecosystem states.

However, unlike for the Lakes, the timing and method of flow delivery had a large impact on the volumes of water needed to achieve particular ecological outcomes (hence the level of variability in the flow volumes needed to prevent the occurrence of degraded ecosystem states). Flow volumes to achieve the same results summarised above under the modified flow sequence (where flows were delivered consistently from year to year; see Section 7 and Heneker 2010) varied by up to 20% on the values given (with some higher and some lower).

The second approach taken to identifying a low-flow requirement for the Coorong was based on a model developed to predict future degraded ecosystem states (Lester *et al.* 2011a; Fairweather & Lester, 2010). This model had a single predictive variable: average annual South Lagoon salinity. When the threshold for this variable (117 g L^{-1}) was crossed, there was a high likelihood of degraded ecosystem states three years in the future (the misclassification rate was 15%). This analysis showed similar results to the first approach. The variability inherent in the relationship between barrage flows and ecological conditions (here represented by the surrogate variable of likelihood of crossing the salinity threshold) was again apparent. Also observed was the large impact that timing and method of flow delivery had on the volumes required to achieve particular results within the Coorong. In this second analysis, assuming that flow delivery could be optimised, it is recommended that the minimum flow requirements in order to prevent the threshold of 117 g L^{-1} being crossed in the South Lagoon are:

- At least 50 GL in any one year as an absolute minimum to prevent certainty that the South Lagoon salinity threshold is exceeded;
- At least 600 GL over any two-year sequence as an absolute minimum to give some likelihood that South Lagoon salinities remain below the threshold value of 117 g L^{-1} ; and
- At least 3000 GL over two years as a minimum target (95% of the time) to prevent salinities in the South Lagoon from exceeding the threshold over which degraded ecosystem states are likely.

Using either approach, the flow regimes developed to meet a salinity target of $1000 \mu\text{S cm}^{-1}$ EC (and thus the larger flows to meet a salinity target of $700 \mu\text{S cm}^{-1}$ EC) in Lake Alexandrina were sufficient to meet these minimum flow requirements. This result was also observed under median and dry future climates where degraded ecosystem states occurred in occasional years, but the vast majority of the model run included only healthy ecosystem states, and the threshold of 117 g L^{-1} for average annual salinity in the South Lagoon was not exceeded when additional environmental water was provided.

The final analysis undertaken to determine any additional environmental flow requirements for the Coorong focused on high flow events. As was indicated above, high flow events have significant benefits in a region such as the Coorong, particularly in estuarine and saline environments. Thus, specifying only a minimum flow requirement is unlikely to meet all of the needs of the CLLMM region.

Very little information was available upon which to base our assessment of high flow requirements in the Coorong as much of the recent work in the region has occurred during times of drought. For example, the ecosystem states model was developed during a period of very low barrage flows and no data were available to calibrate it for higher flow events. Thus, these analyses and recommendations should be treated with caution (Lester *et al.* 2011a) and further work should be undertaken to verify the volumes recommended.

A similar approach was used to that described above for the presence of degraded ecosystem states, although in this instance we related barrage flows to the proportion of site-years in the Healthy Hypersaline state across the three climate scenarios (i.e. historical, median future and dry future). Again, two-year sequences were best related, using the current year and the previous year in this instance (compared to the previous year and two years previous in the analysis of degraded ecosystem states).

Significant variability in the flows required to result in some site-years being in the Healthy Hypersaline state were apparent. Under the historical pattern of flow delivery, more than 6000 GL year⁻¹ was required before any sites were predicted to be in the Healthy Hypersaline state, with flows of more than 12 000 GL year⁻¹ required to ensure that the state was present. Flow delivery pattern had less impact upon high flow requirements than for low flows, with the modified flow-delivery sequence again indicating the flows of more than 6000 GL year⁻¹ were required to produce any sites in the Healthy Hypersaline state (or 13 500 GL year⁻¹ before all South Lagoon sites were predicted to be in that state). Over two years, a minimum of 9000 GL were needed to produce sites in the Healthy Hypersaline state under the modified flow delivery pattern.

The scenarios in which additional water was provided to meet a salinity target of 1000 $\mu\text{S cm}^{-1}$ EC (or those to meet the salinity target of 700 $\mu\text{S cm}^{-1}$ EC) in Lake Alexandrina did not prove sufficient to regularly trigger the Healthy Hypersaline state in the South Lagoon when the reduced flow volumes associated with climate change were assessed. Thus additional large flows are likely to be required to ensure that all components of a healthy estuarine system are present in the Coorong.

The frequency with which these flows should occur is difficult to address in the absence of any data to test. Thus, we recommend that high-flow events should be maintained at the frequency at which they currently occur. Under the historical climate scenario, with current extraction levels, this would result in flows greater than 6000 GL and 10 000 GL having ARFs of 3 and 7, respectively. Under the median future climate scenarios, these ARFs are predicted to increase to 5 for flows greater than 6000 GL and of 17 for flows greater than 10 000 GL. At this stage, it is not possible to quantify the effects that such an increase is likely to have on the ecological character of the Coorong in the long term (see the limitations of the current data and analysis above), so we cannot confidently state that such an increase could maintain the Ramsar-nominated ecological character, and thus recommend maintaining these flow events at the current levels (i.e. at ARFs of 3 and 7 years, respectively).

It should be stressed that the impact of flow delivery on the ecological condition of the Coorong needs to be further investigated. The flow volumes specified here, particularly as minimum flow requirements, are almost certainly dependent on the manner in which they are delivered. Thus, smaller flow volumes may be equivalent, if flow delivery can be further optimised. However, the reverse is also likely to be true, and sub-optimal delivery methods will mean that larger volumes of water will be required to achieve the same results.

Finally, this analysis did not separately model the effect of these flows on Mouth openness. Mouth openness is not a simple concept to define, with a significant degree of variability occurring intra- and inter-annually in the size of the Murray Mouth naturally. Also, no one single volume can be identified that is sufficient to keep the Mouth 'open' as there is an increasing relationship between flow volumes and the relative openness of the Mouth (i.e. more flow means that the Mouth will be more open; I. Webster, pers. comm.). Thus, we consider the degree of Mouth openness that allows sufficient exchange between the Coorong and the ocean to support the healthy ecosystem states of the Coorong. Previous work has demonstrated the effect of Mouth closure on both the hydrodynamics and ecosystem states of the Coorong (see Lester *et al.* 2011a), and similar increases in the proportion of degraded

ecosystem states were not observed for the modelled flow sequences, giving us confidence that flow regimes designed to maintain a salinity of $1000 \mu\text{S cm}^{-1}$ EC in Lake Alexandrina would also be sufficient to maintain functional connectivity at the Mouth in the majority of years. This means that these flow volumes would be sufficient to meet ecological objectives without the need for dredging. Further discussion of the relationship between barrage flows and Mouth openness is given in Lester *et al.* (2011a).

10.1 Summary

- Investigation of the low-flow requirements for the Coorong based on ecosystem state modelling indicate that volumes to meet the **target of $1000 \mu\text{S cm}^{-1}$ EC** in Lake Alexandrina were sufficient to maintain the ecological character of the Coorong as well.
- High-flow requirements, again modelled using the ecosystem state model, were not satisfied by these flow delivery rules, and additional flows of 6000 and 10 000 GL year⁻¹ were required at their current frequency of every 3 and 7 years, respectively.
- These flows are considered sufficient to maintain the Murray Mouth open to a degree that is ecologically functional in the majority of years.

11. The recommended environmental water requirement for the CLLMM region

Based on the effects of the various flow regimes on the mix of ecosystem states predicted for the Coorong (particularly under climate change) and the effects on freshwater biota in Lake Albert, we recommend that a target of a maximum average annual salinity $1000 \mu\text{S cm}^{-1}$ in 95% of years be adopted for Lake Alexandrina with an absolute maximum of $1500 \mu\text{S cm}^{-1}$ in a single year. This would ensure that sufficient water passes through the Coorong to maintain its current ecological character, without the frequent occurrence of degraded ecosystem states, and that the Mouth was maintained open to a degree that is ecologically functional without the need for frequent dredging. Adopting this target would also result in a maximum annual salinity in Lake Albert of $1700 \mu\text{S cm}^{-1}$, at which point the tolerances of numerous freshwater biota are likely to be periodically exceeded and sub-lethal impacts in evidence. Setting a salinity target at a higher level would likely result in the loss of saline-sensitive taxa from that region and also affect the ecological condition of the Coorong.

A lower salinity target of an average annual salinity of $700 \mu\text{S cm}^{-1}$ in Lake Alexandrina has been recommended in the past (Phillips & Muller 2006). According to our analyses, meeting this target would provide a high likelihood of maintaining the Ramsar-nominated ecological character in the region. However, in this analysis, there is insufficient evidence to differentiate between this target of an average of $700 \mu\text{S cm}^{-1}$ and the somewhat higher target of a maximum of $1000 \mu\text{S cm}^{-1}$. Thus, sufficient evidence is lacking to warrant categorical recommendation of this more stringent target (but refer to Lester *et al.* 2011a for additional discussion of some of the limitations of this work that are likely to be relevant).

However, $700 \mu\text{S cm}^{-1}$ EC is the long-term historical average salinity in Lake Alexandrina and so should be considered to be the primary long-term target for that region, with the higher targets of a maximum of $1000 \mu\text{S cm}^{-1}$ in 95% of years and never exceeding $1500 \mu\text{S cm}^{-1}$ to be treated as maxima. Furthermore, it is important that the potential 5% of years exceeding the $1000 \mu\text{S cm}^{-1}$ not occur sequentially. This somewhat cautious approach is likely to ensure the ecological character of the region as a whole in the future, despite uncertainties associated with climate change and future water allocations.

Thus, in order to meet the salinity target of a maximum of $1000 \mu\text{S cm}^{-1}$ in Lake Alexandrina, the following minimum barrage outflows have been identified for any one year as the maximum of:

1. 650 GL
2. $4000 \text{ GL} - F_{X-1}$
3. $6000 \text{ GL} - F_{X-1} - F_{X-2}^*$, where F_{X-1} is the flow volume from the previous year and F_{X-2}^* is minimum of the flow volume from two years previous and 2000 GL.

To meet the more conservative target of $700 \mu\text{S cm}^{-1}$ EC in Lake Alexandrina, which represents a higher degree of certainty that the Ramsar-nominated ecological character could be maintained in the region, minimum barrage outflows have been identified for any given year as the maximum of:

1. 3150 GL
2. $8000 \text{ GL} - F_{X-1}$
3. $12\,000 \text{ GL} - F_{X-1} - F_{X-2}^*$, where F_{X-1} is the flow volume from the previous year and F_{X-2}^* is minimum of the flow volume from two years previous and 4000 GL.

For the Coorong specifically, the following minimum flow requirements were identified:

- There should be no years in which no flow passes over the barrages. The absolute minimum barrage flow should be between 50 and 120 GL.
- Over any two-year period, at least 600 GL should be released to the Coorong to prevent certainty that South Lagoon salinity thresholds (of 117 g L⁻¹) being exceeded.
- At least 2500 GL over two years as a minimum target (95% of the time) to prevent the Coorong from existing in degraded states across the entire region.

