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Understanding and quantifying the ecological benefit of dredging the Murray Mouth

A report prepared for the South Australian Murray-Darling Basin Natural Resource Management Board

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Executive Summary

Dredging of the Murray Mouth has occurred in the Coorong since the Mouth began to close in 2003 due to low River Murray inflows. The purpose for the dredging program was to maintain the ecological condition of the Coorong, but, to date, there has been very little or no scientific evidence to evaluate whether dredging was having the desired effect. Given that dredging has continued uninterrupted for more than five years, the South Australian Murray-Darling Basin Natural Resource Management Board, commissioned this research to quantify the benefits (and any disbenefits) of the current dredging operation at the Murray Mouth.

A review of the literature on the effects of dredging on aquatic communities showed that the vast majority of dredging operations are undertaken for anthropogenic purposes (as opposed to primary environmental objectives). In addition, many of the identified impacts associated with dredging were negative, with a loss of water quality, seagrasses and benthic macroinvertebrates identified. Potentially positive impacts included increased seagrass growth in some areas, and the creation of new habitats associated with the dredged area. Should dredging continue in the Murray Mouth region, an assessment of any potentially negative impacts on aquatic macrophytes and macroinvertebrates should be undertaken so that the impact can be minimised.

Having a suite of robust indicators of ecological condition is an important part of successfully managing an ecological asset such as the Coorong. In addition to providing information regarding the baseline condition of the asset, they will also provide managers with information regarding the response of the ecosystem to specific management interventions, such as the current dredging operation. The species characteristic of each of the eight ecosystem states of the Coorong can provide an assessment of which states are present in the region at any point in time. A combination of macrophytes, fish, birds and macroinvertebrates would be the most robust indication of ecosystem state. The hydrodynamic drivers of ecosystem states, as well as other environmental variables could also be monitored to allow managers to assess the ecosystem states present, and thus the overall ecological condition of the Coorong.

In order to assess the effect of dredging of the Murray Mouth, we used a hydrodynamic model and an ecosystem state model for the Coorong in sequence to assess the likely consequences of possible future scenarios for the Coorong. The hydrodynamic model used forcing data for climate, tides, winds and flows over the barrages to provide hourly predictions of water levels and salinity along the length of the Coorong for a 20-year model run. The ecosystem state model uses these simulations together with flows over the barrages as inputs to a scheme for predicting the resultant mix of ecosystems states along the length of the Coorong.

The frequency with which dredging may be required at the Murray Mouth into the future was assessed by comparing the sequence of ecosystem states observed in the Coorong under an historic climate and median and extreme future climate projection. Under either the historic or median future climates, the current drought sequence is the only one (out of 114 years) where an intervention such as dredging would be recommended. Other dry sequences have lasted less than three years, and are likely to be within the capacity of the
ecosystem to recover without intervention. Under an extreme future climate, however, the picture is very different. Here drought sequences, or recovery lasting less than three years, occurred in half of all years, indicating that under an extreme climate change future, interventions such as dredging may be required on an ongoing and frequent basis at current levels of extraction within the Murray-Darling Basin.

The effect of the current dredging operation, when assessed for a prolonged drought situation (i.e. no barrage flows) was clear for both the hydrodynamic condition or ecosystem states of the Coorong. In the absence of dredging, no site-years within the Coorong were predicted to be in healthy ecosystem states. Water levels dropped to levels substantially lower than those observed in the past and salinity projections skyrocketed to unrealistic values in the 1000s (i.e. well outside the tolerance levels for Coorong biota). This was the case regardless of the climate investigated, various degrees of sea-level rise, or the implementation of either the Coorong South Lagoon Flow Restoration scheme (proposed by the Department of Water, Land and Biodiversity Conservation) or the South Lagoon Salinity Reduction Strategy. Thus, in the absence of barrage flows, dredging of the Murray Mouth provides a source of water to replace evaporative losses, and is likely to be preventing the ecological collapse of the region.

Changing the level of dredging undertaken made relatively little difference to the hydrodynamics of the Coorong (once the Murray Mouth reached an effective depth of approximately -1 m AHD). There was little difference in the water levels, depths, annual ranges in water level or salinity associated with dredging levels between -1 m AHD and -4 m AHD. This was not, however, the case for the ecosystem states of the Coorong. There was a continuing increase in the ecological condition of the Coorong with greater levels of dredging, with -4 m AHD having the most positive impact, and -0.5 m AHD the least. This was particularly evident in the South Lagoon, where more sites for more years were predicted to be in a healthy ecosystem state with higher levels of dredging. These findings were consistent regardless of the other interventions implemented, although the ecological condition of the Coorong increased as additional interventions were included. This apparent incongruence between the hydrodynamic and ecological findings is as a result of non-linearities in the response of ecological communities to their environments, and highlights the importance of considering both when making natural resource management decisions. The final decision regarding the most appropriate level of dredging at the Murray Mouth will need to be taken in light of engineering and budgetary constraints, but from an ecological perspective, higher levels of connectivity within the Coorong, and thus higher dredging levels, lead to better ecological condition, in times of low or no barrage flow.
1. Introduction

Reduced freshwater inflows through the Coorong barrages in the last 5 years have resulted in salinity in the South Lagoon reaching levels that have precluded the presence of a healthy ecosystem in the lagoon. In particular, salinity has exceeded the tolerance levels for survival and reproduction of most molluscs, crustacea, insect larvae, fish, and aquatic plants that comprise the food resource for the many species of waterbirds for which the Coorong is renowned. During this period of low barrage flows, the Murray Mouth has been in danger of closing, in the absence of intervention. In order to prevent this, dredging has occurred at the Murray Mouth since 2003. The expense of the on-going operation has been justified by the contention that dredging provides major ecological benefits to the Coorong, but there has been little solid scientific evidence to support this notion.

The South Australian Murray-Darling Basin Natural Resource Management Board (SA MDB NRM Board) has commissioned CSIRO and Flinders University to investigate the ecological benefit that derives from dredging the Murray Mouth. The particular focus is dredging as it is applied as an amelioration strategy during periods of low or zero barrage discharge when the Mouth tends to close up due to siltation. The level to which dredging occurs, the frequency with which dredging is likely to be required under climate change and sea-level rise, along with the effect of other interventions such as the South Lagoon Salinity Reduction Scheme (SLSRS) and the Coorong South Lagoon Flow Restoration (CSLFR) scheme (proposed by the Department of Water, Land and Biodiversity Conservation) are all relevant in the on-going decision-making process regarding the dredging effort at the Murray Mouth.

This report presents the results of analysis investigating these factors. It considers the effect of dredging in isolation, and also in combination with other proposed interventions. It considers the relative benefits of the current dredging operation, how this interacts with climate change and sea-level rise, and any interactions with the effects of other management interventions. In the first instance, the benefits are defined in terms of impacts on salinity and water level regimes and these are then assessed in terms of their ecological desirability.

The report is organised as follows: The hydrodynamic model used to simulate how salinity and water level respond to management action is described first including an evaluation of model reliability. Next, we present conceptual models of the Coorong hydrodynamics and how the benefits of management intervention can be explained, followed by a description of how the model is applied to evaluate the scenarios. We then describe the ecosystem state model that has been developed for the Coorong, including the changes that were necessary to apply it to this analysis. Next, we outline the scenarios that have been investigated as a part of this analysis, and present the results of both the hydrodynamic modelling and the ecosystem state modelling. Finally, we compare the outcomes for various scenarios and draw conclusions on the relative benefits of each.
2. Review of effects of dredging on estuarine ecosystems

Very little information was available regarding the potential positive effects of dredging on estuarine ecosystems. In the vast majority of reports and papers found, dredging was regarded as having a negative impact. This was largely due to the objectives of the dredging programs investigated. Dredging tended to be undertaken for non-environmental purposes, rather than for ecological benefit, as is the case for the Coorong. Instead, common objectives included improving navigation and to facilitate infrastructure.

In these contexts, dredging typically occurred in deep channels, often in muddy substrates, and disturbance levels on surrounding ecosystems was often high. Table 2.1 summaries some of the research findings related to the impact of dredging in these circumstances. Both physical and biotic impacts have been detected, in South Australian waters and elsewhere.

Common physical impacts have included changes in bathymetric and hydrodynamic conditions (Erftemeijer & Lewis, 2006). Changes to water quality and sediment characteristics have been noted both locally in South Australia (Cheshire & Miller, 2000) and elsewhere (Erfemeijer & Lewis, 2006). Many of the changes in sediment quality are related to the increased level of disturbance of the sediments (e.g. increased sediment plumes, release of heavy metals).

Biological impacts that were noted also tended to be negative. Studies focused on aquatic vegetation and benthic macroinvertebrates, which were most likely to be affected by dredging efforts. For both macrophytes and benthic macroinvertebrates, dredging tended to reduce species diversity and resulted in a loss of individuals (Morton, 1996; Long et al., 1996). However, other impacts also included increases in seagrass growth associated with additional nutrients from dredge spoil (Long et al., 1996), and the creation of new habitats for macroinvertebrates were created by dredging in some areas (Erftemeijer & Lewis, 2006). Overall, the level of adverse environmental impacts caused by dredging depended on factors including the quantity, method, frequency and duration of dredging and the physical dimensions of the dredging location (e.g. water depth, sediment grain-size composition) (Erftemeijer & Lewis, 2006).

Should dredging continue to be necessary in the future for the Coorong, it would be advisable to investigate the localised effects of dredging around the Murray Mouth, and the identification of ways to minimise any negative effects, particularly to aquatic macrophytes and benthic macroinvertebrates.
<table>
<thead>
<tr>
<th>Physical impacts</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical processes</td>
<td></td>
</tr>
<tr>
<td>• Changed bathymetry</td>
<td>Erftemeijer &amp; Lewis (2006)</td>
</tr>
<tr>
<td>• Altered current velocities and wave conditions</td>
<td></td>
</tr>
<tr>
<td>Water quality</td>
<td></td>
</tr>
<tr>
<td>• Increased turbidity</td>
<td>Long <em>et al.</em> (1996)</td>
</tr>
<tr>
<td>Substratum</td>
<td></td>
</tr>
<tr>
<td>• Altered sedimentation regime</td>
<td>Quigley &amp; Hall (1999); Cheshire &amp; Miller (2000); Erftemeijer &amp; Lewis (2006)</td>
</tr>
<tr>
<td>• Removal of sediment</td>
<td></td>
</tr>
<tr>
<td>• Creation of sediment plume</td>
<td></td>
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<tr>
<td>• Altered sediment particle-size distributions</td>
<td></td>
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<tr>
<td>• Oxidation of sediments</td>
<td></td>
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<tr>
<td>• Increased release of heavy metals</td>
<td></td>
</tr>
<tr>
<td>• Increased eutrophication</td>
<td></td>
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<tr>
<td>• Increased sedimentation</td>
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<tr>
<th>Biotic impacts</th>
<th>Reference</th>
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<tbody>
<tr>
<td>Benthic invertebrates</td>
<td></td>
</tr>
<tr>
<td>• Removal of individuals</td>
<td>Morton (1996); Quigley &amp; Hall (1999); Lewis <em>et al.</em> (2001); Erftemeijer &amp; Lewis (2006); Wilber <em>et al.</em> (2007)</td>
</tr>
<tr>
<td>• Shifts in the dominance and patterns of recolonisation and community structure</td>
<td></td>
</tr>
<tr>
<td>• Reduced abundance and species diversity</td>
<td></td>
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<tr>
<td>• Creation of new habitats in the dredged area, including changed slopes</td>
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</tbody>
</table>

<table>
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<tr>
<th>Macrophytes &amp; vegetation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Removal of seagrass</td>
<td>Long <em>et al.</em> (1996)</td>
</tr>
<tr>
<td>• Smothering of seagrasses</td>
<td></td>
</tr>
<tr>
<td>• Increased growth of seagrass associated with additional nutrients from dredge spoil</td>
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</tbody>
</table>

Table 2.1. Key Impacts on aquatic environments as a result of dredging
3. Hydrodynamic model

3.1 Model description

Here we provide a brief description of the hydrodynamic model applied to investigate the impacts of management intervention on water levels and salinities within the North and South Lagoons of the Coorong. The model structure, calibration and validation have been described in more detail by Webster (2007).

The base hydrodynamic model simulates water motions and water levels along the Coorong from the Mouth to the south end of the South Lagoon as these respond to the driving forces associated with water level variations in Encounter Bay (including tidal, weather band, and seasonal), the wind blowing over the water surface, barrage inflows, flows in Salt Creek (Upper Southeast Drainage Scheme; USED), and evaporation from the water surface. The model domain extends from the Mouth to the south end of the South Lagoon (~5 km past Salt Creek) and is shown in Figure 3.1 with the major inflows. This domain is divided into 102 cells each 1 km long in which a momentum equation and an equation describing conservation of mass are solved. Major channel constrictions occur at the Mouth and in the channel connecting the two lagoons past Parnka point (Parnka channel).

The depth of the Mouth is highly dynamic, increasing during times of significant outflows and tending to infill when flows are small or zero. The last 6 years have experienced very small barrage flows, so it has been necessary to maintain the Mouth in an open condition by dredging. In the model, the Mouth channel is assigned a width of 100 m and a length of 1500 m which approximate the dimensions seen in satellite imagery. Even though the bathymetry of the Mouth channel is highly complex, a single bed elevation is assigned. Infilling, scouring by barrage flows, and dredging of the Mouth channel are represented as changes in the elevation of the channel bed.

The channel connecting the two lagoons is highly complicated and convoluted. Rather than attempting to resolve the details of the channel shape, the model assumes that the section of severely-constricted channel is 100 m wide and 1000 m long, dimensions approximately...
consistent with satellite images of the region. The optimal elevation of the Parnka channel was determined to be -0.19 m AHD through calibration.

