An investigation into interactions between the proposed Upper South East Drainage (USED) Scheme and Barrage Flows

A report prepared for the South Australian Department for Environment and Natural Resources

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Executive summary

Recent prolonged drought led to salinity levels in the Coorong that were so extreme as to preclude the presence of a healthy ecosystem, particularly in the South Lagoon. As a result, managers have explored a range of options for providing additional fresh water to the region to prevent future drought from having a similar impact.

One possibility is to divert additional fresh water from the southeast of South Australia, via the Upper South East Drainage (USED) scheme, which includes an outlet to the Coorong via Salt Creek. Proposed expansions to this scheme may permit the use of sufficient surface water from the southeast of South Australia to complement minimum flow volumes provided from the Murray-Darling Basin, thus maintaining conditions which support the desired ecology of the Coorong.

Previous investigations into the potential impact of such an expansion focused on the best-case outcomes (i.e. modelling the impact of flows with 0 $\mu S\ cm^{-1}$ electrical conductivity via Salt Creek) of flows from the USED scheme under extreme drought (i.e. no barrage flow conditions), but recommended that a minimum flow of 60 GL $year^{-1}$ would be required to have a substantial impact on Coorong hydrodynamics and provide insurance against ecological degradation. Smaller volumes would be of benefit in minimising the most extreme conditions, but would not be sufficient to maintain the ecological condition of the South Lagoon or support water levels and salinities within historic bounds in the absence of barrage flows

This investigation was designed to provide an improved understanding of the effect of proposed changes to the USED scheme in such a way that the impact of different types of changes (e.g. changes in flow volumes compared to the quality of the water) could be identified and extrapolated. This would, in turn, enable managers to make decisions in months to come as design specifications become available for the proposed USED expansion. Thus, the simulations included herein use synthetic sequences of repeating flows for each year, to enable climatic variability to be separated from differences due to flow volume, timing and water quality.

Generally, the Coorong shows a distinct seasonal pattern in salinity and water levels in both Lagoons. This appears to be driven largely by seasonal climatic factors (e.g. local sea level, evaporation) as well as seasonal patterns in the distribution of flows, both from the River Murray and via the USED scheme. For the North Lagoon, local sea levels appeared to be the primary driver, while in the South Lagoon, the timing of hydrologic disconnection between the North and South Lagoons was critical. The timing of this disconnection is influenced both by local sea levels and the timing and volume of barrage flows.

Climatic variability had a large impact on the hydrodynamics of the Coorong. Local conditions alone drove substantial variation in both water levels and salinity. For example, there was variability of up to 40 g L^{-1} in average annual South Lagoon salinity, simply as a result of differences in sea level and local evaporation. This impact was exacerbated when barrage flows were low and indicates that a confidence interval is needed when specifying the likely impact of any given flow volume on the hydrodynamics of the Coorong. A buffer around ecological thresholds (e.g. 117 g L^{-1} as a maximum annual average salinity in the South Lagoon) may also be required to ensure that adverse weather conditions do not cause ecological degradation.

The volume of flow arising from the USED scheme had greater impact on Coorong salinities than water levels. Salinities were up to 50 g L^{-1} lower in the South Lagoon when 90 GL $year^{-1}$ was discharged from the USED scheme compared to flows of 10 GL $year^{-1}$. In particular, maximum salinities were reduced, which are mostly likely to cause ecological damage, but there was little impact on the mix of ecosystem states simulated for the Coorong, with no scenario sufficient to eliminate degraded ecosystem states. Water levels remained relatively constant regardless of the volume investigated.

Barrage flow volume, on the other hand, affected both Coorong salinities and water levels. Salinity in both lagoons responded quickly and proportionally to the volume of water, with differences in maximum annual salinity of more than 50 g L^{-1} associated with barrage flow volumes of 1000 to 8000 GL $year^{-1}$. Water levels responded proportionally in the South Lagoon, but there was an interaction between mouth openness and water level in the North Lagoon, resulting in a complex relationship between barrage flow volume and water level. The ecological impact of the barrage flow volumes, as simulated by the ecosystem states model for the Coorong, was relatively small (i.e. there was little impact on the mix of ecosystem states simulated for the Coorong), demonstrating that the flow volume is not always the driver of ecosystem states, and that flow timing is also important.

Thus, both barrage and USED flow volumes were found to influence salinity, in particular, with USED flows having a greater impact when barrage flows were low. This suggests there may be some potential for use of additional USED flows in times of low flow, taking advantage of the interaction on Coorong conditions observed between flows from different sources, at least with respect to North and South Lagoon salinity outcomes.

Changes in USED water quality (explored using three salinity levels) affected Coorong salinity but not water quantity. Lower USED salinities resulted in lower maximum South Lagoon salinities, but there was no effect on the ecosystem states simulated for the Coorong, suggesting that any of the salinity levels for USED inflows explored herein (i.e. up to 15 g L^{-1}), may not be prohibitively high. However, seasonal variability in salinity or higher overall salinities may have a different impact.

Altering the timing and distribution of barrage flows had potentially large effects on Coorong hydrodynamics and ecosystem states. Shifts of 50 or 100 days either forwards or backwards from the median distribution of historical barrage flows resulted in lower maximum salinities, lower ranges in annual water levels (i.e. so more-consistently higher water levels) and fewer degraded ecosystem states compared with those simulated under the Baseline scenario. There was some variability, both in the impact on hydrodynamics and ecosystem states, depending on the relative volume of USED and barrage flows, but the overall pattern was relatively constant.

When the timing of barrage flows had been shifted, additional shifts to USED flow timing had no discernible impact on Coorong hydrodynamics or ecosystem states, despite the additional changes to seasonal patterns of flow. In the absence of shifts to barrage timing, shifting USED flows either forward or back tended to result in higher salinities than resulted from the historical distribution. The mechanism driving this result has not been tested, but may be related to the inability of USED flows to affect water levels in the South Lagoon, and thus a lack of impact on the timing of effective hydrologic disconnection between the two lagoons. This suggests that there is little value in alternative flow timing and distribution patterns, and any storage capacity in the USED scheme should aim to maintain, rather than alter, historical flow patterns.

The impact of reducing or shifting barrage flows on Lakes ecosystems was also explored, using the Lakes ecosystem state model. This model did not detect differences associated with any of the scenarios investigated. The Lakes are known to be less sensitive to the timing of barrage flows than the Coorong, but it is also likely that limitations to the model have reduced its ability to detect likely ecological degradation, so caution should be applied in interpreting those results. We recommend that any alterations made between flows from the Murray-Darling Basin via the barrages and USED flows maintain minimum flow requirements for barrage flows as described by the environmental flow recommendations for the region (i.e. that minimum flows necessary to support the water quality of the Lakes are preserved).

This study is the first element of investigations required to develop a broader operating strategy for the region once the Murray-Darling Basin Plan and the final form of any USED expansion are finalised.

1 Introduction

Due to a recent prolonged period of no barrage flows between 2007 and late 2010, salinity levels in the South Lagoon have precluded the presence of a healthy ecosystem (Brookes et al. 2009). In particular, salinity has exceeded tolerance levels for survival and reproduction of many aquatic taxa, including fish and invertebrates, and the plants that comprise the food resource for many species of waterbirds for which the Coorong is renowned (Brookes et al. 2009). As a result, in order to lower salinity levels in the South Lagoon, additional fresh water is required to enter the Coorong (Brookes et al. 2009).

As a result of significant drainage of swampland and some localised diversions to the ocean in the South East of South Australia, Salt Creek is thought to have been a more-significant source of water historically than it has in recent years. Part of this drainage system, the Upper South East Drainage (USED) scheme, uses Salt Creek as an outlet and thus has acted as a source of some relatively-small volumes of fresh water to the Coorong in recent years. Current proposals to expand the current USED scheme to provide additional freshwater to wetlands in the South East and to the South Lagoon are under consideration. In addition, a number of possible flow paths are being considered, with different inherent losses and different potential maximum capacities (Montazeri et al. 2010; Lester et al. 2009). Thus, larger volumes have been proposed than have flowed through Salt Creek in recent years (i.e. 1980s to present). Given the location of the input (i.e. in the often-hypersaline South Lagoon), it is possible that these inputs may have a large effect on water levels and salinities in the South Lagoon compared with River Murray water.

Previous investigations on additional USED freshwater flows into the Coorong were undertaken on an earlier version of the expansion proposal. The effects of the various flow paths, climate change and the effect of flow volumes (with potential delivery timing) from the South East on the hydrodynamics and ecological condition of the Coorong were modelled (Lester et al. 2009). This investigation was centred on the maximum effect of USED flows, so it assumed continued drought, or zero barrage flow conditions. As a result, this work cannot be used as an indication of the interactions between the flows from the USED scheme and the River Murray, although the findings are a useful starting point for this investigation.

The main findings from Lester et al. (2009) included:

- An average volume of 60 GL $year^{-1}$ was recommended as a target for the USED scheme, as positive effects from additional water were optimised at this volume;
- Larger volumes of water (i.e. larger than the 60 GL $year^{-1}$) would also be required with increasing levels of climate change;
- The greatest positive impact of the proposed configurations on the hydrodynamics and ecological condition of the Coorong, particularly under extreme climate conditions, were seen using proposed flow path 2D (which involved diversion of additional flow from Drain M via a flow path including Reedy Creek, Blackford Drain and Morella Basin; Peters et al. 2009) with a maximum diversion of 250 ML day^{-1};
- One possibility for improving the impact of additional water may be to store a portion for release during late spring or early summer to minimise the impact of the seasonal hydrologic disconnection of the Coorong lagoons over summer and limit evapoconcentration of South Lagoon water; and
- If climate change progresses at a rapid rate, the inclusion of additional freshwater from the South East may be necessary, in conjunction with other management interventions, in order to support a range of ecosystem states in the Coorong at times of no barrage flows (Lester et al. 2009).

In this report we aim to explore the interactions between flows from the River Murray and the USED scheme to determine the likely effect on Coorong hydrodynamics and ecosystem states. In order to do this, an investigation into how augmented USED flows (i.e. for a range of recurring flow volumes, salinities and timing of flows) might affect the hydrodynamics and simulated ecosystem states in the Coorong, specifically focused on mitigations of any adverse salinity conditions or the occurrence of degraded ecosystem states. The effect of a range of barrage flow volumes and changes to the timing of those flows was also investigated to examine how this interacts with USED flows to affect hydrodynamics in the Coorong and the simulated ecosystem states of the region.