Minimum-flow requirements determined for the Coorong were met in the vast majority of years when environmental flows were sufficient to maintain a salinity of 1000 $\mu\text{S cm}^{-1}$ in Lake Alexandrina. Thus, no additional low-flow requirements have been specified.

However, high-flow conditions in the Coorong were not sufficiently addressed by the minimum-flow requirements. In addition to those minimum flows outlined above, high flows of at least 6000 GL and 10 000 GL should be maintained at their current frequency. Thus, flows of at least 6000 GL are recommended with an ARF of 3 and flows of at least 10 000 GL every 7 years.

Additional work determined that these recommended environmental water requirements did not exceed flow volumes that would have been available under natural conditions in any single year (e.g. even the exceptionally dry 2007) under an historical climate. Under climate change, however, the additional water required to meet these rules was not available under natural conditions in extremely dry years (e.g. 2007 assuming a dry future climate projection) so, an additional caveat has been placed on this EWR that the maximum additional flow volume not exceed the inflows available under natural conditions.

11.1 Summary

- **A maximum salinity of 1000 $\mu\text{S cm}^{-1}$ EC in Lake Alexandrina should be maintained in 95% of years, never exceeding 1500 $\mu\text{S cm}^{-1}$ EC.**
- **An average annual salinity of 700 $\mu\text{S cm}^{-1}$ EC in Lake Alexandrina is the long-term average and should be the target for most years.**
- **In order to meet the target of 700 $\mu\text{S cm}^{-1}$ EC in Lake Alexandrina, flows over the barrages in any given year should be the maximum of:**
 - 3150 GL
 - 8000 GL - F_{X-1}
 - 12 000 GL - $F_{X-1} - F^*_{X-2}$, where F_{X-1} is the flow volume from the previous year and F^*_{X-2} is minimum of the flow volume from two years previous and 4000 GL.
- **In dry years (up to 5% of the time), where the 700 $\mu\text{S cm}^{-1}$ EC cannot be met, flows over the barrages in any given year should be the maximum of:**
 - 650 GL
 - 4000 GL - F_{X-1}
 - 6000 GL - $F_{X-1} - F^*_{X-2}$, where F_{X-1} is the flow volume from the previous year and F^*_{X-2} is minimum of the flow volume from two years previous and 2000 GL.
- **Flows to maintain salinities of 1000 or 700 $\mu\text{S cm}^{-1}$ EC in Lake Alexandrina were sufficient to maintain predominantly healthy ecosystem states the Coorong.**
- High flows of 6000 and 10 000 GL year⁻¹ should be maintained at their current frequency of every 3 and 7 years in the Coorong.
- It is likely that proposed lake level regimes would also be met by these water requirements.

12. Implications of delivering less water to the CLLMM region

In order to explore the implications of delivering smaller volumes of water than the recommended environmental water requirement, two methods were used. The first focussed on dry sequences within the median and dry future climate scenarios. These sequences were investigated to determine the impact of those low-flow years on salinity in Lakes Alexandrina and Albert (Heneker 2010) and the North and South Lagoons of the Coorong (Lester *et al.* 2011a). The second method focused on the Coorong, and looked for thresholds in the trajectory of decline for salinities, water levels and the percentage of degraded ecosystem state when EWR recommendations were not met. This allowed us to determine what volumes below the EWR were likely to be associated with increasingly high levels of risk to the ecological condition of the Coorong.

12.1 The impact of dry sequences on the Lower Lakes and the Coorong

The implications of delivering less water than has been recommended have been explored for inflows, barrage outflows and for salinity in both Lakes Alexandrina and Albert, and for salinities and ecosystem states in the Coorong. This was done by exploring flow sequences in the median future climate scenario (C_{mid}) and similar flow sequences under a dry future climate scenario (C_{dry}).

The implications of delivering less water than has been recommended for Lake Alexandrina can be clearly seen in Figure 6 below. This figure shows the sequences of 1892 to 1916 under median future climate change, which represents a dry period within that sequence. While each of the sequences showing the effect of the rules-based addition of water remain below the target threshold (as intended), the sequence where additional water is not included, and lower flow volumes are delivered, results in large peaks in average annual salinity in Lake Alexandrina. During this period, salinity regularly exceeded the highest salinity threshold set (of 1500 $\mu\text{S cm}^{-1}$ EC, which is higher than the maximum salinity recommended for Lake Alexandrina), with peaks of more than 2000 $\mu\text{S cm}^{-1}$ EC. Continuous periods over the recommended maximum salinity of 1000 $\mu\text{S cm}^{-1}$ EC extend for up to four years.

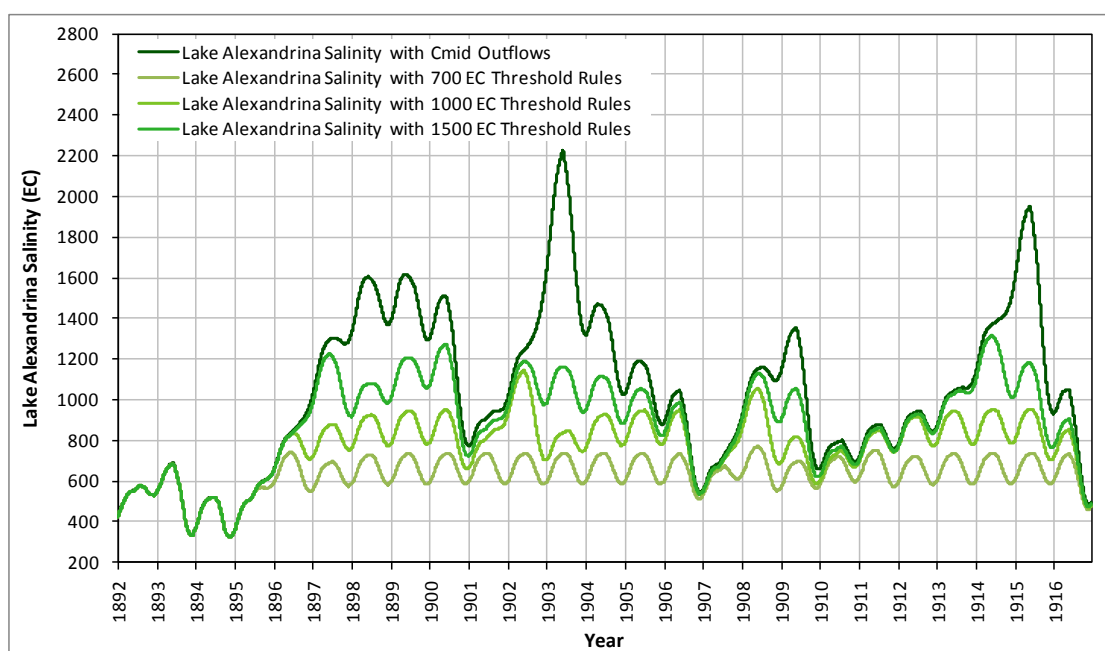


Figure 6: Lake Alexandrina salinity with adjusted median future (C_{mid}) barrage outflows showing the addition of environmental water to meet all thresholds, for the period between 1892 and 1916 (source: Heneker 2010)

The corresponding figure for Lake Albert shows similar trends but with higher salinities, due to the limited connectivity between that lake and Lake Alexandrina (Figure 7). Similar patterns for both Lakes are also apparent when the sequence of 1975 to 2007 was analysed (Heneker 2010).

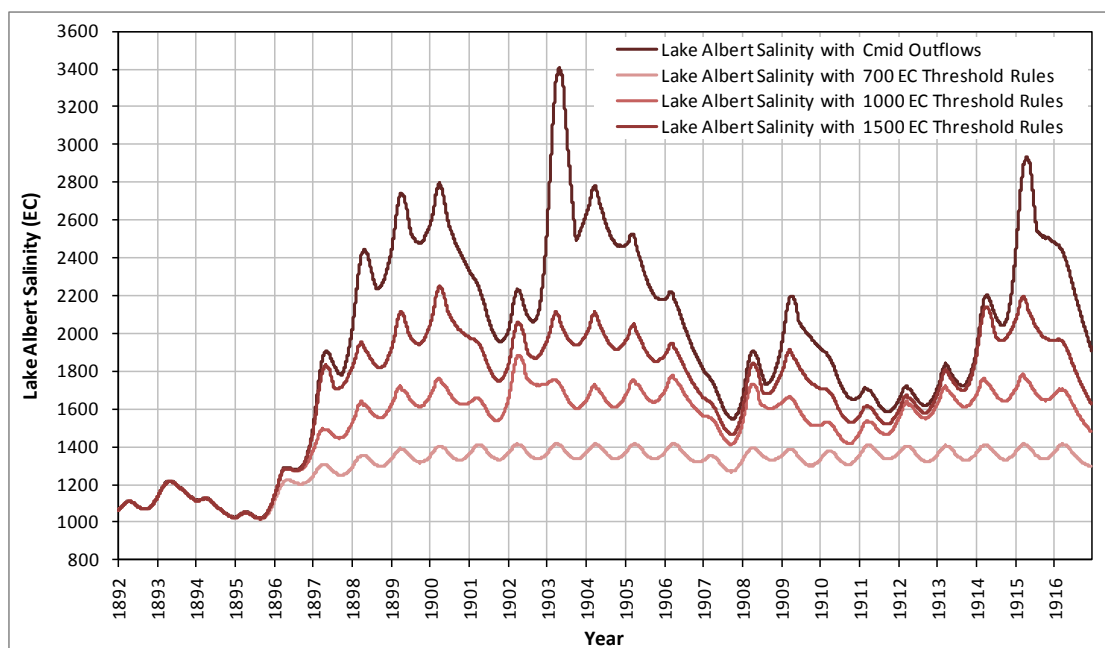


Figure 7: Lake Albert salinity with adjusted median future (C_{mid}) barrage outflows showing the addition of environmental water to meet all thresholds, for the period between 1892 and 1916 (source: Heneker 2010)

A similar situation emerges for the North and South Lagoons of the Coorong (Figures 8 and 9, respectively). The sequence analysed was slightly shorter (due to the need for several years of data to start up the Coorong hydrodynamic model) covering 1895 to 1916. Under the standard (or unaltered) delivery sequence of barrage flows predicted under median future climate change, average annual salinities in the North Lagoon were greater than twice that of seawater for the majority of the period shown, with peaks of almost 100 g L^{-1} (Figure 8). Maintaining salinities in Lake Alexandrina of $1500 \mu\text{S cm}^{-1}$ EC resulted in average annual North Lagoon salinities of around 40 g L^{-1} , with target estuarine average annual salinities only occurring when flows were sufficient to maintain salinities of $700 \mu\text{S cm}^{-1}$ EC in Lake Alexandrina.

In the South Lagoon, average annual salinity remained over 100 g L^{-1} for the majority of the time period with standard barrage flows and no additional water, and for decade-long periods when the flow sequence was adjusted (Figure 9). Only with additional flow volumes were salinities of an order that is likely to support the Ramsar-nominated ecological character.

