Trajectories of ecological change in the Coorong and Lower Lakes, in response to climate change

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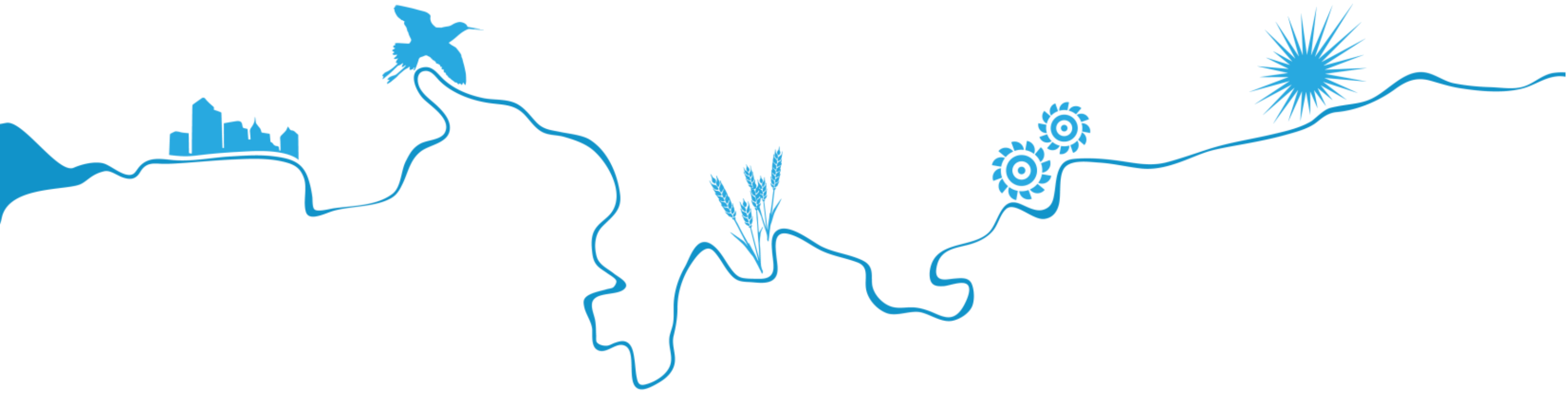

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This report documents output from one step in an overall climate adaptation methodology, and should be read in connection with other reports in this series to understand the context and use of this information.

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Respect and reconciliation

Aboriginal people are the First Peoples and Nations of South Australia. The Coorong, connected waters and surrounding lands have sustained unique First Nations cultures since time immemorial.

The Goyder Institute for Water Research acknowledges the range of First Nations' rights, interests and obligations for the Coorong and connected waterways and the cultural connections that exist between Ngarrindjeri Nations and First Nations of the South East peoples across the region and seeks to support their equitable engagement.

Aboriginal peoples' spiritual, social, cultural and economic practices come from their lands and waters, and they continue to maintain their cultural heritage, economies, languages and laws which are of ongoing importance.

Acknowledgments

This project is part of the South Australian Government's *Healthy Coorong, Healthy Basin* Program, which is jointly funded by the Australian and South Australian governments.

We thank the participants of three expert workshops that were held to test, validate and add detail to the scenarios (Part I). Their experience and intimate knowledge of the Coorong and how it has responded to past changes was invaluable for this activity. We are grateful for very useful comments on the draft of Part I from workshop participants and two independent reviewers, and on the draft of Part II from two different independent reviewers.

Executive summary

The Coorong is culturally, environmentally and economically important at local, national and international scales but has experienced a long-term decline in its ecological condition due to reductions in inflows. The Millennium Drought (1996 to 2010) imposed severe stresses on the Coorong, Lower Lakes and Murray Mouth (CLLMM) region. While there has been recovery of some elements of the Coorong ecosystem associated with increased inflows since the Millennium Drought, the South Lagoon has not recovered to pre-Millennium Drought conditions. Research into the ecological responses that occurred during the drought, combined with subsequent research into the ecological responses since the Millennium Drought, provide insights into how the CLLMM is likely to respond to ongoing climate change.

The Phase One Trials and Investigations (T&I) Project (2020−2022) is part of the *Healthy Coorong, Healthy Basin* (HCHB) program and involves a series of research components that will collectively provide knowledge to inform the future management of the Coorong. Component 6 - Climate Adaptation, examined how the CLLMM might be affected by continuing climate change, how this could affect the various values people hold for the CLLMM and the options for preserving values in the face of change.

This report describes the output from two activities. The first activity (Activity 6.2 of the T&I project) involved a review of the literature to understand the breadth of different types of ecological impacts of climate change that may affect the CLLMM and the potential magnitude of key changes. This synthesis then provided the underpinning knowledge for Activity 6.5 'Trajectories of ecological change in the Coorong', which developed two scenarios based on key drivers of change and described the ecological consequences of those scenarios. In this report, the scenarios are described first in Part I, and the more detailed ecological and biophysical basis for the scenarios is presented in Part II. The scenarios were developed to be a key input for a vulnerability analysis (Activity 6.6) and an adaptation pathways analysis for the CLLMM (Activity 6.8).

Scenarios of change

The CLLMM is expected to change, potentially significantly, as the climate continues to change over coming decades leading to a cascade of ecological impacts. The timing and detail of these changes is uncertain, but it is very likely that ecological change will occur and it has the potential to alter the character of the CLLMM. Therefore, there is a need for tools and analyses to help people explore and prepare for the consequences of these possible changes. Part I of this report presents two scenarios of change that lie at different times along a trajectory of 'greatest plausible change' in the physical and ecological dynamics in the CLLMM system in response to climate change. Our intention is that well-informed, compelling narratives of plausible future change will help people imagine and prepare for ecological and social consequences and identify actions that could be taken now to prepare for future adaptation. The scenarios are intended to be compelling descriptions of how the system may change over the longer term (50–100 years) to help people vividly imagine the ecological and social consequences of future transformational changes, and identify actions that could be taken now to prepare more effectively for a future with uncertain, but potentially significant, change. The picture is largely qualitative, as there is considerable uncertainty about many aspects of climate change and its impacts, but the quantitative information that is provided about climate change and ecological sensitivities gives a sense of the magnitude of possible future ecological change.

The scenarios were initially drafted based on our review of anticipated long-term ecological impacts of climate change in the CLLMM (Part II of this report). The climate and hydrological modelling used to inform this report was carried out in 2015. The draft scenarios were validated and revised in a series of workshops with participants from the Department for Environment and Water (DEW), South Australian Research and Development Institute (SARDI) and The University of Adelaide who brought a deep knowledge of the system and in particular its dynamics during severely reduced inflows from the River Murray. Workshop participants engaged constructively with the scenarios, endorsing the logic of the trajectory, verifying and challenging key assumptions, and providing extra details to enrich the scenarios.

An overarching conceptual trajectory of change was developed by overlaying the key drivers of increasing temperature, decreasing inflows of freshwater and rising sea level. The trajectory has three phases: a drying phase driven by decreasing freshwater flows; a transition phase as the influence of sea-level rise begins to become apparent; and a phase where water levels across the CLLMM are dominated by a rising sea level. The project team developed two scenarios of ecological change, one describing ecological conditions in the transition phase, and the other describing conditions in the sea-level rise phase. These scenarios were described for the Lower Lakes and Coorong.

- **Lower Lakes – Scenario 1 (minimum inflows).** Combined inflows of freshwater (from the River Murray) and seawater (from sea-level rise) into the CLLMM are at a minimum. There is an increase in the frequency of low flow years, and the frequency of medium and high flow years decreases. This reduces average water levels in the Lower Lakes, with significant water level fluctuations within years and between drought and wet periods. Acid sulfate sediments (ASS) are exposed and periodically flooded, increasing acidity and the concentration of metals. There is frequently reduced connectivity between Lake Alexandrina, Lake Albert and fringing wetlands, and salinity increases across the lakes. Evapo-concentration processes and reduced freshwater flushing result in increasing nutrient concentrations that drive algal blooms, water quality deterioration, anoxic water, rapid nutrient cycling and impacts on benthic invertebrates. There are significant changes in the abundance and distribution of emergent and submerged macrophytes with the decreased water levels. Increased turbidity also limits light for benthic plants, while there is an increase in terrestrial vegetation and weeds fringing the Lower Lakes. Barrage flows often fail to meet current management targets. Fishways only operate during wet seasons and years. Loss of habitat and connectivity for fish communities has led to localised extinction of small-bodied threatened freshwater fish that require vegetation habitat for breeding. Diadromous fish abundances are greatly reduced, and potentially to zero, due to system disconnection, and large-bodied fish have been affected by reduced flow. Waterbird diversity and abundance have generally declined; some taxa may increase in abundance due to declines in habitat elsewhere in the region or due to changes in conditions creating habitat suitable for species not usually present in the region. The Lower Lakes continue to be valuable drought refuge. There is increased proliferation of salt-tolerant species in Lake Alexandrina. Sensitive frog species populations are greatly affected.

- **Lower Lakes – Scenario 2 (sea-level rise dominates).** There has been increasing exchange of seawater between the Southern Ocean and Lake Alexandrina as sea level has risen, to the extent that the average level of the Lower Lakes is largely determined by sea level. Water levels in the Lower Lakes are higher than present-day levels and much more stable with a tidal influence near the estuary. Significant portions of the barrier islands are frequently inundated. Salinity in Lake Alexandrina is variable, from largely fresh during and after prolonged periods of high River Murray flows, through to brackish to marine during protracted dry periods. There is generally a salinity gradient across Lake Alexandrina. Salinity is less variable and high in Lake Albert. There is no new exposure of ASS. Freshwater habitat declines significantly, but remains permanently present in small refuge areas and expands during periods of significant freshwater inflow. Emergent macrophytes have colonised fringing habitats, and there is a loss of freshwater submerged macrophytes. Estuarine taxa are now a key part of the fish and macroinvertebrate community. Diadromous fish and other migratory species are present in the Lower Lakes and upstream.

- **Coorong – Scenario 1 (minimum inflows).** Inputs of freshwater into the Coorong have declined and are at a minimum, and sea-level rise is not yet having a significant impact on water levels. There are long periods with no effective freshwater flows over the barrages, and the North and South Lagoons are poorly connected annually for long periods of time. The South Lagoon is hypersaline most of the time and there is a self-reinforcing cycle of nutrient accumulation, algal blooms, sediment deoxygenation and loss of benthic invertebrates, plants and animals. There is a loss of estuarine habitats and reduction in habitat diversity, and *Ruppia tuberosa* and other aquatic macrophytes and the species that they support are no longer present in the South Lagoon. Ecosystem processes and food web dynamics are altered, including a decline in migratory shorebirds, waders and piscivorous birds, as a result of reduced food resources (macroinvertebrates and fish).

- **Coorong – Scenario 2 (sea-level rise and high exchange)**. Sea-level rise is the dominant driver of water level in the Coorong. This scenario includes the assumption that higher sea level has resulted in higher rates of exchange through the Murray Mouth, into the Coorong and between the North Lagoon and South Lagoon, which have good connectivity most of the time. There is less seasonal variation in water level and salinity. There remains a gradient of increasing salinity from the Murray Mouth to the South Lagoon. The South Lagoon continues to be hypersaline, but the salinity levels are lower than in Scenario 1 and avoid very high peaks. Nutrient concentrations are lower than Scenario 1 due to increased flushing exchanges with the sea along the Coorong and possibly enhanced with pumping or other infrastructure, however, nutrient concentrations remain relatively high. The system is predominantly marine, selecting for marine taxa with occasional estuarine habitats re-establishing in some locations for short periods after episodes of significant freshwater flow. Periods of higher salinity lead to temporary loss of estuarine-dependent fish species. There has been, and continues to be, significant change in the location of habitats, including the loss of existing and creation of new areas of macrophytes, saltmarsh and mudflats as coastal land is inundated.

The scoping and description of these scenarios focused on the physical and ecological outcomes, rather than the policy, management and infrastructure options that might contribute to them, however they do include some management-related assumptions. For example:

- Scenario 2 assumes high exchange of sea water with Lake Alexandrina, so that sea level is the primary driver of average water levels in the Lower Lakes.
- Each scenario assumes allocations of water for the environment specified in the Basin Plan will be implemented in full and will not be significantly increased or decreased in the face of climate-related decreases in inflows at the Murray–Darling Basin (Basin) scale.
- Each scenario assumes that the Murray Mouth will remain open, with dredging where needed, and this may need to be enhanced if rising sea level leads to increase in sand transport into the estuary.

The trajectory of change and the scenarios are intended to help CLLMM researchers and stakeholders vividly imagine climate-related futures, and enable deliberation about preparing for future change; they are not intended as predictions. They were used in subsequent activities in the Climate Adaptation project, assessing vulnerability and developing adaptation pathways for the CLLMM; and the trajectory and scenarios may also be useful in other contexts, such as highlighting long-term issues in discussions around infrastructure options to improve the ecological health of the CLLMM and setting future objectives.

1 Introduction

The Coorong, Lower Lakes, and Murray Mouth (CLLMM) (Figure 1) is culturally, environmentally and economically important at local, national and international scales but has experienced a long-term decline in its ecological condition due to reductions in freshwater inflows. While there has been recovery of some elements of CLLMM ecosystems associated with increased inflows since the Millennium Drought, the Coorong South Lagoon has not recovered to the levels expected. The ecosystem experienced a switch from being dominated by aquatic plants to algae, associated with eutrophication (nutrient enrichment) with subsequent impacts on invertebrates, fish and waterbirds. These changes in the ecosystem and the lack of recovery is likely caused by a number of complex, interacting factors, which are not well understood (DEW, 2021).

The Phase One Trials and Investigations (T&I) project of the *Healthy Coorong, Healthy Basin* (HCHB) program consists of a series of integrated components that collectively provide knowledge to inform the future management of the Coorong. Component 6 - Climate Adaptation, examines how the CLLMM might be affected by continuing climate change, how this could affect the various values people hold for the CLLMM and the options for preserving values in the face of change. It is structured into four phases that implement a sequence of steps over a two-year period which are designed to build the understanding and capacity of decision makers and other stakeholders. These phases and steps include:

Context:

- Synthesise the long history of environmental and social changes in the Coorong and Lower Lakes, as a context for analysing current and future change.
- Review anticipated long-term environmental and ecological impacts of climate change in the Coorong and Lower Lakes, with a focus on the breadth of change processes as well as the possible magnitude of change, to provide a robust understanding of future changes.
- Clarify the range of current management and research activities, and how they are expected to lead to behavioural and physical changes that contribute to the current objectives for the Coorong (using 'Theory of Change').
- Explore the sensitivity of current activities (above) and ecological objectives to climate change.

Vulnerability

- Develop a set of trajectories of environmental and ecological change for the Coorong to provide a common platform for anticipating the implications of future change.
- Understand the diversity of values for the Coorong and Lower Lakes resulting from the multiple relationships different communities and stakeholder groups have with the Coorong and Lower Lakes and clarify the biophysical elements of those value relationships (the 'things' that are valued).
- Explore how these biophysical elements and values might be affected by different trajectories of change, recognising that depending on the specific trajectory many features and values might persist despite significant change.

Adaptation pathways:

- Construct visions of a 'healthy Coorong and Lower Lakes', or other versions of 'success', for different stakeholders in the face of significant ecological change.
- Scope alternative sets of key decisions, changes in management or new interventions (collectively making 'adaptation pathways') that would be needed to achieve the visions of a 'healthy Coorong' under different change trajectories.
- Assess the requirements for those decisions to be made in an informed manner.

- Identify near-term actions and interventions that will strategically overcome the decision-making barriers and increase the range of options available to manage the Coorong into the future.

Translation:

- Draw on insights gained during the project analyses to identify issues and opportunities to build DEW's capacity to assess, deliberate on and plan for future transformational impacts of climate change, both within DEW and with First Nations, the general community and other stakeholders.

This report brings together the outputs from two activities of the Climate Adaptation project. Activity 6.2 'Synthesis of the anticipated ecological impacts of climate change on the Coorong' reviewed literature to understand the breadth of different types of climatic, hydrological, biogeochemical and ecological impacts of climate change that may affect the CLLMM and gauge the potential magnitude of impacts for a range of changes. This synthesis provided the underpinning knowledge for Activity 6.5 'Trajectories of ecological change in the Coorong', which developed two scenarios based on key drivers of change and described the ecological consequences of those scenarios. In this report, the scenarios are described first in Part I, and the more detailed ecological and biophysical basis for the scenarios is presented in Part II. The scenarios were designed to be used as a basis for a vulnerability analysis (Activity 6.6) and an adaptation pathways analysis (Activity 6.8) for the CLLMM later in the Climate Adaptation project.