An assessment of how significant inter-annual (i.e. between years) variation in sea level and local meteorological conditions might affect the Coorong’s physical response was also explored. In order to address these questions, results presented in this are grouped into five main research questions which address the influence of combinations of barrage and USED flow volumes, timing and distributions and USED salinity scenarios.

These research questions are:

1. What is the influence of climatic factors for a given sequence of USED and barrage flows?
2. What is the influence of changing USED flows for a given sequence of barrage flows?
3. What is the influence of changing barrage flows for a given sequence of USED flows?
4. What is the influence of USED water quality (i.e. salinity) for a given sequence of USED and barrage flows? and
5. What is the influence of timing and distribution of USED and barrage flows
6. What is the influence of changing barrage flow volumes on Lakes ecosystems?

2 Methods

2.1 Hydrodynamic modelling

The hydrodynamic model used to represent the Coorong is a computer model that simulates water motions and water levels at a series of locations along the Coorong from the Mouth to the south end of the South Lagoon. The model requires as input, time series of barrage flow volumes, USED flow volumes, sea level, wind stress, precipitation and evaporation rates. Salinities are simulated daily in 14 cells between the Mouth and the south end of the South Lagoon (Figure 1). Water levels are simulated at 1-km intervals over the same distance. Overall, the model has been able to adequately represent time series of water levels and salinities throughout the Coorong system, as it has been validated and calibrated against water level and salinity measurements in the Coorong that extend back to 1963 (for further details on the hydrodynamic model see Webster 2007; 2010; Webster et al. 2012).

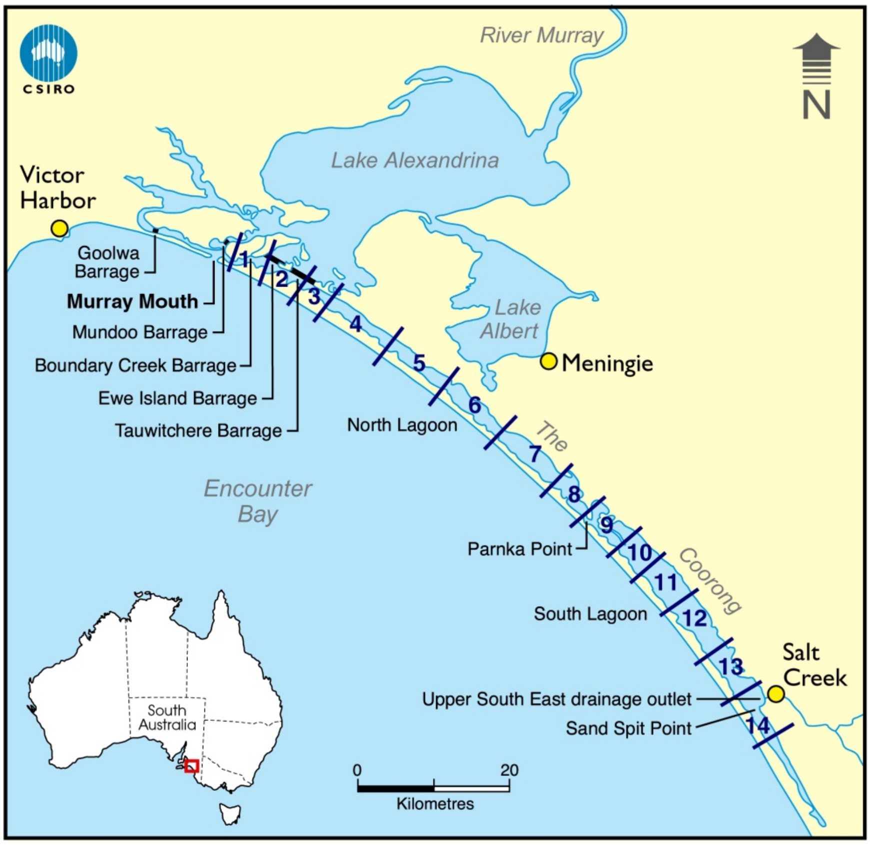

Figure 1: The Coorong, Lower Lakes and Murray moth showing the extent of the hydrodynamic model used in the study and the location of salinity cells within that model

2.2 Ecosystem state model

The ecosystem states model was developed for the Coorong to predict changes in ecological condition under a range of possible future scenarios. The model translates information about the physical and chemical characteristics (i.e. from the hydrodynamic model) of the region into predictions regarding how the various biota will respond to changed conditions. Hence, the ecosystem states model is a state-and-transition model which assumes that there are a discrete number of ‘states’ in which the ecosystem can exist across the region. Each state is a mix of physical conditions and the organisms (e.g. a mixture of birds, fish, vegetation and invertebrates) that are associated with those conditions at a particular location at a particular time. The ecosystem state model identified eight distinct states, named Estuarine/Marine, Marine, Unhealthy Marine, Degraded Marine, Healthy Hypersaline, Average Hypersaline, Unhealthy Hypersaline and Degraded Hypersaline. For further detail on the ecosystem states model see Lester and Fairweather (2011) and Webster et al. (2012).

A similar ecosystem states model was also developed for the Lower Lakes. This model includes distance to the nearest freshwater source, average daily flow, electrical conductivity, coastline direction and bathymetric depth as driving variables. This model simulates one of 10 ecosystem states for the Lakes.

The hydrodynamic drivers of the Coorong ecosystem states that are presented in this report are the average maximum salinity per year, the average annual range in water level, average annual depth from two years previous and average annual water level, unless otherwise specified. Thus all variables are annual averages across the model runs (i.e. from 1983 to 2008).

2.3 Scenario analyses

In order to assess the likely outcomes of potential barrage and USED flow types (i.e. including volumes, timing and distributions), the predictive model was applied to a set of possible scenarios for the Coorong. These scenarios contained a series of combinations of barrage volumes between 0 and 10 000 GL year^{-1}, USED volumes between 10 GL and 90 GL year^{-1}, and USED salinity between 0 and 15 g L^{-1}. All scenarios run from 1/1/1983 to 3/12/2007, a period of 25 years. In each scenario, flow volumes, timing and salinities were held constant year-to-year, while meteorological conditions varied according to the historical record, in order to investigate the impact of each variable on the hydrodynamics and ecosystem states of the Coorong under quasi-steady state conditions. These scenarios can be grouped into sets and are defined in Table 1.

Table 1: Summary of scenarios investigated

Note: '-' denotes no change from modelled Baseline conditions.'+1SD' indicates a shift in the timing of maximum flows by one standard deviation later than the median distribution. '-1SD' represents a shift of one standard deviation earlier than the median distribution. For barrage flows, one standard deviation was a shift of 50 days, while for USED flows, one standard deviation was a shift of 22 days. * All scenarios investigating the effect of flow timing used a USED salinity of 10 g L^{-1}, which is not specified in the name

Scenario Number	Scenario Name	Barrage Flow (GL $year^{-1}$)	USED Flow (GL $year^{-1}$)	USED Salinity (g L^{-1})	Barrage Timing	USED Timing
Scenarios investigating benchmark conditions:						
1	Medium barrage & SE flows, medium salinity (Baseline scenario)	2000	50	10	-	-
Scenarios investigating the effect of changing USED flows:						
2	Medium barrage & low SE flows, medium salinity	2000	10	10	-	-
3	Medium barrage & high SE flows, medium salinity	2000	90	10	-	-
Investigating the effect of changing barrage flows:						
4	Low barrage & medium SE flows, medium salinity	1000	50	10	-	-
5	High barrage & medium SE flows, medium salinity	4000	50	10	-	-
Scenarios investigating the effect of USED salinity:						
6	Low barrage & medium SE flows, low salinity	1000	50	5	-	-
7	Low barrage & medium SE flows, high salinity	1000	50	15	-	-
8	Medium barrage & low SE flows, low salinity	2000	10	5	-	-
9	Medium barrage & low SE flows, high salinity	2000	10	15	-	-
10	Medium barrage & SE flows, low salinity	2000	50	5	-	-
11	Medium barrage & SE flows, high salinity	2000	50	15	-	-
12	Medium barrage & high SE flows, low salinity	2000	90	5	-	-
13	Medium barrage & high SE flows, high salinity	2000	90	15	-	-
14	High barrage & medium SE flows, low salinity	4000	50	5	-	-
15	High barrage & medium SE flows, high salinity	4000	50	15	-	-
Scenarios investigating the effect of flow timing:*						
16	Low barrage & medium SE flows, barrage timing +1SD	1000	50	10	+1SD	-
17	Low barrage & medium SE flows, USED timing +1SD	1000	50	10	-	+1SD
18	Low barrage & medium SE flows, barrage timing -1SD	1000	50	10	-1SD	-

Scenario Number	Scenario Name	Barrage Flow (GL $year^{-1}$)	USED Flow (GL $year^{-1}$)	USED Salinity (g L^{-1})	Barrage Timing	USED Timing
Scenarios investigating the effect of flow timing cont.:*						
19	Low barrage & medium SE flows, USED timing -1SD	1000	50	10	-	-1SD
20	Low barrage & medium SE flows, USED & barrage timing +1SD	1000	50	10	+1SD	+1SD
21	Low barrage & medium SE flows, USED & barrage timing -1SD	1000	50	10	-1SD	-1SD
22	Medium barrage & low SE flows, barrage timing +1SD	2000	10	10	+1SD	-
23	Medium barrage & low SE flows, USED timing +1SD	2000	10	10	-	+1SD
24	Medium barrage & low SE flows, barrage timing -1SD	2000	10	10	-1SD	-
25	Medium barrage & low SE flows, USED timing -1SD	2000	10	10	-	-1SD
26	Medium barrage & low SE flows, USED & barrage timing +1SD	2000	10	10	+1SD	+1SD
27	Medium barrage & low SE flows, USED & barrage timing -1SD	2000	10	10	-1SD	-1SD
28	Medium barrage & SE flows, barrage timing +1SD	2000	50	10	+1SD	-
29	Medium barrage & SE flows, USED timing +1SD	2000	50	10	-	+1SD
30	Medium barrage & SE flows, barrage timing -1SD	2000	50	10	-1SD	-
31	Medium barrage & SE flows, USED timing -1SD	2000	50	10	-	-1SD
32	Medium barrage & SE flows, USED & barrage timing +1SD	2000	50	10	+1SD	+1SD
33	Medium barrage & SE flows, USED & barrage timing -1SD	2000	50	10	-1SD	-1SD
34	Medium barrage & high SE flows, barrage timing +1SD	2000	90	10	+1SD	-
35	Medium barrage & high SE flows, USED timing +1SD	2000	90	10	-	+1SD
36	Medium barrage & high SE flows, barrage timing -1SD	2000	90	10	-1SD	-
37	Medium barrage & high SE flows, USED timing -1SD	2000	90	10	-	-1SD
38	Medium barrage & high SE flows, USED & barrage timing +1SD	2000	90	10	+1SD	+1SD
39	Medium barrage & high SE flows, USED & barrage timing -1SD	2000	90	10	-1SD	-1SD
40	High barrage & medium SE flows, barrage timing +1SD	4000	50	10	+1SD	-
41	High barrage & medium SE flows, USED timing +1SD	4000	50	10	-	+1SD
42	High barrage & medium SE flows, barrage timing -1SD	4000	50	10	-1SD	-
43	High barrage & medium SE flows, USED timing -1SD	4000	50	10	-	-1SD
44	High barrage & medium SE flows, USED & barrage timing +1SD	4000	50	10	+1SD	+1SD
45	High barrage & medium SE flows, USED & barrage timing -1SD	4000	50	10	-1SD	-1SD