The currents, water levels, and mixing regimes simulated by the basic hydrodynamic model were used to drive a module representing the salinity dynamics. Salinity was modelled in the 14 cells shown in Figure 3.2 which extend across groups of cells used in the base hydrodynamic model. The salinity module solves equations for the conservation of the mass of salt in each cell and requires the prescription of the salinity of sea water and of the USED scheme. The salinity of the sea in Encounter Bay was set at 36.7 g L\(^{-1}\) and that of the USED to be 16.1 g L\(^{-1}\). The latter is the calculated flow-weighted average of salinity in the Salt Creek discharge between 2001 and 2008.

![Figure 3.2. Map of the Coorong showing boundaries of cells used in the salinity module.](image)

### 3.2 Calibration

Calibration of the model required the specification of the continuously changing elevation of the bed of the Mouth channel and of four fixed parameters. For its calibration, the elevation of the bed of the Mouth channel is continuously adjusted to achieve the best fit between modelled and measured diurnal water level variations measured at Tauwitchere.
barrage. The time series of bed elevations of the Mouth channel obtained in this way for the calibration run is shown in Figure 3.3. Prior to 2001, one can see the annual cycle of Mouth deepening that results from barrage flows followed by Mouth infilling when barrage flows were small or zero. Note that Mouth flow in the figure is the calculated flow in through the Mouth and is effectively the negative of the barrage flow (i.e. flow tends to occur out of the mouth). Dredging commenced in the Murray Mouth region in October 2002, and one can see the gradual decrease in Mouth elevations after that time. Annual variations in elevations result from seasonal variation in the dredging effort. One can also see that the Mouth elevation approaches 0 m AHD following the periods of low flow in 1997-1998 and in 2001-2002.

Figure 3.3 Mouth elevations and Mouth flows

The first fixed calibration parameter in the hydrodynamic model is a factor applied to the wind stress estimated from wind measurements made at Meningie on the southeastern side of Lake Albert. This factor was adjusted so that the modelled water level spectra at Tauwitchere and at Sand Spit Point matched the measured spectra. The optimal factor is 1.6. Wind measurements at the Post Office in Meningie were made twice a day so the value of the factor (above 1.0) is due to a number of reasons including the inability of the wind record to account for gustiness and the separation and terrain differences between Meningie and the Coorong. The second parameter is an evaporation correction factor applied to measured evaporation rates from a Class A pan on Hindmarsh Island. The factor used in modelling has a value of 1.0. The third factor is the horizontal coefficient of mixing for the two lagoons (61 m² s⁻¹) and the fourth is the effective elevation of the bed of the Parnka channel (-0.19 m AHD). Parameters 2, 3, and 4 were adjusted to obtain the optimal fit using a least-squares approach between measured and modelled salinities in the North and South Lagoons and between measured and modelled water levels at Sand Spit Point in the South Lagoon. The calibration data used for salinity were obtained at 12 sites along...
both lagoons on 35 occasions by the SA EPA and DEH between 1997 and 2005. The calibration parameters all differ to some extent from the parameters reported by Webster (2007) in an earlier calibration of the model. The differences are due to several factors including a difference in how the effect of wind stress is represented in the model, the addition of two more years of calibration measurements, and differences in the assumed value of the salinities of the sea and of the USED.

### 3.3 Model uncertainty and validity

All models are imperfect representations of reality. It is necessary to know how credible hydrodynamic model simulations are and particularly how well they are able to represent variation in the system in response to changes in the drivers. An analysis of hydrodynamic model capability for simulating salinity and water level, but the main results are summarised here. In addition to the salinity data used for calibration, there have been additional data obtained by various researchers for the periods 1963-1967, 1976-1979, 1981-1985, 1993, and 2005-2007 that can be used to check the model response to conditions that are quite different from those encountered during the calibration period. In particular, barrage flows prior to 2002 tended to be substantially larger than those after this time.

When modelled and measured salinity values are plotted against one another for sections of each lagoon, the slope of the linear regression is ~0.9 for both the calibration and non-calibration periods. Average modelled salinity and measured salinity differ from one another by an average of 2 g L\(^{-1}\) in the North Lagoon and by less than 1 g L\(^{-1}\) in the South Lagoon. There is scatter around these regressions, which represents the limitation of the model’s ability to simulate the instantaneous salinity at a particular sample collection site. The root mean square (RMS) differences between modelled and measured salinity are 16 and 11 g L\(^{-1}\) in the North and South Lagoons, respectively. We have attributed much of this scatter to the incongruity of comparing salinities in cells that are effectively averaged along 5-10 km along the Coorong and across its width of several kilometres with spot measurements that are mostly obtained at the shore. There are certain to be heterogeneities in the salinity structure that are introduced by local evaporation or water input or by swirls in the current that are not resolved by the model. Other errors in the model are certain to be introduced through inaccuracies in prescribing the wind stress, barrage inflows, bathymetry, evaporation rates, and by the neglect of groundwater inputs and losses that are unknown. Structural simplifications in the model will lead to further error including the simplified bathymetry and the assumption of constant mixing coefficients.

The model does well in simulating both the weather-band response (less than 10 day period) and the longer-term seasonal fluctuations in both lagoons. Due to limitations in the form of the meteorological data available, the response of the system to wind fluctuations having periods less than a day is not represented in the model, but for longer periods the measured and modelled level variances differ by 10% or less. Overall, the model does a credible job of simulating the response of the system in both salinity and in water level. The model is capable of explaining ~90% of salinity changes in the system in a statistically-averaged sense, but it should be recognised that an individual modelled salinity value is
expected to differ from a measurement due to a number of reasons, but that the bias of the modelled salinity is close to zero.

### 3.4 The implementation of management scenarios

#### 3.4.1 Conceptual basis of scenario effectiveness

In this report, we examine the impact on the Coorong of the degree of dredging which is represented as the elevation to which the Mouth channel is dredged. In several scenarios, dredging is undertaken in combination with other management actions including augmentation of discharges through channel diversions in the South East (CSLFR scheme) and excavation of the channel connecting the North and South Lagoons. The conceptual basis of why these interventions should improve the condition of the Coorong is provided in the reports Lester et al. (2009b & c), but is summarised here.

The Coorong is an inverse estuary; that is, its salinity tends to increase away from its Mouth. The conceptual model which underlies this estuary type is illustrated in Figure 3.4.

**Figure 3.4 Conceptual model of the Coorong**

Water is lost from along the length of the estuary through evaporation. To maintain the water level within the estuary, sea water flows in from the estuary mouth (Figure 3.4 top). The salt that is carried with the sea water tends to accumulate within the estuary. Back-and-forth water motions (oscillatory flows) within the estuary arise due to sea-level variations including the tides as well as seiching due to varying winds blowing over the water surface. These motions serve to mix the salt accumulating within the estuary back towards its mouth (long-channel mixing). Over the long term, the inflow of salt associated with evaporated water loss balances the transport of salt in the opposite direction due to oscillatory mixing. Super-imposed on this model of long-term salt transport within the Coorong are seasonal variations associated with the annual cycle of sea-level variation and

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of evaporation (and precipitation) rate, but fundamentally this underlying salt balance pertains on an average basis.

Dredging of the Mouth channel facilitates the transmission of sea-level variations into the Coorong which enhance long-channel mixing within the system. Excavation of the channel near Parnka Point as a part of the SLSRS allows for increased water exchange and mixing between the two lagoons. Increasing the flow from the Upper South East via the CSLFR reduces the flow required from the sea necessary to replace the evaporative loss so less salt is drawn into the system from the sea. Pumping water from the South Lagoon as a part of the SLSRS removes salt directly from the South Lagoon. A flow through the Mouth is required to compensate, but the salinity of this flow (sea water) is much less than that in the South Lagoon so pumping removes much more salt than flows in. All of these interventions tend to increase the effectiveness for removing salt from the Coorong and so tend to result in a lower salinity.

### 3.5 Model application

The hydrodynamic model was run for 39 scenarios. These scenarios involved combinations of different degrees of Mouth dredging, two modelled USED drainage flows, two climate scenarios, three sea-level rises, and the option of imposing a South Lagoon Salinity Reduction Strategy (SLSRS) (see section 5 for details). Dredging in the model is specified as the elevation of the bed of the Mouth channel. The maximum Mouth elevation tested was 0 m AHD, which effectively means no dredging. The minimum elevation (maximum dredging) was -4.0 m AHD. The present level of dredging effort in the Coorong results in an effective bed elevation of ~-2.0 m AHD as represented by the model (Figure 3.3).

Two time series of USED flows were used in the scenarios. What will be termed the baseline USED inflow is the average of measured flows on each day of the year between 2001 and 2008. This scenario is used to represent the present discharge from the USED even though it is recognised that in the period 2001-2008 there was a very large amount of variability in the measured Salt Creek flows. In addition, as part of the project investigating the effectiveness of diversion works in the South East (the CSLRS) a series of possible USED flows were modelled and their impacts on the Coorong assessed (Lester et al., 2009b). We have chosen to use a derivative of this analysis to assess the effect of future South East diversions. The CSLFR scenario for South East flows represents an average of the modelled flow paths 1D, 1WC, 2D, 2WC and 3 using historic climate and a 250 ML day\(^{-1}\) maximum channel capacity. This scenario is referred to as the composite 250 Historic scenario in Lester et al. (2009b). The Baseline and CSLFR flow scenarios are compared in Figure 3.5. The CSLFR scenario has an average annual discharge of 107 ML day\(^{-1}\) versus 19 ML day\(^{-1}\) for the Baseline scenario.
CSIRO and the Bureau of Meteorology developed climate change projections for Australia that estimated changes in meteorological parameters as a result of climate change (Pearce et al., 2007). Temperature, evapotranspiration, rainfall, wind speed, relative humidity, and solar radiation all changed to some degree. For the median future climate projected for 2030, the temperature is expected to increase by 0.8 °C for the Coorong region. We have calculated that a temperature increase of this size by itself would increase the evaporation rate in the Coorong by 7%. Most of the scenarios were run using the current climate, but several of them were run under conditions of the 2030 median climate with an evaporation rate increased by the factor 1.07.

Sea-level rises resulting from climate change were included in some scenarios. Although most scenarios were simulated with no sea-level rise, rises of 0.2 and 0.4 m were also considered. For the latter scenarios, the Mouth bed elevation was assumed to rise with the sea-level change. This assumption is based on the observation that the Mouth channel has been highly dynamic continuously tending to fill in the absence of barrage flows. However, in the simulations, sea-level rise does cause an equal increase in the depths of all Coorong channels (except for the Mouth channel), including the depth of the channel at Parnka Point connecting the two lagoons.

The barrage flows in all scenarios were set to zero. Basically, the intention of the analysis is to investigate the effectiveness of dredging in the absence of barrage flows such as has occurred over the last five years. The model developed simulations for the period 1/7/1982 to 31/12/2008. The USED flow scenarios provided by DWLBC commenced on 1 January 1986 and the results of the simulations were analysed from this date. The extra 3.5 years of

Figure 3.5. Comparison between the two the USED discharge time series used in the analysis
run-time at the beginning was used to allow the model to settle down, but it required that the USED flows (for the CSLFRS case) be extended forward in time. The first section of the CSLFRS time series was simply a copy of the flows from 1/7/1986 to 31/12/1989. The model is forced with measured wind speeds, sea-levels, evaporation and precipitation up to the end of the run.

Several of the scenario runs involved the imposition of the South Lagoon Salinity Reduction Strategy (SLSRS) which involved pumping brine from the middle of the South Lagoon to the sea. As it is represented in the model, the pumping commenced at the beginning of the model run and terminated 3.5 years later on 1/1/1986. The pumping rate was set to 150 ML day$^{-1}$. Where this scenario was undertaken, the channel at Parnka Point was excavated to a bed elevation of -0.4 m AHD compared to its assigned elevation of -0.19 m for all the other scenario simulations.
4. Ecosystem states model

4.1 Developing an ecosystem states model for the Coorong

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

Unlike the hydrodynamic model described above, the ecosystem states model is not based on a deterministic understanding of how ecosystems behave. That is, it is not based on equations describing the interactions between each species, their environments, and their competitors and predators, amongst other components. Instead, it is a statistical model, where existing data for the region has been statistically analysed and modelled to identify associations and relationships between the biota that occur within the system at any one point in time and the environmental conditions under which these biota occur.

The ecosystem state model developed for the Coorong under CLLAMMecology identified eight distinct ecosystem states. These could be divided into two ‘basins’, a marine basin and a hypersaline basin that are most often located within the North and South Lagoons respectively. Within each, there were four states, ranging from a healthy state to a degraded state. The biota and conditions characterizing each of these states are given in Appendix A. Additional information regarding the development and testing of the model is given in Lester and Fairweather (2009 a, b) available on the CSIRO website.

One of the key driving parameters for the ecosystem model described in Appendix A was the occurrence of freshwater flows over the barrages. This meant that only limited changes in ecological conditions could be modelled unless such flows were present. Given that the scenarios investigated here are designed to be alternatives to having freshwater flows in the short term, we developed a new set of models to describe the behaviour of the system without reference to the flows over the barrages.

In order to do this, we maintained the eight ecosystem states identified for the Coorong, and related them to the salinities, water levels, depths and meteorological conditions in the Coorong. The best results were obtained when the two basins were modelled separately. The model for the marine basin (assumed to occur in the North Lagoon under the current conditions) is shown in Figure 4.1a. It describes the ecosystem state of the Coorong relative to the water level, the previous year’s water level and depth from two years ago. This model correctly classified 72% of the training data set used and 70% of the test data set, indicating that it discriminated well between the marine ecosystem states.
Figure 4.1 Ecosystem state models for the Coorong excluding flow parameters as predictive variables.

a) Marine (or northern) basin, b) Hypersaline (or southern) basin

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This figure above presents logic trees which can be followed to identify the ecosystem state for a given location and time in the Coorong. Each white box contains a splitting parameter and a threshold value. Where the value for the parameter is less than or equal to the threshold value, then the tree should be followed to the left. Where it is higher, the tree should be followed to the right. When a grey terminal node box is reached, the state has been identified.