As climate change continues, sea-level rise, warming and drying, in combination with ongoing water extractions from the River Murray, have the potential to drive significant ecological changes in the CLLMM system, potentially altering its 'ecological character'[1]. While the timing and detail of these changes is uncertain, the significant nature of them suggests a need to help people understand and prepare for the consequences of these possible changes. This study chose to focus on changes at the higher end of the range of possible climatic and ecological changes, with the idea that if people are prepared for a trajectory to higher level changes, they will also be prepared for lower-level changes. Climate projections are based on a set of choices by the analyst, including the emissions scenarios, future dates and climate models; each one of these choices affects the outputs. Impact analyses are often conducted with all combinations of these factors, providing numerous projections of multiple different climate parameters, providing a very wide spread of resultant climate impacts. While these numerous projections do give a picture of the range of outcomes that might eventuate, they also provide a volume of data that is often overwhelming and can be readily misinterpreted. One strategy is to analyse the spread of results and treat the average as if it were a prediction of the 'most-likely outcome'. However, technically, this does not provide a most-likely outcome and it can lead to poor decision making. In this report, we identify scenarios of 'greatest plausible change', following Climate Compass, the Australian Government's guidelines on climate adaptation (CSIRO, 2018) and the Australian Government's methodology for assessing the vulnerability of Ramsar wetlands (Dunlop and Grigg, 2019). Planning using greatest plausible change scenarios, coupled with an adaptation pathways approach (Wise et al. 2014); (Activities 6.7, 6.8), ensures that decision makers are ready to respond to the full range of climate impacts, reducing the risk associated with just planning for one set of anticipated impacts.

Similarly, while some impact and adaptation analyses focus on near-term impacts, with the rationale that management plans only have a 5–10 year timeframe, the Climate Adaptation project considered long-term impacts. This is on the grounds that long-term impacts often have material implications for the decisions that might be taken in the near term (Stafford-Smith et al. 2011), as the decisions taken to address near-term (smaller) levels of change can significantly alter the range of options available to decision makers facing larger

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[1] A 'change in ecological character' for an Australian Ramsar wetland has a specific meaning under the Ramsar Convention and can only be determined through a detailed assessment process, which is followed by notification to the Ramsar Secretariat by the Ramsar Administrative Authority within the Australian Government.

impacts in the longer term. Again, uncertainties associated with rates and magnitudes of impacts over time will be addressed explicitly using the adaptation pathways approach.

The two scenarios represent states of significant change along a single trajectory of ‘greatest plausible change’. Together, the scenarios integrate physical and ecological responses to the sea-level rise and altered hydrology. The scenarios are intended to be compelling descriptions of how the system may change over the longer term (50–100 years) to help people vividly imagine the ecological and social consequences of future transformational changes, and identify actions that could be taken now to prepare more effectively for a future with uncertain but potentially significant change.

The trajectory of change integrates hydrodynamic drivers and their ecological consequences. Climate change will drive a series of physical changes to the environment that will directly affect different biota, as well as affecting how biota interact with each other. The impacts will cross all biotic groups, from the base levels of food webs (bacteria/algae and their processes), through to top consumers such as fish and birds.

The scenarios are based on the synthesis of the likely ecological impacts (Part II of this report) that identified the *wide range* of potential ecological change processes and provided indication of the *large magnitude* of future change, which people may need to plan to accommodate. The picture is largely qualitative, as there is considerable uncertainty about many aspects of climate change and its impacts, but the quantitative information that is available about climate change and ecological sensitivities provided a sense of the magnitude of possible future ecological change.

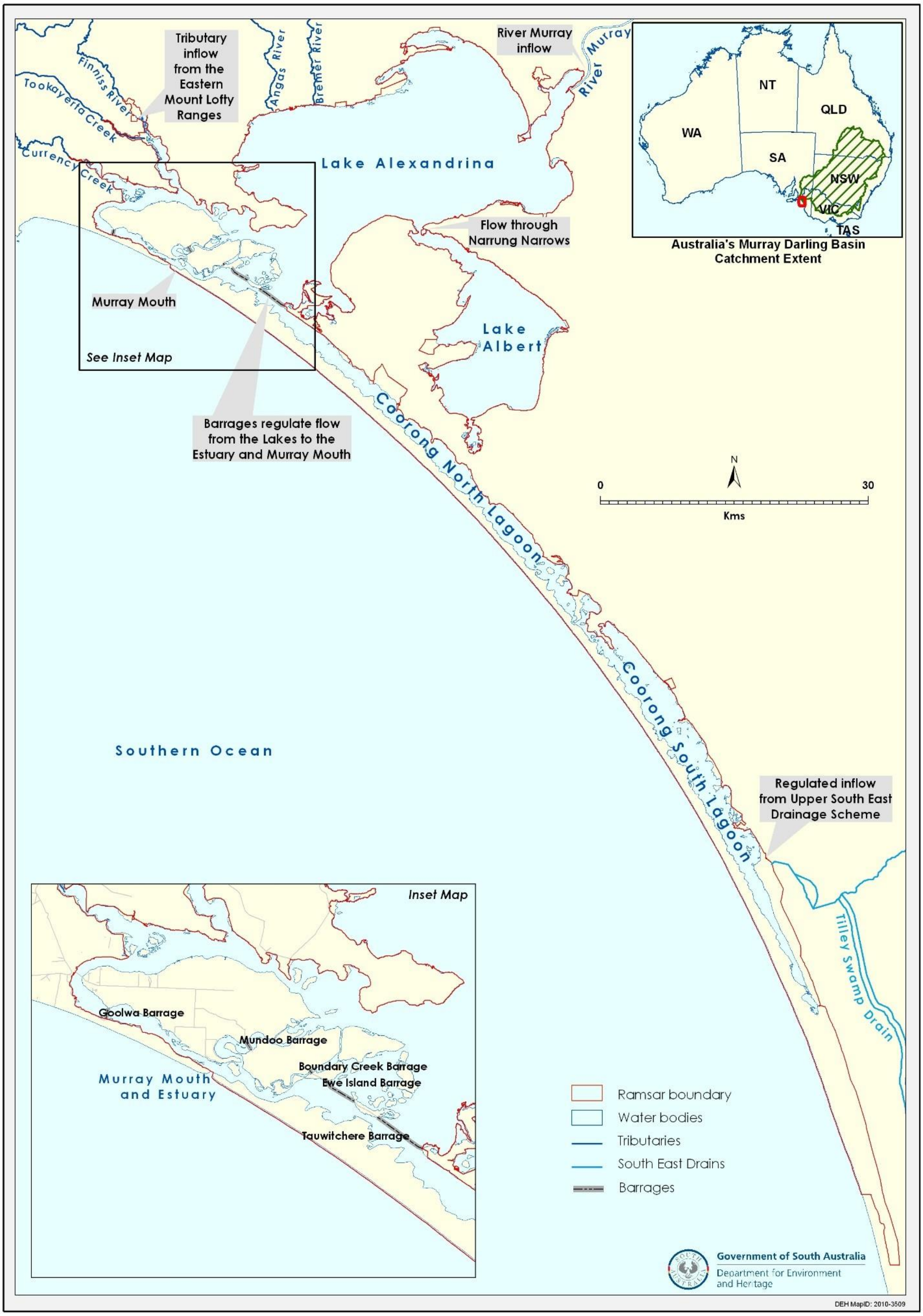

Figure 1. Map of the Coorong, Lower Lakes and Murray Mouth. The Ramsar boundary is marked in red.

Part I Scenarios of ecological change in the Coorong and Lower Lakes, in response to climate change

Introduction to Part I: Scenarios

1.1 Background and aims

'Trajectories of ecological change for the Coorong and Lower Lakes' (Activity 6.5 of Component 6 – Climate Adaptation of the T&I project of the HCHB program) developed a set of plausible scenarios of change for the CLLMM that integrate critical physical and ecological dynamics, which could result from climate change over the long term. The scenarios describe conditions in the Coorong and Lower Lakes that are very different from the present, as might be experienced by the end of the 21st Century, but they do not have set timeframes. The scenarios were developed specifically for use in subsequent activities in the Climate Adaptation project. They may also be useful for other projects and situations to help managers, policymakers and stakeholders explore the implications of future transformational change for decision making in management, policy and society.

1.2 Context

As climate change continues, sea-level rise, warming and drying, in combination with ongoing water extractions from the River Murray, have the potential to drive significant change to the ecological character of the CLLMM system. While the timing and detail of these changes is uncertain, there is a need to help people explore and prepare for the consequences of these possible changes. The scenarios of change in the CLLMM were developed in this project to meet this need. Each scenario represents a state of significant change along a single trajectory of 'greatest plausible change' (Figure 2). Together, the scenarios integrate physical and ecological responses to the sea-level rise and altered hydrology.

These scenarios were designed to be used in vulnerability analyses and adaptation pathway planning, where participants in workshops are encouraged to imagine the consequences of long-term transformational changes, then identify actions that could be taken along a trajectory, from the present through to intermediate levels of change to large change. It is important to acknowledge that the rate and end point of the trajectory are currently unknowable and will only be discovered as change unfolds over time, but planning for that change will need to occur well before the details of it are clear. The adaptation pathway process is specifically designed to elicit key uncertainties and help plan to accommodate them in future decision making.

The scenarios are intended to be compelling descriptions of how the system may change over the longer term (50–100 years) to help people vividly imagine the ecological and social consequences of future transformational changes, and identify actions that could be taken now to prepare for more effective decision making in a future with uncertain but potentially significant change.

The scenarios are built upon a trajectory that integrate hydrodynamic drivers with possible ecological responses. Possible ecological responses are described from bacteria and algae, higher plants, to top consumers such as fish and birds. They are largely qualitative, but their development was informed by existing quantitative analyses and modelling where available.

2 Methods

This activity builds on a review of anticipated long-term environmental and ecological impacts of climate change in the CLLMM (presented in Part II). That review provided qualitative details of the wide range and complexity of possible environmental and ecological changes processes, and a quantitative understanding of the possible magnitude of projected climate impacts by 2100. Draft descriptions were developed for three key ‘drivers’ of change (outlined in detail below), a ‘trajectory’ of plausible change integrating the drivers, and two ‘scenarios’ or snapshots along the trajectory, each for the Lower Lakes and the Coorong (including the Murray Mouth).

We use the term ‘scenario’ to describe the state of the system at points along a single trajectory. Typically, in scenario planning, scenarios depict *alternative* trajectories that represent key uncertainties in a set of biophysical and social drivers of change. In the CLLMM, there are two major hydrological drivers whose broad actions are very likely (with uncertain detail), but whose actions will be somewhat countervailing and likely to operate on different time scales. Rather than consider these drivers as acting independently, it was more logical in this case to combine the drivers into a single U-shaped trajectory (Figure 2).

Our scenarios represent states of the evolving system that are very different from each other and from the present. The scenarios are also described separately for two locations: the Lower Lakes and Coorong. This scenario framework reflects the nature of the climate adaptation challenge in the CLLMM system, where it is apparent that there is likely to be a sequence of very different system states as climate change unfolds in the region, each state will need to be managed differently but in the context of the longer-term trajectory of change, and there are two parts of the system whose fates are very different but linked. There are some physically feasible alternatives that have not been considered, for example increases in River Murray flows or allowing the Murray Mouth to close. Increases in River Murray flows (so that flows are greater than present and remains so despite climate change) could maintain the CLLMM in its currently-recognised state, significant increases in flow could improve the condition of the CLLMM.

The scenarios represent ‘greatest plausible changes’; that is, they correspond to the higher level of ranges of change that might be considered plausible. In developing them, we were guided by climate projections based on the highest-level greenhouse gas concentrations assessed by the Intergovernmental Panel on Climate Change (RCP[2] 8.5). Lower levels of change are possible if the global greenhouse gas concentrations peak at a lower level; but higher levels of change could also result from higher concentrations or particular Earth system dynamics that are feasible but considered unlikely or poorly understood (such as melting of the Greenland ice sheet, which would lead to much faster and higher sea-level rise).

Draft descriptions of the proposed trajectories and scenarios of change were developed by the project team based on the literature review of the possible ecological impacts of climate change in the CLLMM (Part II). The draft scenarios were validated, updated and enriched through a series of expert workshops held between 5–11 March 2021, with representatives from DEW (six representatives), SARDI (one) and The University of Adelaide (two), each of whom had extensive experience of the Coorong and Lower Lakes including with the dynamics of the system during and after the Millennium Drought.

In the workshops, we specifically sought input to:

- confirm the overall logic of this trajectory as a plausible future
- check that the details of the drivers and their consequences were accurate
- add details to enrich the description of the trajectory (e.g. additional ecological variables)
- confirm the points on the trajectory chosen for the scenarios were meaningful and useful
- develop compelling descriptions of the scenarios that were likely consequences of the trajectories.

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[2] Representative Concentration Pathways (RCP) are the alternative scenarios of atmospheric greenhouse gas concentration used by the Intergovernmental Panel on Climate Change and the international climate modelling community.

Workshop participants engaged very constructively with the trajectory and scenarios, accepting the logic, verifying and challenging key assumptions, and providing additional details to develop the scenarios. The scenarios were then reviewed by two independent experts, and the synthesis of impacts (Part II) was reviewed by two independent experts. Note, further layers of details were added to these scenarios while using them in Activity 6.6 Vulnerability Analysis of the Climate Adaptation project.

3 Scenario framework

This chapter describes the key drivers for the scenarios of climate change in the CLLMM region that were used in the Climate Adaptation project: (i) decreasing freshwater inflows from the River Murray and the South East Drainage System and other tributaries; (ii) increasing sea level; and (iii) warming of land and water. All three drivers are occurring simultaneously, but the extent of their influence on the CLLMM varies over time. The combined impact of the hydrological drivers leads to three distinct sequential phases: (i) decreasing freshwater inflows; (ii) a transition period (minimum of combined inflows); and (iii) increased sea level dominating CLLMM water levels. This trajectory is presented in Figure 2 and a summary of the scenarios (including the factors that went into creating them) is presented in Figure 3.

Increasing temperature and rising sea level are projected with *very high confidence* for both the near (2030) and long term, and there is *high confidence* that cool season rainfall will decline later in the century (2090) (Timbal et al. 2015). Increasing temperature, with increasing evapotranspiration, and declining seasonal and annual rainfall are likely to lead to very significant declines in catchment inflows in the Basin and flows into the CLLMM (Chiew et al. 2022). The *high confidence* in these drivers means that they can be integrated into a single conceptual **trajectory** of change where the *directions* of change for these drivers are robust, and the uncertainties lie in the specifics of *how much* change, *by when* and *with what impacts*. These specifics will be determined by complex, unpredictable ecological and societal responses. Hence, our trajectory of change relates to those drivers for which there is high certainty about the direction of change and the sequence in which different changes will occur. The vulnerability and adaptation analyses conducted later in the project will be driven by the scope of changes that are most robust, and it will create an understanding of what uncertain details are important for future decision-making and develop strategies for addressing the uncertainty.

The three major **drivers** of change to the CLLMM, likely to result from global climate change, are:

- Decreasing freshwater inflows from the River Murray, the South East Drainage System and Eastern Mount Lofty Ranges tributaries.
    - This will be experienced as a drying trend overlaid with high variability from droughts and wet years. The projected rate of drying across the Basin is from slightly wetter to 43% decrease in catchment inflows by 2090 (Timbal et al. 2015; Zhang et al. 2020).
    - This will result in decreased River Murray flows, but the extent of that decrease will depend on catchment hydrodynamic processes, how river operation rules respond to reduced inflows and any future changes to water entitlements and allocation rules.
- Increasing sea level
    - This is likely to be experienced as a gradually accelerating smooth rise due to thermal expansion of ocean waters. Projected increases are from 0.39 to 0.84 m by 2090 for a high-level climate change scenario (RCP 8.5), but it will continue for hundreds of years due to inherent lags. Tidal activity and storms will provide short-term variability. Faster rates and much higher levels of change are possible if ice sheet and glacier melt becomes significant (Timbal et al. 2015).
    - The impact of high levels of sea-level rise on the CLLMM will depend in part on uncertain medium- to long-term factors including sedimentation, management and new infrastructure.
- Warming of land and water
    - Experienced as steady rise (currently accelerating), with some inter-annual variability. Warming is certain, as long as global greenhouse gas concentrations increase or remain high.

Projections are from 2.7 to 4.5 °C by 2090 for a high-level climate change scenario (RCP 8.5) (Timbal et al. 2015).

While each of these climate change drivers are projected to have future impacts that are potentially very significant, the action of these drivers started decades ago, occurring simultaneously with upstream water extraction and management of flow regimes.

The concentration of carbon dioxide in the ocean is also likely to increase, leading to acidification of the sea water. The pH of sea water is estimated to head towards 7.7 by 2100 (RCP 8.5) (Hoegh-Guldberg et al. 2014). It is anticipated this will not exceed critical thresholds for fish and benthic macroinvertebrates, particularly in comparison to the other major drivers, and so we have not considered pH change as a key driver in our trajectory and development of scenarios. However, less is known about the impact of acidification on carbonate dependent lifeforms, for example corals and tubeworms and this driver may warrant consideration in the future.