Corresponding analyses were undertaken for the same years under a dry future climate (C_{dry}) projection. Without additional flow volumes delivered to Lake Alexandrina, conditions were predicted to deteriorate rapidly. Salinities in Lake Alexandrina were predicted to exceed the recommended threshold continuously for sequences of up to nine years at a time. Because of the extreme conditions without additional flows, it was difficult to see differences between the three additional flow scenarios, but all three effectively reduce average salinity to below their respective target (Heneker 2010). The implications of less water, however, were clear, with large differences between the additional flow scenarios and the scenario which modelled a dry future climate without additional environmental water.

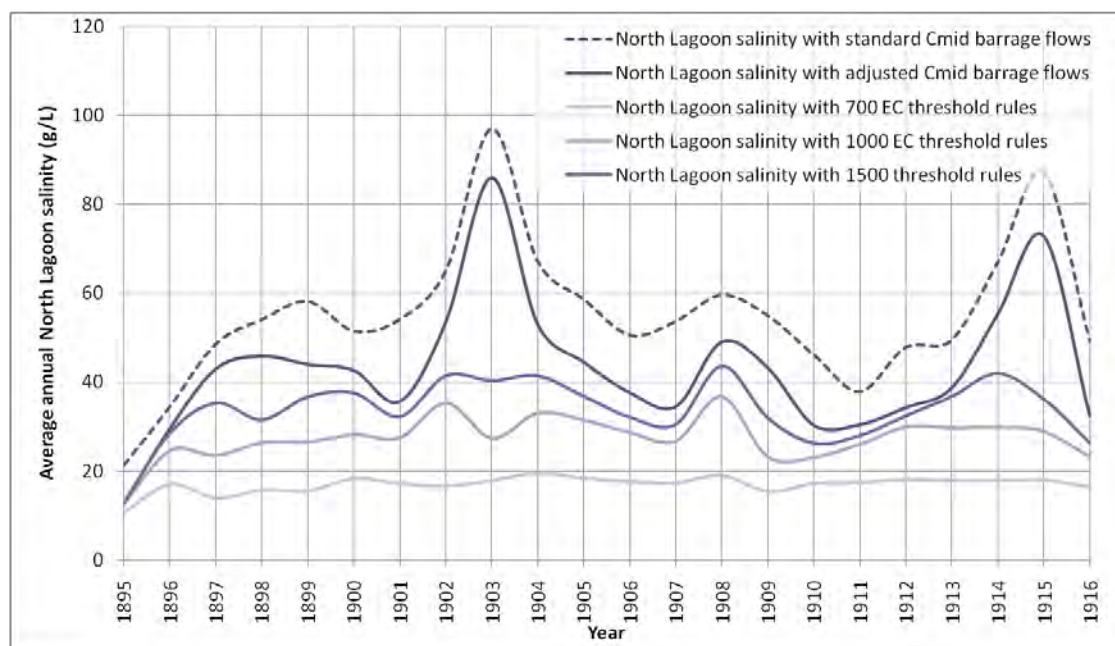


Figure 8: Average annual North Lagoon salinity with standard and adjusted median future (C_{mid}) barrage outflows showing the addition of environmental water to meet all thresholds, for the period between 1895 and 1916 (source: Lester et al. 2011a)

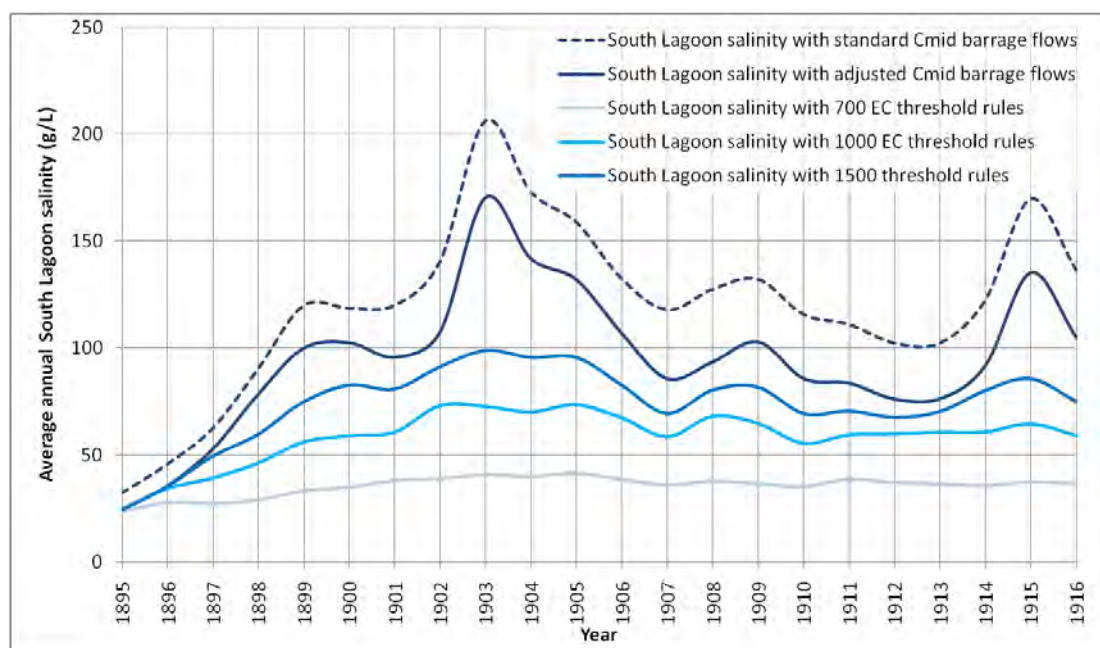


Figure 9: Average annual South Lagoon salinity with standard and adjusted median future (C_{mid}) barrage outflows showing the addition of environmental water requirements to meet all thresholds, for the period between 1895 and 1916 (source: Lester et al. 2011a). Note the change in scale from Figure 8.

Analysis of the same sequence of years for Lake Albert under a dry future climate showed a similarly-bleak prospect. Salinities in that lake, without additional environmental water peaked at over $9000 \mu\text{S cm}^{-1}$ EC and exceed recommended levels for almost the entire sequence continuously. Again, the effect of delivering less water than is recommended here was clear, with additional environmental water to meet any of the salinity targets a vast improvement on the conditions predicted under a dry future climate with no additional environmental water. Again, as for the

median future climate projection, the sequence for 1975 to 2007 shows similar patterns (Heneker 2010).

Salinities in the Coorong were also predicted to rise dramatically under a dry future climate. For that climate, under the standard flow-delivery scenario, average annual salinities in the North Lagoon peaked at levels that are currently associated with degradation in the South Lagoon (i.e. $>120 \text{ g L}^{-1}$). No years of estuarine salinities were predicted under either the standard or adjusted flow delivery scenarios in the absence of additional water. Maintaining salinities in Lake Alexandrina of $1500 \mu\text{S cm}^{-1}$ EC resulted in much lower average annual North Lagoon salinities of usually less than 40 g L^{-1} (although with occasional spikes of higher salinities). Meeting either of the two lower salinity targets in Lake Alexandrina was sufficient to maintain an estuarine North Lagoon for the majority of the time.

In the South Lagoon, predicted annual average salinities under a dry future climate, in the absence of additional environmental water, were unrealistically high (due to complex changes in water chemistry at extremely high salinities), but were certainly predicted to be above the tolerances for most, if not all, coastal lagoon biota. The provision of sufficient environmental water to meet a salinity target of $1500 \mu\text{S cm}^{-1}$ EC in Lake Alexandrina dramatically reduced the simulated salinities, but was insufficient to maintain average salinities below the suggested target of 100 g L^{-1} . Again, meeting either of the two lower salinities targets for Lake Alexandrina was sufficient to lower South Lagoon salinities to a point where current ecological character would be likely to be supported.

In both lagoons of the Coorong, the effect of flow delivery can be seen for both the median and dry future climate projections under dry conditions, with less even flow delivery than modelled likely to result in greater variability in the average annual salinity of each lagoon (note the difference between the standard and adjusted sequences without additional flows in Figures 8 and 9). Thus, the salinities shown here should be treated as a minimum, despite the extreme nature of some of the predictions. Also, the salinities shown are averaged across each of the lagoons, and across the months of the year, meaning that much spatial and temporal variability around these figures is likely (again indicating that localised salinities in some areas will be higher than is indicated by these figures). An analysis of the proportion of degraded ecosystem states in the Coorong over a similar time period (1896 to 1916) was undertaken for both the median and dry future climates. This showed that under the standard median future scenario, 45% of site-years were from degraded ecosystem states. This proportion dropped to 24% with the adjusted median future scenario (but no additional barrage flows), then to 2% with additional barrage flows to support salinities below either 1500 or $1000 \mu\text{S cm}^{-1}$ EC in Lake Alexandrina and 0% with when maintaining an average salinity of $700 \mu\text{S cm}^{-1}$ EC in the lake.

Under the dry future climate scenario, for the same period, 89% of site-years were predicted to be in degraded ecosystem states under the standard dry future climate scenario. This proportion fell marginally to 85% under the adjusted dry future scenario. With the addition of environmental water to meet salinity targets in Lake Alexandrina, the proportion of site-years predicted to be in degraded ecosystem states over that sequence of years fell again to 11% for the $1500 \mu\text{S cm}^{-1}$ EC target, and 0% for either the 1000 or the $700 \mu\text{S cm}^{-1}$ EC targets, respectively.

This sequence (1892 to 1916) is one of the drier periods in the two future climate change scenarios, but similar sequences would occur more frequently under increasingly dry future climates (see Lester *et al.* 2011). The pattern of significant and sudden spikes in salinity is likely to have a dramatic impact on the ecological character of the region. While some freshwater and estuarine biota are capable of withstanding occasionally higher salinities, they almost always require a gradual increase in that salinity, which is unlikely to be the case according to these simulations. It is also likely that there would be a limit to the length of time that the

biota would be capable of withstanding high salinities, and sequences of even up to four years (as predicted under a median future climate) are unlikely to be tolerable, let alone those predicted under a dry future climate. The indicator taxa, assemblages and processes would be substantially, and likely catastrophically, affected by changes of this order (refer to Lester *et al.* 2011a for known salinity tolerances), particularly in Lake Albert and in the South Lagoon of the Coorong. Conditions in either of these management units with lower volumes of water than recommended are reminiscent of current conditions, with the ongoing contraction and loss of biodiversity.

It is very unlikely that a healthy marine or hypersaline ecosystem would replace the freshwater and estuarine biota in the Lakes under these conditions either. This is due to the large and sudden fluctuations in salinity (and also water level) that are predicted. Marine and hypersaline biota and processes also operate within a range of salinities (just higher overall compared with freshwater or estuarine biota), and it is likely that the values predicted here would include periods where salinities were too low, as well as where salinities are likely to be too high for these biota and processes to continue (e.g. the experience in the South Lagoon of the Coorong). In essence, it is the overall variability that is likely to be problematic, as well as the maximum salinities that have been predicted. In addition, these results indicate that even flows to maintain salinities of $1500 \mu\text{S cm}^{-1}$ EC in Lake Alexandrina are insufficient to support the ecological character of the Coorong in all years, indicating that even if healthy marine or hypersaline biota were present in the Lakes, a significant proportion of the system would remain in a degraded condition if lower flow volumes only were delivered.