The hypersaline basin model (used to describe current South Lagoon states) identified a combination of average water level, water level from the previous year, the range in water levels over the year (i.e. change between the maximum and minimum water level over the year) and the maximum salinity for the year as driving the ecosystem state of the basin (Figure 4.1b). The hypersaline basin model correctly classified 87% of the training data set and 80% of the test data set under cross-validation. This is a high degree of predictive success given the variability inherent in ecological data sets.

All of the parameters identified as driving the ecosystem states of the Coorong can be calculated from output from the hydrodynamic model. The hydrodynamic model simulates hourly water levels and salinities along the length of the Coorong for each scenario. These data are then used to calculate the average water levels, depths and salinities as required by the ecosystem response models (i.e. Figure 4.1). By using these parameters as input for the ecosystem response model, we are able to predict the mixture of ecosystem states present in the Coorong each year for the duration of the model run at each of the 14 salinity cells, which we have referred to as ‘sites’. Each site can potentially support a different state in each subsequent year, so results have been presented by site, by year, which we refer to as ‘site-years’.

The major area of uncertainty inherent in the ecosystem response model is in its ability to correctly predict the recovery of the system. The model was developed using data from 1999 to 2007, which was a particularly dry period, and one during which the ecological condition of the Coorong was deteriorating. Therefore, the model behaves as though the trajectory of decline is the same as the trajectory of recovery and that both occur over the same length of time. This is unlikely to be true, and represents a major uncertainty of the model but, until data describing the recovery of the system are available, there is no way to quantify the scale of the uncertainty. Should any change in the dredging program undertaken at the Murray Mouth occur, any data collected after that change could be used to refine the model to address this uncertainty about recovery trajectories.

### 4.2 Defining criteria for ecological assessment

The marine and hypersaline basin models of ecosystem states were used to identify parameters that would provide guidance about the ecological condition of the southern North Lagoon and the South Lagoon. These were used to assess the scenarios investigated within this report. Maximum salinity in the South Lagoon, depth in the North Lagoon and average water levels in both lagoons, were selected as being most likely to identify scenarios that would have the greatest impact on the ecological condition of the Coorong.

A detailed assessment of the ecological impact was also undertaken for each scenario. This was done by identifying the ecosystem states present over time, using the ecosystem state models described above, and investigating the proportion of site-years classified in each of the eight ecosystem states and the proportion that are in states considered to be degraded.
(that is, have been without barrage flows for more than 339 days). This allowed the interaction between the various parameters and the non-linearities inherent in the ecosystem’s response to be fully addressed, and for scenarios to be objectively compared.
5. Research objectives and scenarios

5.1 Research objectives

This research was designed to address three main objectives regarding the ecological impact of the current dredging operation at the Murray Mouth.

These objectives were to:
1. identify the key ecological indicators of a productive, healthy Coorong;
2. quantify the ecological benefit of the current dredging operation at the Murray Mouth; and
3. investigate if any incremental ecological benefits could be obtained by altering the current dredging operation.

The second and third research objectives could be further divided into more specific research questions. For the second research objective, we addressed the following questions:

a. How often does the Coorong require dredging at the Murray Mouth?

b. How does climate change influence the effect of the current dredging operation on Coorong ecosystems?

c. How do other interventions interact with dredging to affect Coorong ecosystems? and

d. How will sea-level rise impact on the effect of the current dredging operation on Coorong ecosystems?

The third research objective could also be divided into several more-specific research questions. These were:

a. What is the impact of changing the dredging level at the Murray Mouth?

b. What is the impact of changing the dredging level at the Murray Mouth after salinities in the South Lagoon have been reset? and

c. What is the impact of changing the dredging level at the Murray Mouth after salinities in the South Lagoon have been reset and additional fresh water provided from the South East?

5.2 Scenarios

The second and third research question involved the use of scenario analyses to gain an understanding of hydrodynamic and ecological responses of the Coorong to changes in climate, management interventions other than dredging and the level of dredging undertaken. These are outlined below, and summarised in Table 5.1.

5.2.1 Quantifying the ecological benefit of the current dredging operation

In order to address Research Question 2 (i.e. quantify the ecological benefit of the current dredging operation at the Murray Mouth), we used a two-stage process. Firstly, we used scenarios developed for CLLAMM Futures investigating the likely effects of climate change
over 114 years (Lester et al. 2009a) to understand how often dredging of the Murray Mouth was likely to be necessary.

The scenarios included were:

1. **Benchmark conditions (hereafter called ‘Baseline’)**
   
   This scenario included historic climate conditions, no interventions (including dredging), average daily discharge as per 2001-2008 for the USED scheme and actual flows over the barrages for a 114-year model run.

2. **Median climate change with current extraction levels (‘Median Future’)**
   
   This scenario included a median 2030 clim (MDB SY Scenario C\(_{\text{mid}}\)), current levels of extraction from the Basin, and average inflows from the USED scheme. This scenario did not include dredging of the Murray Mouth.

3. **Future climate change with current extraction levels (‘Extreme Future’)**
   
   This scenario included an extreme 2030 clim (MDB SY Scenario C\(_{\text{dry}}\)), current levels of extraction from the Basin, and average inflows from the USED scheme. This scenario did not include dredging of the Murray Mouth.

In order to assess the benefits of the current dredging operation in dry periods, a series of 12 scenarios were analysed. These scenarios were grouped into sets according to the more-specific question being addressed. They are defined as follows:

**Scenarios investigating the influence of the current dredging effort:**

4. **Historic Dredging**
   
   This scenario included a historic climate, with 1986 to present extended dry (no barrage flows) conditions and the intervention of dredging.

5. **Historic No dredging**
   
   This scenario also included a historic climate, 1986 to present extended dry (no barrage flows) conditions, but without the intervention of dredging.

6. **Median dredging**
   
   This scenario included a medium projection of 2030 clim, 1986 to present extended dry (no barrage flows) conditions and the intervention of dredging.

7. **Median No Dredging**
   
   This scenario included a medium projection of 2030 clim, 1986 to present extended dry (no barrage flows) conditions, but without dredging.
Scenarios investigating the influence of the current dredging effort after the SL Reset:

8. Historic, SL Reset Dredging
   This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions, the SLSRS intervention (i.e. pumping of water out of the South Lagoon and dredging Parnka Channel to -0.4 m AHD) and current dredging efforts.

9. Historic, SL Reset No dredging
   This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions, the SLSRS intervention and no dredging.

Scenarios investigating the influence of the current dredging effort after the SL Reset and including the CSLFR:

10. Historic CSLFR Dredging
    This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions and dredging with the average flow from the three possible flow options in the CSLFR intervention.

11. Historic No CSLFR Dredging
    This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions, without dredging and with the average flow from the three possible flow options in the CSLFR intervention.

Scenarios investigating the sea-level rise impact on the effect of the current dredging effort:

12. Median Dredging +20 cm SLR
    This scenario included median climate with +20 cm sea-level rise, with 1986 to present extended dry (no barrage flows) conditions and dredging.

13. Median No dredging +20 cm SLR
    This scenario included median climate with +20 cm sea-level rise, with 1986 to present extended dry (no barrage flows) conditions, and without dredging.

14. Median Dredging +40 cm SLR
    This scenario included median climate with +40 cm sea-level rise, with 1986 to present extended dry (no barrage flows) conditions and dredging.

15. Median No dredging +40 cm SLR
    This scenario included median climate with +40 cm sea-level rise, with 1986 to present extended dry (no barrage flows) conditions, and without dredging.
5.2.2 *Investigating the effect of changes to the dredging depth at the Murray Mouth*

When assessing the effect of changing the depth of dredging at the Murray Mouth on the ecosystems of the Coorong, we also grouped scenarios into sets according to the more-specific questions being addressed. The scenarios are defined as follows:

Scenarios investigating the effect of changing the dredging depth:

Note: this comparison also uses the Historic No Dredging scenario, defined previously.

16. Dredging -0.5 m
   
   This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions and dredging to -0.5 m AHD at the Murray Mouth.

17. Dredging -1 m
   
   This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions and dredging to -1 m AHD at the Murray Mouth.

18. Dredging -1.5 m
   
   This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions and dredging to -1.5 m AHD at the Murray Mouth.

19. Dredging -2 m
   
   This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions and dredging to -2 m AHD at the Murray Mouth.

20. Dredging -2.5 m
   
   This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions and dredging to -2.5 m AHD at the Murray Mouth.

21. Dredging -3 m
   
   This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions and dredging to -3 m AHD at the Murray Mouth.

22. Dredging -3.5 m
   
   This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions and dredging to -3.5 m AHD at the Murray Mouth.

23. Dredging -4 m
   
   This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions and dredging to -4 m AHD at the Murray Mouth.
Scenarios investigating changing the dredging depth with the SL Reset:

24. SL Reset Dredging -0.5 m

This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions and dredging to -0.5 m AHD at the Murray Mouth with the addition of the SLSRS intervention.

25. SL Reset Dredging -1 m

This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions and dredging to -1 m AHD at the Murray Mouth with the addition of the SLSRS intervention.

26. SL Reset Dredging -1.5 m

This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions and dredging to -1.5 m AHD at the Murray Mouth with the addition of the SLSRS intervention.

27. SL Reset Dredging -2 m

This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions and dredging to -2 m AHD at the Murray Mouth with the addition of the SLSRS intervention.

28. SL Reset Dredging -2.5 m

This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions and dredging to -2.5 m AHD at the Murray Mouth with the addition of the SLSRS intervention.

29. SL Reset Dredging -3 m

This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions and dredging to -3 m AHD at the Murray Mouth with the addition of the SLSRS intervention.

30. SL Reset Dredging -3.5 m

This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions and dredging to -3.5 m AHD at the Murray Mouth with the addition of the SLSRS intervention.

31. SL Reset Dredging -4 m

This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions and dredging to -4 m AHD at the Murray Mouth with the addition of the SLSRS intervention.
Scenarios investigating changing the dredging depth with SLSRS intervention and including the average volume which could be available from the three possible flow paths in the CSLFR intervention:

32. SL Reset CSLFR Dredging -0.5 m

This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions and dredging to -0.5 m AHD at the Murray Mouth with the addition of the SLSRS intervention and with the average flow from the three possible flow options in the CSLFR intervention.

33. SL Reset CSLFR Dredging -1 m

This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions and dredging to -1 m AHD at the Murray Mouth with the addition of the SLSRS intervention and with the average flow from the three possible flow options in the CSLFR intervention.

34. SL Reset CSLFR Dredging -1.5 m

This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions and dredging to -1.5 m AHD at the Murray Mouth with the addition of the SLSRS intervention and with the average flow from the three possible flow options in the CSLFR intervention.

35. SL Reset CSLFR Dredging -2 m

This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions and dredging to -2 m AHD at the Murray Mouth with the addition of the SLSRS intervention and with the average flow from the three possible flow options in the CSLFR intervention.

36. SL Reset CSLFR Dredging -2.5 m

This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions and dredging to -2.5 m AHD at the Murray Mouth with the addition of the SLSRS intervention and with the average flow from the three possible flow options in the CSLFR intervention.

37. SL Reset CSLFR Dredging -3 m

This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions and dredging to -3 m AHD at the Murray Mouth with the addition of the SLSRS intervention and with the average flow from the three possible flow options in the CSLFR intervention.
38. SL Reset CSLFR Dredging -3.5 m

This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions and dredging to -3.5 m AHD at the Murray Mouth with the addition of the SLSRS intervention and with the average flow from the three possible flow options in the CSLFR intervention.

39. SL Reset CSLFR Dredging -4 m

This scenario included historic climate, with 1986 to present extended dry (no barrage flows) conditions and dredging to -4 m AHD at the Murray Mouth with the addition of the SLSRS intervention and with the average flow from the three possible flow options in the CSLFR intervention.
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Table 5.1. Summary of scenarios investigated in this report
Table 5.1. Summary of scenarios investigated in this report cont.

Note: ‘+’ denotes present in the scenario and ‘-’ indicates none or not present in the scenario.
6. Research Objective 1: Key ecological indicators of a productive healthy Coorong

This section presents the results, discussion and conclusions for the first research question. That is: what are the key ecological indicators of a productive healthy Coorong? The section is based on the definitions of the ecosystem states of the Coorong, as described in Lester and Fairweather (2009b). Key ecological indicators are provided for each identified states, based on the species that typify each state, and those that distinguish between each state (Tables 6.1 and 6.2). A mixture of fish, birds, macroinvertebrates and aquatic macrophytes have been included as potential taxa to provide the greatest flexibility in structuring monitoring efforts. In addition, we have also included ranges for a number of important environmental characteristics, including those that distinguish between the ecosystem states and those that are likely to be routinely monitored.

Key biological indicators for each ecosystem state are presented in Tables 6.1 and 6.2. The key macrophyte for the Coorong is *Ruppia tuberosa*, particularly for hypersaline basin ecosystem states (i.e. Healthy, Average, Unhealthy and Degraded Hypersaline). In the past, *Ruppia megacarpa* and seagrasses such as *Zostera* spp. were also indicators of marine ecosystem states (i.e. potentially Estuarine/Marine, Marine, Unhealthy and Degraded Marine), but these macrophytes have not been found for some years in the Coorong (Geddes & Francis 2008). Periodic surveillance monitoring of regions where these macrophytes have occurred in the past during recovery phases of the Coorong would be advisable to ensure that any recolonisation was detected.

Several fish species are good indicators of the ecosystem state of the Coorong, and many are commercially-fished, limiting the need for specific biological (fishery-independent) surveys. Estuarine and marine species such as mulloway *Argyrosomus japonicus*, bony *Nematolosa erebi* and black bream *Acanthopagrus butcheri* and bronze whaler sharks *Carcharhinus brachyurus* are typical of some marine basin states. Australian salmon *Arripis truttaceus* and sandy sprat *Hyperlophus vittatus* are also important species, as is the salinity-tolerant species, the yellow-eyed mullet *Aldrichetta forsteri*. In the hypersaline basin, the small-bodied and schooling small-mouthed hardyhead *Atherinasoma microstoma* is the key fish indicator of ecosystem state. This species is, however, not fished commercially and targeted biological surveys would be required to monitor its presence and abundance in the Coorong.