Scenario Number	Scenario Name	Barrage Flow (GL $year^{-1}$)	USED Flow (GL $year^{-1}$)	USED Salinity (g L^{-1})	Barrage Timing	USED Timing
Scenarios investigating the effect of flow timing cont.:*						
46	Low barrage & medium SE flows, barrage timing +2SD	1000	50	10	+2SD	-
47	Low barrage & medium SE flows, USED timing +2SD	1000	50	10	-	+2SD
48	Low barrage & medium SE flows, barrage timing -2SD	1000	50	10	-2SD	-
49	Low barrage & medium SE flows, USED timing -2SD	1000	50	10	-	-2SD
50	Low barrage & medium SE flows, USED & barrage timing +2SD	1000	50	10	+2SD	+2SD
51	Low barrage & medium SE flows, USED & barrage timing -2SD	1000	50	10	-2SD	-2SD
52	Medium barrage & low SE flows, barrage timing +2SD	2000	10	10	+2SD	-
53	Medium barrage & low SE flows, USED timing +2SD	2000	10	10	-	+2SD
54	Medium barrage & low SE flows, barrage timing -2SD	2000	10	10	-2SD	-
55	Medium barrage & low SE flows, USED timing -2SD	2000	10	10	-	-2SD
56	Medium barrage & low SE flows, USED & barrage timing +2SD	2000	10	10	+2SD	+2SD
57	Medium barrage & low SE flows, USED & barrage timing -2SD	2000	10	10	-2SD	-2SD
58	Medium barrage & SE flows, barrage timing +2SD	2000	50	10	+2SD	-
59	Medium barrage & SE flows, USED timing +2SD	2000	50	10	-	+2SD
60	Medium barrage & SE flows, barrage timing -2SD	2000	50	10	-2SD	-
61	Medium barrage & SE flows, USED timing -2SD	2000	50	10	-	-2SD
62	Medium barrage & SE flows, USED & barrage timing +2SD	2000	50	10	+2SD	+2SD
63	Medium barrage & SE flows, USED & barrage timing -2SD	2000	50	10	-2SD	-2SD
64	Medium barrage & high SE flows, barrage timing +2SD	2000	90	10	+2SD	-
65	Medium barrage & high SE flows, USED timing +2SD	2000	90	10	-	+2SD
66	Medium barrage & high SE flows, barrage timing -2SD	2000	90	10	-2SD	-
67	Medium barrage & high SE flows, USED timing -2SD	2000	90	10	-	-2SD
68	Medium barrage & high SE flows, USED & barrage timing +2SD	2000	90	10	+2SD	+2SD
69	Medium barrage & high SE flows, USED & barrage timing -2SD	2000	90	10	-2SD	-2SD
70	High barrage & medium SE flows, barrage timing +2SD	4000	50	10	+2SD	-
71	High barrage & medium SE flows, USED timing +2SD	4000	50	10	-	+2SD
72	High barrage & medium SE flows, barrage timing -2SD	4000	50	10	-2SD	-

Scenario Number	Scenario Name	Barrage Flow (GL $year^{-1}$)	USED Flow (GL $year^{-1}$)	USED Salinity (g L^{-1})	Barrage Timing	USED Timing
Scenarios investigating the effect of flow timing cont.:*						
73	High barrage & medium SE flows, USED timing -2SD	4000	50	10	-	-2SD
74	High barrage & medium SE flows, USED & barrage timing +2SD	4000	50	10	+2SD	+2SD
75	High barrage & medium SE flows, USED & barrage timing -2SD	4000	50	10	-2SD	-2SD

3 Results

3.1 Hydrodynamic features of the Baseline scenario

A series of combinations of barrage volumes between 1000 and 4000 GL year^{-1}, USED volumes between 10 and 90 GL year^{-1}, and USED salinity between 0 and 15 g L^{-1} were used in the simulations explored in this report. In order to illustrate features of the simulations where flow characteristics were altered, a Baseline scenario was considered which had barrage and USED volumes of 2000 GL year^{-1} and 50 GL year^{-1}, respectively, and a USED salinity of 10 g L^{-1}. Figure 2 shows the time series of salinity in the main bodies of the North and South Lagoons defined here as salinity cells 4 to 7 and cells 10 to 13 for the two lagoons, respectively (see Figure 1). These lagoon sections avoid cells that were directly subject to either barrage or USED flow input, where localised impacts may well exceed the impacts on the main lagoon basins, and therefore an average of the values for these four cells provide the most representative assessment of the conditions in each of the respective lagoons.

With repeated barrage and USED flow inputs the salinity response in both lagoons underwent a regular seasonal cycle (Figure 2). It was apparent that there was a degree of inter-annual variation in salinity cycle, and this was more pronounced in the South Lagoon than in the North Lagoon. This was partly due to inter-annual variation in meteorological factors including evaporation and precipitation rates and wind strength that affect the horizontal mixing of water along the lagoons. Inter-annual variations in the weather systems that cross Australia also caused the seasonal cycle of sea level to vary from year to year causing a significant impact on water exchange along the Coorong and with the sea. In addition, salinity in the Coorong was mediated by:

- seasonal cycles of barrage and USED flows;
- seasonal cycles of evaporation and precipitation; and
- back and forth oscillatory flows along the Coorong caused by winds and seasonal variation in sea level.

Figure 3 illustrates average salinity contours along the Coorong over a single 'typical' year (i.e. averaged across all years in the simulation). Generally, salinity increased along the Coorong from the Mouth towards the south end of the South Lagoon. The localised impacts on salinity of the barrage and USED flows were clearly seen near their discharge points in the North and South Lagoons, respectively. However, these flows also influenced salinity along the entire length of the Coorong to some degree (Figure 3), although the overlap in the timing of barrage and USED flows made it difficult, from this figure, to assess the relative impact of each (see Research Questions 2 and 3 below).

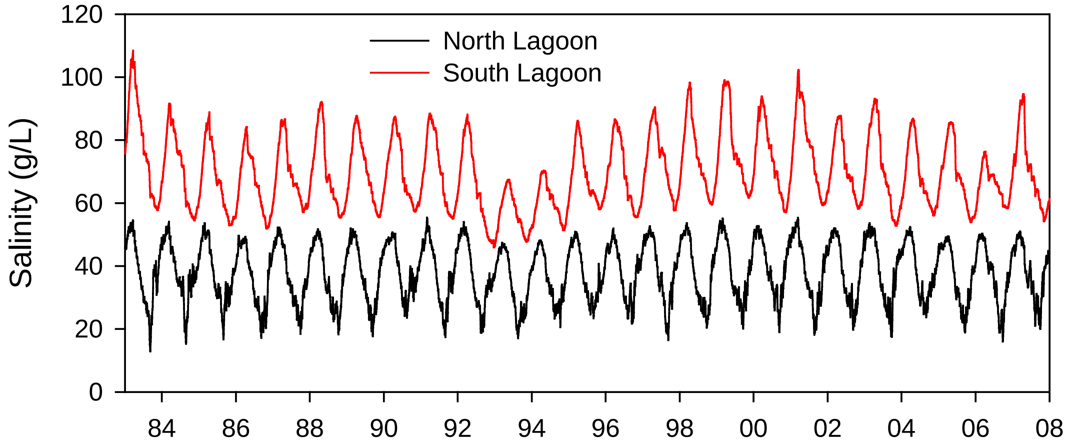

Figure 2: Average daily salinities simulated in the main bodies of the North and South Lagoon between 1983 and 2007 for the Baseline scenario (2000 GL year^{-1}; 50 GL year^{-1} & 10 g L^{-1})

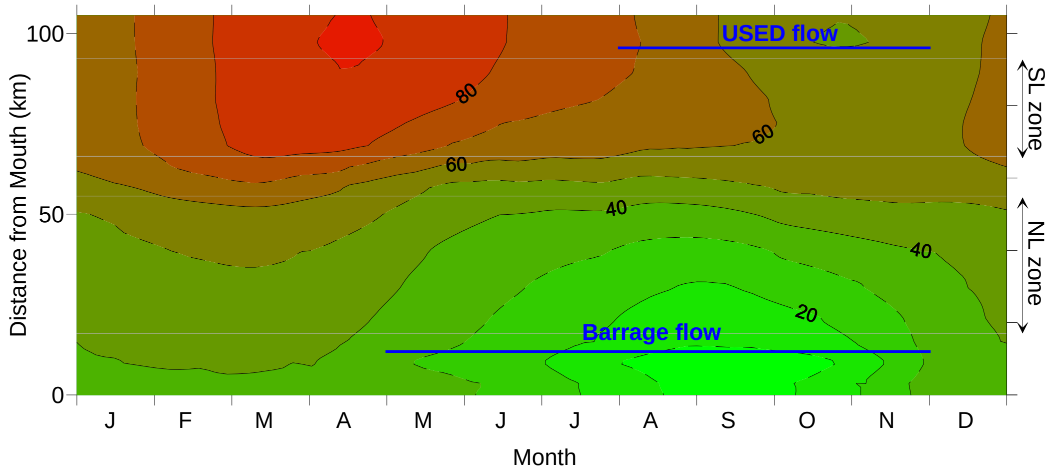

Figure 3: Contours of average salinity over a 'typical' year along the length of the Coorong for the Baseline scenario (2000 GL year^{-1}; 50 GL year^{-1} &10 g L^{-1}). The extent of the main bodies of the two lagoons is shown as the pairs of horizontal grey lines. Typical periods of barrage and USED flows in the year are shown in blue at their respective distances from the Mouth

Water levels also showed a pronounced and regular seasonal cycle (Figure 4), when a 'typical' year was explored. In such a typical year, sea level was at a maximum in winter and a minimum in summer. For most of the year, North Lagoon water levels reflected those in the sea, but during times of strong barrage flows, water backed up behind the Mouth channel, causing lagoon levels to rise significantly above those in the sea. By early summer, sea level and barrage flows had dropped sufficiently that the channel connecting the North and South Lagoons became very shallow and flow between the two lagoons became severely constricted (referred to subsequently as a 'hydrologic disconnection'). Without replenishment from the North Lagoon, summertime evaporation caused the South Lagoon water levels to continue to drop below those in the North Lagoon. Subsequent evapoconcentration in the South Lagoon was then responsible for elevating salinities in the South Lagoon relative to those in the North lagoon. When sea levels rose again in autumn, refilling occurred with water from the North Lagoon and South Lagoon water levels also rose.