We identify three phases along the trajectory:

- **First phase: Decreasing freshwater (River Murray) inflows,** increased evaporative losses, reduced exchanges through the Murray Mouth, and declining water levels throughout most of the Lower Lakes and Coorong. The system has experienced many decades of drying conditions, largely as a result of water extractions from the Murray–Darling system. Climate change will add to and continue this drying trend into the future.
- **Second phase: Transition period,** when the influences of decreased freshwater flows are significant, but rising sea levels have not yet permanently affected the Lower Lakes and have limited and variable impact on Coorong water levels.
- **Third phase: Increased sea level,** leading to an increase in water levels throughout the system. There may be increases in exchange through the Murray Mouth and into the Coorong, and increased exchange of salt and nutrients along the Coorong. However, this depends on sedimentation rates in the Murray Mouth and Murray estuary, changes to the tidal prism and remains a key uncertainty. Similarly, the impact of a rising sea level on the Lower Lakes will depend on a range of factors, including future management and infrastructure decisions. For this scenario, it is assumed that once the barrier islands and barrages are regularly inundated, decisions are made to enable a high level of exchange between the Southern Ocean, the Lower Lakes and the Coorong.

This trajectory can be characterised by a U-shaped curve (see Figure 2). This curve represents a conceptual model of the interaction between the drivers, it does not necessarily correspond to any physical variables.

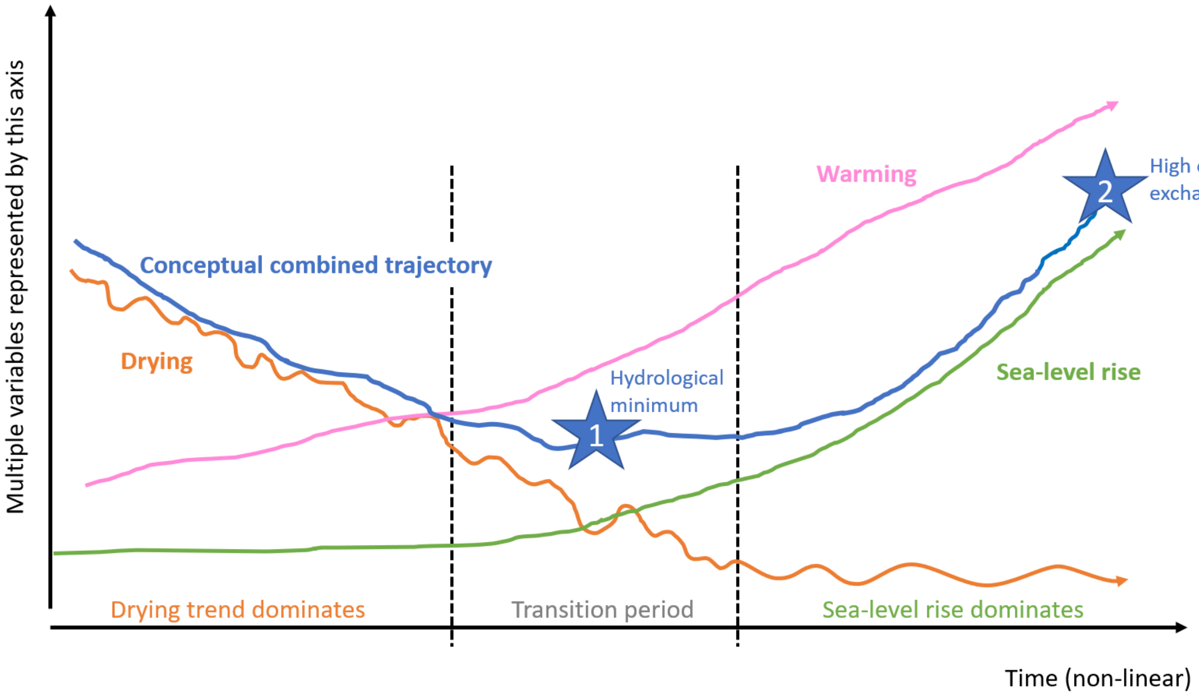

Figure 2 Plausible trajectory of change resulting from a combination of drivers operating over different time scales. The orange line represents drying (decreasing freshwater inflows and increasing evaporation), the green line represents sea-level rise, and the pink line represents warming. These combine into a conceptual plausible trajectory of change, represented by the blue line. For each of the Coorong and the Lower Lakes, we describe a scenario at the point of minimum combined inflows (1), and a point when sea-level rise has become significant (2).

The axes in Figure 2 are qualitative to avoid giving a false impression of precision from quantitative estimates of change. For example, a large source of uncertainty is the rate and level of future atmospheric greenhouse gas concentrations. While we envisage this trajectory unfolding over the next century, the timing and the magnitude (depth) of the low point of the U-shape will be affected by a number of global, regional and local factors, including levels of global greenhouse gas concentration, rates of ice sheet melting, how rainfall changes play out, management of water for the environment and sedimentation. Smaller declines in rainfall may decrease the depth of the U. The timing of the lowest point may differ by decades, and the nature of it could be similar to the Millennium Drought or it could see the CLLMM enter an even drier, saltier state. The qualitative conceptualisation of the U-shaped trajectory is robust to these uncertainties and emphasises changes that are well known. The trajectory is intended to be used to foster deliberation about what actions would be wise to take in the near term given the potential trajectories and the uncertainties ahead, and what actions managers might need to start planning for future implementation.

The vulnerability and adaptation pathway analyses conducted subsequently in the Climate Adaptation project were designed to use the available qualitative and uncertain information, they did not rely on quantitative measures being available. Those analyses, using the qualitative trajectory, can be used to identify if there might be key thresholds and triggers that are critical to future decision-making, and if these need to be known in advance. These can then be investigated, from the literature or further research and monitoring. For example, what the threshold might be, when it might be crossed, possible lead indicators, specific ecological or societal responses, triggers prior to the thresholds that might indicate a need to change management? Or, assessment might conclude that the thresholds cannot be quantified or practically monitored, suggesting that decision-making processes will have to be adapted to cope with the uncertainty.

In the future, it is likely that decision makers will continue to manage the system in response to a complex suite of climatological, hydrological, ecological and social phenomena. Nobody can predict now which changes, indicators or trigger values will be important to stakeholders and embedded in legislation, policy, targets or management plans. This conceptual trajectory and the scenarios can be used to anticipate the issues future decision makers will face, scope out the kinds of research and monitoring that could inform those decisions, and the social and governance processes that would be needed to bring about different research, monitoring and management to enable effective and timely responses to continuing ecological changes.

To guide subsequent vulnerability and adaptation pathway analyses in the Climate Adaptation project, we chose to describe scenarios occurring during the transition phase (period of minimum combined water inputs) and in the third phase when rising sea levels are dominating water levels in the CLLMM. The system is currently part-way through the drying phase, including transitioning from the impact of an extreme drying event (i.e. Millennium Drought). Scenarios are described separately for the Lower Lakes and for the Coorong and Murray Mouth (Figure 3). While we describe different scenarios across components of the CLLMM, the outcomes will be coupled as a result of the action of the drivers and integrated management of the whole system.

The following considerations shaped the development of the scenarios and should be borne in mind when using them:

- The rates of change and the relative levels of change will be determined by external and internal processes that cannot be predicted accurately. These include management interventions such as allocations of water for the environment and management of the Lower Lakes and Coorong with current and future infrastructure. In this activity, our focus was on the outcomes for the system, not the specific details of management interventions.
    - We assumed the Murray Mouth will be kept open, by dredging when necessary (possibly more than current), and that it will be open to a level that ensures a rate of ocean exchange such that, on average, the system is a net exporter of salt and nutrients (rather than acting as a net sink).
    - We assumed that significant reductions in freshwater inflows within the Murray–Darling system will lead to significant reductions in net River Murray flows into Lake Alexandrina from natural flow, return flows and water for the environment. Any future *increases* in inflows (e.g. increases in allocation of water for the environment), if of a similar magnitude to reductions in inflows, could slow the rate of progression of the drying phase and create different hydrodynamics and ecological outcomes in the sea-level rise phase.
    - Sustained sea-level rise will lead to the barrier islands and barrages becoming regularly inundated. When this occurs, it will almost certainly lead to significant changes in the management of the barrages, such as their operation and decisions about upgrading, moving or removing them.
- Biological responses along the trajectory will be strongly determined by the changes in hydrodynamics and biogeochemical dynamics. This means, while high levels of change are very likely, the details of biological changes will always be sensitive to processes that are hard to predict.
- The drying phase will see continued gradual and event driven accumulation of salt and nutrient in the Coorong South Lagoon, but it is uncertain the exact level concentrations of salt and nutrients will reach before sea-level rise is sufficient to lead to net export.

- The effects of drying and sea-level rise will vary across the system. The descriptions below provide some spatial differentiation but the high level of geographic and ecological diversity across the system, along with management, will mean there is high spatial variability in actual changes and ecological responses.
- Progress of the system along this trajectory will be characterised by variability, which will be determined by the sequence of inevitable but unpredictable periods of drought, high rainfall, heat waves and possibly winds and storms. We assume that episodes of higher rainfall along the trajectory will lead to periods of recovery of the freshwater and estuarine conditions, but that the opportunity for such responses will be gradually reduced by persistent drying and seawater inputs. If this reduced resilience is fundamentally compromised at some point, then change could occur very rapidly or as a series of steps after droughts.
- The timeframes of the drivers will determine whether there is a clear transition period, or if there is a continuum of change across time. Future management could actively reduce the depth of the U in the trajectory, or lengthen and deepen it.
- Both scenarios involve a transformation in the physical and ecological character of the Lower Lakes and Coorong. They are intended to help identify and characterise future decision problems that may arise as changes progress, such as how and when to change management strategies in an adaptive, effective and timely manner.

The following sections provide more detail about the drivers of change, a broad series of ecological consequences and descriptions of the scenarios for the Lower Lakes and for the Coorong. The source material for the environmental and ecological changes discussed below is presented in a literature review included as Part II of this report.

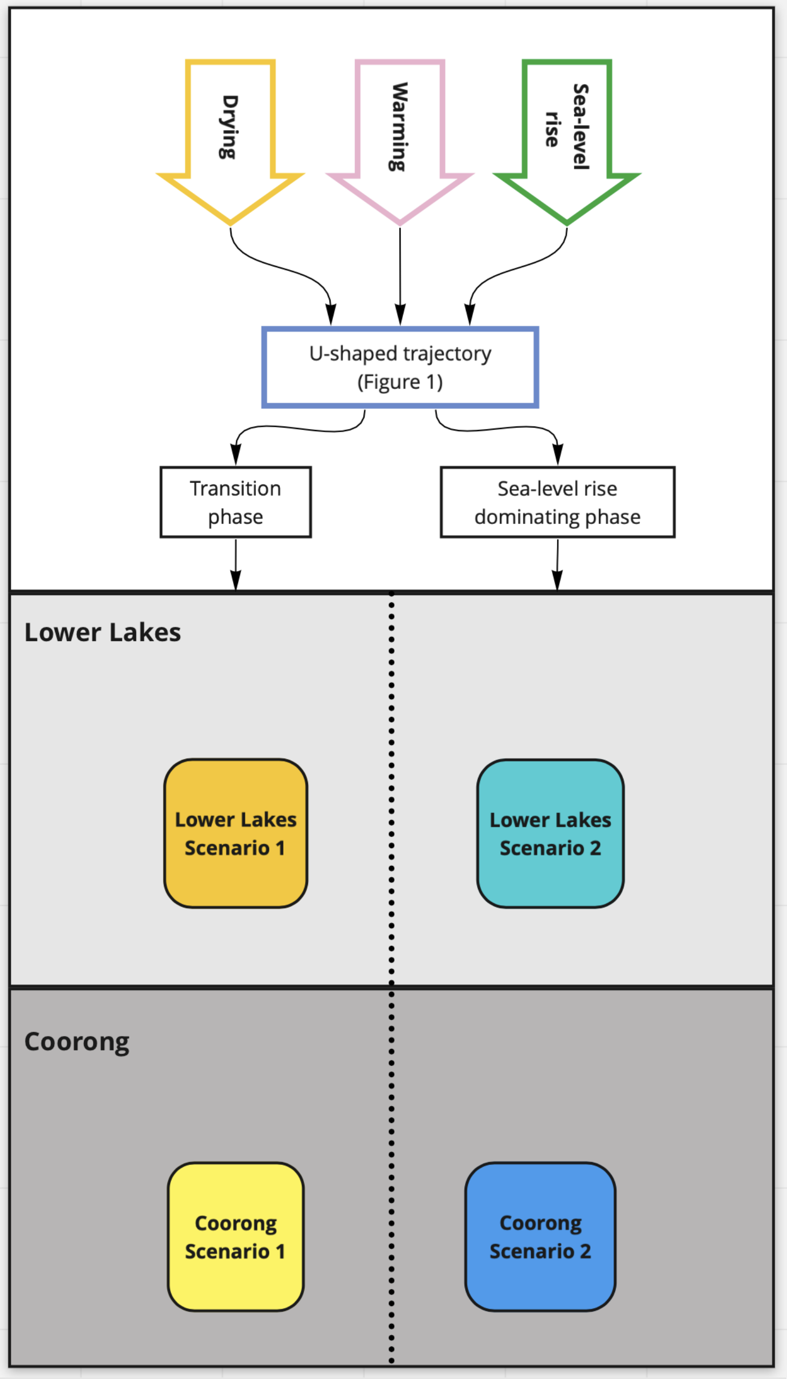

Figure 3 Scenarios of change for the Lower Lakes and Coorong, and the drivers considered in their development.

4 The Lower Lakes

This chapter gives detailed descriptions of Scenario 1: minimum inflows and Scenario 2: sea-level rise dominates, for the Lower Lakes, including details of the drivers of those scenarios and the biophysical and ecological consequences.

4.1 Driver 1: Reduced freshwater inflows

Climate change will lead to reduced flows into Lake Alexandrina and reduced flow will be a key driver of change to the Lower Lakes. Specifically:

- Decreased rainfall in the Basin combined with increased evapotranspiration will lead to decreased runoff, leading to reduced River Murray inflows.
- The actual amount of decreased runoff will be a combination of reduced (and altered) rainfall, and increased evapotranspiration from native vegetation, pastures and crops, and increased crop demand combined with any future changes to water allocation arrangements.
- Flows from the Eastern Mt Lofty Ranges tributaries are low and potentially cease for periods.

Increased temperature will increase evaporation from the Lower Lakes, which is equivalent to an additional reduction in freshwater inflows.

There will be variability in inflows over time, with occasional high and low flow periods, and there may be some changes in the seasonality of flows. This variability will significantly shape ecological responses, but it will have limited overall effect on the long-term trajectory.

A series of biophysical and ecological responses will occur as a consequence of decreased inflows into the Lower Lakes.

Physical, biological and ecological consequences

These hydrological changes will lead to a cascade of other physical and ecological responses:

- Median flows will be lower and periods of very low flows will be more frequent and of longer duration in the Basin.
- Lake Alexandrina and Lake Albert water levels will fluctuate and will frequently be lower than during the Millennium Drought. Lower water levels will increase the evaporation rate to volume ratio, which will be exacerbated by increased temperature within the water bodies. There will be competing needs in maintaining water in the Lower Lakes and while continuing discharge to the Coorong to maintain a healthy estuary and lagoon system.
- As Lake water levels drop more frequently or for longer periods of time, more sea water may seep through or around the barrages, subject to management.
- Salinity in Lakes will increase due to reduced freshwater inputs and increased evapotranspiration.
- There will be increased exposure of existing potential acid-generating sediments (ASS), which could decrease pH to acute levels and mobilise toxic metals from sediment when rewetted.
- While groundwater contribution to Lake Alexandrina will continue to be minor, reduced groundwater recharge in the region as a result of decreasing rainfall may affect some small wetlands. The groundwater contribution to Lake Albert will continue, with the saline shallow water table feeding seasonal and permanent salt-water marshes in depressions or swales around the lake edge.

- Lake fringes and associated wetlands will be increasingly colonised by terrestrial species, including pest plants.
- There will be reduced connectivity between Lakes Alexandrina and Albert, more frequent loss of connectivity between the lakes and the Coorong, reduced connectivity to fringing wetlands.
- Decreased flows in other streams flowing into the Lower Lakes will lead to further loss of habitat complexity and connectivity across the freshwater components of the system.
- There will be loss of submergent macrophytes, and emergent macrophytes may colonise the lake as waters retreat, but will not be in good condition, due to decreasing lake level and increasing salinity.
- The tubeworm (*Ficopomatus enigmaticus)* will spread into the Goolwa Channel and Lake Alexandrina as salinity increases.
- There will be a loss of fish habitat with the loss of submergent macrophytes in the Lower Lakes. Some small-bodied fish breeding and recruitment will decline and may cease as a consequence, causing some localised extinctions. Small-bodied generalists such as Murray hardyhead will survive, but southern pygmy perch is likely to be extirpated. The capacity for fish to survive will depend on their life histories combined with the dynamics of freshwater flows, salinity regimes and macrophytes re-establishment. There will be declines in salt-sensitive fish species, and increases in salt tolerant species.
- Operation of the fishways will significantly reduce or cease, particularly affecting diadromous species movement and recruitment, due to insufficient hydrological connectivity, flow velocity and chemical signal gradients, resulting in decreased abundances of congolli, lamprey and galaxias.
- Invasive fish species will be increasingly present, threatening survival of vulnerable small-bodied native fish species due to predation and competing habitat and food resources.
- There will be declines and possible loss of frog taxa (e.g. southern bell frog) due to habitat declines and changes to water regime and quality.