Many of the bird indicators of marine ecosystem states tended to be fishing birds or waterfowl. Cormorants *Phalacrocorax* spp., Australian white ibis *Threskiornis molucca*, hoary-headed grebe *Poliophalus poliocephalus* and whiskered tern *Chlidonias hybridus* were the key piscivorous bird species. Duck species of interest included Australian shelduck *Tadorna tadornoides*, musk duck *Biziura lobata*, Pacific black duck *Anas superciliosa* and grey teal *Anas gracilis*. The black swan *Cygnus atratus* was another waterfowl indicative of ecosystem states. Two wader species were also key indicators of marine ecosystem states; curlew sandpiper *Calidris ferruginea* and banded stilt *Cladorhynchus leucocephalus*, with the later indicative of
the Degraded Marine state. For the hypersaline-basin states, waterfowl and waders made up the majority of bird indicators. Grey teal *Anas gracilis* and chestnut teal *Anas castanea*, along with Australian shelduck and black swan were the waterfowl indicative of hypersaline states. Species of waders that characterised hypersaline ecosystem states included red-necked avocet *Recurvirostra novaehollandiae*, red-necked stilt *Calidris ruficollis* and banded stilt. Masked lapwing *Vanellus miles* and silver gull *Larus novaehollandiae* were also characteristic of the Degraded Hypersaline state.

Several invertebrate groups have been identified as indicators of the various marine-basin ecosystem states. Amphipods, the bivalve *Arthritica helmsi* and polychaete worms such as *Simplisetia aequisetis*, *Nephtys australiensis* and *Capitella* spp. are all characteristic of one or more of the three healthiest marine-basin states. The Degraded Marine state was characterised by only chironomid larvae. For the hypersaline basin, juvenile insects and amphipods characterised the healthier ecosystem states, while chironomid larvae were the only indicators of more-degraded hypersaline states.

Environmental indicators of ecosystem state are largely determined by the ecosystem state model, which identifies the physico-chemical drivers of each state. These include the average daily tidal range, the maximum number of days without any flow over the barrages, the average annual water level, the average annual water depth from the previous year, and the average annual salinity (refer to Appendix A). The alternative ecosystem state model can also be used to identify environmental indicators of ecosystem state, particularly during interventions designed to replace barrage flows (including dredging of the Murray Mouth). These models are presented in Figure 4.1, and the indicators of ecosystem state include the average annual water level for the current and previous year, depth from two years previous, range in annual water level (i.e. the maximum water level for the year minus the minimum water level for the year), and the maximum salinity for the year.

In addition to these environmental drivers of ecosystem state, other environmental variables can also be used as indicators of the current state of the Coorong. These are presented in Table 6.3 and include variables describing the flow, water quantity and water quality characteristics of the Coorong. Typical values for each of the ecosystem states are presented at an annual time-step. Combinations of the variables can provide indicators for the current ecosystem state. For example, very high salinity with very low phosphate concentrations may be indicative of the Degraded Hypersaline state, while high turbidity, high nitrate concentration and high chlorophyll b concentrations, in conjunction with moderate salinity levels, may be indicative of the Healthy Hypersaline state.
### Table 6.1. Biological characteristics of each ecosystem state (marine-basin states)

<table>
<thead>
<tr>
<th></th>
<th>Estuarine/Marine</th>
<th>Marine</th>
<th>Unhealthy Marine</th>
<th>Degraded Marine</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Macrophytes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Ruppia tuberosa</em></td>
<td>-</td>
<td></td>
<td><em>Ruppia tuberosa</em></td>
<td>ND</td>
</tr>
<tr>
<td><em>Ruppia megacarpa</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Zostera sp.</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fishes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>yellow-eyed mullet</td>
<td>Australian salmon</td>
<td>yellow-eye mullet</td>
<td>small-mouthed</td>
<td></td>
</tr>
<tr>
<td>mulloway</td>
<td>bronze whaler shark</td>
<td>bony bream</td>
<td>hardyhead</td>
<td></td>
</tr>
<tr>
<td>Australian salmon</td>
<td>black bream</td>
<td>Australian salmon</td>
<td>yellow-eyed mullet</td>
<td></td>
</tr>
<tr>
<td>bony bream</td>
<td></td>
<td></td>
<td>sandy sprat</td>
<td></td>
</tr>
<tr>
<td><strong>Birds</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cormorant spp.</td>
<td>musk duck</td>
<td>cormorant spp.</td>
<td>whiskered tern</td>
<td></td>
</tr>
<tr>
<td>Australian white ibis</td>
<td>Pacific black duck</td>
<td>hoary-headed grebe</td>
<td>red-necked stint</td>
<td></td>
</tr>
<tr>
<td>Australian shelduck</td>
<td></td>
<td>curlew sandpiper</td>
<td>banded stilt</td>
<td></td>
</tr>
<tr>
<td>curlew sandpiper</td>
<td></td>
<td>black swan</td>
<td>grey teal</td>
<td></td>
</tr>
<tr>
<td><strong>Macroinvertebrates</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>amphipod spp.</td>
<td>amphipod spp.</td>
<td>Capitella spp.</td>
<td>chironomid larvae</td>
<td></td>
</tr>
<tr>
<td><em>Simplisetia aequisetis</em></td>
<td></td>
<td>Capitella spp.</td>
<td><em>Simplisetia aequisetis</em></td>
<td></td>
</tr>
<tr>
<td><em>Capitella spp.</em></td>
<td><em>Nephtys australiensis</em></td>
<td>Arthritica helmsi</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*While the data used did not show the presence of the macrophyte and vegetation species, historical evidence indicates that this is an important species. ND = indicates that no data was available for that particular group for that state and '-' indicates that no species from that taxonomic group were identified as characterising that ecosystem state.*
Table 6.2. Biological characteristics of each ecosystem state (Hypersaline States)

<table>
<thead>
<tr>
<th>Ecosystem State</th>
<th>Healthy Hypersaline</th>
<th>Average Hypersaline</th>
<th>Unhealthy Hypersaline</th>
<th>Degraded Hypersaline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macrophytes</td>
<td><em>Ruppia tuberosa</em></td>
<td><em>Ruppia tuberosa</em></td>
<td><em>Ruppia tuberosa</em></td>
<td>ND</td>
</tr>
<tr>
<td>Fishes</td>
<td>ND</td>
<td>ND</td>
<td>small-mouthed hardyhead</td>
<td>small-mouthed hardyhead</td>
</tr>
<tr>
<td>Birds</td>
<td>grey teal</td>
<td>banded stilt</td>
<td>banded stilt</td>
<td>banded stilt</td>
</tr>
<tr>
<td></td>
<td>black swan</td>
<td>red-necked stint</td>
<td>hoary-headed grebe</td>
<td>red-necked stilt</td>
</tr>
<tr>
<td></td>
<td>chestnut teal</td>
<td>red-necked avocet</td>
<td>Australian shelduck</td>
<td>silver gull</td>
</tr>
<tr>
<td></td>
<td>red-necked avocet</td>
<td>grey teal</td>
<td>red-necked avocet</td>
<td>masked lapwing</td>
</tr>
<tr>
<td>Macroinvertebrates</td>
<td>juvenile insects</td>
<td>amphipod spp.</td>
<td>chironomid larvae</td>
<td>ND</td>
</tr>
<tr>
<td></td>
<td>(ex. chironomids)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*While the data used did not show the presence of the macrophyte and vegetation species, historical evidence indicates that this is an important species. ND = indicates that no data was available for that particular group for that state and ‘-’ indicates that no species from that taxonomic group were identified as characterising that ecosystem state.
Table 6.3. Environmental characteristics of each ecosystem state

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estuarine/Marine</th>
<th>Marine</th>
<th>Unhealthy Marine</th>
<th>Degraded Marine</th>
<th>Healthy Hypersaline</th>
<th>Average Hypersaline</th>
<th>Unhealthy Hypersaline</th>
<th>Degraded Hypersaline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum number of days since flow over the barrages (days)</td>
<td>127</td>
<td>376</td>
<td>376</td>
<td>376</td>
<td>NA</td>
<td>152</td>
<td>376</td>
<td>557</td>
</tr>
<tr>
<td>Water quantity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Annual tidal range (m)</td>
<td>1.1</td>
<td>0.9</td>
<td>1.1</td>
<td>0.7</td>
<td>0.4</td>
<td>1.1</td>
<td>1.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Average water level (m AHD)</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
<td>0.4</td>
<td>0.2</td>
<td>0.1</td>
<td>-0.3</td>
</tr>
<tr>
<td>Average depth (m)</td>
<td>1.6</td>
<td>2.4</td>
<td>1.3</td>
<td>0.9</td>
<td>1.4</td>
<td>1.3</td>
<td>1.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Water quality</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum salinity (g L⁻¹)</td>
<td>57.6</td>
<td>48.1</td>
<td>61.6</td>
<td>88.2</td>
<td>139.3</td>
<td>123.3</td>
<td>176.5</td>
<td>203.8</td>
</tr>
<tr>
<td>Average turbidity (NTU)</td>
<td>14.6</td>
<td>1.7</td>
<td>11.1</td>
<td>35.0</td>
<td>22.0</td>
<td>17.6</td>
<td>23.5</td>
<td>14.8</td>
</tr>
<tr>
<td>Average [total phosphate] (mg L⁻¹)</td>
<td>0.14</td>
<td>0.05</td>
<td>0.12</td>
<td>0.35</td>
<td>0.29</td>
<td>0.27</td>
<td>0.50</td>
<td>0.59</td>
</tr>
<tr>
<td>Average [TKN] (mg L⁻¹)</td>
<td>1.9</td>
<td>0.6</td>
<td>1.2</td>
<td>6.6</td>
<td>8.4</td>
<td>5.6</td>
<td>6.9</td>
<td>5.6</td>
</tr>
<tr>
<td>Average [Chlorophyll b] (µg L⁻¹)</td>
<td>2.4</td>
<td>0.5</td>
<td>2.3</td>
<td>4.2</td>
<td>16.0</td>
<td>10.4</td>
<td>7.1</td>
<td>2.8</td>
</tr>
</tbody>
</table>

NA = indicates that no data was available for that particular group for that state. TKN stands for Total Kjeldahl Nitrogen, the sum of organic nitrogen, ammonia, and ammonium.
6.1 Discussion of outcomes and conclusions

Having robust indicators of ecological condition is an important part of successful management of ecological assets including the Coorong. Here, we have based our selection of indicators on the characteristic taxa for each ecosystem state and the environmental conditions under which each occurs. This provides managers with a suite of species and environmental variables that can be monitored to ensure that ecological conditions meet the targets set for the region.

In identifying the key biotic indicators of the various ecosystem states, it should be stated that the presence of one or more of these indicators on its own is not diagnostic of a single ecosystem state. The combinations of species and, in particular, absence of species characteristic of healthier ecosystem states may tend to point to a degraded system. Higher abundances of several of the key indicators, particularly across the range of fish, birds, invertebrates and aquatic vegetation would also be another good indication of a particular ecosystem state. Also, the species that are identified are not necessarily the most abundant and are certainly not the only species that occur within each of the ecosystem states. The selection of species was based on the similarity of biota among site-years that supported the state in question, so species that drove this similarity were selected (even if they were not the most abundant). Additional information regarding relative abundances of each indicator species can be found in Lester and Fairweather (2009b). Finally, environmental conditions corresponding to the ecosystem state in question would also corroborate the identification of a given state.

The suite of indicators identified applies whether the Coorong is in good ecological condition or in poor ecological condition. By monitoring, for example, the bird populations, the relative mix of species will provide an idea of what that ecological condition is, based on the species mix and abundances of indicator species. The suite of species for the more-degraded states is not intended to be used as a replacement set in times of poor ecological condition, reverting back to a ‘healthy’ set of indicators when flow return. Instead, the relative health of the Coorong is the outcome derived from monitoring the indicators identified here. Environmental indicators such as nutrient concentrations, for example, would be likely to be monitored whatever the condition of the Coorong, and the relative levels would provide pointers to where on the continuum of ecosystem health the system was currently sitting.

Listing potentially important species to be detected is only the first step in indicator development. It would require some further effort to develop a full indicator system (i.e. including, for each indicator, providing a clear protocol for measurement and routine monitoring, mathematical calculations for deriving an index, agreed decision rules around critical index values, and a report card) that is outside the scope of this report.
7. Research Objective 2a: How often does the Murray Mouth need to be dredged?

In order to assess Research Objective 2 (i.e. what are the ecological benefits of the current dredging operation at the Murray Mouth?), we investigated the hydrodynamics and ecosystem states arising in the Coorong over a long sequence of years under three contrasting climate scenarios. These were the historic climatic record, a median future climate projection and an extreme future climate projection (i.e. historic, median and extreme, consistent with the above definitions).

The scenarios that are presented for this research question differ from those presented for the following sections (i.e. Sections 8 and 9). In those sections, all scenarios were presented for a 20-year model run at 14 sites that were approximately evenly spaced along the Coorong. Here, in order to determine how often dry periods occur we have included scenarios that were originally run for the CLLAMMecology Research Cluster (Lester & Fairweather 2009b, Lester et al. 2009a) that extend for 114 years. The reason for this was to provide a direct point of comparison between the work presented here and that of CLLAMMecology, which includes 17 other scenarios (most of which also have 114-year model runs) that may be of interest (Lester et al. 2009a).

The sites that are presented here are the 12 focal sites used within CLLAMMecology (Lester et al. 2009a). Again, this provides a direct point of comparison. Here the first three sites are in the vicinity of the Murray Mouth, with the next 6 in the North Lagoon, and the last 3 sites in the South Lagoon. Note that these are not evenly distributed throughout the system, so there will be a greater proportion of site-years allocated to marine-basin states. These scenarios were also assessed with the original CLLAMM Futures ecosystem state model, which is described in Lester and Fairweather (2009b), again for consistency with the other long-term scenarios investigated.