While in some years, the addition of somewhat less water than has been recommended may be sustainable for the region, when combined with adverse weather patterns, or in sequences of more than one year, delivering less water has the potential to have a catastrophic impact on the ecological character of the region. Thus, we strongly recommend that the absolute maximum salinity of $1500 \mu\text{S cm}^{-1}$ EC for Lake Alexandrina be adhered to, with sufficient water delivered to the region to make even these salinities a rare occurrence.

12.2 Identifying thresholds in the trajectory of decline for the Coorong

The second method that was used to assess the implications of less water being delivered to the CLLMM region focussed on the Coorong and increasing levels of degradation associated with decreasing flow volumes. This analysis used only the years in which EWR recommendations were not met but assessed the impact of the three salinity targets for Lake Alexandrina (i.e. 700, 1000 and $1500 \mu\text{S cm}^{-1}$ EC) and the historical, median future and dry future climates.

Here we developed a range of flow-related variables that described how severe the barrage flow shortfall was, compared to the EWR. Variables included the shortfall (or 'discrepancy') between the recommended flow volume and the modelled flow volume in one year, the cumulative discrepancy through time where shortfalls continued for more than one year (i.e. the addition of flow discrepancies for each single year across the whole period in which EWRs were not met) and the actual volume delivered over the barrages.

For all of the hydrodynamic and ecological responses investigated (including North and South Lagoon water levels, North and South Lagoon salinities and the percentage of degraded ecosystem states), thresholds could be identified which, when crossed, resulted in additional degradation in the Coorong. For the most part, these thresholds were identified for the discrepancy in flow volume compared to the EWR in one year, or the cumulative discrepancy across multiple years.

Figure 10 summarises the thresholds and the outcomes associated with crossing these thresholds for South Lagoon salinity. For all three salinity targets in Lake Alexandrina,

thresholds were identified in the cumulative discrepancy of flow volumes (compared to the recommended EWR) through time. The largest discrepancies were associated with the 700 $\mu\text{S cm}^{-1}$ EC salinity target, as this had the highest recommended flow volumes. For each salinity target, a range of outcomes (the number of which varied between three and four, depending on the scenario) were associated with each of the thresholds. As the thresholds were crossed, a new outcome was predicted for South Lagoon salinity (these outcomes are shown as different colours in Figure 10). So, for a hypothetical cumulative shortfall in the recommended EWR of 25 000 GL (across a number of years, potentially; represented in Figure 10 by the vertical dashed line) compared to the 700 $\mu\text{S cm}^{-1}$ EC target, it would be likely that South Lagoon salinities would be $90 \pm 30 \text{ g L}^{-1}$, provided that shortfall did not exceed the next threshold of 45 038 GL. Given that some typical South Lagoon biota have salinity tolerances of up to 120 g L^{-1} , this may be considered to be an acceptable condition, at least in the short term, and thus represent an acceptable level of risk.

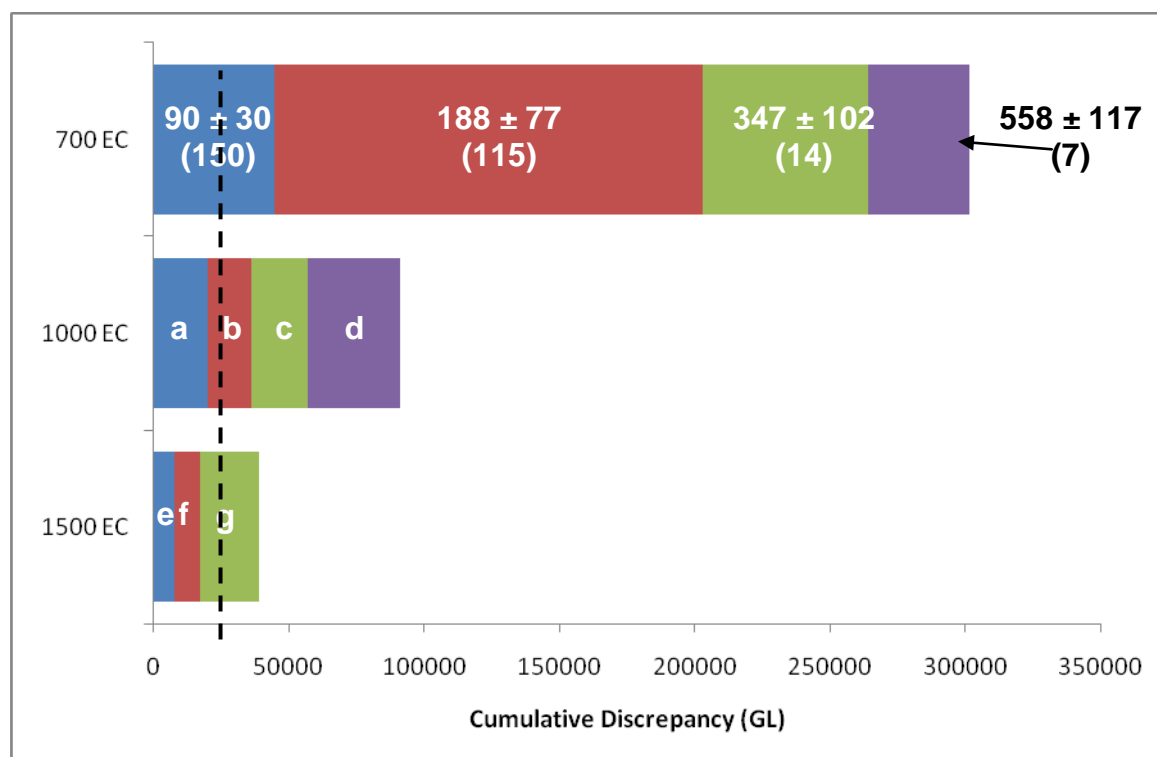


Figure 10: Summary of the steps of decline for South Lagoon salinity (source: Lester *et al.* 2011a)

Each coloured bar represents one outcome in the decline trajectory for each salinity target. The numbers shown over each outcome bar illustrate the average salinity (g L^{-1}) and the number of cases for that outcome. Note: a = 120 ± 35 (124); b = 209 ± 56 (35); c = 316 ± 74 (18); d = 453 ± 137 (17); e = 152 ± 49 (75); f = 294 ± 47 (17); and g = 435 ± 121 (20). The maximum (i.e. maximum within each bar) value shown is the maximum cumulative discrepancy in barrage flows (compared to the volume prescribed by the EWR) reached within the data set for each salinity target modelled (i.e. represents the model experience). The vertical dashed line is used to illustrate the outcome of a particular cumulative discrepancy on South Lagoon salinities in the text.

However, should the EWR be set to maintain a maximum salinity of $1000 \mu\text{S cm}^{-1}$ EC in Lake Alexandrina (which has a lower minimum recommended flow), a shortfall of 25 000 GL compared to that target (again, potentially over a number of years), crosses the first threshold (identified at 20 302 GL), making it likely that salinity in the South Lagoon will be $209 \pm 56 \text{ g L}^{-1}$. This salinity is much higher than the thresholds for most South Lagoon biota, so could be considered to be an unacceptable outcome, and thus an unacceptably high level of risk. The same shortfall compared to the $1500 \mu\text{S cm}^{-1}$ EC target would cross the first threshold (identified at 10 151 GL), making it likely that salinity in the South Lagoon will be $152 \pm 49 \text{ g L}^{-1}$. This salinity is also much higher than the thresholds for most South Lagoon biota, so could be considered to be an unacceptable outcome, and thus an unacceptably high level of risk.

cm^{-1} EC target crosses two thresholds into the most severe outcome, with salinity predicted to be an unrealistically-high $435 \pm 121 \text{ g L}^{-1}$.

Salinities are so much higher for the same cumulative shortfall under the higher salinity targets because much less water is needed in the first place to meet the $1000 \mu\text{S cm}^{-1}$ EC compared to the $700 \mu\text{S cm}^{-1}$ EC target for Lake Alexandrina. Thus the same shortfall (here of 25 000 GL), actually represents a much lower total barrage flow.

A similar summary figure (Figure 11) is presented for North and South Lagoon water levels, which had the same thresholds for each of the salinity targets for Lake Alexandrina. Similar summary diagrams could not be constructed for North Lagoon salinity and the percentage of degraded ecosystem states because the thresholds identified for the different scenarios used different variables (e.g. cumulative discrepancy for one target and discrepancy in a single year for another), but similar threshold do exist and the level of risk for each target can be identified individually (see Lester *et al.* 2011a).

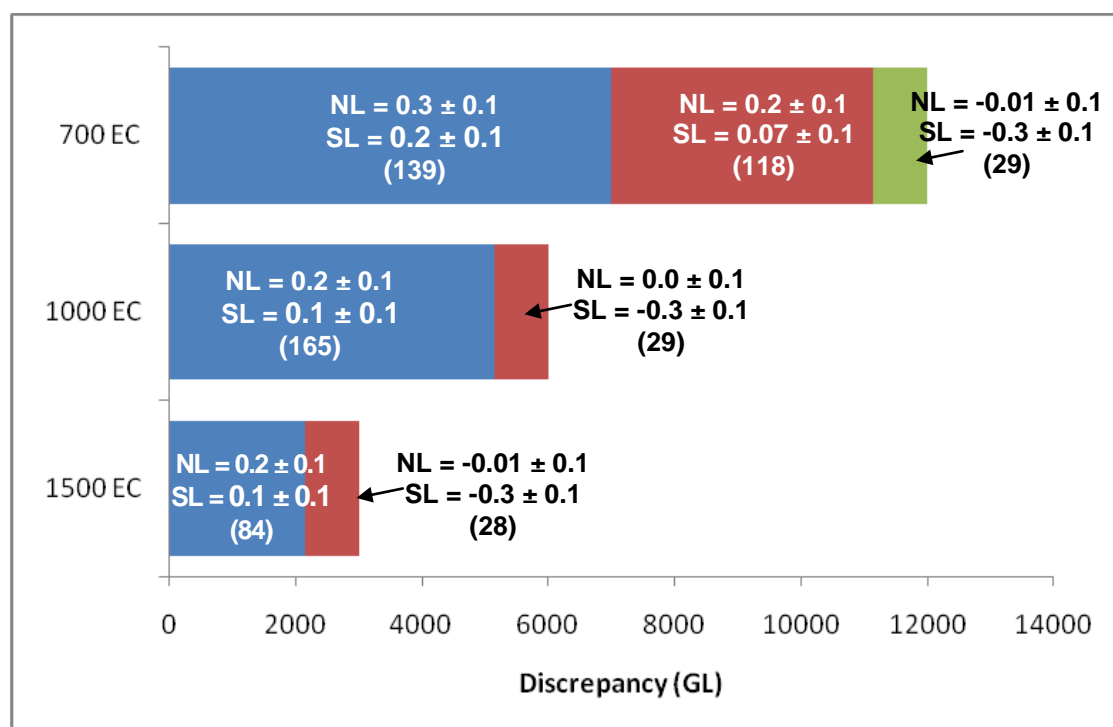


Figure 11: Summary of the steps of decline for North and South Lagoon water levels (source: Lester *et al.* 2011a)

Note that the steps in the trajectory of decline and the thresholds were consistent for water levels in the two lagoons across the three salinity targets. Each coloured bar represents one outcome in the decline trajectory for each salinity target. The numbers shown over each bar illustrate the average water level (m AHD) \pm SD and the number of cases for that outcome in parentheses, with NL representing North Lagoon values and SL representing South Lagoon values. The maximum (i.e. maximum within each bar) value shown is the maximum discrepancy in barrage flows in any one year (compared to the volume prescribed by the EWR) reached within the data set for each salinity target modelled (i.e. represents the model experience).