Some changes will be particularly sensitive to variability in water inflows, especially the longer lasting impacts of severe drought conditions. Periods of recovery can be expected during sustained above-average freshwater inputs, but the potential for this recovery is likely to decline as median flows reduce and dry periods become longer and harsher.

4.2 Driver 2: Sea-level rise

Sea-level rise, leading to increased connectivity between Lake Alexandrina and the ocean will have a major effect on the biophysical and ecological condition of the Lower Lakes. Specifically:

- A gradually and accelerating rising sea level, possibly combined with an increase in the intensity and frequency of storms, will lead to an overall increase in water level in the estuary.
- There will be reduced opportunities for freshwater releases from the barrages.
- Over time, the barrier islands and the barrages will be overtopped more often and for longer periods, leading to increasing exchange of seawater and lake water, with net inflows of seawater during periods of low river flows and high evaporation. There will be some tidal influence in Lake Alexandrina near the estuary. Eventually there will be an overall increase in the water level of the Lower Lakes.

Physical, biological and ecological consequences

These hydrological changes will lead to a cascade of other physical and ecological responses:

- Increased sea level will reduce the ability of the Lower Lakes to flow to the sea, increase salinity and alter carbon and nutrient dynamics, leading to water quality declines.
- A salinity gradient will form towards the River Murray. The strength of the gradient, and location of any boundary will depend on River Murray flows.
- There will be occasional periods of flushing during episodes of high River Murray flows, leading to much lower salinities.
- Increasing salinity will affect all biota, from phytoplankton through to top consumers such as fish. There will be continued loss of salt-sensitive taxa which will be replaced by more salt-tolerant taxa, including some estuarine and marine species.
- Connectivity between Lake Albert and Lake Alexandrina will increase.
- Maintenance of lake water levels by seawater will reduce the extent to which ASS are periodically exposed. However, increased salinity from seawater (also rich in sulfate) may increase the formation of the sulfidic minerals in the sediments. If these sulfide-rich sediments are subsequently exposed though changes in water level and a reduction in buffering capacity from the absence of seawater, then there is potential for acid generation to occur.
- Frequent seawater exchange will increase connectivity, favouring many estuarine and diadromous fish species.
- There will be gradual establishment of tidal and estuarine ecosystems in the Lower Lakes, such as seagrass, mud flats and salt marshes.
- Salt-tolerant vegetation will replace salt-sensitive species in fringing habitats, and there will be similar change in submerged aquatic macrophytes.
- Seawater will inundate freshwater wetlands and the diverse habitat associated with tributaries, leading to an overall loss in diversity of habitat for higher trophic organisms.
- There will be loss of fish habitat, particularly from loss of macrophytes in the Lower Lakes. Small-bodied freshwater fish are likely to be extirpated from the Lower Lakes, resulting in localised extinctions of threatened fish (i.e. southern pygmy perch) species.
- Loss of habitat for frogs (e.g. southern bell frog) will lead to localised decline and or extinction.
- Occasional periods of lower salinity will favour freshwater species, possibly allowing for episodic increases in population sizes and ranges, but these periods will become less frequent.

4.3 Driver 3: Temperature increase

Climate change will lead to gradual increases in air and water temperature, and increased incidence of terrestrial and marine heatwaves. Increased temperature is intrinsically linked with greater evaporation and transpiration, both components of the drying driver.

Physical, biological and ecological consequences

- Increasing temperature will have a direct effect on all biogeochemical processes, increasing rates of carbon and nutrient dynamics.
- Faster growth rates of organisms such as algae (phytoplankton, benthic and filamentous) will occur. There will be more prevalent cyanobacterial communities. Growth of some algae will also be enhanced by increasing carbon dioxide level in water.
- Increasing temperatures will change zooplankton community composition, as different taxa respond differently to change in temperature.

- The responses of higher trophic-level organism will vary between species. In general, fish reproduction and recruitment will be reduced by temperature increases (the extent varying among species). There is some evidence of temperature having a direct physiological effect on birds, however, in the context of climate change, indirect effects are likely to be more important (e.g. temperature impacts on water availability and quality, food resources, etc.)

4.4 Lower Lakes scenarios

This section provides descriptions of the two scenarios that were developed for the Lower Lakes, based on the anticipated physical and ecological drivers and responses described above. The scenarios correspond to the two key points identified on the trajectory of change (Figure 2).

Scenario 1. Transition / water-level minimum

- The Lower Lakes are experiencing a minimum in combined inflow of freshwater and seawater.
- There has been a decrease in the frequency of years with flows corresponding to 'previous'[3] median and high flows, which are important for replenishing the Lower Lakes.
- Lake levels on average have become lower, fluctuating significantly between drought and wet periods.
- There is frequent reduction in connectivity between Lake Alexandrina and Lake Albert and other fringing wetlands.
- Overall, there is an increase in salinity throughout the Lower Lakes, and Lake Albert is frequently several times the salinity of Lake Alexandrina.
- Nutrient levels have increased as a result of reduced flushing and evapoconcentration. This has resulted in frequent algal blooms and deterioration of water quality as algae die and decompose, leading to anoxic water and rapid nutrient cycling. Similarly, turbidity has increased, putting pressure on benthic algae. Sediment oxygen levels are affected leading to changes in macroinvertebrate communities.
- ASS are exposed and potentially rewet with wind-driven water movement and small floods during wet years which leads to a decrease in water quality (decreased pH and increased metal concentrations).
- Loss of submerged vegetation, and while emergent vegetation species are present, they are in poor condition. This coincides with an increase in terrestrial vegetation and presence of weeds fringing the Lower Lakes. Fringing wetlands have reduced in extent.
- Fishways only operate when there are sufficient inflows.
- Loss of habitat and connectivity for fish communities has led to localised extinction of fish requiring vegetation habitat for breeding (e.g. southern pygmy perch and Murray hardyhead). There has been a loss of migratory fish, due to disconnection of the system, as congolli has not been able to migrate to the ocean, and lamprey not able to migrate from the sea to Lake Alexandrina and River Murray.
- There is ingress of some estuarine species (e.g. tube worms, fish etc.) into Lake Alexandrina.
- Vulnerable frog species have declined and some are locally extinct.

Scenario 2. Sea level dominates Lake water levels

- Sea-level rise has resulted in tidal flows of seawater into Lake Alexandrina, leading to sea level being the dominant driver of the water level of the Lower Lakes. During periods of low river flow and high evaporation, water levels are lower in Lake Alexandrina leading to a net inflow of seawater. During high river flow events, water levels are higher in both lakes, leading to flooding.

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[3] Note, as these future scenarios are written in the present tense, 'previous' refers to the current (~2020) conditions.

- On average, the level of the Lower Lakes has increased to ‘previous’ high water levels. Connectivity between Lake Alexandrina and Lake Albert has been restored, and there is permanent connection between Lake Alexandrina and the Murray Estuary, with a tidal influence in Lake Alexandrina near the estuary.
- Both Lakes are permanently influenced by seawater inflows, resulting in restrictions of freshwater habitats.
- There are continued inflows from the River Murray but with less influence, resulting in a salinity gradient across Lake Alexandrina. The salinity gradient varies in extent and location between dry and wet years. Temporary salt wedges form but their extent and duration is dependent on wind action which mixes the water column.
- During times of lower freshwater inflows and reduced outflow from Lake Alexandrina, salinity in the Lower Lakes increases (due to evaporation) and salinity progresses up the River Murray. Salinity in Lake Albert is much higher and less variable, and it may become hypersaline.
- During episodes of prolonged high River Murray flows, there is a flushing of Lake Alexandrina, leading to much lower salinities and an expansion of freshwater habitats.
- Many fringing habitats have been re-vegetated, with more salt-tolerant species, as a result of higher and more stable water levels. Submergent freshwater aquatic macrophytes have declined but submergent estuarine and marine macrophytes, such as *Ruppia* spp. are present. There have been significant increases in estuarine habitats including seagrass, mudflats and salt marshes.
- Areas of freshwater habitat do occur, but there extent is dynamic in space and time, depending on rainfall and freshwater inflows.
- Wetlands on the fringes of the Lower Lakes are reconnected, but many are now brackish most of the time.
- Estuarine taxa and generalist species have become a key part of the fish and invertebrate communities and freshwater specialist taxa are largely absent.
- Diadromous fish (e.g. lamprey) species have returned to the Lake Alexandrina and upstream, due to improved hydrological connectivity.

5 Coorong and Murray Mouth

> *This chapter gives detailed descriptions of Scenario 1: minimum inflows and Scenario 2: sea-level rise dominates, for the Coorong and Murray Mouth, including details of the drivers of those scenarios and the biophysical and ecological consequences.*

5.1 Driver 1: Reduced freshwater inflows

Decreasing freshwater inflows from the River Murray and the Mt Lofty Ranges, and increasing evaporation in the Lower Lakes, lead to decreasing barrage flows, with combined with decreases in inflows from the South East Drainage System, leading to decreasing freshwater input into the Coorong and the estuary and reduced outflow through the Murray Mouth.

Physical, biological and ecological consequences

- Sedimentation will increase in the Murray Mouth, leading to increased potential for the Murray Mouth to close, and decreasing exchange between the sea, Murray estuary and Coorong.
- There will be more frequent and longer periods of disconnection between the Coorong North and South Lagoons and there will be minimal freshwater inputs from Lake Alexandrina.
- There will be continuing reduction of flushing of salt and nutrients, combined with increasing influx of salt and evaporation leading to greater accumulation of salt and nutrients throughout the Coorong.
- The South Lagoon will increasingly experience prolonged periods of hypersalinity, eutrophication and low water levels.
- The North Lagoon will begin to experience impacts similar to those of the South Lagoon during the Millennium Drought.
- There will be increasing rates of biogeochemical processes (carbon and nutrient dynamics), cascading to an increasing frequency and longer duration of algal blooms.
- There will be changes to the planktonic basal food resources, combined with direct effects on invertebrate communities that will also drive changes to food web structures. Similar responses will occur with benthic food resources, with marine invertebrates dominating. Biomass and diversity of benthic food resources are reduced.
- There will be decreasing inundation of saltmarsh and mudflats and persistent decreases in submerged vegetation (seagrass and macrophyte communities) throughout the Coorong and particularly in the South Lagoon. This will lead to losses of habitat and food resources for wading birds and fish, but increasing habitat for species tolerant of hypersaline conditions.
- Changes to the water regime within the North Lagoon could see it increasingly develop a character similar to the current state of the South Lagoon, supporting vegetation and fish communities that prefer higher salinities.
- Decreasing connectivity across the entire system will affect those fish that require hydrological connectivity for movement and recruitment.
- There will be continuing change in fish communities, with increases in marine and salt-tolerant taxa.
- There will be changes to shorebird, wader and waterfowl communities, reflecting changes in habitat size and location and food availability.

5.2 Driver 2: Sea-level rise

Sea-level rise will increase water levels in the Murray Mouth, and Coorong North and South Lagoons, leading to significant biophysical changes in the system.

- There is uncertainty about the extent to which rising sea level will increase tidal exchange between the Murray Mouth and the Coorong. A rising sea may increase the transport of sand into the Murray estuary through the Murray Mouth counteracting increased lake water levels. Enhanced dredging of the Murray Mouth could mitigate this increase in sedimentation.
- Increasing depth and tidal inflows along the estuary and Coorong would lead to increases in water exchange between the Coorong and the Southern Ocean.

Physical, biological and ecological consequences

- Increasing sea levels will result in increases in water levels in the Murray estuary and Coorong.
- The connection between the North and South Lagoons will improve, allowing flux of nutrients and salinity out of the South Lagoon and along the Coorong. This may be augmented by pumping or other infrastructure interventions. This will lead to a reduction in peak salinity and nutrient levels. However, this process may take a long time due to the extensive accumulation of salt and nutrients in the South Lagoon and generally slow exchange along the Coorong.
- The estuarine conditions that presently exist through the Murray estuary towards the North Lagoon will become increasingly marine, depending on the volume and salinity of flows from Lake Alexandrina.
- Higher water levels will potentially increase habitat area and suitable conditions for seagrass and macrophytes, which inhabit the Murray estuary and the Coorong.
- High sea-level rise may in turn lead to loss of mudflats and saltmarsh in the Coorong, depending on the extent to which new suitable habitat is formed by inundation and tidal regime.
- Sea-level rise and aridification will also affect the sand dunes along the Younghusband and Sir Richard Peninsulas, tending to cause erosion of the seaward dunes and dune vegetation loss leading to dune destabilisation. However, it is unlikely the Sir Richard or Younghusband Peninsulas would be breached by the sea-level rise anticipated for the end of the century. Erosion that may lead to landward advance of the dunes is possible, and this may change the depth profile of the North and South Lagoons.
- Increasing water levels and tidal influence in the Coorong will increase the diversity of habitats for macroinvertebrates, fish and birds as compared to the drying phase. The reductions in salinity and eutrophication will support some recovery of macroinvertebrate communities and remains a key driver of the biota that are present in the lagoons. Fish diversity in the Coorong will be primarily comprised of marine taxa.

5.3 Driver 3: Temperature increase

Climate change will lead to a gradual increase in air and water temperature, and increased incidents of terrestrial and marine heatwaves. Increased temperature leading to greater evaporation and transpiration will also be one of the components of the drying driver.

Biological and ecological consequences

- Warming will increase rates of nutrient cycling and the frequency of algal blooms (subject to nutrient conditions). Cyanobacterial blooms are likely to become more prevalent, which will change food resources for higher organisms.

5.4 Coorong and Murray Mouth scenarios

This section provides descriptions of the two scenarios that were developed for the Coorong and Murray Mouth, based on the anticipated physical and ecological drivers and responses described above. The scenarios correspond to the two key points identified on the trajectory of change (Figure 2).

Scenario 1. Transition / water-level minimum

- The Coorong is experiencing a minimum in combined inflows of freshwater and seawater.
- The North and South Lagoons receive significantly less freshwater input than ‘previously’ as a result of reduced flows into Lake Alexandrina. There are long periods with no effective freshwater flows and disconnection occurring across the system. There has been a decrease in the frequency of years with flows corresponding to ‘previous’ median and high flows, which are important for replenishing the Coorong and Murray Mouth.
- Reduced barrage flows have led to high levels of sedimentation in the Murray estuary, resulting in reduced tidal flow of seawater into the Coorong, exacerbating reduced inflows of freshwater. Low flows and increased evaporation have reduced water levels in the North and South Lagoons, with the South Lagoon disconnected annually for extended periods.
- The South Lagoon is hypersaline and the North Lagoon has periods of hypersalinity. Nutrient concentrations are elevated in both lagoons.
- Water temperatures have increased, due to high air temperatures and shallower depths.
- Algal blooms have become more frequent. A self-reinforcing state of nutrient accumulation and rapid cycling predominates. A high organic load to sediments reduces survival of macroinvertebrates and macrophyte populations, so reducing bioturbation and bioirrigation oxygenation of sediments, decreasing sediment denitrification and increasing nutrient accumulation and sediment nutrient fluxes to the water column.
- There has been a loss of estuarine habitats from the North Lagoon for most of the time, resulting in a significant reduction in habitat diversity, particularly seagrass and saltmarsh habitats.
- Distributions of many species (fish, macroinvertebrates, etc.) are restricted to areas with near marine salinities, generally to the north of the Coorong and in the Murray Mouth and estuary.
- The aquatic macrophyte *Ruppia tuberosa* is no longer present in the South Lagoon due to high salinity and low water level; this as combined with declines in sediment quality leading to a loss of benthic macroinvertebrates and changes in planktonic macroinvertebrate community, cascading to changes in foodwebs reliant on these resources.
- Waterbird diversity and abundance has generally declined due to changes to habitat, although the abundance of some waterbird species has increased due to a decline in wetland habitat elsewhere in the region and continent.
- The Coorong and especially the South Lagoon only receives significant inflows during extended periods of high rainfall in the Basin. These result in short but critical episodes of reduced salinity, higher water level

and exchange of salt and nutrients, increasing habitat diversity and providing for occasional opportunistic recruitment of plants, invertebrates, fish and birds.