It is important to note that while the scenarios run for 114 years, they do not represent a sequence of evolving climate conditions. The entire model run is intended to give an idea of the variability inherent in a particular climate projection. For example, the Median Future climate scenario represents 114 years at a median 2030 future climate, rather than a progression from a current climate to a median future climate over the 114 years. This is due to limitations in the ability of climate models to predict how climate change will actually develop (Chiew et al. 2008).

7.1 Hydrodynamic results

Climate change has the potential to dramatically affect the hydrodynamic drivers of ecosystem states within the Coorong (Figure 7.1). Climate change reduces barrage flows and increases evaporation rates from the Coorong Lagoons. Both salinity and the maximum number of days without flow over the barrages will be affected substantially.
The median predictions for a 2030 climate (Median Future scenario) showed an increase in the median number of days without flow over the barrages relative to the Baseline scenario (186 compared to 135 days, respectively; Figure 7.1). Median salinity was similar between the Baseline and Median Future scenarios (35.5 and 40.4 g L\(^{-1}\), respectively), but the range of values increased from 203 to 273 g L\(^{-1}\) under the Median Future climate. This included salinity predictions of up to 275 g L\(^{-1}\) in the South Lagoon of the Coorong under the Median Future climate.

**Figure 7.1. Boxplots showing the comparison between variables driving the ecosystem states of the Coorong for the climate change scenarios (114 years)**

- a) Water levels (m AHD), b) water depths from the previous year (m), c) salinities (g L\(^{-1}\)), d) Maximum number of days since flow (MaxDSF, days) and e) tidal range (m)
- Information on how to read the figure is presented in Appendix B.

While this may seem extreme, it pales in comparison to predictions made under an extreme 2030 climate at current extraction levels (Extreme Future). Under this scenario, the maximum number of days without flows over the barrages ballooned to 2778 days, with a median value of 320 days (or almost 11 months). Median salinity increased to 59.5 g L\(^{-1}\) and the maximum modelled salinity for the Extreme Future scenario was an unrealistic 460.7 g L\(^{-1}\). It should be noted that salinity starts to have a pronounced effect on evaporation rate (i.e. it reduces it) and on the volumetric behaviour of the brine once salinity exceeds ~200 g L\(^{-1}\) and these effects are not accommodated within the model. Thus very high salinities simulated by the model should be taken to be indicative only. While the exact concentration may not...
be able to be predicted, we are confident that it will be very high, and outside the tolerance limits for the vast majority of taxa in the region (Lester et al. 2008).

These results indicate that as climate change becomes more severe, there will be more dry periods in which intervention is required by the Coorong. This intervention is likely to include dredging the Murray Mouth.

### 7.2 Ecological results

Complementing the differences observed in the hydrodynamic results, there were clear differences in the mix of ecosystem states as a result of climate change, both in the North and South Lagoons (Figure 7.2). There was an increase in the proportion of site-years predicted to be in states considered degraded with increasingly extreme climate change scenarios (6% for the Baseline scenario, 11% under a Median Future scenario and 46% for the Extreme Future scenario).

![Figure 7.2. Comparing the proportion of site-years in each ecosystem state for the climate change scenarios (114 years)](image)

*Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DH = Degraded Hypersaline.*

See Appendix B for information on how to read the figure.
This increase in the proportion of degraded site-years was seen in both the North and South Lagoons with increasing numbers of site-years classified as Marine, Unhealthy Marine and Degraded Marine (particularly for the Extreme Future scenario).

However, based on these results, it is difficult to determine how often dry periods occur, so we have included figures illustrating the sequence of states for each site-year under the three possible future climate scenarios.

Under an historic climate, the vast majority of years were classified as Estuarine/Marine in the North Lagoon or Average Hypersaline in the South Lagoon (Figure 7.3). There were occasional years where this status quo is interrupted, with wet years resulting in South Lagoon sites being classified as Healthy Hypersaline. Dry periods occur around a decade into the simulation, again at around year 20 and then near year 50. The final dry period, at the end of the simulation, represents the current drought, and was the most severe observed. With the exception of this last dry period, all other dry spells were short-lived (i.e. 2 years or less) and were likely to fall within the ability of the Coorong ecosystems to recover naturally.

A runs analysis indicated that changes in state were more common further south in the system. In the Murray Mouth region, 7.0 changes in state occurred, on average, across the sites, with states remaining stable for an average of 21.3 years. In the North Lagoon, states remained stable for an average of 16.6 years, with 13.5 transitions on average per site. In the South Lagoon, this increased to 30.3 transitions per site, with states only remaining stable for 4.6 years at a time.

![Figure 7.3. Distribution of states for each site-year under the Baseline 114-year scenario](image)

Figure 7.3. Distribution of states for each site-year under the Baseline 114-year scenario

Each dot shows the distribution of the states within each site across the 114-year model run. The changes in the dot colours represent the transitions between states. For each dot, colours represent the following states: dark blue = Estuarine/Marine, light blue = Marine, light green = Unhealthy Marine, dark green = Degraded Marine, yellow = Healthy Hypersaline, orange = Average Hypersaline, red = Unhealthy Hypersaline and purple = Degraded Hypersaline. See Appendix B for additional information on how to read the figure.
When the distribution of states for each site-year was mapped for the Median Future climate, there was relatively little change from the Baseline scenario (Figure 7.4). Some additional dry periods were evident, but again, these lasted for relatively short periods of time (i.e. less than 3 years), with the exception of the final dry period at the end of the model run.

Runs analysis showed a slight increase in the average number of transitions per site, compared to the Baseline scenario. In the Murray Mouth region, sites changed state an average of 13.0 times, with each state remaining stable for an average of 10.7 years. In the North Lagoon, the number of transitions increased to 18.8 per site, with states remaining stable for 9.0 years. The pattern in the South Lagoon was similar to that observed under the Baseline scenario, with an average of 29.7 transitions per site, and states remaining stable for 4.8 years on average.

Figure 7.4. Distribution of states for each site-year under the Median Future 114-year scenario

Each dot shows the distribution of the states within each site across the 114-year model run. The changes in the dot colours represent the transitions between states. For each dot, colours represent the following states: dark blue = Estuarine/Marine, light blue = Marine, light green = Unhealthy Marine, dark green = Degraded Marine, yellow = Healthy Hypersaline, orange =Average Hypersaline, red = Unhealthy Hypersaline and purple = Degraded Hypersaline.

The picture is rather different under an extreme future climate projection. Here, the recent drought at the end of the model no longer stood out as the most-severe drought in the sequence. Instead, there were six other periods that appeared as dry or worse (Figure 7.5). This suggests that intervention such as dredging of the Murray Mouth would be required in the Coorong for approximately half of all years.

Runs analysis supports this conclusion, with increased numbers of transitions per site, and a shorter time over which states remain stable. In the Murray Mouth, states were stable for 4.8 years, on average with 20.3 transitions per site over the 114 years. In the Murray Mouth, there were 35.2 transitions per site, with states remaining stable for 3.7 years, on average, and in the South Lagoon, states were also stable for 3.7 years, with 28.0 transitions per site.
Figure 7.5. Distribution of states for each site-year under the Extreme Future 114-year scenario

Each dot shows the distribution of the states within each site across the 114-year model run. The changes in the dot colours represent the transitions between states. For each dot, colours represent the following states: dark blue = Estuarine/Marine, light blue = Marine, light green = Unhealthy Marine, dark green = Degraded Marine, yellow = Healthy Hypersaline, orange = Average Hypersaline, red = Unhealthy Hypersaline and purple = Degraded Hypersaline.

7.3 Discussion of outcomes and conclusions

How often dredging of the Murray Mouth is likely to be required to support the Coorong ecosystem is not a straightforward question to answer. Estuarine ecosystems are traditionally quite resilient, and have adapted to changing environmental conditions, including occasional dry and very dry years. It is likely that the majority of species would persist for short droughts, making the investment associated with having dredging equipment on standby unnecessary if droughts are short (e.g. less than three years in duration, as an arbitrary cut-off point). It is only when dry years begin to accumulate into extended droughts that ecological resilience is unlikely to allow ecosystem states to recover without management intervention.

Under an historic climate, the present drought is the only one that is of a duration long enough to make Murray Mouth dredging necessary. This is also true of a median future climate projection. Under the median future climate, there were additional drought years evident in the mix of ecosystem states, but these remained of short duration. There is an additional risk to ecological health associated with frequent changes in ecosystem state. As conditions fluctuate more often between healthy and degraded, the biota become more vulnerable to chance events, potentially leading to local extinctions (for example, see Beissinger, 1995).

An extreme future climate, however, sees extended drought conditions in approximately half of all years modelled. This assessment includes years where dry conditions extend for more than two years, and those where recovery has commenced, but occurs for two years or less, which is unlikely to be sufficient...
recovery time from a severe drought (Lake 2000). This indicates that dredging would be required on a regular and ongoing basis.

In summary, dredging of the Murray Mouth is unlikely to be required by the Coorong on a regular basis under either historic or median future climates, because the current drought was the only one severe enough to result in a closed Murray Mouth for an extended period under either scenario, thereby warranting the investment. Under an extreme future climate, however, the intervention would be required in approximately half of all years. Current climate science also suggests that the current meteorological conditions are as, or more, severe than most climate projections had forecast, so planning for an extreme future climate may well be prudent.

The next step in assessing the ecological benefits of dredging the Murray Mouth is to investigate the benefits of the current dredging program, and any incremental improvements associated with altering the scale of the dredging effort in dry periods when dredging would be deemed necessary. The next sections of the report focus on these questions.
8. Research Objective 2b-d: Ecological benefits of the current dredging operation at the Murray Mouth

The remaining questions under research objective 2 (i.e. how does climate change influence the effect of dredging on the Coorong ecosystems; what is the interaction between dredging and other interventions; and how will sea-level rise impact on the effects of dredging?) were investigated using scenarios simulating a prolonged drought in the Coorong. This was in order to assess the maximum ecological benefit of the current dredging operation, in the absence of barrage flows, as is currently the case. The hydrodynamic and ecological results are presented, and then a discussion of the outcomes follows, where we draw conclusions as to the benefit of the current operation.

8.1 Hydrodynamic results

Figure 8.1 shows an example of the results of the hydrodynamic simulations for scenarios representing dredging of the Mouth channel to elevations of -1, -2, and -4 m AHD. The time series shown are for average salinity in the South Lagoon and were obtained using a historic climate and represent scenarios 17, 19, and 23 (Table 5.1).

![Figure 8.1. Average modelled salinity in the South Lagoon for dredging to Mouth bed elevations of -1, -2, and -4 m (scenarios 17, 19, and 23).](image)

The benefits of increasing the depth of dredging are clearly seen. Decreasing the dredged elevation of the bed from -1 m to -2 m results in a decrease of South Lagoon salinities by ~60 gL⁻¹. A further decrease in the bed elevation to -4 m decreases the salinity by a further ~20 gL⁻¹. Decreases in the salinity in the North Lagoon associated with increased dredging are more modest, but are still significant. The results for
both lagoons show that the relative benefits of increased dredging diminish markedly as the dredged depth increases.

8.1.1 Benefits under climate change

There was a dramatic difference between the hydrodynamic variables for those scenarios with dredging compared to those with no dredging (Figure 8.2). Median maximum salinities were substantially lower where dredging was implemented under both historic and median climate conditions, at 105.7 g L$^{-1}$ and 117.6 g L$^{-1}$, respectively, compared to those with no dredging. The median depth from two years previous was greater under the dredging scenarios for both climatic conditions, compared to without dredging under the same climate (Figure 8.2). Median water levels were also higher under both dredging scenarios, compared to those without dredging, at positive levels between 0.15 and 0.17 m AHD. Median annual ranges under dredging scenarios were also higher with the implementation of dredging compared to no dredging, at approximately 0.95 and 0.72 m, respectively.
Figure 8.2. Boxplots comparing hydrodynamic variables driving the ecosystem states of the Coorong for the effect of dredging under climate change scenarios

a) Maximum salinity (g L\(^{-1}\))

b) Water depths from two years previous (m)

c) Water levels (m AHD)

d) Annual changes in water levels (m)

Note: Hist Dredge = Historic Dredging, H No Dredge = Historic No dredging, Med Dredge = Median Dredging, M No Dredging = Median No dredging.

Compared to the Historic Dredging scenario (with an historic climate, no barrage flows and dredging to -2 m AHD), the effect of climate change was insignificant compared with the effect of dredging (Figure 8.3). The vector showing the Median Dredging scenario was indistinguishable from the origin, while the Historic, No dredging and Median, No dredging scenarios represented a large deterioration in both water levels and depths in the North Lagoon. A similar pattern was obvious for the South Lagoon, with the Historic, No dredging and Median, No dredging scenarios showing a deterioration in both salinity and water levels, while the Median Dredging scenario was not visible over the origin (Figure 8.4).
Figure 8.3. Comparison of the effect of dredging under climate change scenarios relative to the Historic Dredging scenario for the North Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Historic Dredging scenario with respect to water levels and depths (with depths from two years previously). Length of each vector is proportional to the strength of the deviation from the Historic Dredging condition (as shown by the 0,0 origin). Vectors in the upper-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and greater depths).

See Appendix B for additional information on how to read the figure.
Figure 8.4. Comparison of the effect of dredging under climate change scenarios relative to the Historic Dredging scenario for the South Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Historic Dredging scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Historic Dredging condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and lower salinities).

See Appendix B for additional information on how to read the figure.