Given that the work is based on the hydrodynamic and ecosystem states model, the associated caveats (described in Sections 8 & 9) apply here also. But, this analysis provides managers with a mechanism for determining the likely conditions, and thus the level of risk of ecological damage, for a given flow volume lower than that recommended by the EWRs and is a useful tool to assist in setting environmental watering plans for the future.

12.3 Summary

- Providing less water than the recommended EWR for the CLLMM region affected the hydrodynamics of all management units investigated, with salinities rising dramatically in both lakes and the two lagoons of the Coorong.
- More-frequent degraded ecosystem states are predicted for the Coorong as the volume of water supplied falls below the recommended EWR.
- Under these conditions, it is highly unlikely that the Ramsar-nominated ecological character would be supported.
- Dramatic and rapid fluctuations in salinity mean that it is also unlikely that healthy estuarine, marine or hypersaline communities would colonise the Lakes instead, and conditions in the Coorong would remain degraded.
- Thresholds were identified for each of North and South Lagoon salinities and water levels and the percentage of degraded ecosystem states that enable managers to estimate the effects of particular volumes of water, where they are lower than the recommended EWRs. This allows some assessment of the level of risk associated with increasingly small volumes of water for the Coorong.

13. Interactions between flows from the barrages and the proposed expansion to the Upper South East Drainage scheme

The final analysis undertaken as a part of the setting of an EWR for the CLLMM region as a preliminary assessment of interactions between barrage flows and flows from the Upper South East Drainage (USED) scheme. This was a result of proposals outlined in the Long Term Plan for the Coorong, Lower Lakes and Murray Mouth Region (DEH 2010) to expand the USED scheme, and a desire to understand whether volumes of the magnitudes being proposed could have a significant impact on the flows required from the River Murray and act as a supplementary source of freshwater to support the Coorong. Further information on the proposed scheme can be found in DEH (2010) and the analyses undertaken in Lester *et al.* (2011).

We analysed rainfall records compared to River Murray flows over a 22-year period to determine whether there was any relationship between potential flows from the USED scheme and River Murray flows. This analysis showed that there was a significant positive relationship between rainfall in the South East of South Australia and flows over the barrages. However, this relationship was only moderate, and in 44% of years, when barrage flows were low, there was more rainfall than estimated by that relationship in the South East. Using rainfall in the SE as a surrogate for potential flows, it seems likely that additional flows from the USED scheme may be available in almost half of years when it needed most. This suggests that the USED scheme could play a role in alleviating the worst effects of drought some of the time, but that its contribution cannot be ensured in all years.

The effects of additional flows via the proposed USED scheme were assessed relative to the baseline (historical climate and barrage flows with dredging when required over a 22-year model run) for Coorong hydrodynamics. Three volumes of additional flow were investigated for each climate ranging from 4 GL year⁻¹ under a dry future climate to 63 GL year⁻¹ under an historical climate. Changes in the flow volumes reflected likely declines in available flows associated with climate change. Inter-annual flow delivery (where a variable delivery pattern was assessed) were based on the average variation in actual flows over the 22 years of available data. Intra-annual flows were allocated using the average of the flow options presented in Peters *et al.* (2009; see Lester *et al.* 2011a for additional detail).

When flows were added in a variable manner from year to year, there was a greater impact than if the same volume was added each year. Additional water from the USED scheme had the largest impact on maximum salinities and increasing volumes of additional water had increasing effects. Very little change, regardless of the additional volume investigated was seen in annual range in water level or depth but there were small but variable effects on water levels. This pattern was consistent across the three climates that were investigated (the historical, median future and dry future projections) and the method of flow delivery (i.e. consistent vs. variable inter-annual flows). The timing and duration of the flow delivery was not investigated as a part of this study.

The impact of additional USED flows on Coorong ecosystem states was also assessed. No volume of additional water under any flow delivery pattern or under any climate affected the ecosystem states in the North Lagoon. In the South Lagoon, increasing volumes via the USED scheme reduced the proportion of Degraded Hypersaline site-years, replacing them with Average Hypersaline site-years. Additions of 63 GL were needed under any climate to prevent the appearance of the Degraded Hypersaline ecosystem state (although a very small number remained even with that flow volume under a dry future climate projection). This represented an increasingly positive influence with more severe climate change. However, no flow volume from the USED was able to trigger additional instances of the Healthy Hypersaline ecosystem state,

which is thought to be associated with high-flow years, suggesting that flows from the USED scheme do not mimic all of the effects of barrage flows, even in the South Lagoon. It does appear, however, the additional flows from the USED scheme could provide some insurance during dry years, by limiting extremes in ecological condition.

The impact of increasing USED flows was also investigated for low, medium and high barrage flow years. Four years were selected for each of the low, medium and high flow categories, and the difference in maximum salinity, minimum water level and the percentage of degraded ecosystems states compared to the baseline scenario was calculated for additions of 18, 36 and 63 GL year⁻¹ from the USED scheme. This gave an assessment of low, medium and high USED flows in each of low, medium and high barrage flow years for each site, so that the magnitude of change and the distance along the Coorong for which change was apparent could be assessed.

As for the hydrodynamic investigation above, the largest change compared to the baseline occurred in maximum salinities. Maximum salinities along the length of the Coorong were affected, with declines of more than 40% in some South Lagoon sites (sites 8-14; Figure 12) when barrage flows were low. Smaller USED volumes, particularly when combined with larger barrage flows had a smaller influence.

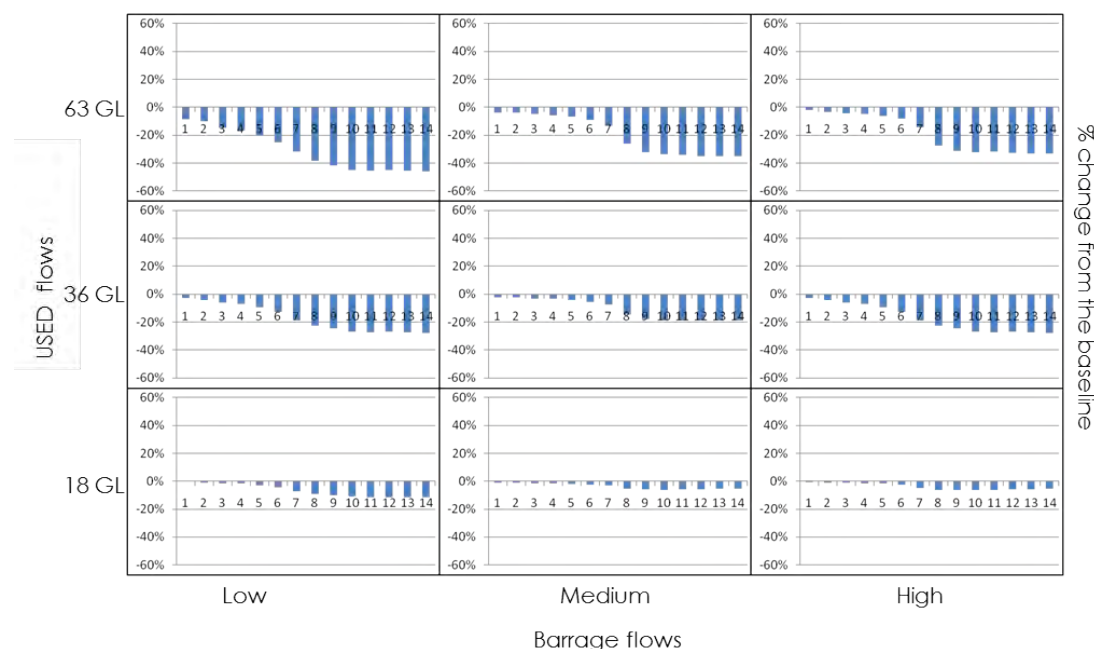


Figure 12. Matrix of interactions of high, medium and low barrage flows with 18, 36 and 63 GL via the USED scheme for percent change in maximum salinity (source: Lester *et al.* 2011a)

Note: Each panel includes the average percent change in maximum salinity across four years (selected from the 22-year model run, divided into low, medium and high years; Lester *et al.* 2011a) based on a variable inter-annual delivery of USED flows. The percent change is calculated relative to the Baseline & dredging scenario. The x-axis shows sites along the length of the Coorong, with site 1 nearest the Murray Mouth, site 7 the southern-most North Lagoon site, site 8 the northern-most South Lagoon site and site 14 at Salt Creek in the South Lagoon.

The influence of USED flows on minimum water level was mixed, with some combinations of USED and barrage flows resulting in lower minimum water levels than were simulated under baseline conditions (Figure 13). Water levels were higher when barrage flows were low, however, and all changes were small.

Changes in the percentage of degraded ecosystem states were also small and variable, with no clear pattern of increasing change with increasing USED flows, or decreasing barrage flows. All predicted changes were limited to the South Lagoon.

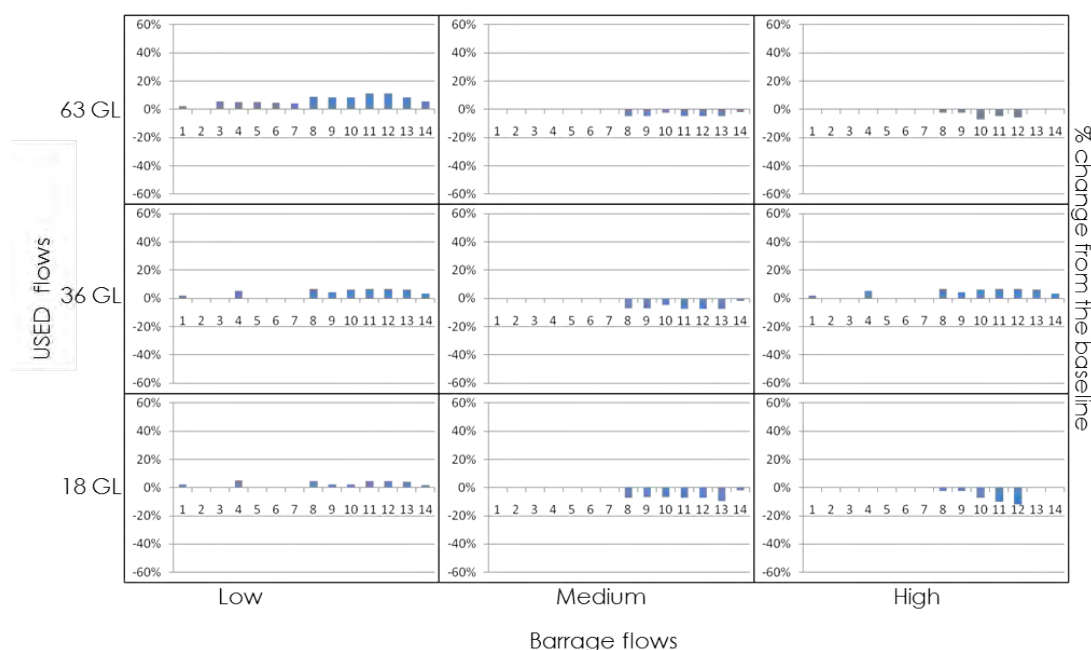


Figure 13. Matrix of interactions of high, medium and low barrage flows with 18, 36 and 63 GL via the USED scheme for percent change in minimum water level (source: Lester *et al.* 2011a)

Note: Each panel includes the average percent change in minimum water level across four years (selected from the 22-year model run, divided into low, medium and high years; Lester *et al.* 2011a) based on a variable inter-annual delivery of USED flows. The percent change is calculated relative to the Baseline & dredging scenario. The x-axis shows sites along the length of the Coorong, with site 1 nearest the Murray Mouth, site 7 the southern-most North Lagoon site, site 8 the northern-most South Lagoon site and site 14 at Salt Creek in the South Lagoon.