Scenario 2. Sea level dominates / high exchange

- Sea level has become the dominant determinant of water level in the Coorong, although water levels remain variable in response to freshwater inflows and evaporation.
- The connectivity between the Southern Ocean and the Murray estuary has increased. Dredging has kept the Murray Mouth open and maintained depth in the estuary to enable tidal flows along the estuary to the Coorong.
- Tidal- and wind-driven exchange along the Coorong plays an important role in the hydrodynamics of the system.
- Connectivity between the South and North Lagoons has improved with increasing water levels and remains good all year round leading to continual exchange occurring.
- Salinity is much lower than during Scenario 1 in the Coorong and Murray Mouth. Most of the time salinity is close to marine at the Murray Mouth and increases through the North Lagoon and South Lagoon. It is variable but does not reach the peaks of hypersalinity experienced during Scenario 1 or the Millennium Drought. Episodes of high freshwater inflows periodically reduce salinity in the Coorong and estuary.
- Nutrient levels are reduced from very high levels in Scenario 1 due to gradual exchange along the Coorong and periodic high freshwater inflows, but they remain relatively high due to the high load from nutrient accumulation in the sediments. There is a gradient of nutrients, increasing from the Murray Mouth, through the North Lagoon to the South Lagoon.
- Nutrient cycling in parts of the South Lagoon remains fast, with high algal loads.
- The system is predominantly marine, with estuarine habitats re-establishing in some locations during episodes of elevated freshwater inflows.
- Calcium carbonate in the Coorong provides some buffering capacity against pH decrease. Increase in carbon dioxide in seawater has favoured growth of some algae.
- Seagrass beds have established in the North Lagoon and parts of the South Lagoon.
- Saltmarsh species and mudflats have established and gradually migrated upslope in sections of the Coorong where salinity, geomorphology and sedimentation has been suitable.
- Overall diversity and abundance of macroinvertebrates has increased from Scenario 1 but is still lower than ‘previously’. Marine species dominate fish assemblages throughout the Coorong, enabled by increased connectivity. Connectivity between the Lake Alexandrina and estuary supports migratory fish species, but limited freshwater habitats and chemical cues restrict the recruitment and movement of some species with freshwater-dependent life history stages.
- Bird diversity and abundance has increased from very low levels in Scenario 1, but remain variable and different from historic conditions.

6 Discussion

This activity developed a set of plausible scenarios of transformational ecological change in the Coorong that integrate critical physical and ecological dynamics, which could result from climate change over the long term. The scenarios are intended to help stakeholders explore the implications of potential future transformational change for decision-making in management, policy and society in the CLLMM system. They were designed to be used in subsequent activities in the HCHB T&I Climate Adaptation Component and may also be useful for other situations.

The scenarios were designed to help people consider the 'greatest plausible change' resulting from the accumulation of logical, well-understood gradual drivers of change acting over a long time. By considering the decisions that may need to be made along a trajectory to these transformation scenarios, stakeholders will also be planning for lower levels of change but doing so *in the context of the possibility of future transformational change*.

The scenarios were based on a conceptual trajectory of change combining trends of decreasing river flows (freshwater inputs), increasing sea level and warming. Decreasing river flows and rising sea level are to an extent countervailing and operate on different timeframes, giving rise to an initial drying of the system before sea level begins to dominate water levels. The project team identified two key points on this trajectory that were likely to have very different ecological and management consequences, and then developed scenarios to describe possible ecological conditions at those points: Scenario 1 – minimum combined inflows; Scenario 2 – sea level dominates CLLMM water levels. Despite the high degree of uncertainty inherent in scenario development, and the unique complexities of the CLLMM system, the logic of the initial trajectory and scenarios that was presented to experts was well supported. Experts enriched the scenarios with additional details relating to their areas of experience and expertise. Due to the hydrological and ecological nature of CLLMM, each scenario was described separately for the Lower Lakes and for the Coorong.

All four scenario descriptions include some very significant differences from the current desired state of the CLLMM, and would likely represent declines or losses in values associated with the system, but none of the scenarios could be described as 'biological deserts' or 'death of the Coorong'. Note that less desirable outcomes for the CLLMM could be possible, if hydrological conditions were even less favourable or species less adaptable than assumed in these scenarios.

Contemporary scenario planning very often focuses on the end points of multiple monotonic trajectories of change that are conceptualised as resulting from differences in the relative influence of various drivers of change that operate independently of each other (e.g. the classic two-by-two scenario planning schema). In the case of the CLLMM, the two main (hydrological) drivers are freshwater inflows and sea-level rise, which are both very likely to be important and are coupled (same root cause), but they will probably operate on different time scales and to *some extent* could cancel each other out. To accommodate this, the project team imagined a single U-shaped trajectory (see Figure 2), with two sequential states of the system that are markedly different from present conditions and each other. We chose to describe these two states as the scenarios for the system. We are not aware of other scenario development exercises that have used a schema like this[4]. This arrangement does introduce some novel planning options, including the possibility of initially seeking to slow progress along the trajectory (essentially the current plan) then seeking to bypass or accelerate the trajectory through the first scenario to head the system directly toward the second scenario. This is an interesting finding associated with this study.

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[4] We also consulted two world leaders in scenario planning.

The adaptation pathway analysis conducted in subsequent activities of the Climate Adaptation project were designed to generate new insights about the decision-making challenges that may confront managers, policy makers and society as they contemplate the long-term implications of climate change. This trajectory may also help with analysis of a number of emerging issues for the Coorong, such as:

- How might different potential infrastructure options be used effectively to improve ecological health at different phases of the U-trajectory?
- Could multiple objectives for the CLLMM be developed in a sequence with adaptive transitions between them planned? This could help accommodate an increasing but uncertain divergence between available water and the water required to meet specific objectives.
- Could these scenarios be avoided through additional river flows or managing the existing flows differently?
- Are there circumstances where consideration might be given to bringing forward the seawater domination phase to bypass the extreme drying phase?

The experts consulted reminded us that societal attitudes and policy about land and water use, across the Basin and Australia more broadly, are highly likely to evolve over the course of the trajectory, possibly in response to changes occurring in the CLLMM, and these may alter the course of change in the Basin and CLLMM. This work assumed that strategic application of water for the environment will continue and will continue to be critical for yielding desirable ecological outcomes. However, we did not investigate the consequences of significantly different levels of water for the environment, although it is entirely possible that environmental flows could be used differently in these scenarios. Scenario 2 assumes that objectives and management will change, in the long-term future, to facilitate exchange of seawater with the Lower Lakes and along the Coorong in response to the prospect of seawater breaching the barrages and barrier islands and possible increased sedimentation in the Murray Mouth and estuary. However, other responses are feasible and would lead to different ecological outcomes. These scenarios focused on the physical and ecological outcomes, rather than any specific interventions and management in response to them.

Part II A synthesis of the anticipated ecological impacts of climate change in the Coorong and Lower Lakes

7 Introduction to Part II: Literature review

7.1 Summary

Part II of this report synthesises the anticipated impacts of climate change on the Coorong. It highlights the wide diversity of hydrological, biogeochemical and ecological change processes that may occur in the CLLMM as a result of climate change, and it provides some indication of the potential magnitude of key change processes. It was prepared to provide a basis for developing scenarios of change to support deliberation with experts and other stakeholders about future impacts and strategies to prepare for change (Part 1).

The main drivers of change in the CLLMM resulting from climate change are: (i) decreased freshwater inflows from the River Murray, the South East Drainage System and Eastern Mount Lofty Ranges tributaries, (ii) increasing sea-level and (iii) warming of land, atmosphere and water.

By 2090, rainfall is expected to decrease significantly across the Basin with projections ranging between a 5% increase to 40% decrease for the high emissions scenario. There is high confidence in an increase in the intensity of extreme rainfall events, and medium confidence in an increase in the time spent in drought. In the South Australian Murray–Darling (SA MDB) and South East South Australian (SE SA) regions, annual rainfall is projected to decrease by 11% to 29% by 2090 with the greatest decreases in spring of 32% to 57%. Combined with increases in evapotranspiration in the landscape, available inflow to the CLLMM is projected to decrease. The rate of sea-level rise is expected to accelerate over the 21st century, with sea level at Victor Harbor projected to rise between 0.39 and 0.84 m by 2090 for the high emissions scenario, relative to 1986-2005 baseline, and could be even higher under certain conditions. Temperature increases in the MDB are expected to be between 2.7 and 4.5 °C by 2090 for a high emissions scenario and between 1.3 and 2.4 °C for an intermediate emission scenario. These projections can be used to develop scenarios of ‘greatest plausible change’, which, coupled with an adaptation pathways approach, ensures that decision makers are ready to respond to the full range of climate impacts.

Decreasing freshwater flows into Lake Alexandrina will have multiple effects. These include exposing submerged macrophyte beds from the littoral zones and drying littoral sediments, which are key areas of habitat and productivity, providing an important food source for birds. In addition, sulfidic sediments with the potential to generate acid will be exposed. Decreasing flows may also lead to reduced openness of the Murray Mouth affecting fish that require migration between the freshwater and sea environments.

Rising sea levels pose a long-term challenge for the Lower Lakes. Decisions will need to be made about accommodating additional saline water in the Lower Lakes on a periodic or permanent basis as the barrier islands and the barrages are over topped; increasing freshwater inflows to ‘balance’ seawater ingress; or upgrading or relocating the barrages. Each of these choices would have a suite of different impacts on various ecological processes across the CLLMM. Rising sea level will also increase water levels throughout the Coorong and could potentially increase the export of salt and nutrients from the South Lagoon limiting the extremes of hypersalinity and eutrophication. This exchange would depend critically on increased exchange through the Murray Mouth; however this could be limited by increased transport of sand in through the Murray Mouth due to higher sea levels and reduced river flows.

Climate change will drive a series of physical changes to the environment that will directly affect different biota, as well as interactions between biota. The effects will cross all biotic groups, from the base levels of food webs (bacteria and algae), through to aquatic vegetation and top consumers such as fish and birds. In many instances, the interactions and cascading effects across different biota demonstrate significant ecological effects across the system. Given the spectrum of environments within the CLLMM (from freshwater lakes to hypersaline waterbody), it is expected that some ecological responses will be locally specific within the system.

Nitrogen, phosphorus, dissolved and particulate organic carbon inputs can be expected to rise through a combination of human activities across the MDB, and evapoconcentration processes and warming will increase overall nutrient concentrations and dynamics in the system. Increased frequency of drying and re-wetting events will increase mobilisation of nutrients from sediments and the formation of acid from some sediments.

Temperature and nutrient availability are critical factors in driving phytoplankton production in freshwater and estuarine environments, leading to a change in the timing, size and biomass of algal cells, as well as shifts in the composition of phytoplankton communities. Salinity drives phytoplankton community structure, which is particularly evident across the Goolwa Channel, Murray estuary and North and South Lagoons of the Coorong. Phytoplankton biomass is positively correlated with salinity, but taxonomic richness is negatively correlated with salinity. Diatoms dominate in the highest salinity (South Lagoon), chlorophytes (green algae) and cyanobacteria have an important presence in the Goolwa Channel. Zooplankton richness and abundance is negatively correlated with salinity, with different communities occurring across the CLLMM. This suggests that salinity and nutrient changes in response to climate change will be a key driver into planktonic communities, and thus affect overall food web structure.

Aquatic macrophytes play an integral part in structuring the overall ecology throughout the CLLMM. Water depth, duration, frequency and timing of inundation, as well as salinity, nutrients, turbidity and wave action all determine the plant communities present. Climate change will affect all these drivers, leading to altered diversity and distribution of aquatic plants throughout the CLLMM. Large stands of emergent macrophytes (*Typha* and *Phragmites*) fringe the Lower Lakes, providing extensive and critical areas of aquatic habitat for other organisms particularly small-bodied fish. *Phragmites* is a relatively resilient species and has the capacity to colonise wetland areas, so will continue to have an important role in maintaining the ecology of the Coorong into the future, if suitable hydrodynamics support its colonisation.

Ruppia tuberosa is a keystone plant species of the Coorong as it provides benthic habitat in the lagoon for invertebrates and the salt-tolerant smallmouth hardyhead that has historically supported vast numbers of different species of bird, thus it is a critical species in determining the ecological status of the Coorong. The loss of populations of *R. tuberosa* from the South Lagoon during the latter part of the Millennium Drought (from 1996 to 2010) had a major impact on the wider ecology of the Coorong. *R tuberosa* populations also represent an example of strong interaction between biophysical conditions (water level and salinity), nutrient concentrations and proliferation of algae, all combining to affect the viability of this important species, and those species that depend on the presence of *R. tuberosa.*

Low flows that lead to reduced openness of the Murray Mouth or operation of the barrages would have implications for fish that have some form of migratory aspect to their lifecycle. The combined changes in temperature and salinity will have a direct effect on fish communities but also through cascading effects upon the entire food webs. Altered salinity in the Coorong, brought about by reduced freshwater flows will directly affect fish populations and community structure throughout the estuarine and saline sections. Similarly, overtopping of the barrages will have a direct effect on the freshwater taxa resident in the Lower Lakes.

Birds are higher level consumers and while factors such as temperature may have direct effects on their physiology, their response to climate change in terms of the Coorong will be strongly driven by the combined effects of alterations to their food resources, habitat for foraging, and depending on species, their suitable habitat for breeding. Fringing habitats and mudflats, which are critical zones for birds, are likely to be directly affected by climate change. Declining freshwater inputs will lead to declines in abundance and diversity, and changes in distribution of waterbirds, although the abundance of some waterbird species could increase due to a decline in wetland habitat elsewhere in the region and continent. Sea-level rise will flood some areas of shoreline habitat (some mudflats and saltmarsh), but inundation will create new areas of shoreline habitat that may support bird populations, but this will depend on the geomorphology and fringing areas that will be suitable for colonisation by vegetation, invertebrates and fish (i.e. food resources).

The wide range of interacting change processes, and the overall large magnitude of the drivers of change, suggest that it is possible to anticipate that significant ecological change will occur in the Lower Lakes and Coorong, although much of the detail of this change will only be known as it occurs.

7.2 Background and aims

Climate change is anticipated to drive a series of physical changes to the environment of the CLLMM that will directly affect different biota, as well as affecting how biota interact with each other. The effects will cross all biotic groups, from the base levels of food webs (bacteria/algae and their processes), through to top consumers such as fish and birds. This Part II provides a synthesis of the anticipated impacts of climate change on the Coorong, as a basis for developing scenarios of change (Part I), and engaging with stakeholders about future impacts.

The synthesis is intended to provide a rich picture of the likely ecological impacts of climate change in the Coorong region. It seeks to span the *wide range* of potential ecological change processes that are likely to affect the CLLMM as well as provide some indication of the *magnitude* of future impacts that people may need to understand in order to deliberate about and plan to accommodate future changes. The picture is largely qualitative, as there is considerable uncertainty about many aspects of climate change and its impacts, but quantitative information about climate change and some ecological sensitivities has been provided to give a sense of the magnitude of possible future ecological change. The intent of the report is not to examine every possible impact, rather it seeks to present a synthesis of existing knowledge of long-term ecological impacts of climate change, combining some site-specific responses with more general principles.

This synthesis was conducted to inform development of scenarios of climate change impacts (Part I), to be used as a basis for engaging with stakeholders about how values might be affected, future objectives and management actions.

7.3 Methods

The project team developed a conceptual framework of how climate change impacts propagate through environmental and ecological systems, as a way of organising the reviewing and presentation of information. It deliberately focuses on describing the breadth of possible types of ecological change, rather than concentrating on changes that are better documented. It therefore differs from many other reviews of climate impacts that are dominated by the subset of change phenomena that are well researched and easily observed or modelled. Details of potential changes resulting from climate change in the CLLMM were drawn from a diverse range of scientific journal articles and technical reports, sourced through Google Scholar and Web of Science literature searches; keywords included Coorong, climate change, estuaries and Lower Lakes. This literature included documented observations of past changes in the CLLMM in response to climate change and variability, especially the Millennium Drought (1996 to 2010). In addition to observations in the CLLMM, ecological responses, modelling and sensitivities that have been observed in wetlands elsewhere in

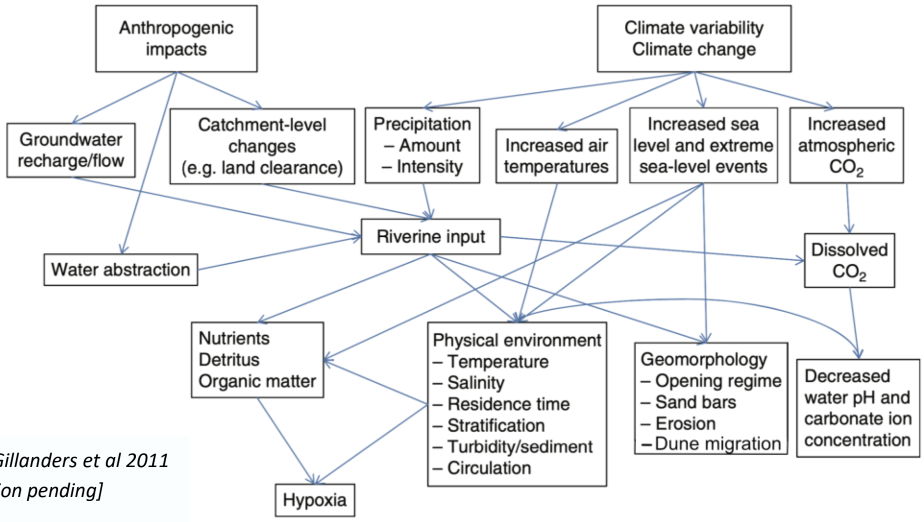
Australia and the world were also included as part of the literature searches. The results have been synthesised into the key messages about future changes in the CLLMM.