8.1.2 Benefits in conjunction with other interventions

The use of dredging resulted in substantially different hydrodynamic variables compared with no dredging, either as a sole strategy or in conjunction with other interventions (Figure 8.5). Median maximum salinities were lower for scenarios with the use of dredging compared to those with no dredging (Figure 8.5). Of the dredging scenarios, the median maximum salinity was lowest at 73.9 g L\(^{-1}\) under dredging and the provision of additional water from the South East (using the CSLFR intervention) and highest at 105.7 g L\(^{-1}\) under Historic Dredging conditions. Median depth from two years previous was higher under dredging conditions, all approximately at 1.32 m, compared to those scenarios without dredging, at between
0.95 and 1.12 m. Median water levels were also greater under the combination of dredging and other interventions scenarios compared with the negative median water levels of those with no dredging. The greatest median water level at 0.19 m AHD was observed when dredging and resetting South Lagoon salinities (via the SLSRS) were implemented together or with dredging combined with the CSLFR scheme and Historic Dredging, both at approximately 0.19 m AHD. Finally, median annual ranges were also greater under dredging scenarios compared to those with no dredging, with the combination of other interventions all between 0.89 and 0.97 m.

Figure 8.5. Boxplots comparing hydrodynamic variables driving the ecosystem states of the Coorong for the effect of dredging with other interventions

a) Maximum salinity (g L\(^{-1}\))
b) water depths from two years previous (m),
c) water levels (m AHD) and
d) annual changes in water levels (m)

Note: Hist Dredge = Historic Dredging, H No Dredge = Historic No dredging, H SLSRS D = Historic SLSRS Dredging, H SLSRS ND = Historic SLSRS No dredging, H D CSLFR = Historic Dredging CSLFR, H ND CSLFR = Historic No dredging CSLFR
Again, the effect of dredging dwarfed that of any other intervention, when compared with the Historic Dredging scenario. In the North Lagoon, no scenarios involving dredging were distinguishable from the origin, indicating that they resulted in very similar water levels and depths to the Historic Dredging scenario (at least in comparison to the scenarios without dredging) (Figure 8.6). When no dredging was undertaken, the Historic CSLFR No dredging scenario was closest to the Historic Dredging scenario, although this was still a deterioration in both water levels and depths. The Historic SL Reset No dredging scenario resulted in the largest negative change in water levels and depths in the North Lagoon.

**Figure 8.6. Comparison of the effect of dredging with other interventions relative to the Historic Dredging scenario for the North Lagoon**

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Historic Dredging scenario with respect to water levels and depths (with depths from two years previously). Length of each vector is proportional to the strength of the deviation from the Historic Dredging condition (as shown by the 0,0 origin). Vectors in the upper-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and greater depths).
In the South Lagoon, a slightly different picture emerged. Again, there was very little difference between scenarios involving other interventions in combination with dredging compared to the Historic Dredging scenario (Figure 8.7). However, in the absence of dredging, various interventions had slightly different impacts on salinities and water levels in the South Lagoon. Resetting South Lagoon salinities via the SLSRS reduced salinities and resulted in some improvement in water levels. Enhancing the USED scheme to include additional water from the South East improved salinities to a slightly greater degree, but had more impact on the water levels, relative to the situation observed under the Historic, No dredging scenario.

**Figure 8.7. Comparison of the effect of dredging with other interventions relative to the Historic Dredging scenario for the South Lagoon**

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Historic Dredging scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Historic Dredging condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and lower salinities).
8.1.3 **Benefits under sea-level rise**

Those scenarios with the use of dredging showed positive trends in the hydrodynamic variables compared to those with no dredging under different sea-level rise conditions (Figure 8.8). Median maximum salinities were much lower with dredging under all of the sea-level rise scenarios, between 85.7 g L$^{-1}$ and 117.6 g L$^{-1}$, compared to those greater than 600 g L$^{-1}$ without dredging. Median depth from two years previous was greater with dredging compared to those scenarios without dredging under sea-level rise (Figure 8.8). Median depth from two years previous was greatest under a historic climate with dredging and +40 cm sea-level rise, at 1.73 m, then 1.53 m and 1.31 m for dredging +20 cm sea-level rise and Median Dredging conditions, respectively. Median water level showed a positive increasing trend between scenarios with dredging under sea-level rise, compared to those without dredging (Figure 8.7). Median annual range was also greater with dredging under sea-level rise, between 0.87 and 0.96 m, compared to those without dredging, between 0.72 and 0.74 m.
Figure 8.8. Boxplots comparing hydrodynamic variables driving the ecosystem states of the Coorong for the effect of dredging under sea-level rise scenarios

- Maximum salinity (g L⁻¹)
- Water depths from two years previous (m)
- Water levels (m AHD)
- Annual changes in water levels (m)

Note: Med Dredge = Median Dredging, M No Dredge = Median No dredging, MD +20 SLR = Median Dredging +20cm sea level rise, MND +20 SLR = Median No dredging +20cm sea level rise, MD + 40 SLR = Median Dredging +40cm sea level rise, MND +40 SLR = Median No dredging +40cm sea level rise.

In the absence of dredging, different levels of sea-level rise did not affect water levels or depths in the North Lagoon, relative to the Historic Dredging scenario (Figure 8.9). Either an increase of +20 or +40 cm SLR resulted in a slight deterioration in both variables. When dredging was implemented, sea-level rise resulted in an improvement in both the water levels and depths in the North Lagoon, compared to the Historic Dredging or the Median Future scenarios. Water levels in the South Lagoon were also positively affected by sea-level rise and dredging (Figure 8.10). There was, however, very little change in salinities in the South Lagoon compared with either the Historic Dredging or Median Future scenarios.
Figure 8.9. Comparison of the effect of dredging under sea-level rise scenarios relative to the Historic Dredging scenario for the North Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Historic Dredging scenario with respect to water levels and depths (with depths from two years previously). Length of each vector is proportional to the strength of the deviation from the Historic Dredging condition (as shown by the 0,0 origin). Vectors in the upper-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and greater depths).
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8.2 Ecological results

This section evaluates each scenario relative to the Historic Dredging scenario and then relative to the other options explored. These comparisons have been based on the ecological response models developed, and the physico-chemical targets set by expert opinion. Results have been presented to include the years between 1988 and 2007. Thus, the ecological results begin two years after the hydrodynamic results (which start in 1986) to allow the inclusion of the depth from two years previous, as appears in the ecosystem state model. The scenarios are grouped according to the research questions outlined above, as was done for the hydrodynamic results.
Figure 8.11 shows the distribution of ecosystem states at each focal site for each year of the model simulation that uses historic climate and current water extraction rules, with dredging at the current level (i.e. the Historic Dredging scenario). It is presented as an example of the spatio-temporal output from the ecosystem state model and is used to illustrate features of the ecological response of the Coorong to environmental drivers over the two decades.

Over the 21-year model run, three of the eight identified ecosystem states were present. The majority of site-years were either in the Estuarine/Marine state or the Degraded Hypersaline state. There were occasional departures from this typical condition for one or two years at a time, with North Lagoon sites occasionally changing to the Unhealthy Marine state and South Lagoons sites switching into the Average Hypersaline states. In addition, the first site in the South Lagoon was routinely in the Average Hypersaline state, rather than the Degraded Hypersaline state like the other South Lagoon site-years.

![Figure 8.11. Distribution of states for each site-year under the Historic Dredging scenario](image)

Each bar shows the distribution of the states within each site across the 21-year model run. The changes in the bar colours represent the transitions between states. For each bar, colours represent the following states: dark blue = Estuarine/Marine, light blue = Marine, light green = Unhealthy Marine, dark green = Degraded Marine, yellow = Healthy Hypersaline, orange = Average Hypersaline, red = Unhealthy Hypersaline and purple = Degraded Hypersaline.

### 8.2.1 Benefits under climate change

As has been demonstrated by work undertaken during CLLAMM Futures (Lester et al. 2009a) and in other reports since (Lester et al. 2009b,c), climate change has the potential to alter the mix of ecosystem states present in the Coorong (Figure 8.12). The biggest change with a moderate projection of future climate was in the proportion of site-years predicted to be in degraded states, particularly in the South Lagoon (i.e. the proportion of site-years predicted to be Degraded Hypersaline).
However, the scale of this change is relatively small compared to the effect of dredging under a prolonged drought scenario. Under the same historic climate conditions, the implementation of dredging resulted in a greater proportion of site-years in the healthy, Estuarine/Marine (45%), compared to that without dredging which had no site-years in the Estuarine/Marine state. In the absence of dredging, the North Lagoon was predicted to consist of site-years in the Unhealthy Marine (7%) and Degraded Marine states (43%). In the South Lagoon, in the absence of dredging, all South Lagoon site-years were predicted to be in the Degraded Hypersaline state (50%).

Under the Median climate scenarios, dredging represented the difference between some site-years predicted to be in healthy states, and none. The Estuarine/Marine state accounted for 38% of site-years, compared to 0% in the absence of dredging (i.e. Median, No dredging compared with Median Dredging). The remaining North Lagoon sites-years (12%) under the Median Dredging scenario were predicted to be Unhealthy Marine. In the South Lagoon, as for the Historic Dredging scenario, the Median Dredging scenario resulted in a mix of Average Hypersaline (4%) and Degraded Hypersaline (46%) site-years. The Median No dredging scenario resulted in all South Lagoon site-years predicted to be in the Degraded Hypersaline state (50%).
Figure 8.12. Comparing the proportion of site-years in each ecosystem state for the climate change scenarios

Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DH = Degraded Hypersaline.

8.2.2 Benefits in conjunction with other interventions

As was apparent for the climate change scenario, the absence of dredging, under prolonged drought conditions, resulted in 100% of site-years predicted to be in degraded states (Figure 8.13). This was the case regardless of any other interventions being implemented and was true in both the North and South Lagoons. When dredging was used in conjunction with the other interventions, significantly greater proportions of the site-years were predicted to be healthy ecosystem states. This was most evident in the South Lagoon. When combined with dredging, the SLSRS resulted in 36% of site-years classified as Average Hypersaline, with the remaining 14% classified as Degraded Hypersaline. The CSLFR scheme, when combined with dredging, resulted in even more site-years being classified as Average Hypersaline (43%). Again, the remaining South Lagoon site-years (8%) were classified as Degraded Hypersaline.

There was less change in North Lagoon site-years when dredging was combined with other interventions. The SLSRS resulted in identical predictions for the North Lagoon, compared with the Historic Dredging scenario (35% of site-years in the
Estuarine/Marine state and 15% in the Unhealthy Marine state). There was a small shift associated with the combination of dredging and the CSLFR scheme, with 37% of site-years in the Estuarine/Marine state.

Figure 8.13. Comparing the proportion of site-years in each ecosystem state for the other intervention scenarios
Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DH = Degraded Hypersaline.

8.2.3 Benefits under sea-level rise
As was the case for the previous scenarios, in the absence of dredging, all site-years were predicted to be in degraded states, despite any effect of sea-level rise (Figure 8.14). For all sea-level rise scenarios, in the absence of dredging, the South Lagoon site-years were predicted to be mostly in the Degraded Hypersaline state (47%), with the remaining 3% of site-years in the Unhealthy Hypersaline state. In the North Lagoon, there was a little more variability. The Median, No dredging scenario resulted in 49% of site-years classified as Degraded Marine, with the remaining 1% as Unhealthy Marine. When +20 cm SLR was incorporated, the proportion of Unhealthy Marine site-years rose to 5%. This was also the case with +40 cm SLR. When dredging was implemented, however, there were benefits associated with sea-level rise for the Coorong, in both the North and South Lagoons. Under the
Median Dredging scenario, 34% of site-years were classified as Estuarine/Marine, with the remaining 16% of site-years (in the North Lagoon) classified as Unhealthy Marine. When +20 or +40 cm SLR was modelled, in conjunction with dredging, all North Lagoon site-years (50%) were classified as Estuarine/Marine.

In the South Lagoon, 4% of site-years were classified as Average Hypersaline, with the remaining 46% classified as Degraded Hypersaline. When +20 cm of sea-level rise was modelled, including dredging, the proportion of Degraded Hypersaline site-years dropped to 4%, being replaced by a combination of Healthy Hypersaline (28%), Average Hypersaline (6%) and Unhealthy Hypersaline (13%) site-years. When the sea-level rise was increased to +40 cm, all South Lagoon site-years were classified as Healthy Hypersaline.

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**Figure 8.14. Comparing the proportion of site-years in each ecosystem state for the sea-level rise scenarios**

Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DH = Degraded Hypersaline.

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### 8.3 **Discussion of outcomes and conclusions**

A very simple message emerged from the comparison of the hydrodynamic and ecological effects of dredging under a prolonged drought (i.e. no barrage flows). This was that there dredging was playing a critical role in supporting the hydrodynamic
and ecological condition of the Coorong in the absence of barrages flows, but providing a source of water (albeit marine water, rather than fresh water) and a pathway for mixing salt out of the Coorong. Of the alternative interventions investigated (SLSRS and CSLFR), none was a viable alternative to dredging to support the ecosystem states of the Coorong.

Under a prolonged drought, in the absence of dredging, no scenario investigated showed any site-years in healthy ecosystem states. This was the case under the historic or median future climate projection, and with the effect of sea-level rise considered. The connection to a source of water and the opportunity to mix salt out of the Coorong was critical. Without this, salinities sky-rocketed and water levels fell dramatically, as evaporation became the main driver of water level in the system. Under these circumstances, Coorong ecosystems would survive very little time and the system would likely collapse.

Dredging at the current level, then, during the current drought does provide significant ecological benefits to the Coorong. The majority of studies reviewed (see Section 2) focused on dredging operations that were undertaken for anthropogenic reasons (such as improved navigation), so the majority of effects we seen as negative. This situation may be unique, however, where dredging is undertaken specifically to enhance ecological values of an asset, and is delivering these ecological benefits.

That is not to say that there are no negative effects of dredging. It is likely that the absence of seagrasses in the Murray Mouth region is partly as a result of dredging, with increased disturbance of sediments often cited as a reason for seagrass loss (for example, see Long et al. 1996). The potential disbenefits of dredging, however, are more than out-weighted by the substantial benefit demonstrated by this scenario analysis.