These analyses suggested that the changes seen in maximum salinities and ecosystem states, while likely to be beneficial, may be of limited ecological significance for the system as a whole. Further examination would be required to examine effect that the timing and volume of flow delivery may have on these results given subsequent proposals for expanding the USED scheme include the potential to re-regulate some flow in some years. However, previous studies have found that long, continuous flow releases have a greater influence on Coorong hydrodynamics than pulsed flows (I. Webster, pers. comm.), so additional benefits may be small. Thus, at this time, it must be concluded that River Murray flows must remain the primary source of fresh water for the Coorong, although an expanded USED scheme has the potential to provide a measure of insurance in dry years, should EWRs not be met.

13.1 Summary

- We made a preliminary investigation into interactions between USED and barrage flows and their effects on Coorong hydrodynamics and ecosystem states.
- This assessment was based on the current proposal for expanding the scheme at the time of writing and any changes to that proposal may affect the likely impacts.
- Additional flows from the USED scheme appear possible in 44% of years when barrage flows are low.
- Additional flows via the USED scheme had the largest influence on maximum salinity, with mixed results on water levels and little influence on ranges in water

level or depth. Only very small changes were simulated for the North Lagoon, and patterns were consistent across climate projections.

- The additional flow volumes investigated were predicted to result in fewer degraded ecosystem states, particularly under climate change, but states thought to be associated with high flows were not induced, and no change was observed in the North Lagoon for any volume under any scenario.
- Additional investigation of the impact of increasing flow volumes under low, medium and high barrage flows show that the largest impacts were on maximum salinities in the South Lagoon when barrage flows were low. Changes in minimum water level were small but there was some reduction in the percentage of degraded ecosystem states. The scale of these changes was not likely to be ecologically-significant across the region as whole.
- The River Murray must remain the primary source of fresh water for the Coorong to ensure the ecological character of the region, but expanding the USED scheme could provide a useful insurance policy for the South Lagoon if EWRs are not met.

14. General Discussion

Several attempts have been made in the past to estimate an environmental water requirement for the CLLMM region (e.g. through The Living Murray initiative). However, these attempts have been limited by a lack of general understanding as to how the ecology of the region links to the hydrology of the region, and then ultimately to River Murray inflows to the site. Instead, they have been necessarily limited to judgements formed on the basis of the amount of water that was likely to be available, or was needed to achieve specific management goals (e.g. operation of fishways for a given proportion of time) without the available resources or information to determine whether this was sufficient or optimal to maintain the ecological character for which the region is recognised. This is the first time that a comprehensive review of this understanding has been undertaken and a concerted effort made to link ecology to water requirements for this site.

In undertaking this process, we remained cognisant that the overall goal for the region was to maintain a “healthy productive and resilient wetland system that maintains its international importance” (DEH 2010; p. 84). This goal aligns with the South Australian and Australian Governments’ international and national obligations, and provides the flexibility to manage the site in terms of large-scale uncertainty (e.g. in the form of climate change and future water allocation policy). As a result, we focused strongly on the ecological processes that constitute a wetland of international importance, and the ecological definitions of ‘healthy’, ‘productive’ and ‘resilient’. This focus led us to a methodology based on ecological first principles, which is somewhat different from many other methods that have been advocated or attempted in the past (e.g. Thoms & Sheldon 2002; Arthington & Pusey 2003), which have often focussed on restoring attributes from the natural hydrograph, or on providing conditions for target key taxa, although aspects of many of these methods have been included here.

The most recently-developed methodologies of which we are aware represented a start in terms of linking environmental water requirements to ecological outcomes. For example, the draft methodology developed by the MDBA (2009b) concentrated on hydrological processes, with the assumption that desirable ecological processes would then necessarily follow. In a natural system, this is likely to be the case, but there is a risk that this would not be the case in such a modified and, in places, degraded system. Rules of thumb such as those suggested by the Wentworth Group of Concerned Scientists (i.e. to restore flow to two-thirds of the natural condition) resulted in similar recommended flow volumes, but also lack an explicit link between hydrology and ecology (Cosier *et al.* 2010). The method described here does explicitly link ecological outcomes to environmental water requirements, and is consistent with the MDBA methodology in that it also uses hydrological processes (here as an interim step) to drive the determination of volumes of water required. Thus, while this methodology is, to our knowledge, relatively unique in the manner in which it approaches the linkages between ecological outcomes and environmental water requirements, the approach is consistent with what has been proposed previously, both for the MDB and elsewhere.

14.1 Applying the method across diverse and changing habitats

By focusing our methodology on linking ecological objectives and outcomes to the environmental water requirement, we have not limited the utility of this process to the Ramsar-nominated ecological character of the region. That is, while the current recommended environmental water requirements are designed to maintain the ecological character, the suite of indicators and thresholds could be used to determine environmental water requirements to support a more-estuarine system, or some other targeted wetland type instead. This means that the methodology which

has been undertaken is robust to large-scale changes like climate change, and that it could be used to help the site adapt over time to changing conditions. Tables outlining the various trade-offs of increasing salinities and decreasing flows are the mechanism by which this can be achieved. By setting different overall goals for the region, different outcomes in terms of the biota and processes supported become acceptable. These tables are also able to be progressively updated if (and when) additional information becomes available. Additional hydrological and ecological modelling would need to be undertaken to understand the volumes and timing of water required to sustain different combinations of biota, but the bulk of the indicators and thresholds would remain relevant.

Another advantage to this approach is that it is also applicable to the diverse range of habitat types and flow regimes that currently exist across the site, which represented a significant challenge in developing an environmental flow requirement. Thus, there was no need to undertake a separate process for the freshwater Lakes versus the variously estuarine, marine and hypersaline parts of Coorong and the objectives and outcomes could be applied to many other wetlands with minimal tailoring (e.g. possible removal of references to salinity gradients for wholly-freshwater systems). In fact, the process could readily be applied elsewhere, with an appropriate choice of taxa and processes and indicators for individual wetland systems, and associated hydrodynamic and/or ecological response modelling done to inform the process. We believe that the methodology, objectives and outcomes are robust and transferable.

While the environmental water requirement that is described here is designed to sustain a healthy, productive and resilient wetland of international importance, it needs to be understood that there will be limits to that resilience, and any transitions between potential ecological states in the region should be gradual. In particular, the recent highly-degraded condition means that resilience is likely to be very low, so the ability of the system to adapt to fast-changing conditions is also likely to be low. Thus, managers should aim to avoid actions that would result in rapid shifts in flow or water quality conditions (e.g. rapidly-increasing salinity associated with flooding of the Lakes via seawater), and adopt a more cautious approach (e.g. if seawater addition was deemed necessary, a very gradual filling could be adopted to minimise the rate of change within the system). This is also true of freshwater flows. The current degraded state of the system means that large unmanaged volumes of freshwater have the potential to have unintended adverse outcomes, such as acidification events, or elimination of refugia for estuarine taxa. Recovery and/or additional management interventions that have the potential to result in rapid change should be carefully planned, managed and monitored in accordance with the adaptive management framework for the region (Higham *et al.* in prep).

14.2 Interpreting thresholds for indicator components and processes

One of the advantages of the method that has been used here to develop relationships between indicator taxa, assemblages and processes and hydrologic conditions is that it is comprehensive. The selection of indicators included a representative range of life-history strategies, threatened taxa, sensitive taxa and processes that integrate ecological function across taxa. An associated disadvantage of this approach is that there is a large amount of information, which can then be difficult to interpret in a management context, and that the method was resource-intensive to apply.

In order for the work contained here to be useful for the monitoring the success of the delivery of environmental flows, consolidation across the suite of indicators needs to occur. A subset of indicators must be selected that will represent the range of other taxa and processes occurring at the site. In addition, limits of acceptable change must be set, and some assessment of how these can be interpreted at a whole-of-site

scale developed. Some of this work is due to undertaken over the coming months, but it is likely that an iterative approach will be needed.

Another limitation is that some of the identified ecological outcomes can be difficult to apply to the indicators. Taxon- (or assemblage-) centric outcomes (e.g. regarding population connectivity) seem incompatible with process indicators, for example, but can be applied when processes are seen to integrate taxon-level activity. Also, when using individual taxa to indicate that outcomes associated with the objective of self-sustaining populations, for example, it seem to require that all indicator taxa meet the outcome, but this is unlikely to be necessary. It is not yet clear, however, many of these must be met individually before we can have confidence that the objective is being met, and whether this varies among outcomes. Making greater use of the ecological process indicators may be a mechanism for avoiding some of these difficulties, but it is likely that a combined approach, including some processes and some taxa or assemblages will provide the best outcome. So, additional work is also required to link outcomes to the indicators identified here.

Also, there are currently limitations associated with the sets of indicators that have been selected and the level to which they have been documented, largely as a result of resource limitations to date and the status of other concurrent work on the region. Birds, amphibians, reptiles and plankton are currently not addressed. Birds, in particular, are likely to respond to hydrological conditions indirectly, via their food and habitat requirements, so excluding them from the first iteration of this work seemed reasonable. Very little is known about amphibians and reptiles in the region, so these were also excluded from this version. Current work on local plankton communities has only occurred relatively recently, so it is not clear how large changes in the region (e.g. the recent return of freshwater flows) will affect those assemblages. However, further work should include these groups, as they are key components of the ecological character within the region, and their response to hydrological conditions should be explored, at the very least.

Additional knowledge gaps may also be able to be filled as additional work is completed. Literature reviews regarding birds and zooplankton, for example, were not available at the time of writing, and may be able to add significantly to the knowledge incorporated here. Additional information regarding linking process indicators to hydrological conditions is also currently required. Conceptual models may be a useful first step in this process.

The work that has been done to identify thresholds for each of the indicators has been heavily reliant on previous work that has been undertaken and the available literature. As a result, most of the hydrological conditions that were investigated (e.g. links to salinity, turbidity, water levels) were considered separately, as very few studies have been done that consider multiple factors simultaneous. Thus, for almost all taxa, where tolerances are known, they are for a single stressor (or condition) in isolation. However, interactions between potential stressors are also known to be important. It is likely that individuals would be able to withstand more extreme conditions under a single stressor than they could for the same stressor when others stressors were also operating. For example, a hypothetical fish may have a salinity threshold of $1500 \mu\text{S cm}^{-1}$ EC in the absence of stress due to low pH (e.g. a pH of around 7.5). When pH was low, however (e.g. a pH of 5.5), this salinity tolerance may drop to only $1000 \mu\text{S cm}^{-1}$. Thus, the values that are reported here as drawn from the literature should be considered to be upper limits of tolerance, as multiple stressors are currently in play in the Lakes and Coorong. Additional research into the interactions between common stressors in the region for a selection of representative taxa (or processes) would be of significant benefit in understanding the magnitude of the effect.