Much of the literature reviewed is already over five years old. HCHB T&I and other research will continue to provide more research findings that enhance and revise our understanding to how the CLLMM system may respond to climate change in combination climate variability and other hydrological, environmental and ecological changes. Like all scenarios, these scenarios should be viewed as ‘living scenarios’ that are revisited and revised as required. We have also sought to emphasise findings that are known with confidence, in order to develop scenarios that are valid and useful despite specific uncertainties.

8 Estuaries, climate change and the Coorong region

This chapter describes the broad hydrological, chemical and ecological linkages between climate change and ecological outcomes in estuaries. The CLLMM is very likely to experience increases in temperature, decreases in rainfall and rises in sea level as a result of climate change.

Estuaries around the world are under a major threat from climate change, with sea-level rise, increased temperatures, changed precipitation and weather regimes, and increased atmospheric carbon dioxide (CO_2) (Figure 4). The primary drivers associated with climate change lead to a series of stressors that will have major consequences on estuarine ecology and ecosystem services. Estuaries are affected by both local climatic changes and changes affecting the hydrology of their catchments, including changes in rainfall affecting how much water flows into estuaries and temperature and potential evapotranspiration affecting waters within the system. Climatic impacts combine with human impacts directly affecting flows, including extractions and land cover, which are themselves influenced by climatic conditions. Estuaries are also affected by changes including sea level, water temperature and acidity. By their nature, many estuaries, and especially the Coorong, are particularly affected by climatic variability, so changes in climate variability and extremes can be expected to drive ecological impacts as much as average changes (Gillanders et al. 2011; Hallett et al. 2018; Scanes et al. 2020b).



Source: Gillanders et al 2011 [permission pending]

Figure 4 Linkages between the primary climate change variables and other anthropogenic impacts and their cascading influences on estuaries.

The peninsulas that form the sea barriers to the Coorong have historically undergone complex changes in response to changes in sea level, climate and wave energy (Dillenburg et al. 2020). Both the Sir Richard Peninsula and Younghusband Peninsula are currently advancing landward, with the Younghusband Peninsula directly affecting the Coorong (Bourman et al. 2019). Sustained sea-level rise will also encourage the ongoing landward migration of the Sir Richard and Younghusband Peninsulas (Bourman and Murray-Wallace, 1991; Bourman et al. 2000), and without intervention this would result in an adjustment of the position and morphology of the tidal channels and islands within the Murray estuary. Sea-level rise, increasing storm frequency, increasing aridity will also affect the sand dunes along the Younghusband and Sir Richard Peninsulas, causing erosion of the seaward dunes and dune vegetation loss leading to dune destabilisation (Townsend, pers. comm).

Climate change will directly affect the Coorong region, but also through the temperature and rainfall impacts across the Basin that influence River Murray inflows (Chiew et al. 2022). Marked variability has dominated historic rainfall patterns in the Basin and variability will continue under climate change. However, there is expected to be considerable drying in the Basin, resulting from warming across all seasons and a decrease in rainfall especially in the cooler months (Timbal et al. 2015). Despite the decline in average rainfall, there is expected to be an increase in the intensity of rainfall events (Timbal et al. 2015). However, by 2090 rainfall in the cooler months, which is important for river flows, is expected to decrease significantly with projections ranging between 5% increase to 40% decrease for the high emissions scenario (Timbal et al. 2015). Future projections for summer rainfall vary considerably. There is high confidence in an increase in the intensity of extreme rainfall events, and medium confidence in an increase in the time spent in drought. In the SA MDB and SE SA region, annual rainfall is projected to decrease by 11% to 29% by 2090 with the greatest decreases in spring of 32% to 57% (Charles and Fu, 2015).

The Basin has already warmed by about 0.8 °C since 1910 (Timbal et al. 2015). Under a higher emission scenario (RCP8.5), temperatures in the Basin are expected to increase by between 2.7 and 4.5 °C by 2090 compared to 1986–2005, and between 1.3 and 2.4 °C for an intermediate emissions scenario (Timbal et al. 2015). The frequency of hot days and maximum temperature reached on hot days are both expected to increase significantly. In the SA MDB and SE SA region, maximum daily temperature is projected to increase 2.7 to 4.5 °C and up to 5.0 °C in spring under high emissions scenario (Charles and Fu, 2015).

Across the Basin, potential evapotranspiration is expected to increase by 1% to 20% annually by 2090, and up to 40% in winter (Timbal et al. 2015). In South Australia (MDB and SE), potential evapotranspiration is expected to increase by 8% to 14% annually by 2090, and up to 16% in spring, and solar radiation is projected to increase 1.5% to 4.5% by 2090 for the high emission scenario, with up to 10% increases in spring (Charles and Fu, 2015). Reduced rainfall and increased evapotranspiration could lead to very significant decreases in catchment inflows in the Basin (median decrease 19%, up to 43% decrease for a high emissions scenario by 2046-2070), translating into reduced baseflows, reduced allocations and more frequent prolonged periods of low flows (Chiew et al. 2020). Higher temperatures will also increase evaporation in the Lower Lakes and Coorong.

There is high confidence that harsher fire weather will be experienced in the Basin with increasing climate change (Timbal et al. 2015), but the details are difficult to project, and the impact on fire regimes is even more speculative as this depends on the dynamics of fuel growth and drying as well as weather.

The rate of sea-level rise is expected to accelerate over the 21st Century, with sea level at Victor Harbor projected to rise between 0.39 and 0.84 m by 2090 for the high emission scenario, relative to 1986-2005 baseline, and could be even higher under certain conditions (Timbal et al. 2015). Sea surface temperatures are also expected to increase by between 1.5 and 3.4 °C by 2090 under a high scenario, and the sea will become more acidic with increasing atmospheric CO_2 concentrations.

Climate Change in Australia provides a tool[5] to identify locations around Australia whose current climates are similar to the projected climate for locations of interest (CSIRO and BOM, 2015). Such 'climate analogues' are shown in Table 1.

Table 1 Locations with current climates that are analogues of the climates projected for selected locations in the CLLMM region in 2090 under a high emissions scenario using a 'hot/dry' model.

Location in the CLLMM region	Locations with analogue climates
Victor Harbor	Hawker, Quorn, Pinnaroo, Kimba, Port Pirie
Murray Bridge	Carnarvon, Denham in the Gascoyne region of WA
Kingston	Wongan Hills, Northam, Corrigin in the WA wheat belt

8.1 Choice of future projections

Climate projections are based on a range of choices, including the emissions scenarios, future dates and climate models. Each one of these choices affects the outputs. Analyses are often done with all combinations of these factors, providing numerous projections of multiple different climate parameters, which often yield a very wide spread of resultant climate impacts. While these numerous projections do give a picture of the range of outcomes that might eventuate, they also provide a volume of data that is often overwhelming and can be readily misinterpreted. One strategy is to analyse the spread of results and treat the average like a prediction of the 'most-likely outcome'; however, technically, this does not provide a most-likely outcome and it can lead to poor decision making. In Part I, we identified scenarios of 'greatest plausible change', following *Climate Compass*, the Australian Government's guidelines on climate adaptation (CSIRO, 2018) and the Australian Government's methodology for assessing the vulnerability to climate change of Ramsar wetlands (Dunlop and Grigg, 2019). Planning using greatest plausible change scenarios, coupled with an adaptation pathways approach (Wise et al. 2014), ensures that decision makers are ready to respond to the full range of climate impacts, reducing the risk associated with planning for just one set of anticipated impacts. Similarly, while some impact and adaptation analyses focus on near-term impacts with the rationale that management plans only have a 5–10 year timeframe; we consider long-term impacts on the grounds that long-term impacts have material implications for the decisions that might be taken in the near term (Stafford-Smith et al. 2011) and that management responses may require long-term planning and development windows. Again, uncertainties associated with rates and magnitudes of impacts over time will be accommodated using the pathways approach.

9 Drivers of change

This chapter describes the key drivers of change in the CLLMM region as i) decreasing freshwater inflows from the River Murray and the South East Drainage System and other tributaries; (ii) rising sea level, and (iii) warming of land and water.

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[5] CSIRO and Bureau of Meteorology, Climate Change in Australia Climate Analogues Tool (https://www.climatechangeinaustralia.gov.au/en/climate-projections/climate-analogues/about-analogues/) Accessed 10/11/2020.

Impacts can occur at multiple levels in ecosystems. At the organism level, specific parameters such as temperature may have some direct physiological effect on individuals, for instance, leading to changed growth rates, increased mortality or similar effects, or an individual's ability to osmoregulate under increasing levels of salinity. Effects will also cascade through communities and food webs as changes at organism level affect populations that may be primary food resources (e.g. phytoplankton), which will influence higher consumers (Figure 4). In addition to aquatic food webs, terrestrial food webs will be affected by climate change, leading to climate-driven responses and interactions between the aquatic and terrestrial environments. Many responses will not be linear, including thresholds and other complex interactions, many of which are not well understood.

Change in hydrology will be a major cause of impacts. Availability of freshwater through River Murray flows into Lake Alexandrina and subsequent distribution throughout the Coorong will be affected by climate impacts across the Basin, in combination with river regulation and extractions (Chiew et al. 2020). Inflows from the South East Drainage System are smaller but significant as they can contribute to flushing flow through the Coorong. The freshwater flows interact with the hydrological tidal inflows from the sea, which will be affected by sea-level rise, leading to altered hydrology throughout the system. Reduced flow from the River Murray will see increased frequency of drying events within the Lower Lakes and exposure of sediments on the lake fringes.

Evaporation also contributes to the hydrological balance of the system. Changes to flows, combined with evaporative losses, will increase the concentration of salts and other constituents across the CLLMM. The changes in concentrations will also be reflected in fluxes of salt, acidity and nutrients, which drive the physical and chemical conditions of the system that in turn drive a cascade of biological processes.

Interactions between freshwater inflows, evaporation and ocean exchange affect salinity, which is a critical factor in ecological processes, and changes in salinity in the entire CLLMM system are expected to be a major driver of climate-change related impacts on multiple components of the food web and overall community structure (Chiew et al. 2020; Lester et al. 2009). Density stratification is also influenced by freshwater inflows, wind actions and evaporation within water bodies and in turn, influences oxygen conditions, which affects many biological processes (Chiew et al. 2020).

Temperature increases have already been recorded across New South Wales estuaries over the past 10 years and this will have an effect on many ecological processes (Scanes et al. 2020a). The extent of the effects will be determined by the individual morphology of given estuaries (Scanes et al. 2020a) and some regions of the Coorong may be affected to different degrees.

It is important to consider climate-induced changes in combination with other anthropogenic changes (Hemraj et al. 2017; Paerl and Huisman, 2009; Paerl and Paul, 2012). For example, nutrients play a key role in determining growth of primary resources within food webs (phytoplankton, benthic algae, plants, etc.) and eutrophication is considered a key threat to ecological systems (Statham, 2012). Climate-driven processes that affect biogeochemical process in water systems, such as carbon (C) and nitrogen (N) cycling, will need to be considered in context with anthropogenic processes that deliver increased levels of nutrients to the Coorong. To add to the complexity, biological responses to changes in environment conditions will be interactive, and non-linear (Paerl and Paul, 2012).

Decreased freshwater flow over the barrages will have significant effects on the condition of the Coorong (Lester et al. 2009). On the other hand, long-term rises in sea levels will increase the hydrodynamic connection between the two lagoons, which could counter the evaporative effect that leads to hypersaline conditions in the Coorong through dilution effects (Lester et al. 2009). Increased tidal flow could help flush hypersalinity and nutrients from the Coorong lagoons. However, any increase in volume of the tidal prism with sea-level rise will be affected by changes in marine sediment transport through the Murray Mouth and into the estuary, which is uncertain and potentially affected by management. Increased sea levels would eventually lead to frequent marine overtopping of the current barrages and the barrier islands in the Murray estuary, leading to saline inputs to Lake Alexandrina (Chiew et al. 2020). The extent of such influences would depend on any future changes to the barrage operations and changes to the barrages themselves. Sea-level rise combined with lower water levels in the Lake Alexandrina can be expected to lead to increased seawater seepage through or around the barrages and groundwater flow into the Lower Lakes.

While modelling provides good predictive capacity regarding individual hydrologic process, given the number of processes and the different time scales at which they operate, it will be hard to predict exactly how all these factors will interplay. Other unpredictable factors, such as water management through River Murray flows, operation of infrastructure and sediment movement and deposition in the Murray Mouth will also affect the hydrodynamics and overall condition of the Coorong system.

The salinity gradient that exists across the Coorong system is due to the relative contributions of freshwater flows into Lake Alexandrina and seawater exchanges through the Murray Mouth, overlaid by internal processes such as evaporation that alter the concentrations and flows through the barrages (Chiew et al. 2020). Freshwater flows predominantly come through the River Murray, with some additional contribution from tributaries that rise from the Eastern Mount Lofty Ranges and groundwater inputs, as well as flow from the South East Drainage System. Flows into Lake Albert occur via a narrow shallow channel. Freshwater flows via the barrages into the North Lagoon of the Coorong and Goolwa Channel. Salinity across this area will vary depending on relative contributions from fresh and marine inputs, but still remain generally estuarine, whereas salinity increases into the South Lagoon, often lead to hypersaline levels.

10 Responses by components of the system

This chapter describes how key components of the system will respond to the key drivers of change. These key components are: (i) nutrients, (ii) ASS, (iii) planktonic communities, (iv) aquatic plant communities, (v) fish communities, (vi) bird communities, and (vii) other relevant taxa.

10.1 Nutrients

Concentrations of nitrogen (N) and phosphorus (P) in the Coorong system, and their internal cycling will be affected by climate change (Statham, 2012). Concentrations of N and P can be expected to rise through a combination of human activities within the River Murray catchment and climate-induced alterations to nutrient dynamics within river systems. Dissolved organic carbon (DOC) and particulate organic carbon (POC) loads are also predicted to increase through modification to upstream catchments (Canuel et al. 2012), although this is less well understood. On the other hand, reduced flows could reduce loads to the Lower Lakes thus the extent to which climate change may alter carbon inputs and internal cycling is not easy to predict (Canuel et al. 2012; Suikkanen et al. 2013; Wetz and Yoskowitz, 2013). Reduced flow will transport smaller loads of other important nutrients (e.g. silicon) to the Lower Lakes. In this case, reduced delivery of silicon will potentially have implications for growth of diatoms, an important group of algae that fuel aquatic food webs.

Any constituent in the water column, including N and P, is subject to evapoconcentration processes and these processes alone are enough to explain the high correlation between salinity and each of TN and TP (Grigg et al. 2009). Nutrient budget analysis that accounted for evapoconcentration dynamics showed that correlations between salinity and chlorophyll-a concentrations can also be explained by evapoconcentration processes (Grigg et al. 2009). Longer-term studies of the nutrient and chlorophyll-a concentrations in the Coorong South Lagoon show that it is persistently hypersaline and hypereutrophic (Mosley et al. 2020). Sea-level rises that lead to more widespread inundation of the Coorong with seawater will play a role in regulating nutrient concentrations through exchange with the ocean and reducing eutrophic status of the hypersaline sections of the Coorong. The extent of internal sources and nutrient cycling in the South Lagoon is not certain (Mosley et al. 2020) and therefore capacity for internal sources to supply nutrients even in the face of dilution is not fully known.

Temperature is a major driver of microbial nutrient dynamics in the water column and sediments (Baldwin and Mitchell, 2000) and this effect will be seen across the Coorong and Lower Lakes. Microbial processes such as nitrification, denitrification and mineralisation of organic material (releasing ammonium), and phytoplankton growth will respond accordingly. Sediment nutrient dynamics are directly linked to wetting and drying cycles. Inundation of dried sediment results in a pulse of carbon and nitrogen from sediments (known as the Birch effect; (Baldwin and Mitchell, 2000) and climate-driven changes to water levels that expose sediment will lead to nutrient release upon re-wetting.

Increased storm frequency and wind action can potentially mobilise sediments, increasing the likelihood of increased nutrient dynamics from sediments and release of nutrient into the water column (Statham, 2012).

10.2 Acid sulfate sediments

Acid sulfate sediments form by the activity of sulfate-reducing bacteria in anoxic sediments when sulfate is present in the presence of organic carbon. Sulfate-reducing bacterial activity in freshwater systems is generally limited by available sulfate, but introduction of sulfate by incursions of water of marine origin (which contains sulfate) will ultimately stimulate sulfate-reducing activity, even in freshwater bodies (Lovley and Klug, 1983; McCarthy et al. 2006; Rees et al. 2010). Well mixed water columns lead to an oxidised (aerobic) layer of sediment over the surface of ASS, and in these situations, ASS do not necessarily represent a problem.