Of the other interventions investigated, the CSLFR scheme had a larger effect on the hydrodynamics and ecosystem states of the Coorong. This is due to its ongoing nature, compared to the short-term interventions via the SLSRS. The model runs used here simulate a 20-year period without any barrage flows. Under these conditions, an intervention that continues over time is always likely to have a greater impact than a short-term intervention. However, it is extremely unlikely that a drought would last such a long time in the Coorong, so the benefits associated with the SLSRS should not be discounted on this basis.

Sea-level had some possibly unexpected benefits for the ecosystem states of the Coorong. This was first highlighted during the CLLAMMecology scenario analyses (see Lester et al. 2009a). Sea-level rise, assuming that the Murray Mouth remains the only connection to the ocean, increases the level of connectivity between the two Coorong lagoons, and improves the ecosystem states of the South Lagoon, by limiting the amount of time that the lagoons are hydrologically disconnected from one another each year. However, again, this effect is not observed in the absence of both barrage flows and dredging.
9. Research Objective 3: Ecological benefits of altered dredging depth

A two-stage process was used to assess whether any changes should be made to the current level of dredging. Eight scenarios were investigated to assess the effect of dredging at a range of levels, beginning with no dredging and increasing in -0.5 m increments to the maximum -4 m AHD. These were then repeated including the effect of the SLSRS and the combined effect of the SLSRS and CSLFR scheme. An investigation of the effects of the various levels of dredging was made for the hydrodynamic variables associated with each of these scenarios.

A more detailed assessment was then made for a selection of these scenarios. The no dredging scenario, along with a low, medium and high level of dredging were further investigated to assess their effect on the hydrodynamics and ecosystem states of the Coorong.

9.1 Hydrodynamic results

9.1.1 Preliminary assessment

This section shows a preliminary assessment of the hydrodynamic drivers of ecosystem states for the range of dredging levels investigated (i.e. from 0 to -4 m AHD in 0.5 m increments).

For each of the four hydrodynamic drivers of ecosystem states (water level, depth from two years previous, annual range in water level and maximum salinity), the range of values occurring under each of the dredging levels was investigated. These ranges, along with the median value, provide an idea of the conditions occurring in the Coorong with each level of dredging effort.

The range of water levels, and the median values, for water levels under each level of dredging effort is illustrated in Figure 9.1. This figure shows that water levels drop to as low as -0.7 m AHD in the absence of dredging (under the Historic SL reset scenario), but once any dredging has been implemented, tend to range between 0.1 and 0.5 m AHD, with a median of around 0.2 m AHD.
Figure 9.1. Change in water level with various levels of dredging at the Murray Mouth

Note: The line for each scenario illustrates the median value for water level for each level of dredging effort. The error bars show the range of values observed for each scenario, that is, they show the maximum and minimum value observed, giving an appreciation of the extremes reached with each level of dredging effort.

There was very little change in the range or median value for depth from two years previous, despite the level of dredging undertaken (Figure 9.2). The range of values was lowest when no dredging was undertaken, but median values were virtually unchanged with increasing levels of dredging.
Figure 9.2. Change in depth from two years previous with various levels of dredging at the Murray Mouth

Note: The line for each scenario illustrates the median value for depth for each level of dredging effort. The error bars show the range of values observed for each scenario, that is, they show the maximum and minimum value observed, giving an appreciation of the extremes reached with each level of dredging effort.

As was the case for depth, there was little variation in the annual range in water levels regardless of the level of dredging undertaken (Figure 9.3). The range of values observed tended to increase slightly with additional dredging effort, and the median value had a slight upward trend as dredging effort increased.
Figure 9.3. Change in annual range in water level with various levels of dredging at the Murray Mouth

Note: The line for each scenario illustrates the median value for annual range in water level for each level of dredging effort. The error bars show the range of values observed for each scenario, that is, they show the maximum and minimum value observed, giving an appreciation of the extremes reached with each level of dredging effort.

Maximum salinity, in the absence of dredging, rose to as high as 3500 g L\(^{-1}\) on occasion (Figure 9.4). As has been noted previously, salinities of over approximately 200 g L\(^{-1}\) cannot be accurately predicted by the hydrodynamic model, due to complex changes in the evaporation dynamics, but the general trend will be represented. Therefore, salinities are likely to rise to levels where very little or no biota could survive in the absence of dredging. Even the median maximum salinity value, or more than 500 g L\(^{-1}\) could not be tolerated by the vast majority of species. The implementation of dredging, even at relatively low levels, had a large impact on both the maximum and median maximum salinity values. By the time dredging had reached -1.5 m AHD, it became difficult to distinguish between the ranges and medians, although there appeared to be a continuing decline in the range of values observed with increasing dredging levels.
9.1.2 Detailed assessment

A more detailed assessment was undertaken for the no dredging scenario, along with three scenarios describing a low, medium and high level of dredging. These levels were -0.5 m AHD (low), -2 m AHD (medium; i.e. the current level of dredging undertaken) and -4 m AHD. The hydrodynamic results are presented below.

9.1.2.1 Effect of dredging level

There was a general positive trend in the hydrodynamic variables with increasing levels of dredging (Figure 9.5). Median maximum salinity was lower under all of the dredging levels compared to no dredging (606.95 g L⁻¹). The lowest median maximum salinity was at -4 m (90.1 g L⁻¹), slightly higher in the Historic Dredging scenario (105.7 g L⁻¹) and higher again at a -0.5 m dredging level (240.85 g L⁻¹).

Median depth from two years previous followed a similar trend, greatest at -4 m and lowest under Historic No dredging conditions, at 1.34 m and 1.00 m, respectively. Median water levels were also much higher in scenarios with dredging compared to no dredging, with the higher dredging level of -4 m having the highest water level (0.18 m AHD; Figure 8.1). Median annual range was also higher under dredging conditions compared to no dredging (i.e. Historic No Dredging scenario). Historic

Figure 9.4. Change in maximum salinity with various levels of dredging at the Murray Mouth

Note: The line for each scenario illustrates the median value for annual range in water level for each level of dredging effort. The error bars show the range of values observed for each scenario, that is, they show the maximum and minimum value observed, giving an appreciation of the extremes reached with each level of dredging effort.
Dredging and Dredging -4 m both had median annual ranges of approximately 1.00 m, with Dredging -0.5 m slightly lower at 0.81 m.

Figure 9.5. Boxplots comparing hydrodynamic variables driving the ecosystem states of the Coorong for the effect of dredging level

- a) Maximum salinity (g L⁻¹)
- b) water depths from two years previous (m)
- c) water levels (m AHD)
- d) annual changes in water levels (m)

Note: Hist Dredge = Historic Dredging, Dredge –0.5 m = Dredging –0.5 m, Dredge –4 m = Dredging –4 m, H No Dredge = Historic No Dredging.

In the North Lagoon, compared to the Historic Dredging scenario, it was not possible to distinguish the different effect of the different levels of dredging on water levels and depths (Figure 9.6). This was due to the very large impact of the Historic, No Dredging scenario. Relative to this scenario, differences due to low, moderate or high levels of dredging were small.
Figure 9.6. Comparison of the effect of dredging level scenarios relative to the Historic Dredging scenario for the North Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Historic Dredging scenario with respect to water levels and depths (with depths from two years previously). Length of each vector is proportional to the strength of the deviation from the Historic Dredging condition (as shown by the 0,0 origin). Vectors in the upper-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and greater depths).

Larger differences between the different dredging levels were evident in the South Lagoon, compared to the Historic Dredging scenario (Figure 9.7). The largest difference relative to the Historic Dredging scenario (which includes dredging at the current moderate level), was the Historic, No Dredging scenario. This again resulted in a deterioration in both salinities and water levels. Dredging at a low level (to -0.5 m AHD) also resulted in a deterioration in both variables, although the difference from the Historic Dredging scenario was much smaller than that observed for the Historic, No Dredging scenario. Higher levels of dredging (to -4 m AHD) resulted in an improvement in both salinities and water levels, although the change was a small one.
9.1.2.2 Effect of dredging level after SL Reset

The hydrodynamic variables showed a positive response dredging after SL Reset compared with no dredging (Figure 9.8). Median maximum salinity was lowest at a dredging level of -4 m AHD (84.65 g L\(^{-1}\)) compared with the other dredging levels of Historic SLSRS Dredging (which included dredging to -2 m AHD), dredging to -0.5 m AHD and no dredging both including the SLSRS, at 97.6 g L\(^{-1}\), 191.3 g L\(^{-1}\) and 410.2 g L\(^{-1}\), respectively. Median depth from two years previous was similar for all of the dredging levels after the SL Reset, all approximately 1.33 m. The median water levels were much higher under all of the dredging levels, between 0.19 and 0.20 m AHD compared with the Historic SLSRS No Dredging scenario (-0.20 m AHD). Median

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Figure 9.7. Comparison of the effect of dredging level scenarios relative to the Historic Dredging scenario for the South Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Historic Dredging scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Historic Dredging condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and lower salinities).
annual ranges were similar for the Historic SLSRS Dredging and SLSRS Dredging -4 m scenarios, between 0.90 and 0.97 m, but higher than those for the Historic SLSRS No dredging and SLSRS Dredging -0.5 m scenarios, at 0.71 and 0.77 m, respectively.

Figure 9.8. Boxplots comparing hydrodynamic variables driving the ecosystem states of the Coorong for the effect of dredging level after the SL reset

a) Maximum salinity (g L\(^{-1}\)) b) water depths from two years previous (m), c) water levels (m AHD) and d) annual changes in water levels (m)

Note: H SLSRS D = Historic SLSRS Dredging, SLSRS D -0.5 = SLSRS Dredging -0.5m, SLSRS D -4 = SLSRS Dredging -4m, H SLSRS N D = Historic SLSRS No dredging.

Resetting South Lagoon salinities, via the SLSRS, did not change the pattern observed in the previous section (Figure 9.9). Scenarios where dredging was implemented, no matter what the level, were indistinguishable, due to the very large decline in both water levels and depths in the North Lagoon resulting from the Historic, No dredging scenario.

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Figure 9.9. **Comparison of the effect of dredging level scenarios relative to the Historic Dredging scenario for the North Lagoon after the SL reset**

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Historic Dredging scenario with respect to water levels and depths (with depths from two years previously). Length of each vector is proportional to the strength of the deviation from the Historic Dredging condition (as shown by the 0,0 origin). Vectors in the upper-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and greater depths).

Differences due to dredging level were small compared to the effect of no dredging in the South Lagoon as well (Figure 9.10). Here, dredging at a low level, with the SLSRS implemented, resulted in an improvement in water levels, but a slight deterioration in salinities in the South Lagoon, compared to the Historic Dredging scenario (which includes dredging to -2 m AHD, but not the SLSRS). Dredging to either -2 or -4 m AHD and implementing the SLSRS resulted in a slight improvement in both salinities and water levels in the South Lagoon.
9.1.2.3 Effect of dredging level after SL Reset and including the CSLFR initiative

With an increase in the dredging level there was positive trend within the hydrodynamic variables after SL Reset and including the CSLFR initiative (Figure 9.11). Median maximum salinities decreased with an increasing dredging level, with the highest median maximum salinity under the Historic CSLFR scenario, at 287.4 g L$^{-1}$ and lowest under the dredging level of -4 m AHD, at 65.35 g L$^{-1}$. The median depth from two years previous were similar among all of the dredging levels (i.e. -0.5, -2 and -4m AHD), at approximately 1.34 m. Median water levels were also...
similar with the dredging levels between 0.19 and 0.20 m AHD, higher than under the Historic CSLFR scenario, at 0.05 m AHD. Median annual range increased with an increasing dredging level at 0.80 m at a dredging level -0.5 m AHD, 0.90 m at -2 m AHD and 0.97 m at -4 m AHD. The median annual range though was slightly higher under the Historic CSLFR scenario, than under the dredging level -0.5 m AHD, at 0.83 m.

The addition of the CSLFR scheme was again overshadowed by the effect of dredging versus no dredging (Figure 9.12). Changes in water level and depth in the North
Lagoon were not obvious between the different dredging levels, due to the large impact of the scenario investigating no dredging with the SLSRS and CSLFR scheme.

Figure 9.12. Comparison of the effect of dredging level scenarios relative to the Historic Dredging scenario for the North Lagoon after the SL reset and CSLFR

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Historic Dredging scenario with respect to water levels and depths (with depths from two years previously). Length of each vector is proportional to the strength of the deviation from the Historic Dredging condition (as shown by the 0,0 origin). Vectors in the upper-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and greater depths).

In the South Lagoon, small differences were observed in salinities and water levels among the three levels of dredging (Figure 9.13). Again, the biggest difference from the Historic Dredging scenario occurred for the scenario excluding dredging, despite the implementation of the CSLFR scheme and the SLSRS. All three dredging levels resulted in a small increase in water levels, with the two higher levels (to -2 and -4 m AHD) also slightly improving salinities relative to the Historic Dredging scenario.
**Figure 9.13. Comparison of the effect of dredging level scenarios relative to the Historic Dredging scenario for the South Lagoon after the SL reset and CSLFR**

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Historic Dredging scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Historic Dredging condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and lower salinities).

### 9.2 Ecological results

Ecological results are presented for the scenarios that were described in more detail in the hydrodynamic results. These include a no dredging scenario, dredging at the current level (i.e. to -2 m AHD), and low and high dredging scenarios (i.e. dredging to -0.5 m AHD and to -4 m AHD)
9.2.1 **Effect of dredging level**

The increase in dredging level generally showed an improvement in the mix of ecosystem states observed across the site-years (Figure 9.14). The same states were observed under both the Historic Dredging and the Dredging -4 m scenarios, but the proportion of healthy states observed was greatest with the increased dredging level (-4 m AHD), at 62%. At a dredging level of -0.5 m AHD there was a decrease in the proportion of healthy states compared with the highest dredging level (-4 m AHD) and Historic Dredging levels, at 37%. This was due to the increase in the proportion of the Degraded Hypersaline state, replacing the Average Hypersaline state observed for the other two dredging scenarios. All scenarios including dredging were a dramatic improvement from the Historic No Dredging scenario, which had 100% of the state proportions being in a degraded condition.