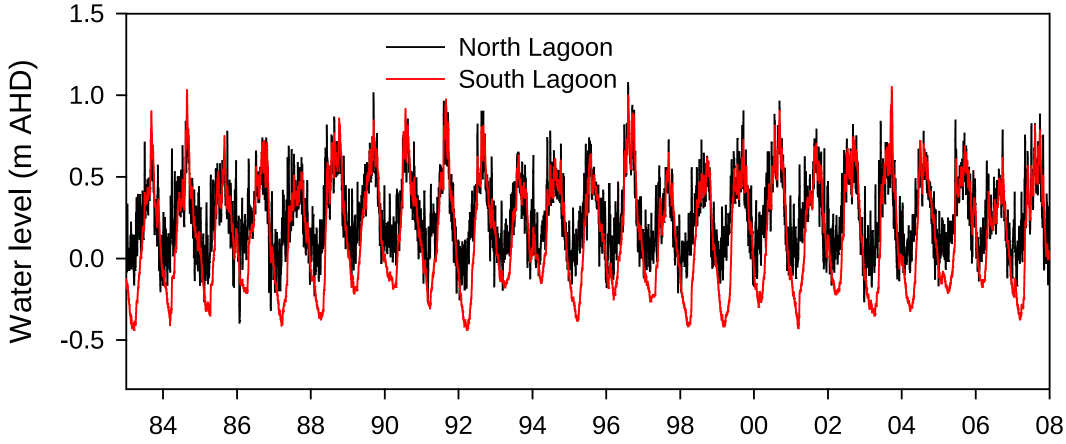

Figure 4: Water levels modelled in the North and South Lagoons for the Baseline scenario (2000 GL year^{-1}; 50 GL year^{-1} &10 g L^{-1})

The years 1993, 1994 and 2006 showed unusually low peak salinities in the South Lagoon (Figure 2) and it appeared that variation in the annual cycle of sea level variation was the main cause. In these years, the fall in sea level was delayed by a couple of months compared to the average timing in the historical record. As a consequence, the two lagoons were not hydrologically disconnected from one another until later into the summer. As a result, evaporative losses in the South Lagoon could be replaced by water flowing from the North Lagoon until later in the year thereby ensuring that salinity did not climb as high as in a typical year.

3.2 Research Question 1: Variation due to local climate

Figure 2 showed that the average salinities in the Coorong lagoons varied from year to year in response to inter-annual variation in local meteorological conditions and seasonal sea level cycle. Figure 5 shows the average daily standard deviation of salinity in the South Lagoon from its long-term seasonal cycle. The standard deviation is a measure of the variability in salinity simulations that is due to inter-annual variability in the driving forces (e.g. local weather) and gives an indication of how much impact those driving forces may have on the exact value of salinity in any given year. For example, under the Baseline scenario (labelled on Figure 5), the standard deviation in the South Lagoon is 12 g L^{-1}. In any given year, salinity would be expected to be within two standard deviations of the average salinity (which is 68 g L^{-1}) for 95% of the time, just due to natural variation, so South Lagoon salinity may be anywhere between 44 and 92 g L^{-1} (i.e. 68 ± 2 x 12 g L^{-1}). The variability increased as barrage and USED flow volumes diminished but, provided barrage flow volume was greater than 1000 GL $year^{-1}$, the standard deviation was less than 20 g L^{-1}. Uncertainty in North Lagoon salinity (not shown) tended to be about half of that in the South Lagoon.

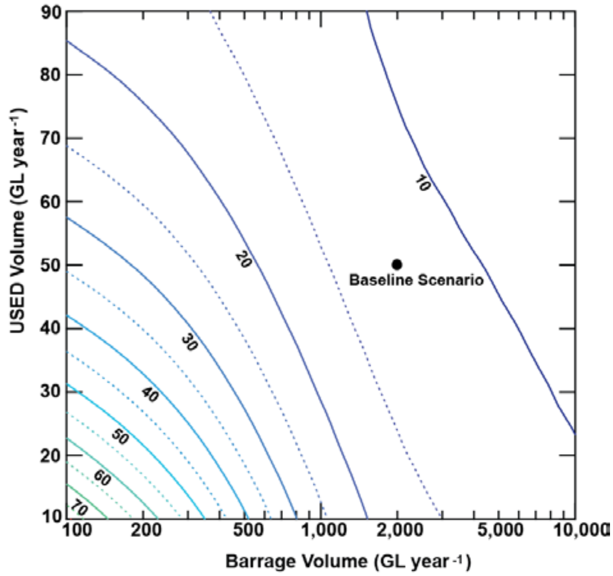

Figure 5: Standard deviation of salinity in South Lagoon from long-term average seasonal cycle, shown in g L^{-1}. USED salinity is fixed at 10 g L^{-1} Note: the x-axis is a log scale

In addition to having variability around the average salinity, there was also variability in the maximum and minimum salinities (Figures 6 and 7), and in the maximum, average and minimum water levels (Figures 8 and 9) in both the North and South Lagoons. The Baseline scenario is shown in Figures 6 to 10, with a constant barrage flow of 2000 GL $year^{-1}$, a USED flow of 50 GL $year^{-1}$ and a USED salinity of 10 g L^{-1} used in each year of the simulation. The only differences from year to year were in the sea level, wind, evaporation and rainfall data that were also needed to run the model, which were allowed to vary as recorded between 1983 and 2007. Thus, these figures show the direct impact that weather and sea level in Encounter Bay can have on the salinity and water level of the Coorong, regardless of freshwater inflows to the system.

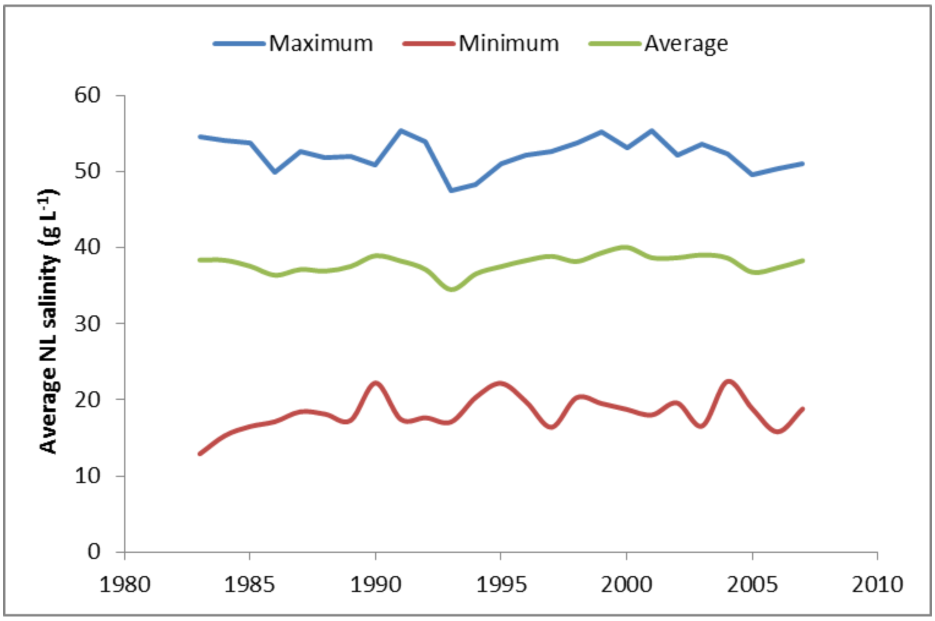

Figure 6: Time series of salinity in the North Lagoon under the Baseline scenario showing the variation from year to year in the maximum, minimum and average values

In the North Lagoon, there appeared to be little relationship between the maximum and minimum salinities observed (Figure 6). In some years, both the minimum and maximum rose together (e.g. in 1994 and 2007), while in others, the maximum salinity fell while the minimum rose (e.g. 1993), or the maximum salinity rose and the minimum fell (e.g. 1998). This suggests that different factors may have been driving the minimum salinity each year, compared to the maximum salinity for the same year.

In the South Lagoon, there was a much closer relationship between maximum and minimum salinity (Figure 7) for most of the time period shown. For the most part, in the South Lagoon, maximum and minimum salinities tended to rise and fall together, suggesting that the same hydrological processes were driving both extremes in salinity each year.

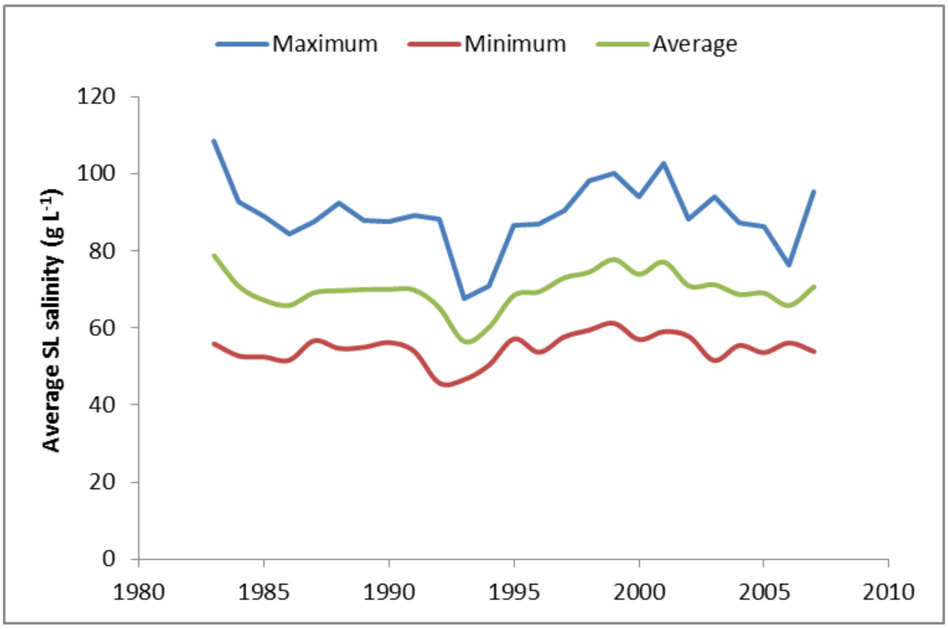

Figure 7: Time series of salinity in the South Lagoon under the Baseline scenario showing the variation from year to year in the maximum, minimum and average values

For water levels, a similar pattern emerged, with little relationship between maximum and minimum water levels in the North Lagoon (Figure 8). The maximum water level tended to vary much more than the minimum or average water level from year to year, and was related to the volume of barrage flows each year. In the South Lagoon, there was again a closer relationship, although here it was an inverse relationship (Figure 9). That is, when maximum water levels tended to rise, minimum water levels tended to fall, and *vice versa*, with the exception of 2007 when water levels fell generally.