14.3 Synthesising modelling outputs

In developing a recommended environmental water regime for the CLLMM region, hydrological, hydrodynamic and ecological response modelling were all used. Chaining models together in this fashion is a relatively new approach to assessing water allocation plans (in this instance an environmental watering plan; Lester *et al.* 2011a), but has the advantage that different options are assessed objectively against a specific set of criteria.

In this instance, these criteria were related to the salinity and water level thresholds and the presence of specific ecosystem states in the region. While this may not be a perfect set of criteria, and it certainly does not cover all possible approaches, each possible flow regime was assessed against the same benchmark. Thus, the recommended flow regime can be considered defensible and relatively robust. In order to ensure that additional important ecological considerations (other than those covered by these criteria) have not been overlooked, we recommend that a qualitative assessment be undertaken by suitable local experts who may be aware of other constraints (for example) which have not yet been identified.

Limitations of the individual models are discussed in depth in the associated reports for each section (Heneker 2010, Lester *et al.* 2011a, Lester & Fairweather 2011) or in the original works describing the development of each model (Lester & Fairweather 2009, Webster 2007, 2010). Those that are most relevant to this work have also been highlighted above.

One of the consequences of the modelling undertaken here, both in the standard flow delivery pattern and the modified flow delivery pattern, was that the model tended to underestimate the peaks in Lakes salinity (see Heneker 2010). This tendency suggests that a cautious salinity target should be set, as there is likely to be considerable variation (particularly short-term high salinities) that is not always picked up by the models. This seems to be particularly the case for the very high salinities in the sequence from 1975 to 2008. In Lake Albert, there is a less-complete record of observed salinities, which made interpretation of the calibration more difficult, but again, the model seems to miss some of the peaks salinities so a similar conservative approach would be warranted.

The modification of the flow sequence tended to exacerbate this problem. While analysis showed that this was of little importance in assessing the annual average salinity in the Lakes, it was of critical importance to the hydrodynamic and ecological conditions predicted for the Coorong. Thus these effects need to be borne in mind. While additional research exploring the optimisation of flow delivery has been recommended, it is also important to understand that this dampening of extremes means that both extremely good and extremely poor conditions may not be adequately captured, and so a conservative approach to the setting of target salinities and target flow regimes may be prudent.

The modelling, for the Lakes in particular, has limited spatial and temporal resolution. We expect that there will be considerable short-term temporal variability and that both salinities and water levels will vary across the lakes. This is a natural part of a large, complex system such as the CLLMM region and is one of the reasons that the area supports such a diversity of biota and is an internationally-recognised wetland. The extent to which the variability occurs and the impact of that variability on recommended environmental water requirements have not been explored as a part of this work.

14.4 Defining a recommended flow regime

Given the degree of variability in historical river flows to the Lower Lakes and through to the Coorong and Murray Mouth, it was not considered appropriate to define a flow regime that would support ecological function in terms of an annual average

outflow target alone. This is because the flow variability around an average value may not ensure that salinities continuously remain below a given threshold.

Based on the work that has been undertaken here, the majority of recommendations regarding environmental flows focus on two- or three-year periods. This is partly due to the relatively short 'memory' (i.e. the length of time in which the influence of a large flow is apparent) both for the Lakes and Coorong. It is also partly due to the unregulated nature of, and thus limited control that can be exerted over, high flow events. We have therefore focused primarily on the low-flow components of the system as those that can be influenced to recover and then maintain ecological character within the region. This should not be taken as a justification for removing the high flow components from the hydrograph, if that were possible. The limited work that has been possible for the Coorong indicates that high flows have a significant and positive effect on the ecosystem states that are present, although additional work is needed to quantify the precise volumes and return frequencies required.

The risks associated with delivering lower flow volumes than recommended are of critical importance to managers during the current planning processes surrounding environmental watering plans. However, the analyses that have been done, both considering flows predicted under climate change and the analysis of low-flow sequences and investigating the thresholds associated with increasing discrepancies of work, are alarming. Based on the work to date, the recommended maximum of 1500 $\mu\text{S cm}^{-1}$ EC for Lake Alexandrina should be thought of as an absolute maximum, to be avoided wherever possible in order to maintain a healthy ecosystem, and adverse conditions start to manifest when discrepancies in barrage flows exceed even 2000 GL in a single year. Should lower flow volumes be delivered, it is unlikely that healthy marine or hypersaline ecosystems would become established, in the Lakes in particular, because low water levels and large fluctuations in salinity that mean conditions are likely to be regularly outside the tolerance limits of the associated biota (e.g. including both salinities that are too high and too low). Thus the fluctuations, and the rate at which these changes occur, are likely to be problematic. Preliminary analyses investigating the effect of the proposed expansion to the USED scheme suggest that it may be able to alleviate the worst conditions in times of low barrage flows, but is not likely to be able to replace the River Murray as the main source of fresh water for the Coorong (assuming the scheme was expanded in the manner investigated here).

The flow regime that is recommended here represents a relatively small increase in flows to the region, particularly if the impact of climate change is moderate. The challenge associated with this regime will be that the additional water is likely to be required in dry periods, where water availability is likely to be low. Operational issues like this (and many others), have yet to be considered, but represent a significant challenge to managers to provide sufficient water to ensure the sustainability of the ecological character of the region.

14.5 Incorporating these findings into the MDBA Basin Planning process

One of the first opportunities to implement the findings of this investigation is as a part of the MDBA Basin Planning process, which is currently underway. MDBA have requested input from the relevant states regarding EWRs for selected high-value wetlands, including the CLLMM region. The draft Basin Plan is currently being developed, and the recommendations arising from this work have been communicated to MDBA. Preliminary indications are that the targets identified here will be of use in evaluating the flow sequences produced by the current modelling exercise with some small translation of terminology and metrics (e.g. ARFs and salinity targets) to be more consistent with the approach being used by MDBA (e.g. whole flow sequences). We are currently working with MDBA to supply our recommendations in the requested format and will continue to collaborate as the Basin Plan progresses.

15. Process going forward

This is the first time that such a comprehensive assessment of the environmental water requirements of the Coorong and Lakes has been undertaken and, to our knowledge, is the first report for the site that has attempted to answer the management question of *How much water is enough for the Coorong and Lakes?* from ecological first principles. Following the principle of continuously improving management tools and information bases, this should be considered the first iteration of the process of determining the environmental water requirements for the site. We have identified a number of areas that require additional work as part of a second, or subsequent, iteration(s) and these are listed below.

1. Additional work is required on the indicator sets described. The possible inclusion of taxa and process indicators such as zooplankton, birds, reptiles, frogs, predation and herbivory should be considered. Linking these indicators to flow requirements is also likely to need additional research and development in the future, as is testing some of the assumptions and hypotheses that have needed to be made.
2. Additional modelling is required to assess the impact of the proposed environmental water regime on water level variability in the Lakes. To date, we have not assessed whether the proposed water-level envelopes are adequately met by the proposed flows. A brief initial assessment did not raise any immediate concerns, but this should be addressed systematically.
3. Additional modelling is also required to understand the small-scale variability within the system, particularly in the Lakes with respect to water level and salinity.
4. A qualitative assessment of the ecological effects of less water would also be wise, given the lack of an ecosystem response model for the Lakes and the acknowledged limitations of the model for the Coorong. This would then identify any taxa-specific requirements that may not be identified using the ecosystem states model. A similar qualitative assessment would also be of use for the high flow requirements of the system for the same reasons.
5. Similarly, it would also be of use to update existing ecological models for the region (e.g. MFAT) based on the knowledge that has been collected since their development. This would be consistent with the tenets of adaptive management and would ensure that limitations of the few models that have been included here (e.g. the ecosystem states model) do not adversely affect the determination of the EWR for the region. In particular, there appears to be a substantial body of knowledge with regard to fish populations and habitat use that has become available in recent years that could be included in updated tools.
6. Understanding which metrics are of most use in interpreting the output of the ecosystem state model requires further investigation. While the developers of the model have experience in interpreting its outputs, there are plans to use this model, and a similar one for the Lakes, in the future management of the site. For this to be successful, a simple, robust method of comparing between scenarios needs to be developed for a lay and initially-inexperienced user. A technology transfer is also needed between the authors of the model and the agencies that who will use them in the future.
7. As yet, this work includes a preliminary investigation into interactions with the USED scheme, but has not considered other interventions in the CLLMM region (e.g. use of local groundwater resources). Interactions between the proposed EWR and these interventions will need to be understood so that the implications can be incorporated into negotiations for a water allocation for the region.

In addition to the above work that is needed to further develop the EWR for the CLLMM region, the following work is required to more effectively manage the region and to ensure that the EWR is meeting the objective of maintaining the CLLMM region as a healthy, productive and resilient wetland of international importance.

1. The development of a sub-set of indicators to assist in the monitoring of success of environmental flows delivered to the region. Which indicators best represent the ecological outcomes, what the limits of acceptable change are for those, and then how these can be combined to give an overall regional perspective all require further work.
2. The work that has been done to consolidate available information about the indicators chosen should be captured in a manner that will allow it to be updated over time and used for other purposes. A database may be a good way to capture this information.
3. Further research is needed into which and how many metrics need to be met concerning the limits of acceptable change for sets of indicators in order to be able to report that the overall vision for the region has been met (or not, as appropriate). This research would continue work undertaken to develop a subset of indicators for evaluating management performance.
4. An assessment of the delivery constraints inherent in the system will be needed to better understand the effect these will have on the practicality of delivering the EWR for the CLLMM region as specified and any trade-offs that may be necessary with current infrastructure and water sharing rules. These have not been incorporated into the development of the EWR, as it is possible that some or all may change under the forthcoming Basin Plan. However, once we have a better understanding of the changes that are likely under the Basin Plan, such an assessment will be necessary to ensure the EWR can be implemented effectively.
5. Finally, the environmental water regime outlined here does not include an allowance for the recovery of the system from its recent state. Recovery to date had not been documented at the time of writing, but complete recovery is likely to require careful management in a staged approach, with active intervention to assist in the recovery of key biota and processes. This will need to be considered elsewhere.

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17. Appendix A: Glossary

Annual return frequency (ARF) – a measure of the rarity of an event, for example, the annual return frequency of barrage flows.

Assemblage – a group of taxa considered collectively, though may not be representative of the entire community at a particular location.

BigMod – a hydrological model developed for simulating flow and salinity in the Murray River including a range of water management policies (e.g. operation of storages and water-sharing rules).

Biogeochemical cycle – the pathway undertaken by a molecule through abiotic and biotic pathways.

Brackish – a relatively informal term to refer to waters that have a salinity range between that of freshwater and estuarine waters.

Community – an assemblage of taxa living close enough together for potential interaction.

Connectivity – the degree to which intra- and inter-specific physical and ecological systems and processes are linked.