![Figure 9.14. Comparing the proportion of site-years in each ecosystem state for the dredging level scenarios](image)

*Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DH = Degraded Hypersaline.*

9.2.2 **Effect of dredging level after SL Reset**

Increasing levels of dredging also showed a general improvement in the proportion of healthy ecosystem states after resetting the South Lagoon salinities, via the SLSRS
(Figure 9.15). The states observed under the Historic Dredging and the Dredging -4 m scenarios were the same, but the proportion of healthy states observed was greater with the higher dredging level (-4 m AHD), at 86% compared to 71% for the Historic Dredging scenario (with dredging to -2 m AHD). At a dredging level of -0.5 m AHD, however, there was a decrease in the proportion of healthy states to 36%, with an increase in the Degraded Hypersaline state in replacement of the Average Hypersaline state. Without dredging after the salinity resetting under the Historic climate, 100% of site-years were predicted to be in a degraded condition, with the presence of only the Degraded Marine and Degraded Hypersaline states.

![Figure 9.15](image-url)

**Figure 9.15. Comparing the proportion of site-years in each ecosystem state for the dredging level scenarios after the SL reset**

Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DH = Degraded Hypersaline.

### 9.2.3 Effect of dredging level after SL Reset and including the CSLFR initiative

There was a progressive improvement in the proportion of healthy states with an increase in dredging level after the SL reset and including the CSLFR initiative (Figure 9.16). Both the dredging levels of -0.5 m and -2 m AHD had the same states present, but a dredging level of -2 m AHD had a much higher proportion of healthy site-years.
than dredging at -0.5 m AHD, at 85% and 46%, respectively. This was predominately due to a shift to a larger proportion site-years predicted to be in the Average Hypersaline state. At the highest dredging level (i.e. -4 m AHD), the proportion of healthy site-years increased slightly compared to a dredging level of -2 m AHD, to 87%, with only three states present, the Estuarine/Marine, Unhealthy Marine and Average Hypersaline. In the absence of dredging, 100% of site-years were predicted to be in degraded ecosystem states, with Unhealthy Marine, Degraded Marine and Degraded Hypersaline states observed under the Historic SL Reset CSLFR No Dredging scenario.

![Figure 9.16. Comparing the proportion of site-years in each ecosystem state for the dredging level scenarios after the SL reset and the CSLFR](image)

9.3 Discussion of outcomes and conclusions

The effect of increased dredging level on the hydrodynamics of the Coorong was very small. It was difficult to distinguish any change, particularly compared to the effect of no dredging on water levels, depths, salinities and annual range in water level. Based on a purely hydrodynamic assessment, it would be difficult to justify a dredging level of more than -1 m AHD (refer to Figures 9.1 to 9.4). This appears to be where the majority of benefit occurs, with only very small additional changes with
increasing levels of dredging. As such, it would be an argument of decreasing the current dredging level (which is the equivalent of -2 m AHD, as represented by this model).

However, the relationship between the hydrodynamics of the Coorong and its ecosystem states is not linear. Small additional improvements have the capacity to have a large impact on the mix of ecosystem states. This was observed for scenarios investigating the level of dredging on its own, in conjunction with the SLSRS and with both the SLSRS and the CSLFR. Here, there was significant additional improvement with each incremental increase in the dredging effort (from none to low at -0.5 m to the current effort at -2 m and to high at -4 m AHD). The difference was most evident in the South Lagoon, where a higher proportion of site-years (both in space and in time) were predicted to be in healthy ecosystem states with each incremental increase in the dredging effort.

As was observed in the previous section, in the absence of dredging (during a prolonged drought), all site-years were predicted to be in a degraded state. As the level of dredging increased, this proportion decreased, beginning in the North Lagoon, and extending into the South Lagoon with increasing levels of dredging.

The implementation of other interventions further increased the proportion of healthy ecosystem states in the Coorong. The SLSRS had a smaller impact on its own compared with when it was implemented in conjunction with the CSLFR scheme, as would be expected. However, even with both schemes in operation, there was insufficient fresh water in the system to observe any site-years in the Healthy Hypersaline state in the South Lagoon without concurrent dredging or barrage flows. This highlights the importance of securing barrage flows for the Coorong in the long term, to ensure the maximum ecological health in the region.

Based on these results, there is additional benefit in increasing the connectivity of the Murray Mouth through additional dredging. The majority of the additional benefit would be observed in the South Lagoon, particularly if the SLSRS and the CSLFR scheme were implemented. The final level of dredging determined on, however, will depend on economic and engineering considerations, as increasing the dredging effort is likely to be problematic in terms of sand movement, and incur greater expense than the current effort.
10. References


11. Appendices

Appendix A - Description of the ecosystem states of the Coorong

The ERM model for the Coorong identified eight distinct ecosystem states. The states are presented as a logic tree (Figure 3.1).

The northern basin consisted of four states, including those named Estuarine/Marine, Marine, Unhealthy Marine and Degraded Marine. These states had greater tidal ranges than those four of the southern basin: Healthy, Average, Unhealthy and Degraded Hypersaline. The biological and environmental characteristics of each state are shown in Table A.1.

While the ecosystem state model performs well in describing the ecosystem states that have occurred in the nine years for which we had sufficient data, we acknowledge that other states are likely to (at least potentially) exist that are not adequately represented within this time frame. One that we have identified as likely to occur is an estuarine state, potentially requiring significant, ongoing freshwater inputs, such as have not occurred during the previous decade. Another is a state even less speciose than the Degraded Hypersaline state in the southern basin, or than the Degraded Marine state in the northern basin. The existence of these states is hinted at in anecdotal accounts of the system, either from the general public or researchers who have worked in the system for many years, and from the trends in data collected during 2008 after the development of these models, particularly in the South Lagoon. The possible existence of other states that fall outside the bounds of the data set is important to keep in mind when interpreting these results with a view to further management of the system.
### Table A.1. Relative biological and environmental characteristics of observed ecosystem states

Terms within the table are internally standardised from very low to very high. ^a Caution should be used in interpreting these results, as only one case for the degraded marine state exists in each of the long-term (1999-2007) and short-term analyses (2005-2007). ^b *Ruppia tuberosa* was only present in the long-term analyses because it was only monitored annually. NA indicates that no data was available for that state for the specified parameters. [TKN] represents concentration of total Kjeldahl nitrogen and [TP] represents concentration of total phosphate.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Estuarine/</th>
<th>Marine states</th>
<th></th>
<th></th>
<th>Hypersaline states</th>
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<tr>
<td></td>
<td>Marine</td>
<td>Unhealthy</td>
<td>Degraded</td>
<td>Healthy</td>
<td>Average</td>
<td>Unhealthy</td>
<td>Degraded</td>
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<td></td>
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<td>Marine</td>
<td>Hypersaline</td>
<td>Hypersaline</td>
<td>Hypersaline</td>
<td>Hypersaline</td>
</tr>
<tr>
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<td></td>
<td>Unhealthy</td>
<td>Marine</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Marine</td>
<td>Unhealthy</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fishing birds</td>
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<td>Moderate</td>
<td>High</td>
<td>High</td>
<td>Very low</td>
<td>Low</td>
<td>Moderate</td>
</tr>
<tr>
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<td>Low</td>
<td>Moderate</td>
<td>Moderate</td>
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<td>Very high</td>
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<td>Moderate</td>
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<td>Moderate</td>
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<td>Very high</td>
<td>High</td>
<td>Low</td>
<td>Very low</td>
<td>Very low</td>
<td>Very low</td>
</tr>
<tr>
<td>Marine fish</td>
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<td>Very high</td>
<td>Very high</td>
<td>Very low</td>
<td>Low</td>
<td>Moderate</td>
<td>Low</td>
</tr>
<tr>
<td>Benthic invertebrates</td>
<td>Very high</td>
<td>Moderate</td>
<td>High</td>
<td>Low</td>
<td>NA</td>
<td>Low</td>
<td>Very low</td>
</tr>
<tr>
<td><em>Ruppia tuberosa</em></td>
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<td>Very low</td>
<td>Low</td>
<td>NA</td>
<td>NA</td>
<td>Very high</td>
<td>High</td>
</tr>
</tbody>
</table>

**Biological characteristics**

**Environmental characteristics**

| Day since flow | Low | Very low | Very low | Very low | High | Very low | Very low | High | Very low |
| Flow volume     | Moderate | Low | Very low | Moderate | High | Very low | Very low | High | Very low |
| Salinity        | Low | Very low | Moderate | High | Very high | Very high | Very high | High | Very high |
| Tidal influence | High | High | High | High | Very low | Very low | Very low | Very low | Very low |
| [TKN]           | Low | Very low | Very low | NA | Very high | High | High | Very high |
| [TP]            | Low | Very low | Very low | NA | Moderate | High | High | Very high |
| Turbidity       | Low | Very low | Low | NA | Very high | Moderate | High | Moderate |
Appendix B – How to read output presented

This appendix provides an introduction to each of the figures that have been presented in this report, and a summary of how to read each. They are presented in the order in which they appear in the report.

B.1 Boxplots

Boxplot figures were presented for each set of scenarios to represent the hydrodynamic model output for the variables that drive ecosystem states in the Coorong.

In a boxplot, the interquartile range is represented by a box (Figure B.1). That is, the limits of the box show the range for which the variable in question falls for 50% of the time. The whiskers on the box show an interval which is 1.5 times the interquartile range, and more extreme values (outliers) are represented by points. Finally, the median is represented by a line through the box at the relevant height.

Boxplots are presented that compare each group of scenarios, in line with the research questions.
Figure B.1. Boxplots comparing hydrodynamic variables driving the ecosystem states of the Coorong for the effect of dredging under climate change scenarios, highlighting points to note in red

a) Maximum salinity (g L\(^{-1}\)) b) water depths from two years previous (m), c) water levels (m AHD) and d) annual changes in water levels (m)

**B.2 Deviations from Historic Dredging scenario**

The second output displaying the hydrodynamic results of the various scenarios compares the deviations of values for key variables from the values obtained in the Historic Dredging scenario (Figure B.2). This was divided into two panels, one for the two key variables in the marine (or northern) basin (i.e. water level and depth from two years previous), and one for two key variables in the hypersaline (or southern) basin model (i.e. water level and salinity). The hypersaline basin also had a third driving variable (i.e. annual range) but this threshold was only relevant for a few site-years, and so, in the interests of two-dimensional display, was omitted from this analysis.

In this figure, the vertical and horizontal lines represent the values of each variable seen in the Historic Dredging scenario. That is, scenarios that fall on the lines had a zero sum deviation compared with the Historic Dredging scenario for that variable, and were not
different. The first panel plots the sum of deviations for water levels and depths without flow for site-years in the northern basin (Figure B.2). Here, an increase in water level and an increase in depth could be considered an improvement, compared with the Historic Dredging scenario. Thus, scenarios where the vector ends in the top-right quadrant represent an improvement on both variables. Scenarios with vectors ending in the opposite quadrant (the bottom-left) represent a deterioration relative to both variables. The other two quadrants are an improvement for one variable, but not the other.

The second figure plots the sum of deviations for salinity and water level in the South Lagoon (Figure B.3). As for Figure B.2, scenarios falling on the horizontal and vertical lines indicate no deviation from the Historic Dredging scenario for the variable in question. In this case, a decrease in salinity and an increase in water level constitutes an improvement. This corresponds to the bottom-right quadrant. Scenarios falling in the opposite quadrant (i.e. the top-left) showed a deterioration with respect to both variables.
Figure B.2. Example of comparison of the effect of dredging with other interventions relative to the Historic Dredging scenario for the North Lagoon, highlighting points to note in red

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Historic Dredging scenario with respect to water levels and depths (with depths from two years previously). Length of each vector is proportional to the strength of the deviation from the Historic Dredging condition (as shown by the 0,0 origin). Vectors in the upper-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and greater depths).
Figure B.3. Example of comparison of the effect of dredging with other interventions relative to the Historic Dredging scenario for the South Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Historic Dredging scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Historic Dredging condition (as shown by the 0, 0 origin). Vectors in the bottom-right quadrant (which is shaded grey) indicate an improvement for both variables (i.e. higher water levels and lower salinities).

B.3 Distribution of ecosystem states in space and time

The distribution of ecosystem states for each site in each year is presented in Figure B.4. Sites are numbered from north to south, seven sites occurring in each lagoon, approximately evenly spaced. All 21 years of a simulation run are shown from left to right. Each site-year is represented by a circle, the colour of which indicates the relevant ecosystem state. A key outlining the colour-coding for each of the eight ecosystem states is given below the figure.
Figure B.4. Example of distribution of states for each site-year under the Historic Dredging scenario

Each dot shows the distribution of the states within each site across the 21-year model run. The changes in the dot colours represent the transitions between states. For each dot, colours represent the following states: dark blue = Estuarine/Marine, light blue = Marine, light green = Unhealthy Marine, dark green = Degraded Marine, yellow = Healthy Hypersaline, orange = Average Hypersaline, red = Unhealthy Hypersaline and purple = Degraded Hypersaline.

B.4 Comparison of the proportion of site-years in each ecosystem state among scenarios

The next figure compares the proportion of site-years in each of the ecosystem states amongst groups of scenarios (Figure B.5). This figure shows the distribution of ecosystem states for the Baseline scenario across the site-years, and compares it with other relevant scenarios, in combinations according to the research questions. A legend with abbreviated ecosystem state names is given, with a key below the figure explaining each of the abbreviations.

This figure gives the total proportion of site-years that were found in each ecosystem state, across the entirety of the model run (21 years). Note that not all states are seen in every scenario. Also the number of colours is not an indicator of ‘diversity’ because some colours represent degraded states (not necessarily a good thing).
Figure B.5. Example of comparing the proportion of site-years in each ecosystem state for the climate change scenarios

Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DH = Degraded Hypersaline.