These figures illustrate the influence of weather systems on the hydrodynamics of the Coorong and the difficulties associated with precise predictions of likely future conditions as a result of the delivery of particular volumes of environmental water, due to uncertainty surrounding sea levels, wind, evaporation and rainfall.

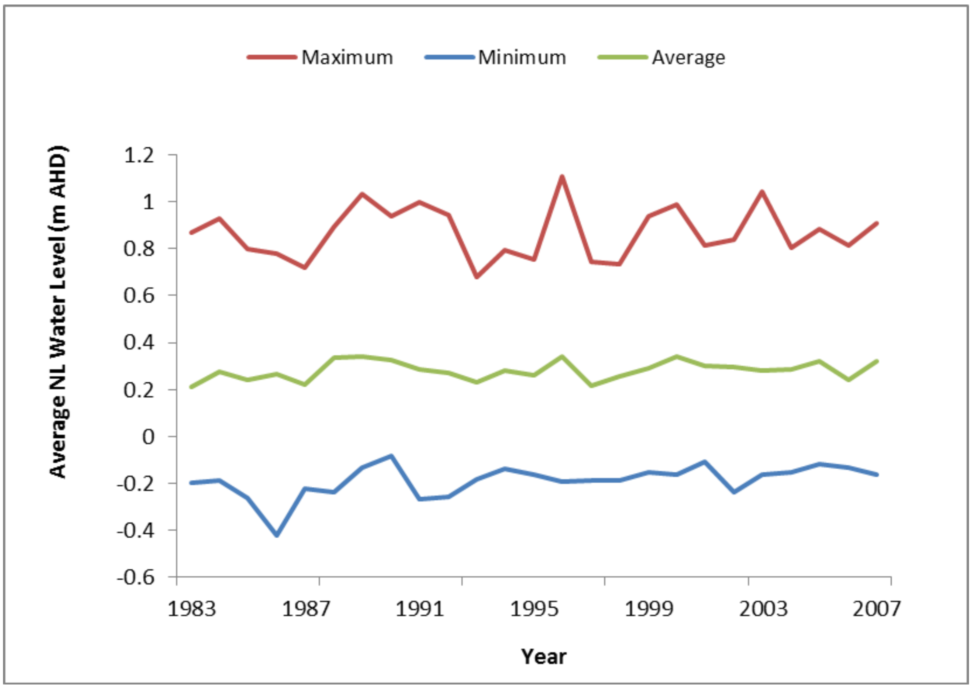

Figure 8: Time series of water level in the North Lagoon under the Baseline scenario showing the variation from year to year in the maximum, minimum and average values

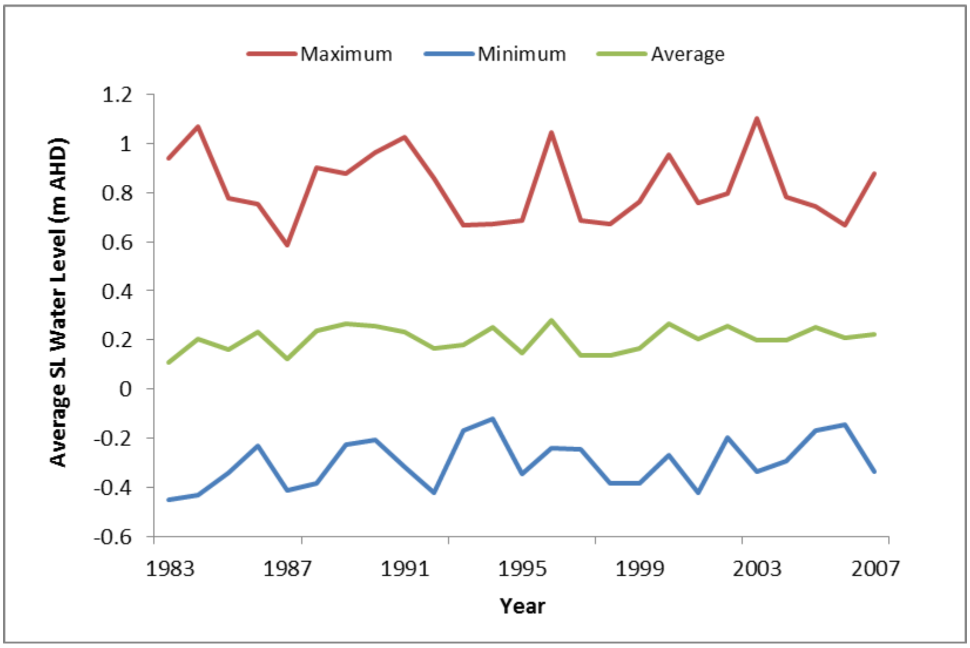

Figure 9: Time series of water level in the South Lagoon under the Baseline scenario showing the variation from year to year in the maximum, minimum and average values

3.3 Research Question 2: Effect of increasing USED flows

Figures 10 to 12 illustrate the impact of USED flow on the average seasonal cycle of salinity in the North and South Lagoon with barrage flow volume fixed at 2000 GL and USED salinity 10 g L^{-1}. The variation in USED discharge between 10 and 90 GL $year^{-1}$ had a modest effect at the north end of the main basin of the North Lagoon (Figure 10), but it had a more significant effect towards the south end where salinity was ~10 g L^{-1} lower for the highest USED discharge compared to the smallest discharge. Salinities in the South Lagoon were significantly affected by variation in USED flow volume (Figure 11). While, peak salinities in the South Lagoon exceeded 130 g L^{-1} at the end of summer with a USED discharge of 10 GL $year^{-1}$, they reduced to less than 70 g L^{1} when the discharge was increased to 90 GL $year^{-1}$. The timing of peak salinities in the South Lagoon was not markedly altered by increasing USED flow volumes.

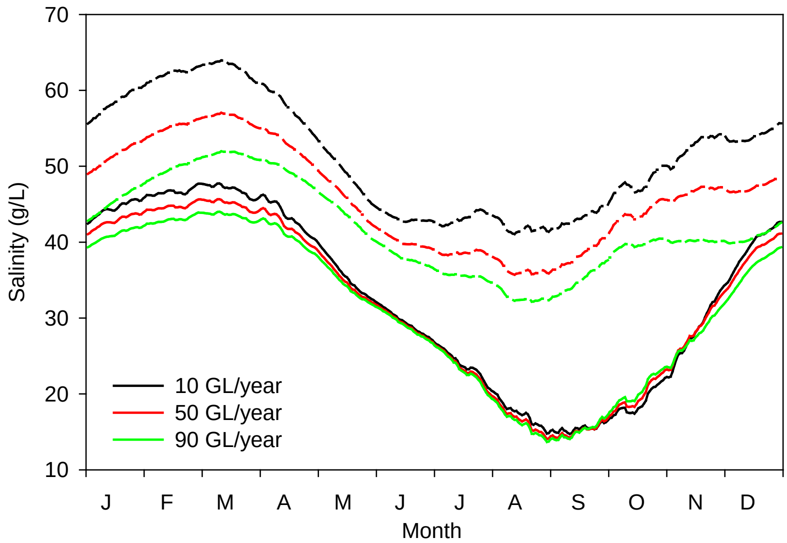

Figure 10: Average yearly cycle of salinity in North Lagoon as a function of USED flow volume with barrage flow of 2000 GL $year^{-1}$ and USED salinity of 10 g L^{-1}. Solid line is salinity in cell 4 and dashed line is salinity in cell 7 (the northern and southern extent of the North Lagoon, respectively; see Figure 1)

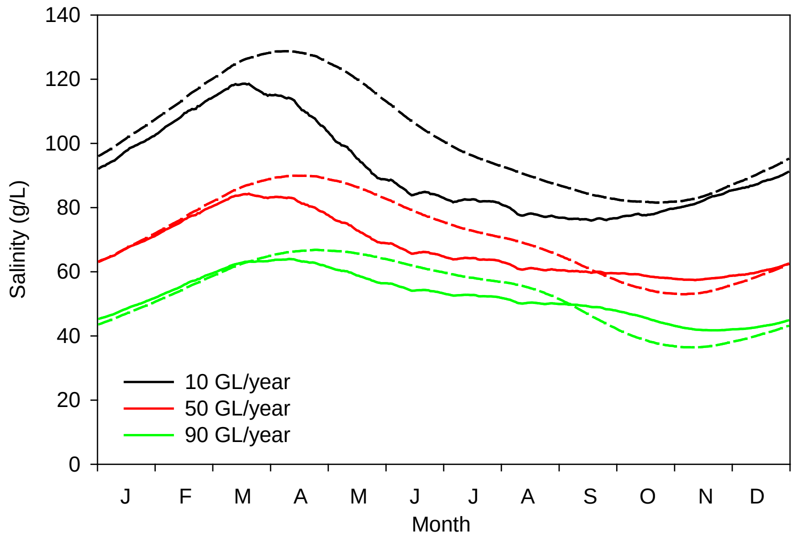

Figure 11: Average yearly cycle of salinity in South Lagoon as a function of USED flow volume with barrage flow of 2000 GL year^{-1} and USED salinity of 10 g L^{-1}. Solid line is salinity in cell 10 and dashed line is salinity in cell 13 (the northern and southern extent of the South Lagoon, respectively; see Figure 1)

The seasonal cycle of water levels in both lagoons was modestly affected by increases in the USED discharge under median flow timings (Figure 12). USED flows terminated in early summer before the channel between the two lagoons effectively closed (i.e. hydrologically disconnected). Thus, USED inflow to the South Lagoon could be balanced by outflow through the channel as the hydrologic connection remained open during USED inflows. Constriction of the exchange in flow between the two lagoons caused water levels to be pushed up in the South Lagoon for the larger USED flow volumes.