The two issues associated with ASS and climate change are: (i) exposure of existing material to the atmosphere and subsequent generation of sulfuric acid as a consequence of decreased freshwater inputs to the Lower Lakes, and (ii) formation of further acid-generating material within the lakes through introduction of sea water. As noted above, future water levels in the Lower Lakes and Coorong will depend on the relative rates of decrease in freshwater inflows into the lakes and increase in seawater inputs due to sea-level rise, compounded by changes in evaporation and groundwater inputs. Overall, sea-level rise will contribute to increased water levels in the Lower Lakes, however, should total inputs to the system decline at a greater rate (combined with evaporation), reducing water levels in the lakes may expose sediments with sulfidic minerals, creating acid-generating conditions (McCarthy et al. 2006). Acid-generating sediments are present in the Coorong, however elevated carbonate levels in the Coorong provide high buffering capacity and can counteract the acidity generated by ASS. Importantly, once acid is generated, the sulfate that is mobilised can be used by sulfate-reducing bacteria in sediments upon re-wetting, re-establishing acid-generating potential for future drying events. Saline groundwater inputs to the Lower Lakes are considered negligible (Gibbs et al. 2019). Predicted increases in sea level changes that lead to any further inputs of seawater, such as overtopping of the barrages, will prevent sediments from being exposed, but the added sulfate will increase the extent to which ASS will be formed, exacerbating any potential acid generation that could occur in future drying events.

10.3 Planktonic community

Microalgae (phytoplankton) and bacteria form important basal resources for food webs in aquatic systems and any changes to the primary resources will have impacts on food web structures. Increased temperature has led to a change in the timing of phytoplankton production, size and biomass of algal cells and shifts in the composition of phytoplankton communities (Sommer and Lengfellner, 2008). In some situations, higher productivity occurred, but was strongly moderated by fishing pressure (human stressor) (Zeng et al. 2019).

Salinity and nutrients drive phytoplankton community structure in the Goolwa Channel and the North and South Lagoons of the Coorong (Hemraj et al. 2017). Phytoplankton biomass is positively correlated with salinity, but taxonomic richness is negatively correlated with salinity. Diatoms dominate in the highest salinity (South Lagoon), chlorophytes (green algae) and cyanobacteria have an important presence in the Goolwa Channel. Warming selects for cyanobacteria as they tend to have higher growth maxima than green algae (Butterwick et al. 2004) and an increase in the frequency of harmful cyanobacterial blooms has been predicted, although actual outcomes will be dependent on specific taxa (Hallegraeff, 2010).

Nutrient enrichment also strongly affects cyanobacterial growth and increases the potential for cyanobacterial blooms to occur in fresh and marine ecosystems (Paerl and Huisman, 2009). The three critical consequences that result from phytoplankton community shifting to cyanobacteria are toxin production, altered food webs and potential to contribute to hypoxia as blooms go through rapid declines and death. Large flows into the Coorong that occurred after the Millennium Drought shifted the cyanobacterial-dominated phytoplankton community to green algae and diatoms, which are known as higher quality foods for consumers (Aldridge et al. 2012). Rapid decomposition of dead algae can lead to formation of anaerobic conditions in sediments, which can alter sediment nutrient dynamics as well as habitat for benthic invertebrates. In extreme circumstances, deoxygenation of the water body can occur at depth (Paerl and Paul 2012). The extent to which this occurs will be determined through a combination of sediment oxygen demand, mixing though wind action and density gradients in the water column.

Increased atmospheric CO_2 is also likely to promote growth of cyanobacterial blooms and in environments where nutrients are in excess of needs, cyanobacteria will show a strong response to increased CO_2 and temperature (Visser et al. 2016). The extent of the CO_2 effect is uncertain in the CLLMM, as compared with other key drivers. These results demonstrate the overall climate-driven response of phytoplankton communities may be complex and that non-linear responses are likely to occur (Hallegraeff, 2010).

Zooplankton richness and abundance is negatively correlated with salinity (Hemraj 2017a) and communities are different at Goolwa Channel, North and South Lagoons. These data indicate that salinity changes in response to climate change will be a key driver into zooplankton communities, and thus affect overall food web structure. Similarly, there is emerging evidence that increasing salinity is having a strong negative effect on the abundance of benthic invertebrates of the South Lagoon, driven numbers close to zero (Mosley et al. 2020).

Increasing temperature has been associated with changes in the size of copepods, an important zooplankter, which can alter the efficiency of trophic transfer to consumers (Marques et al. 2018; Rice et al. 2015). Changes with zooplankton populations, combined with changes to phytoplankton communities will lead to reduced energy for consumers (Suikkanen et al. 2013). Timing of production is also implicated in disconnecting estuarine food webs, with changes in phytoplankton production timing leading to less efficient energy transfer to zooplankton (Sommer and Lengfellner, 2008). Temperature has been a key driver of biotic changes in the Gironde estuary (France) (Chaalali et al. 2013). Modelling of 30-year data on the Gironde estuary has also shown a disconnect between predator–prey relationships, with an earlier peak in zooplankton production occurring that led to a disconnect with entrance of fish into the estuary. There was also a combined decrease in the residence of both groups in the estuary (Chevillot et al. 2017).

10.4 Aquatic plant communities

Water depth, duration, frequency and timing of inundation are key drivers of aquatic plant communities. Given that the CLLMM system ranges from freshwater lakes, through estuarine conditions, to saline lagoons, salinity, turbidity and wave action will also play a part in structuring the plant communities (Nicol et al. 2019). Changes to any of these factors, brought about through climate change have the potential to affect plant communities, but given the wide diversity of habitat and water conditions across the CLLMM system, each part of the system will respond differently and it is likely that the region will continue to provide habitat for a diversity of plant communities.

Plants generally have specific tolerances to different levels of salinity. Salinity has important physiological effects on plant growth and is key to the structure of the current distribution of plants throughout the CLLMM system. Nicol et al. (2019) recognised a range of functional plant groups that occurred across the salinity gradient (from the Lower Lakes to the South Lagoon of the Coorong). Some of the notable communities included submerged macrophytes within the Lower Lakes, and through into the Goolwa Channel, extensive beds of emergent macrophytes (*Typha domingensis* and *Phragmites australis*) around fringes of the lakes, some areas of swamp paperbark in regions of the lakes and edges of wetlands around the Coorong, the halotolerant samphire and salt marsh communities in regions where there is moderate to high salinity (Seaman, 2003). *Typha* and *Phragmites* provide extensive and critical areas of aquatic habitat for other organisms (Gehrig et al. 2012; Nicol et al. 2017). Both species are reasonably resilient and given sufficient time, are able to establish in environments with appropriate water regime. *Phragmites* resilience and capacity to colonise is such that it has even been considered an invading plant in many situations (Hershner and Havens, 2008). Given the ecosystem services associated with *Phragmites* beds (including within the Coorong system), the species will continue to have a very useful role in maintaining the ecology of the Coorong into the future.

Adequate water regime, along with appropriate light regime and shelter are required by submerged macrophytes. A range of submerged macrophytes, for instance, *Vallisneria australis*, *Myriophyllum* spp. and *Potamogeton* sp. are distributed throughout the sheltered, freshwater parts of the CLLMM system (Nicol et al. 2019) and their most immediate threat is reduced inundation. Loss of these plants will lead to a loss of habitat for a range of animals.

The dominant submerged macrophytes of the central and South Coorong is a mix of *Ruppia tuberosa* and *Althenia cylindrocarpa* (Asanopoulos and Waycott, 2020). *R. tuberosa* is considered a keystone plant species of the Coorong and is a major source of food for many waterbirds (Asanopoulos and Waycott 2020). The loss of populations of *Ruppia tuberosa* from the South Lagoon has had a major impact on the wider ecology of the Coorong as it provided benthic habitat in the lagoon for invertebrates and the salt-tolerant smallmouth hardyhead that has historically supported vast numbers of different species of birds (Paton et al. 2015). Appropriate levels of inundation at appropriate times are required for growth and persistence of *R. tuberosa* (Paton et al. 2015; 2017). The reduced abundances of *R. tuberosa* at water depths >0.6 m suggests light limitation and that *R. tuberosa* is a high-light–adapted species, contributing to its sensitivity to appropriate inundation, in conjunction with overall water quality.

Salinity is an important driver for freshwater emergent macrophytes; *Typha* is reported to die when exposed to salinity greater than 8000 µS.cm^{-1} and *Phragmite*s show signs of stress at 15,000 µS.cm^{-1} (Bailey et al. 2002). However, healthy stands were reported in the Goolwa Channel with water of 20,000 µS cm^{-1} (seawater has an EC of approximately 50,000 µS cm^{-1}) (Gehrig et al. 2011). In the short term, fringing emergent vegetation is likely to be able to survive variations in salinity. This is not likely in conditions of persistently high (e.g. marine) levels of salinity. If salinity is not limiting, both *Typha* and *Phragmites* do have the potential to reproduce and colonise other areas of the lake fringes, although this would be limited by the extent of suitable areas to inhabit and the extent of the periods of dryness.

Salinity is also considered important for the persistence of *R. tuberosa*, its disappearance from the South Lagoon occurring when salinities reached as high as three times seawater (about 115–120 g/L). Optimum salinities for shoot abundance have occurred at salinity between 19 and 70 g/L, declining between salinities of 70 and 110 g/L, but increasing between 115 and 120 g/L (Kim et al. 2015; Kim et al. 2013). If favourable salinities for germination and growth occur during autumn and winter, *R. tuberosa* is able to survive elevated spring salinities and persist through either sexual reproduction or the production of turions, depending on salinity levels.

On the other hand, decreased salinity indirectly affects growth of *R. tuberosa* as salinity, in combination with temperature are important in driving growth of filamentous green algal community comprising *Ulva paradoxa, Cladophora* sp. and *Rhizoclonium* sp. The extreme proliferation of filamentous green algae has seen a major decline of *R. tuberosa*, due to smothering. Salinity between 35 and 90 g/L and temperature of 35 °C are optimum conditions for growth of *U. paradoxa* (Waycott et al. 2019).

Historical accounts suggest that water quality changes led to significant changes in the ecology, with the South Lagoon of the Coorong switching from *Ruppia megacarpa* dominance to *Ruppia tuberosa* (Dick et al. 2011; Krull et al. 2009). *R. megacarpa* is less salt-tolerant than *R. tuberosa* and its loss from the North Lagoon has been attributed to altered salinity regimes (Nicol, 2005). A *R. tuberosa* seed bank was still detected in 2002 but that seed bank was not present in 2007 (Nicol et al. 2019).

Temperature is an important driver for submerged macrophytes and populations have been shown to be under threat in the Chesapeake Bay (USA) where temperature increase of 2–6 °C is predicted to see a loss of *Zostera marina* (eel grass) from the bay, while favouring more heat tolerant species such as their native *Ruppia maritima* and non-native seagrass (*Halodule* spp.) (Arnold et al. 2017). Increased competition from algae is also expected with increases in temperature. There may be some offset with *Zostera* as it shows increased growth in the presence of elevated CO_2 concentration. The extent of submerged macrophytes has been proposed as an ideal integrating indicator for climate response, given its importance, but also their strong feedback with water quality (Wainger et al. 2017).

The samphire and saltmarsh communities are widespread throughout the Coorong regions in areas where there is moderate to high salinity (Seaman, 2003). Both types of vegetation community are generally intolerant of long-term inundation but grow well in waterlogged soil (Sainty and Jacobs, 2003). Saltmarsh communities are particularly vulnerable to changing climate though changed salinity, inundation regimes and potentially smothering by mobilised sediment (Saintilan and Rogers, 2013). There is a flow-on effect for animals that rely on habitat and food resources provided by the saltmarsh. There are predictions that saltmarshes will be replaced by alternate vegetation communities in the event of sea-level rises (Crosby et al. 2017; Saintilan et al. 2014). Saltmarshes would, in theory, be able to colonise new areas as inundation occurs, but the extent that this occurs will be constrained by suitable habitat with morphology that provide appropriate inundation (Saintilan and Rogers, 2013). The nature of these changes will be determined by the extent of inundation that would occur in the Coorong, micro-topology of submerged substrate and any salinity changes that would occur.

Wave action has physical effect on plants and is a key reason why the open areas of the Lower Lakes do not support extensive submerged macrophytes, but plants are present in areas that have suitable shelter. The extent to which increased extreme climatic events alter wave action in the Coorong has not been considered extensively in the literature and remains speculative.

10.5 Fish communities

Fish assemblages in the freshwater sections are strongly influenced by the flow from the River Murray, maintaining suitable habitat, particularly vegetation. The freshwater habitats include both the Lower Lakes as well as the lower reaches of and terminal areas of the tributaries rising from the Mount Lofty Ranges. The tributary inputs may have a locally important role by providing some diversity of habitat across the freshwater components of the system, but overall, they contribute a small proportion to the overall freshwater discharge to the system (Chiew et al. 2020). The southern pygmy perch (*Nannoperca australis*) and Murray hardyhead (*Craterocephalus fluviatilis*) are two examples of species whose habitat requirements are met by conditions within the Lower Lakes. Yarra pygmy perch (*Nannoperca obscura*) is critically endangered and the Lower Lakes provide *N. obscura* with its required habitat. Decreased water levels during drought led to loss of habitat, increased salinity and populations of Yarra pygmy perch became locally extinct from the Lower Lakes (Bice et al. 2019).

Low flows that lead to reduced openness of the Murray Mouth will have implications for fish that have some form of migratory aspect to their lifecycle (Gillanders et al. 2011). For example, the adult stage of the pouched lamprey (*Geotria australis*) occurs in the marine environment and it requires upstream migration into freshwaters to spawn. Similarly, the congolli (*Pseudaphritis urvillii*) and short-fined eel (*Anguilla australis*), spend adult life in freshwaters and migrate to the sea to spawn, so will be immediately affected by restricted flow to the ocean.

Not surprisingly, salinity is a key driver of the fish assemblages across the entire CLLMM (Bice et al. (2019) and references therein). Given different saline environments across the system, it is useful to consider their ecological responses separately.

Any climate-driven increases in salinity will have a direct effect on freshwater fish as they generally exhibit low tolerance to salinity. Throughout the Millennium Drought, fish surveys recorded declines in some fish assemblages, including abundance of threatened taxa, but an increase in taxa considered to be more generalist (e.g. Australian smelt). Given the connection between the components of the CLLMM, an increase in salinity can also lead to an increase in the presence of estuarine species, as happened with the lagoon goby during the Millennium Drought. These changes were attributed to a combination of salinity increase, water level changes and subsequent loss of vegetation and habitat for fish (Bice et al. 2011; Bice et al. 2014; Wedderburn et al. 2012).

While the diets of the abundant fish of the Coorong are generally known, this is not the case for all fish species, particularly the larval growth stages (Ye et al. 2020). This lack of knowledge reduces the capacity to predict overall food web responses to climate change.

A strong interplay of the Murray estuary food web and fresh water has been described whereby the marine-estuarine opportunist sandy sprat (*Hyperlophus vittatus*) diet included freshwater zooplankton and carbon derived from freshwater sources (Bice et al. 2016). Furthermore, the abundant sandy sprat is a food resource for larger bodied fish as well as piscivorous fish such as mulloway (*Argyrosomus japonicus*) (Lamontagne et al. 2016). In this way, primary productivity in the freshwater components of the system can have direct effects on food webs in the estuarine components of the system, a process known as resource subsidy (Bice et al. 2016; Giatas and Ye, 2015). What is not known is whether the freshwater zooplankton are consumed simply because they are there, whether estuarine taxa if suitably abundant would equally be consumed, or indeed if higher productivity derived from Lake Alexandrina is required to maintain productivity in the Murray estuary.

Reduced freshwater flow and subsequent evapoconcentration of dissolved constituents in the water column leads to very high salinities in the South Lagoon, which has direct effects for ecological processes in this waterbody. Small-mouthed hardyhead (*Atherinosoma microstoma*) feed on microcrustaceans and insects (Lintermans and Commission, 2007) and tolerate a wide range of salinities. It is typically abundant in the South Lagoon where it is often the only species of fish present (Bice et al. 2019). Reduced flow also has a secondary effect for small-mouthed hardyhead as it prefers edge habitats amongst submerged macrophytes such as eel grass, or in the case of the South Lagoon, *Ruppia tuberosa*. Small-mouthed hardyhead is a major source of food for birds in both the North and South Lagoons, in particular the South Lagoon where it is a food resource for the vulnerable south eastern Fairy tern (*Sterna nereis nereis*) (Paton et al. 2019). Drivers of change have cascaded from reduced water inputs and increased salinity affecting plants, ultimately affecting bird communities.

10.6 Bird communities

The CLLMM is host to a wide range of waterbirds and the extent of the bird populations was a primary basis for the CLLMM being listed as an internationally important wetland under the Ramsar Convention (Paton et al. 2019). Large numbers of migratory and non-migratory waders, piscivorous birds and waterfowl are present in the system at different times, particularly through the summer months. The CLLMM system also has an important role as a drought refuge.