Ecological character – the taxa, communities and habitats that are found in a location and the processes and system drivers which make a place unique to Australia or elsewhere.

Ecological function – the physical and ecological processes that take place in an ecosystem.

Ecological health – the degree at which the integrity of ecological processes are sustained.

Ecological process – a process that involves a change or a response in the ecological functioning of the system, rather than simply a physicochemical response. Ecological processes occur between individual organisms, within populations or among communities.

Ecosystem – the biotic community as well as the environment with which the organisms interact.

Ecosystem states – distinct ecological states which are combinations of co-occurring biota and the environmental conditions with which they are associated, arising directly from the ecosystem states model (Lester & Fairweather 2011), which have been used to assess the ecological condition of the Coorong.

Electrical Conductivity (EC) – a measure of the water's ability to conduct an electrical current. Electrical conductivity (measured at 25°C in units of mS cm⁻¹ or µS cm⁻¹) can be used to estimate salinity because a relationship exists between the levels of dissolved salts in a water body and its conductivity.

Environment – all the biotic and abiotic factors that affect an individual organism at any point in its life cycle.

Environmental water requirement (EWR) – the amount of water required by an ecosystem to remain or return the ecosystem to a desired state, often expressed as a minimum and/or relative to natural (i.e. without development) flow conditions.

EPBC – An abbreviation for the *Environment Protection and Biodiversity Conservation Act 1999*. Australian Government environmental legislation which provides a legal framework to protect and manage nationally- and internationally-important flora, fauna, ecological communities and heritage places.

Estuarine – refers to water that has a salinity between that of fresh and marine waters (i.e. 2-20 ppt).

Euphotic zone – the zone within a waterbody where light penetrates the water sufficiently for photosynthesis to occur.

- Exoskeleton** – the external skeleton that supports and protects an animal's body.
- Flow regime** – the timing and magnitude of flows delivered in an aquatic system, including inter- and intra-annual variability in those flows.
- Freshwater** – refers to water that has a salinity less than 2 ppt.
- Habitat** – an area or environment where an organism or ecological community lives or occurs. A habitat is made up of physical (e.g. range of temperature, salinity and water level) and biotic (e.g. availability of food and presence of predators) factors.
- Homogenisation** – the act of making something uniform in composition.
- Hydrograph** – a mathematical curve depicting the changes in flow or water level over a given time period.
- Hydrology** – the properties, distribution and circulation of water. Represents the water cycle including evaporation, precipitation and flow.
- Hydrodynamics** – changes in hydrology through time, including flow, water levels and salinity.
- Hypersaline** – refers to water that is more saline than marine waters (i.e. >40 ppt).
- Keystone** – used to describe a taxon that plays a critical role in maintaining the structure of an ecological community. For example a keystone taxon refers to a taxon whose impact on the community is greater than would be expected based on its relative abundance or total biomass.
- LC50** – the concentration of a chemical that results in 50% mortality of test animals in a given time.
- Life stage** – an individual stage in the life of an organism. For example, larval, juvenile and adult forms are all life stages for different organisms.
- Limits of acceptable change** – a process developed to deal with the issue of natural variation in a resource which provides a framework to prevent significant adverse environmental effects during resource use.
- Management units** – separate units used by natural resource managements to assist in the task of assessing and managing a complex region. In the CLMM region, seven units are commonly used, which are: the Lower Murray River, Lake Alexandrina, Lake Albert, the Goolwa Channel, the Murray Mouth region, the North Lagoon and the South Lagoon.
- Marine** – water that has salinity values between estuarine and hypersaline waters (i.e. 20-40 ppt).
- Mean** – a measure of the centre of a distribution calculated by adding all values and dividing by the number of values (i.e. so it is a measure that can be influenced by small numbers of very large or very small values).
- Ramsar Convention** – a colloquial name for The Convention on Wetland of International Importance that was developed in Ramsar, Iran to provide a framework to ensure the conservation and wise use of wetlands that are listed under the convention.
- Recruitment** – addition to a population, usually from young animals or plants entering the adult population.
- Redundancy** – the number of pathways (e.g. different taxa, processes) by which similar roles in an assemblage can be performed and among which substitution may be possible with little impact on ecosystem function.
- Resilience** – the capacity of a ecosystem to withstand disturbance while still retaining its basic function and structure (Walker & Salt 2006).
- Salinity (ppt or g L⁻¹)** – the dissolved salt concentration of a volume of water. Parts per thousands (ppt) is approximately grams of salt per kilogram of solution. Can also be measured in grams per litre (g L⁻¹).
- Sclerotised** – a term used to describe the harden body parts of invertebrates.
- Stressor** – an environmental condition that causes lethal or sub-lethal stress to an organism.

Surrogacy – a concept by which an easily-measured taxa, assemblage or process could act as a representative for the ecological character of a broader range of taxa, assemblages or processes. Several different types of surrogacy have been proposed (e.g. umbrella taxa).

Taxa/taxon – a grouping of organisms/single organism given a formal taxonomic name such as family or genus. The taxonomic level is not specified. Taxa is the plural form of taxon.

Threshold – a point at which a change in conditions (e.g. change in a quality, property or phenomenon) produces a disproportional response/shift. For an example, a decline in water level to a point where a sudden shift in the ecological community is observed.

Total Kjeldahl nitrogen (TKN) – the sum of all organically-bound forms of nitrogen (organic nitrogen, ammonia and ammonium) in the chemical analysis of water or sediment.

Trophic level – functional level of classification of organisms in a community according to their feeding relationships.

Turbidity – the amount of suspended sediment in the water column.

USED – Upper South East Drainage scheme where agricultural drainage from the South East of South Australia is diverted to the South Lagoon of the Coorong via Salt Creek.

Water quality – the physical, biological and chemical characteristics of water. It is a measure of the condition of water relative to the requirements of a single taxon or multiple taxa and ecosystem health.

Wind seiching – water oscillations in a water body caused by wind or other resonance.

Zooplankton – animals that drift within the water column and typically include single-celled organisms and the larvae of some fish and invertebrates.

18. Appendix B: Ecological outcomes and associated outcomes

Objective 1. Self-sustaining populations

Outcomes:

- i. Successful recruitment of local breeding taxa occurs through time (i.e. individuals recruit often enough to sustain the population)
- ii. Suitable habitat exists for breeding, feeding, shelter and development of individuals to accommodate all life history stages (Closs *et al.* 2004)
- iii. Suitable food resources exist for a variety of taxa (Closs *et al.* 2004)
- iv. Water quality within tolerances for all life history stages for a variety of taxa for the majority of time (Boulton & Brock 1999; Closs *et al.* 2004)

Objective 2. Population connectivity

Outcomes:

- v. Exchange of taxa occurs between Lakes, Coorong, from upstream habitats, regional wetlands and tributaries (including South East of South Australia), the ocean (and possibly other nearby estuaries) and terrestrial environments to enable spatial connectivity (Closs *et al.* 2004)
- vi. Viable propagule banks exist to enable temporal connectivity (Boulton & Brock 1999)
- vii. No barriers to connectivity (either physical, temporal or seasonal) exist that prevent eventual intraspecific connectivity amongst life history stages/sexes for the purpose of breeding or recruitment (Closs *et al.* 2004)

Objective 3. Hydraulic connectivity

Outcomes:

- viii. Floodplains (& mudflats, island habitats etc.) are hydraulically connected to permanent water bodies (e.g. via a variable flow regime) (Boulton & Brock 1999; Edgar 2001)
- ix. Residence times for water in each of the management units are not infinite
- x. The River, Lakes, tributaries, Coorong, ocean and South East are hydraulically connected. Ideally this would mimic natural levels of connectivity but at a minimum it needs to occur often enough during periods that are critical for ecological functionality (e.g. seasonally and inter-annually) (Boulton & Brock 1999)
- xi. Exchange of energy, nutrients and carbon between management units, and from upstream or to downstream of the site (Boulton & Brock 1999; Edgar 2001)
- xii. Pollutants delivered to the site are passed through and do not accumulate at abnormally high rate (e.g. sediment, salinity, acid, metals, agrochemicals)
- 'iv. Water quality within tolerances for all life history stages for a variety of taxa for the majority of time (Boulton & Brock 1999; Closs *et al.* 2004). Note: Outcome iv is repeated under this objective.

Objective 4. Habitat complexity

Outcomes:

- xiii. A diverse range of habitat units exist across the site both above and below the water line (e.g. submerged plants to reed beds to paperbark or samphire to ephemeral mudflats to clean shorelines)
- xiv. There is temporal and spatial variability in available habitats

Objective 5. Persistent salinity gradient across site

Outcomes:

- xv. A range of salinities are represented across the site (with no areas outside maximum salinity tolerances for all life histories of a variety of taxa for extended periods or across extended areas) (Edgar 2001)
- xvi. Salinities vary through time (with no areas outside maximum salinity tolerances all life histories of a variety of taxa for extended periods or across extended areas) (Edgar 2001)
- xvii. Communities requiring a variety of salinity regimes are supported across the site (e.g. ranging through fresh, estuarine, marine and hypersaline) (Edgar 2001)

Objective 6. Flow and water level variability

Outcomes:

- xviii. A range of flow volumes are delivered to the site through time (Boulton & Brock 1999)
- xix. Seasonality of flows exists (mimicking the pattern of the natural hydrograph) (Boulton & Brock 1999)
- xx. Seasonality of water levels exists (mimicking natural patterns) (Boulton & Brock 1999)
- xxi. Communities requiring a variety of hydrological conditions are supported across the site (e.g. patches of dry, ephemeral and permanently-inundated habitats)
- xxii. Communities and processes requiring occasional flooding (e.g. to cue spawning or stimulate germination) are supported by the site
- xxiii. A tidal signal is apparent in the Murray Mouth region

Objective 7. Redundancy and appropriateness of ecological function

Outcomes:

- xxiv. Complex, diverse food webs across the site
- xxv. Multiple taxa are present that are capable of performing similar functions (e.g. shredding of organic matter, microbial processing, food sources) within the site
- xxvi. Working, efficient and appropriate cycling of nutrients and carbon occurs throughout the site with appropriate biogeochemical pathways present at each location (also with connections to upstream/downstream etc.)

- xxvii. Invasive taxa do not dominate and are not spreading uncontrollably through the region (Walker & Salt 2006)
- xxviii. Proportions of acid-tolerant, saline-tolerant and terrestrial taxa remain approximately constant in the medium to long term (although these should vary spatially and on short temporal scales)

Objective 8. Aquatic-terrestrial connectivity

Outcomes:

- xxix. Variable water levels allow wide riparian and littoral zones to develop and persist through time (both as plants and as propagules) (Boulton & Brock 1999)
- xxx. Interconnected mosaic of diverse vegetation from terrestrial, through riparian and submerged down to the extent of the euphotic zone (Boulton & Brock 1999)
- xxxi. Ecosystem supports a balanced mix of terrestrial and aquatic taxa through space and time
- xxxii. Exchange of energy, nutrients and carbon occurs between aquatic and terrestrial ecosystems (Boulton & Brock 1999)
- xxxiii. Variable water levels regularly oxidise sulfidic material and limit the formation of new acid sulfate soils around the shallow water margin.



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