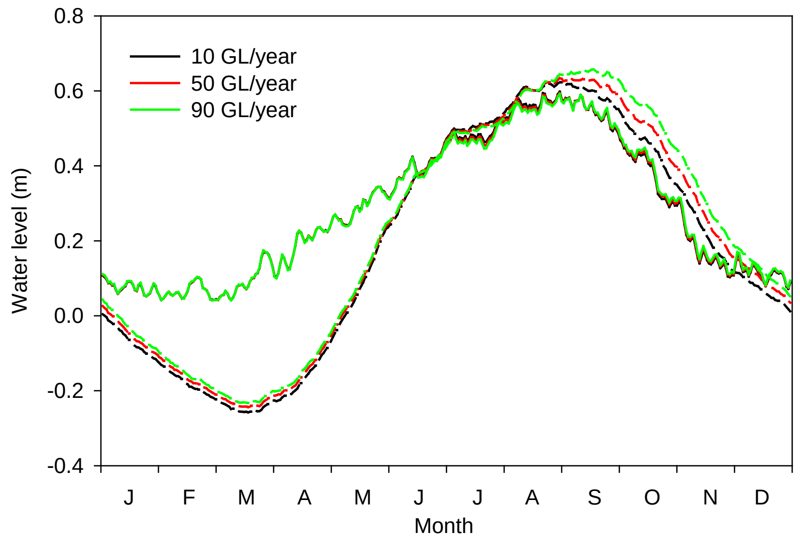

Figure 12: Average yearly cycle of water level in North Lagoon (solid line) and in South Lagoon (dashed line) as a function of USED flow volume with barrage flow of 2000 GL year^{-1} and USED salinity of 10 g L^{-1}

When the effects of increasing USED flow volumes were investigated on the hydrodynamic drivers of ecosystem states (i.e. maximum salinity, annual range in water level, average depth from two years previous and average water level, which were found to be the most important variables in determining ecological condition using the ecosystem states model; Lester and Fairweather 2011), there was little influence on annual range in water levels, average depth from two years previous and average water level (Figure 13a, c & d). The largest influence was on maximum salinity, with less saline conditions simulated in the scenario with the highest USED flow volume (i.e. 90 GL year^{-1}). The median maximum salinity across the entire Coorong for the 25-year model run declined from 74 g L^{-1} under the USED 10 GL year^{-1} scenario to 62 g L^{-1} under the 50 GL year^{-1} and 53 g L^{-1} under the 90 GL year^{-1} scenarios. Most evident though, was the difference in the range (i.e. maximum minus minimum) of salinity values found under each of the scenarios, with the 10 GL year^{-1} scenario having the largest range at 81 g L$^{-1,}$ indicating the most variable conditions in space and time, to a range of 23 g L^{-1} under the 90 GL year^{-1} scenario, indicating a more stable, as well as lower overall, salinity regime.

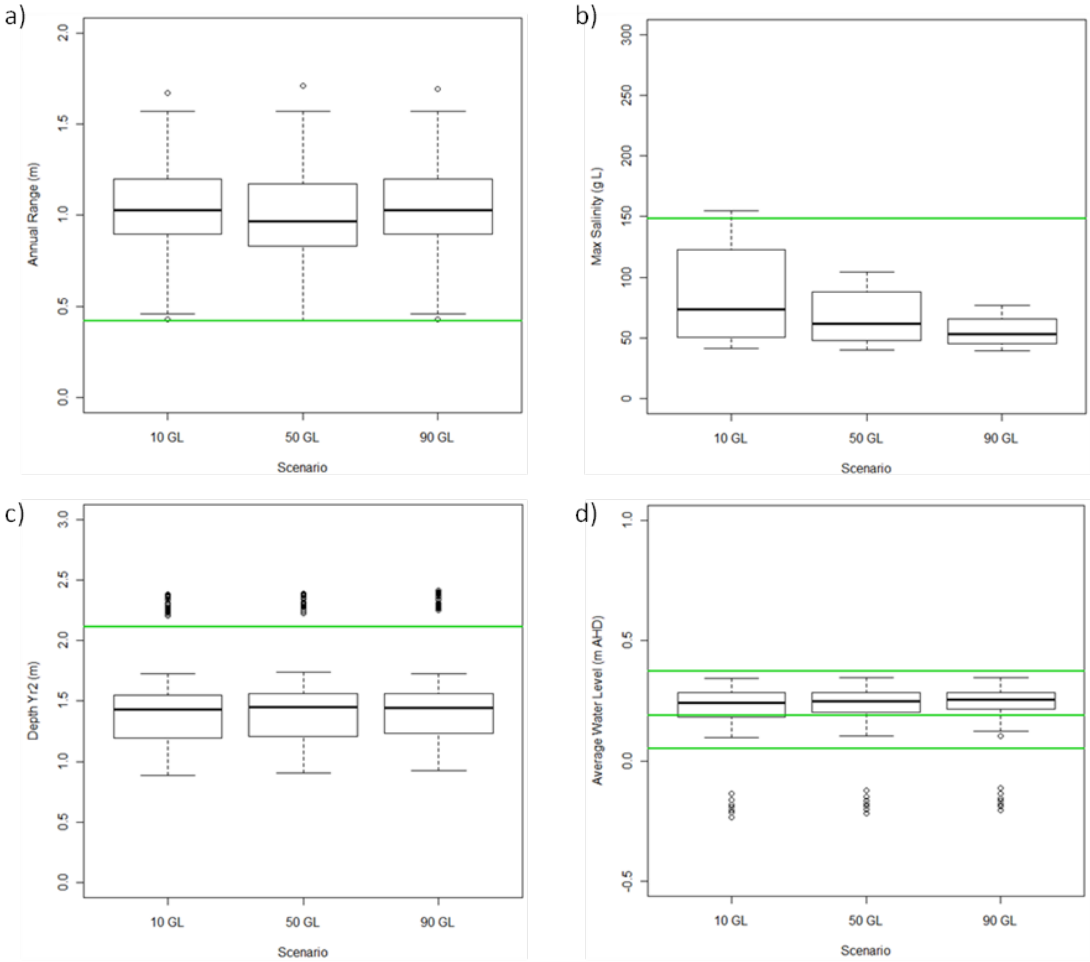

Figure13: Boxplots showing the distribution of values for each of the variables driving the ecosystem states of the Coorong for the effect of increasing USED flow volume scenarios. a) Annual range in water level (m), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Average water level (m AHD) Note: 10 GL is the medium barrage & low SE flows, medium salinity scenario (Scenario 2), 50 GL is the medium barrage & SE flows, medium salinity scenario (Baseline scenario, Scenario 1), and 90 GL is the medium barrage & high SE flows, medium salinity scenario (Scenario 3; Table 1)

The cumulative difference in space and time compared to the Baseline scenario for North Lagoon hydrodynamic drivers was very small, with little deviation in water levels and depth from two years previous, for either the addition of 10 GL or 90 GL of USED flow added per year (i.e. the vectors were almost indistinguishable from the origin; Figure 14).

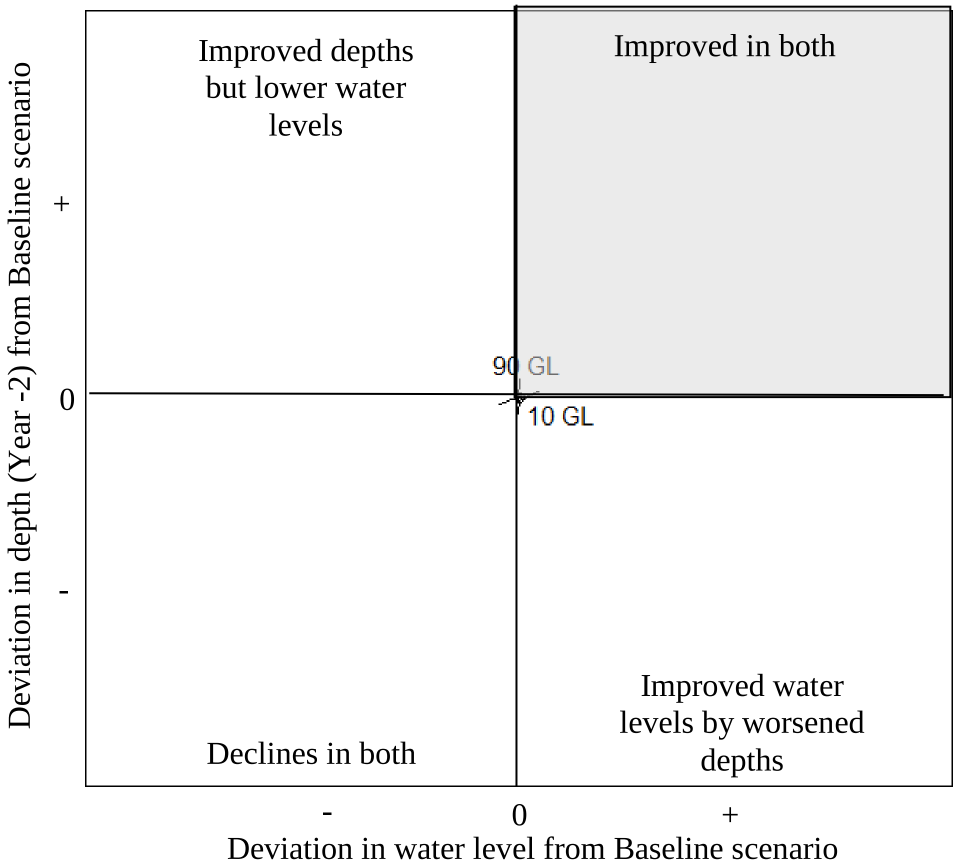

Figure14: Comparison of the effect of increasing USED flow volume scenarios for the North Lagoon
This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline scenario with respect to water levels and depths (with depths from two years previously). Length of each vector is proportional to the strength of the deviation from the Baseline scenario condition (as shown by the 0,0 origin). Vectors in the top-right quadrant indicate an improvement for both variables (i.e. higher water levels and greater depths). 10 GL is the medium barrage & low SE flows, medium salinity scenario (Scenario 2), 90 GL is the medium barrage & high SE flows, medium salinity scenario (Scenario 3; Table 1)

The cumulative impact on South Lagoon hydrodynamics was more pronounced (Figure 15). In that Lagoon there was an improvement in both maximum salinity and water level with an increased USED flow volume of 90 GL was added each year, compared to the Baseline scenario (i.e. 50 GL year^{-1}). However, when 10 GL of USED flow was added per year there was deterioration in both maximum salinity and water levels. Therefore, the change in cumulative impact was relatively linear based on the volume of water introduced via Salt Creek, with larger volumes of water resulting in bigger improvements in salinity and water levels in the South Lagoon.