Birds are higher level consumers and while factors such as temperature may have direct effects on their physiology, their response to climate change in terms of the Coorong will be strongly driven by the combined effects of alterations to their food resources, habitat for foraging, and depending on species, their suitable habitat for breeding.

A large number of different shore birds only use the Coorong, which supports large numbers of wading birds, including red-necked stints (*Calidris ruficollis*), banded stilts (*Cladorhynchus leucocephalus*), sharp-tailed sand pipers (*Calidris acuminata*) among others. There are some species that predominantly use the Lower Lakes (e.g. cormorants) and others such as several of the waterfowl and pelicans that are found throughout the system. Overall, more birds are generally present in the Coorong compared with the Lower Lakes (Paton et al. 2019).

The margins of the Lower Lakes and Coorong lagoons are sites of highest productivity as well as offering habitat, and are the areas where >90% of the waterbirds are active (Paton et al. 2019). Given the importance of the margins, any climate-driven changes that affect the margins will have greatest immediate effect on these birds. Water disconnection from fringing vegetation is a key threat to bird communities as reduced water levels will directly affect productivity of invertebrates, plants and fish (i.e. food resources). Current indications from observations of foraging are that food resources for herbivorous birds are not as abundant as fish resources for piscivorous fish (Paton et al. 2019). If this is the case, then herbivorous bird communities will be more immediately susceptible to alterations in water level that reduce food availability.

Mudflats are especially important for birds foraging in the Coorong, although birds do not fully exploit exposed mudflats. Overall predicted sea-level increase will lead to increased inundation of the current mudflats. New areas of inundation could theoretically be formed (subject to localised geomorphology), which will alter the current distribution of available habitat within the Coorong. Fringing vegetation is also key breeding habitat for birds such as the pied cormorants (Paton et al. 2019).

The salinity gradient in the Coorong supports different food webs and in general, the species richness declines with increasing salinity. Trend analysis has shown there were both ‘winners’ and losers’ amongst the waterbird populations during the latter part of the Millennium Drought (2000 to 2010) and after (Prowse, 2020). Where trends were significant, 16 species showed declining trends post drought (Prowse 2020). During the latter part of the Millennium Drought, salinity increased significantly in the South Lagoon and southern reaches of the North Lagoon and smallmouth hardyhead and salt-tolerant chironomids retracted from the South Lagoon. The prevailing salinity selected for large numbers of brine shrimp, which in turn supported large populations of banded stilt (*Cladorhyncus leucocephalus*) (Paton et al. 2019). The combined loss of *R. tuberosa* (as described above) and smallmouth hardyhead meant food resources were not available for herbivorous and piscivorous birds and none remained in the South Lagoon (Paton et al. 2019). These combined effects are the likely future outcome under hypersaline conditions of the South Lagoon. There are instances where loss of one food resource is replaced by animals consuming an alternative. For example, changes in salinity are thought to have contributed to the loss of *R. megacarpa* from the North Lagoon. However, in its place, the red alga (*Gracilaria chilensis*) may provide herbivorous waterfowl with an alternative food source (Paton et al. 2019).

Breeding colonies of piscivorous birds occur in the Coorong, but different species have responded differently to changes in the immediately available food resources. Changes in fish have not necessarily affected numbers of Caspian terns (*Hydroprogne caspia*) and pelicans as they travel some distance to feed. This compares with Fairy terns (*Sternula nereis)*, who have left breeding sites when fish were absent from the South Lagoon.

Given their mobility across landscapes, it is not surprising that bird populations are strongly influenced by factors beyond the CLLMM itself. For example, most of the Coorong waterfowl move to breed; this is assumed to occur in wetlands and swamps in the South East of South Australia (Paton et al. 2019). Climate changes that affect wetlands across other regions will therefore have an effect on the populations seen in the Coorong. Similarly, birds that migrate between the Coorong and northern hemisphere will be affected by climate impacts and other pressures at their breeding sites and along their flyways.

10.7 Other taxa

Salinity is a key driver of the benthic macroinvertebrate community structure in estuaries and it is commonly assumed that the salt tolerances of different macroinvertebrates will respond to climate-driven increases in salinity in estuaries (Little et al. 2017). While benthic communities have responded to salinity, salinity acted within a hierarchy of other factors that included physical aspects such as types of substratum, organic content and oxygen status, and biological factors such as competition between taxa and predator–prey relationships.

Macroinvertebrates are very important prey items for a range of consumers, particularly in the littoral zones where bird feeding is at its highest. In the Coorong, the macroinvertebrate community composition and abundance strongly reflect the salinity gradient within the system. As described above, within any given level of salinity, dissolved oxygen within sediments is an important driver. High levels of organic material stimulate microbial activity and reduce the available oxygen for benthic dwelling animals. For example, biogeochemical processes that lead to decreased oxygen in sediments will favour taxa such as Chironomidae (Dittmann et al. 2019). Changes in abundance of macroinvertebrates in response to any secondary climatic response clearly will have implications for food availability for consumers (birds, etc.). While macroinvertebrate composition is well recognised, it is not known if a change in the diversity of macroinvertebrates has any wide-ranging effect on the nutritional landscape, or nutritional quality available for consumers. Biomass of the food resource is also an important consideration and will have consequences and potential energetic costs if fewer organisms of low food value are present.

Frogs are an important component of the food web, consuming invertebrates while being prey for other consumers. They are important in the Lower Lakes and tributaries of the CLLMM. Their niche means they are involved in bioturbation and decomposition processes within sediments. Frogs rely on an appropriate water regime to inundate vegetation or equivalent forms of physical habitat to provide shelter and anchoring of eggs (Gonzalez et al. 2011). *Litoria ewingi* (a tree frog species) in particular uses the *Typha* and *Phragmites* beds as habitat and will be vulnerable to short-term loss of macrophytes (Mason and Turner, 2019). The vulnerable southern bell frog (*Litoria raniformis*) represents a further example of reductions in frog density due to reduced flows having an effect on suitable habitat for their persistence (Mason and Turner, 2019).

Current understanding suggests that climate change has already had a wide effect on amphibians in general, through a combination of loss of suitable habitat, combined with increased temperature changing breeding phenology (Lemckert and Penman, 2012).

11 Discussion

This chapter synthesises several key narratives about change it the Lower Lakes and Coorong that link together the hydrological, biogeochemical and ecological change processes reviewed above. Key uncertainties are also identified, along with some implications for strategies for managing uncertain future change.

11.1 Synthesis

The intent of this review was to provide a broad understanding of how climate change can be expected to affect hydrological, biogeochemical and ecological outcomes in the CLLMM. It drew on a wide range of literature about the dynamics of the CLLMM and on climate impacts in estuaries and wetlands in Australia and globally. The review describes the *breadth* of change processes operating in the system and the possible *magnitude* of changes for key processes where available. This information has been synthesised, below, as a series of narratives about the ecological responses to climate change in the CLLMM.

- Decreasing freshwater flows into Lake Alexandrina will have multiple effects. These include exposing submerged macrophyte beds from the littoral zones and drying littoral sediments, which are key areas of habitat and productivity, providing an important food source for birds. In addition, sulfidic sediments with the potential to generate acid will be exposed. Decreasing flows will restrict barrage flow and may also lead to reduced openness of the Murray Mouth affecting fish that require migration between freshwater and sea environments.
- Rising sea levels pose a long-term challenge for the Lower Lakes. Decisions will need to be made about either accommodating seawater inputs into Lake Alexandrina on a periodic or permanent basis; increasing freshwater inflows from the River Murray; or upgrading the barrages. Each of these would have a suite of impacts on different ecological processes across the CLLMM.
- In the South Lagoon, reduced water levels in spring have previously prevented the macrophyte *R. tuberosa*, (a keystone species), from completing its growth and reproductive cycles. During the Millennium Drought, low water levels and increased salinity combined resulted in the loss of *R. tuberosa* from the South Lagoon and with it the extensive population of smallmouth hardyhead both of which are important food resources for birds. The brine shrimp population rose dramatically in

the highly saline waters, which favoured the banded stilt. Populations of *R. tuberosa* re-established in the South Lagoon by 2016–2017, however, extensive growth of the filamentous alga *Ulva paradoxa* smothered the *Ruppia*, interrupting reproduction and preventing the formation of a seed bank necessary for sustained population growth. Growth of the *Ulva* has been attributed to increased nutrients and decreased salinity. The abundance of *Ulva* has a major impact on sediment biogeochemistry and nutrient cycling; as the *Ulva* dies large amounts of readily biodegradable carbon are deposited into the sediment, which are rapidly mineralised, contributing to the formation of anoxic sediments. The nutrients in the sediments then remain readily available for further growth of *Ulva* when salinity and temperature are favourable.

- Sea-level rise will permanently inundate currently important mudflat habitat making them unable to sustain high abundances of wading birds. It is likely that new areas of suitable habitat will establish as a result of inundation, but the extent will depend on the morphology and sediment dynamics of the various parts of the Coorong.
- The combined changes in temperature and salinity will have a direct effect on fish communities but also affect them indirectly through cascading impacts upon the entire food web. Increases in nutrients and temperature will likely select for different phytoplankton communities leading to an overall shift in phytoplankton communities, with increases in cyanobacteria, which will have a combined effect on the whole food web though decreased food quality, and potentially altered timing of predator–prey relationships.
- Research has demonstrated that both the Sir Richard Peninsula and Younghusband Peninsulas are currently advancing landward, directly affecting the Coorong system. The migration will affect vegetation within the dunes and shoreline habitats, and the species that use them. However, the rates of change are such that there is little risk to the overall integrity of the peninsulas in the foreseeable future.
- Temperature, rainfall, fire and atmospheric CO_2 will have major effects on catchments and in particular, the terrestrial vegetation, affecting habitat, and the dynamics of catchment runoff and groundwater recharge. While altered fire regimes are likely in the region, the net impacts on the Coorong are unknown.
- Resource subsidies between the freshwater ecosystems of the Lower Lakes and the estuarine ecosystems of the Coorong have been detected, further highlighting the importance of understanding the biotic linkages between the Lower Lakes and the Coorong.

From these narratives, we can conclude with a high level of confidence that:

- climate change will manifest physically in multiple ways in the CLLMM
- a wide range of ecological processes and functions are likely to be affected
- impacts vary between taxonomic groups, species and places in the CLLMM
- impacts interact with each other, positively and negatively, and with other environmental conditions
- levels of sensitivity are very high for many processes and species, so large impacts can be expected over time, with many complex details that will be impossible to predict accurately.

11.2 Knowledge gaps

While significant change is highly likely and a lot is currently known about the ecology of the CLLMM, there are likely to be many persisting uncertainties about the details of how climate change will affect the ecological dynamics and outcomes in the region. Key gaps in our current understanding (based on the literature review for this project) include:

- Understanding of how organisms such as native fish respond to factors such as temperature is important. This includes different life stages (larvae, juvenile and adult responses), all of which are expected to have different responses to temperature.
- Metabolic theory predicts that consumers will show a greater response to increased temperature than producers (O'Connor et al. 2009; Yvon-Durocher et al. 2010). This approach to modelling responses of food webs across estuaries in general may provide some unifying understanding of consequence of climate changes but has not been explored widely, particularly in the Australian context.
- Increasing temperature, altered vegetation structure and extreme events will drive changes in fire activity in catchments. Heavy rainfall after fire can move large amounts of ash, soils, metals and nutrients with significant impacts on river systems and potentially estuaries (McInerney et al. 2020). These impacts have mainly been observed to date in forested catchments; how altered fire regimes would impact the Coorong is not known, but increased fire activity followed by extreme rainfall within the tributary catchments could readily see material transported into the Lower Lakes and Coorong system affecting their biogeochemistry and ecology.
- Hypoxic blackwater events in the Lower Lakes are rare but have occurred. There is uncertainty as to the frequency of such events into the future and the extent to which hypoxic blackwater events would affect the Lower Lakes.
- There are some reports on the potential emergence of disease amongst fish as temperatures increase (Marcos-López et al. 2010), however this aspect of fish response is not well known for Australian native fish.

Research will narrow some of these and other knowledge gaps, however the nature and magnitude of many impacts and the overall outcomes from the accumulation of multiple impacts across time and space will only be revealed in detail with the passage of time as they occur or possibly in the years after they have occurred. Stakeholders and managers will need to adapt to these unpredictable changes as they are observed. Anticipating these changes can assist in the design of monitoring programs to enable rapid detection and informed decision making.

In Part 1, we presented scenarios that capture key aspects of the anticipated future changes in the Lower Lakes and Coorong that can be reasonably well characterised along with some less certain changes. These will be used to help stakeholders explore the possible impacts on valued features of the system of future climate change. This will then be used to help managers and policymakers analyse the extent to which various interventions might be effective as climate change progresses over coming decades, identifying key decision points that may need to be made in response to unfolding change and scoping targeted monitoring and research as well as community engagement that will enable support of those decisions.

List of shortened forms and glossary

Term	Long form or definition	Source
Anoxic water	Water that has low levels of dissolved oxygen	
ASS	Acid Sulfate Soil / Sediment	Fitzpatrick et al. (2008); Hall et al. (2006)
Basin	Murray–Darling Basin	
Bioturbation/bioirrigation oxygenation	The process describing burrowing organisms mixing surface layers of sediment, which leads to oxygenation and introduction of water deeper into sediments. The overall effect eliminates anoxic conditions occurring at the surface of sediment	
CLLMM	Coorong, Lower Lakes, Murray Mouth	
Driver	A physical process that is external the CLLMM and has the potential to lead to significant change of the CLLMM	
Evapoconcentration	Evapoconcentration describes the concentration of constituents (e.g. nutrients, salts etc.) within a water body, as a consequence of water evaporation	
Greatest plausible change	The greatest of the range of plausible changes that people may reasonably need to consider. A greatest plausible change scenario provides a meaningful future that the community, policy makers, managers, businesses and researchers can plan to be ready for. If they consider a pathway of adaptation needs and options along the trajectory to that scenario, they are effectively considering responses to lower-level scenarios in the context of the possibility of large impacts	Dunlop and Grigg (2019); CSIRO (2018)
HCHB	*Healthy Coorong, Healthy Basin*	
Millennium Drought	A drought which impacted the Murray–Darling Basin over the period 1996-2010, and substantially impacted the Coorong over the period 2001-2010	
MDB	Murray–Darling Basin	
Scenario	A description of the physical and ecological conditions of the Coorong or Lower Lakes at a specific point along a trajectory of change. Note: 'scenario' is sometimes used to refer to a trajectory.	This work
RCP	Representative Concentration Pathways (RCP) are the alternative scenarios of atmospheric greenhouse gas concentration used by the Intergovernmental Panel on Climate Change and the international climate modelling community	
T&I	Trials and Investigations	
Trajectory	The continuous change in the hydrological drivers of the CLLMM and the physical and ecological conditions in response to the drivers	
Turbidity	The muddiness, cloudiness or milkiness of water. Related to the amount of suspended sediment in the water	DEH (2010)

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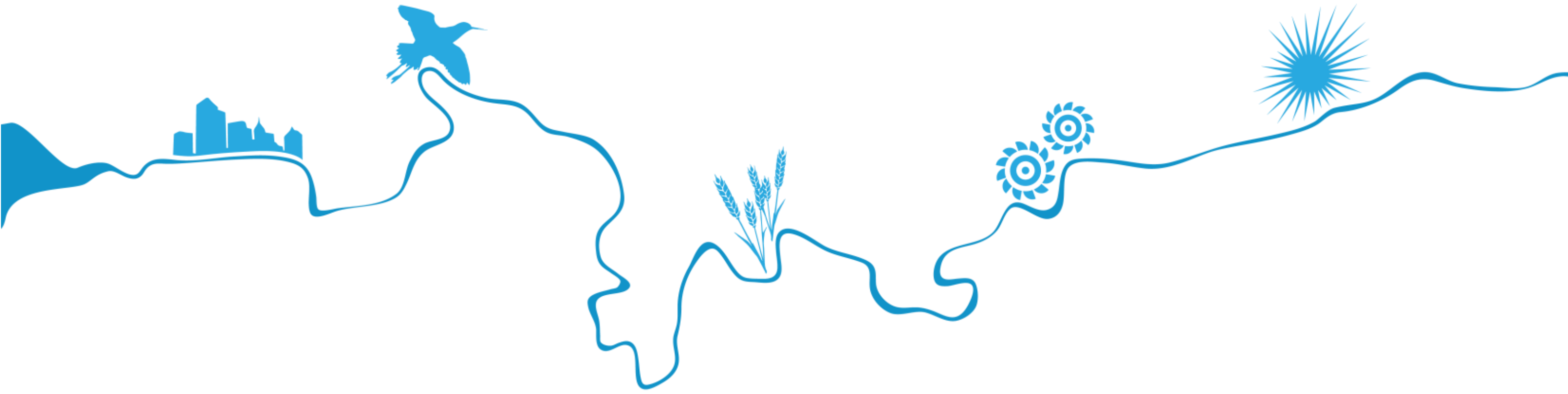

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