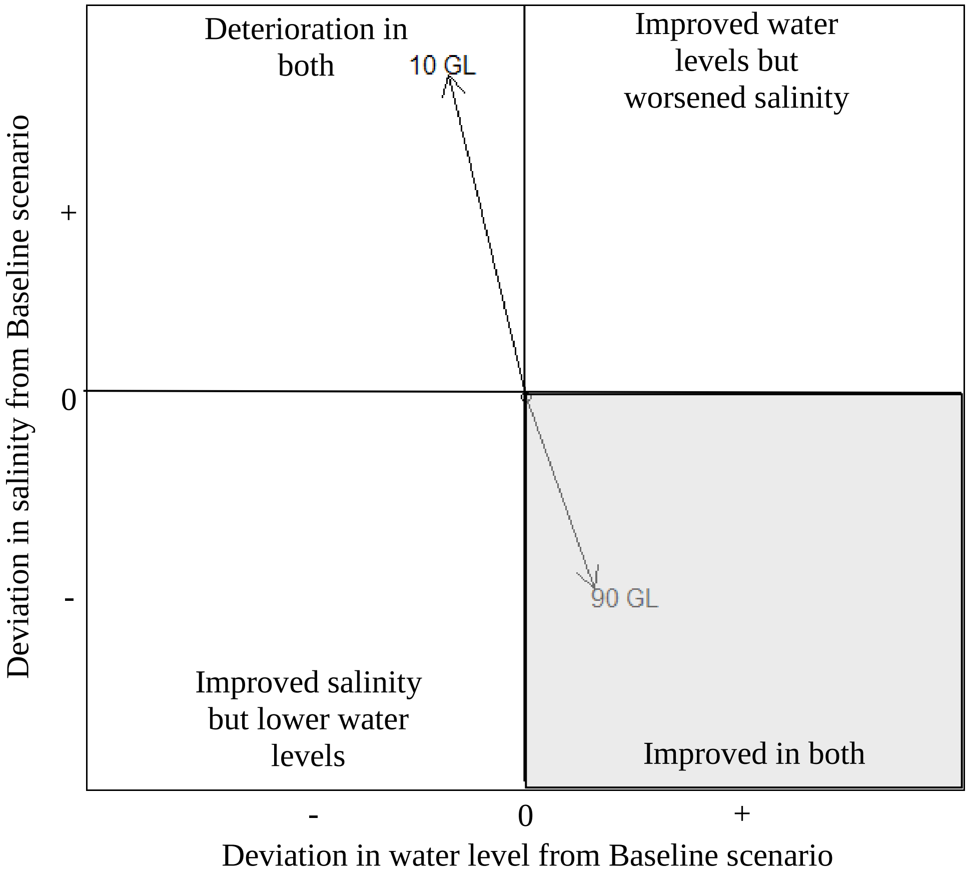

Figure 15: Comparison of the effect of increasing USED flow volume scenarios for the South Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Baseline scenario condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant indicate an improvement for both variables (i.e. higher water levels and lower salinities). 10 GL is the medium barrage & low SE flows, medium salinity scenario (Scenario 2), 90 GL is the medium barrage & high SE flows, medium salinity scenario (Scenario 3; Table 1)

The effect of increasing USED flow volumes on the ecosystem states of the Coorong was subtle (Figure 16). The addition of 90 GL year^{-1} did not change the relative proportions of ecosystem states compared to the Baseline scenario (i.e. the addition of 40 GL year^{-1} above that included in the Baseline scenarios). The reduction of USED inflow volume from 50 GL to 10 GL of USED flow volume per year did alter the relative proportions of the ecosystem states, but the difference was very small with less than 0.05% of site-years in the model run changing from Average Hypersaline to Degraded Hypersaline (Figure 17).

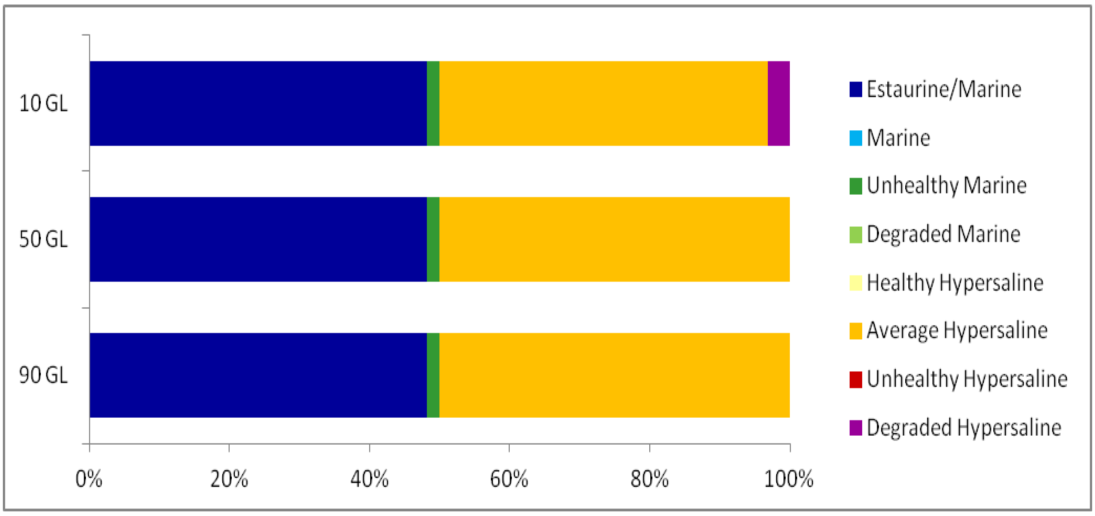

Figure 16: Comparing the proportion of site-years in each ecosystem state for the effect of increasing USED flow scenarios

This indicates that increasing volumes delivered via Salt Creek had some impact on the ecosystem states of the Coorong, with moderate volumes (i.e. >50 GL year^{-1}) sufficient to reduce the proportion of site-years simulated to support degraded ecosystem states, and so indicating a potential improvement in overall ecological condition. However, additional volumes in the range investigated were not sufficient to completely eliminate degraded ecosystem states from the model simulations with 2% of site-years simulated to support degraded ecosystem states even with the addition of 90 GL year^{-1} from the USED scheme. The additional water was also insufficient to trigger the increased presence of the Healthy Hypersaline state, which is associated with high barrage flow conditions. This suggests that the effect of increasing USED flows did not replicate the effect of increasing barrage flows, at least in the ranges investigated.

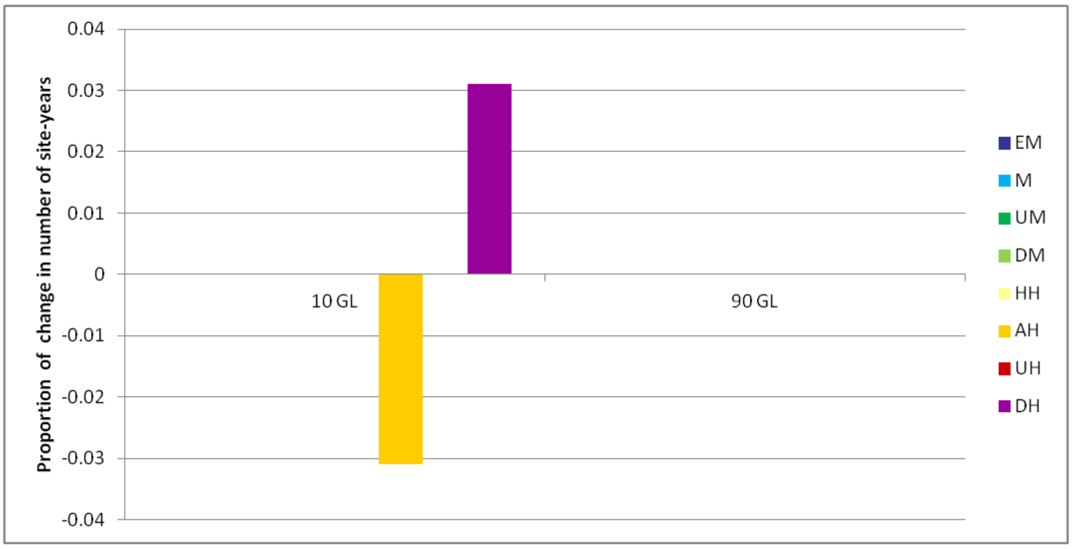

Figure 17: Deviation in the proportion of site-years in each ecosystem state compared to the Baseline scenario for the comparison of increasing USED flow volumes Note: 10 GL is the medium barrage & low SE flows, medium salinity scenario (Scenario 2), 90 GL is the medium barrage & high SE flows, medium salinity scenario (Scenario 3; Table 1)

3.4 Research Question 3: Effect of changes in barrage flow volumes

Figures 18 to 20 illustrate the impact of barrage flows on the average seasonal cycles of salinity and water level in the North and South Lagoons with USED flow volume fixed at 50 GL $year^{-1}$ and USED salinity at 10 g L^{-1}. For the salinity plots, time series are presented for the salinity in the cells at either end of the main body of each lagoon which illustrate the significant long-lagoon variation (Figures 18 and 19). In contrast, average water level tended to be fairly uniform at each time so only the average water level in each lagoon was plotted (Figure 20).

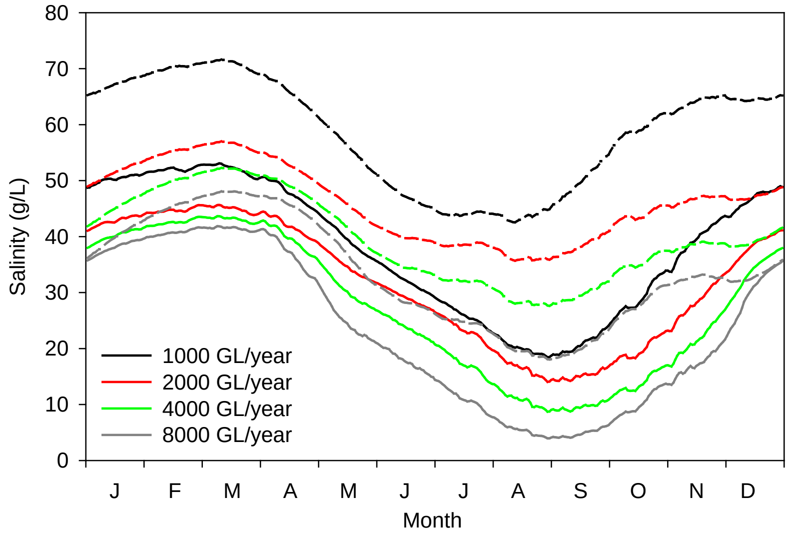

Figure 18: Average yearly cycle of salinity in North Lagoon as a function of barrage flow volume with USED flow of 50 GL year^{-1} and USED salinity of 10 g L^{-1} See Figure 10 for additional explanatory detail

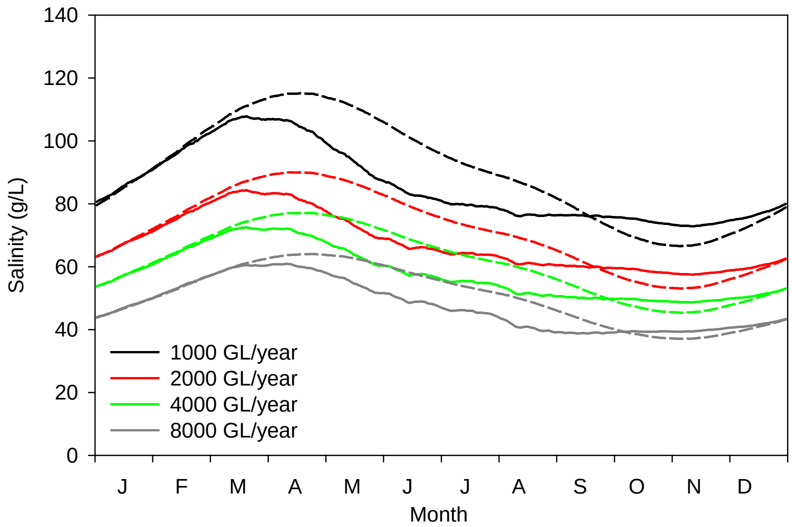

Figure 19: Average yearly cycle of salinity in South Lagoon as a function of barrage flow volume with USED flow of 50 GL year^{-1} and USED salinity of 10 g L^{-1} See Figure 11 for additional explanatory detail

Barrage flows clearly had a profound impact on salinity. With the lowest flow volume of 1000 GL, salinities near the south end of the North Lagoon (cell 7) were simulated to reach 70 g L^{-1} (Figure 18), and those in the South Lagoon to exceed 110 g L^{-1} (Figure 19), whereas the 8000 GL year^{-1} flow volume was predicted to reduce maximum North and South Lagoon salinities to less than 50 g L^{-1} and less than 60 g L^{-1} respectively. Salinity was simulated to always increase significantly away from the Mouth between cells 4 and 7 in the North Lagoon. In the South Lagoon, however, salinity was fairly uniform across the main body during summer. A significant long-lagoon gradient established in the South Lagoon in autumn when relatively lower salinity water flowed into its north end from the North Lagoon as sea level commenced its seasonal rise. The gradient was reversed once the USED flow commences and started to freshen the south end of the lagoon.

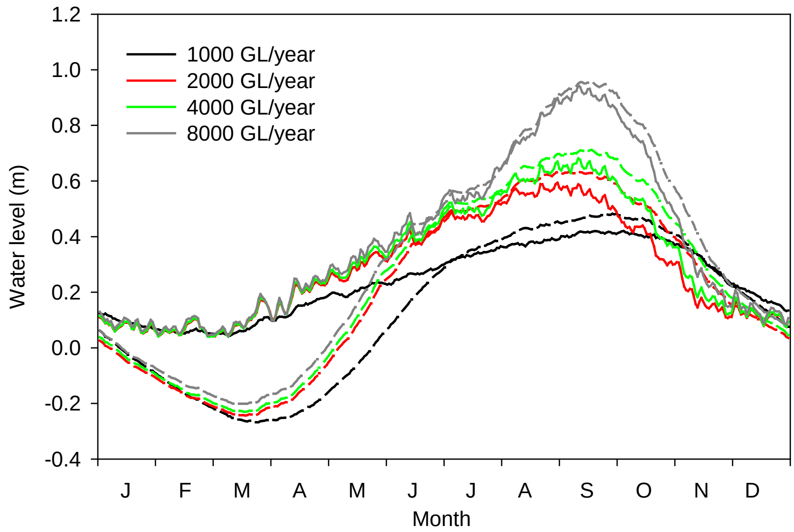

Figure 20: Average yearly cycle of water level in North Lagoon (solid line) and in South Lagoon (dashed line) as a function of barrage flow volume with USED flow of 50 GL year^{-1} and USED salinity of 10 g L^{-1}

Between December and March, water levels in both lagoons were not significantly affected by the barrage flow (Figure 20). Sea levels in the North Lagoon started to rise again in March and these levels were pushed up further by the barrage flows when they commenced in April. After the channel connecting the two lagoons was re-flooded, water levels in the two lagoons started to rise together. It was apparent that water level peaks in both the North and South Lagoons increased proportionally with barrage flows (i.e. the higher the barrage flow the higher the water level peak). This occurred in early spring (i.e. coinciding with peak barrage outflow). With a barrage flow volume of 8000 GL, the water level was simulated to reach almost +1 m AHD in the North Lagoon, which is at the full height of the barrages. If the water level ever reached this height, then barrage flow would necessarily stop, as occurs naturally at times of very high flow in the Coorong. Thus, for this scenario the water level predictions should be discounted.

When the effect of changes in barrage flow volumes was investigated, there was little influence on depth from two years previous and average water levels (Figure 21). The hydrodynamic driver of ecosystem states with that varied most was maximum salinity. For maximum salinity, conditions became less saline as increased volumes of barrage flow were added. The median maximum salinity declined from 80 g L^{-1} under the 1000 GL year^{-1} scenario to 62 g L^{-1} under the 2000 GL year^{-1} (Baseline) scenario and 56 g L^{-1} under the 4000 GL year^{-1} scenario. The median values for the annual range in water level were also highest with the greatest volume of barrage flow added (i.e. 4000 GL), at 1.12 m.

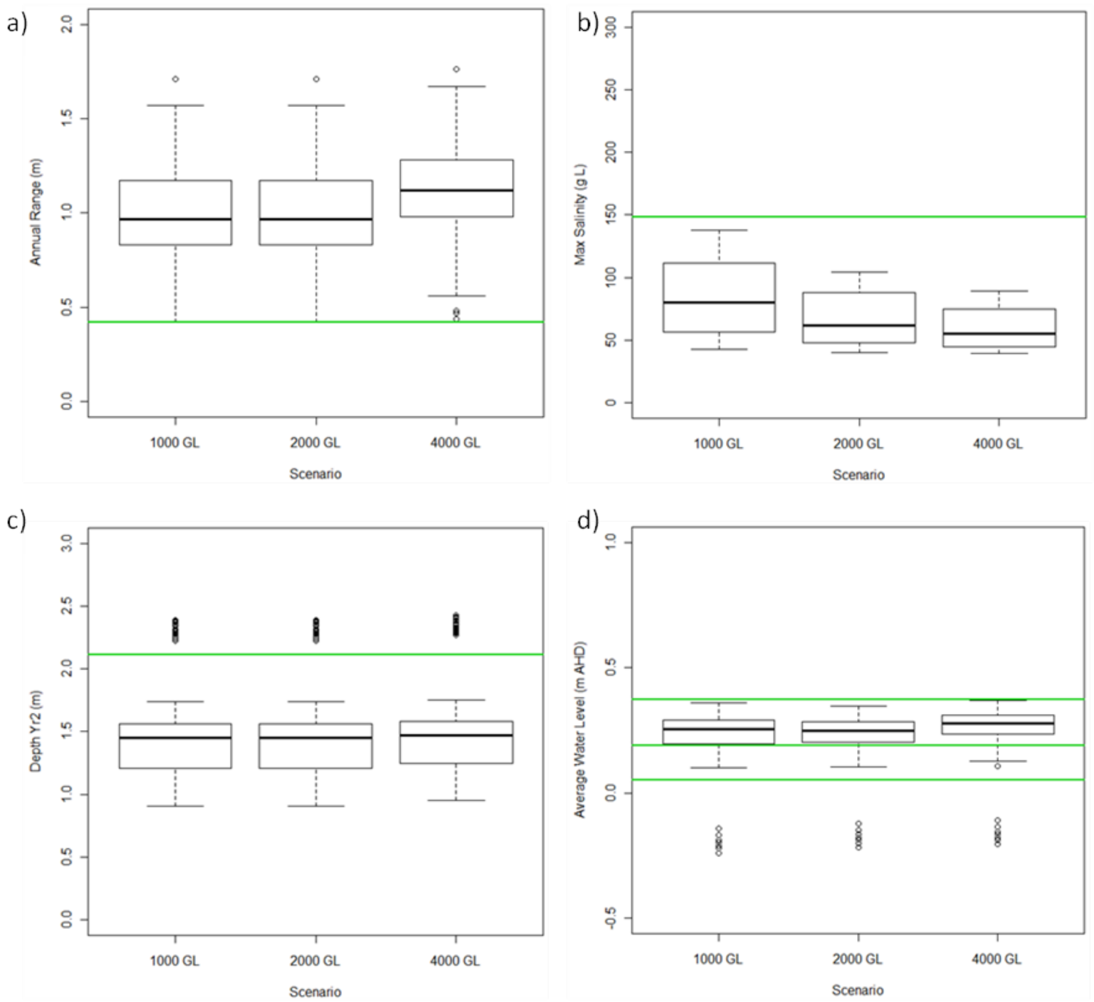

Figure 21: Boxplots showing the distributions of values for each of the variables driving the ecosystem states of the Coorong for the effect of decreasing barrage flow volume scenarios. a) Annual range in water level (m), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Average water level (m AHD) Note: 1000 GL is the low barrage & medium SE flows, medium salinity scenario (Scenario 4), 2000 GL is the medium barrage & medium SE flows, medium salinity scenario (Baseline scenario, Scenario 1) and 4000 GL is the high barrage & medium SE flows, medium salinity scenario (Scenario 5; Table 1)

There was a positive cumulative difference in North Lagoon hydrodynamic drivers, increasing in magnitude with increasing volumes of barrage flow (Figure 22). This represented an improvement in both average water levels and depth from two years previous, compared to the Baseline scenario (i.e. which had a 2000 GL $year^{-1}$ barrage flow volume). This difference is somewhat counterintuitive, given the improvement in water levels and depths with a smaller barrage flow overall (i.e. 1000 GL $year^{-1}$ compared with 2000 GL $year^{-1}$). This is a phenomenon that we have encountered before, and it is a result of the complex interaction between the effect of barrage flows on holding water above local sea levels and in scouring out the Murray Mouth. Thus, there is not always a linear improvement in water levels and depths as a result of higher barrage flows (Webster et al. 2012).

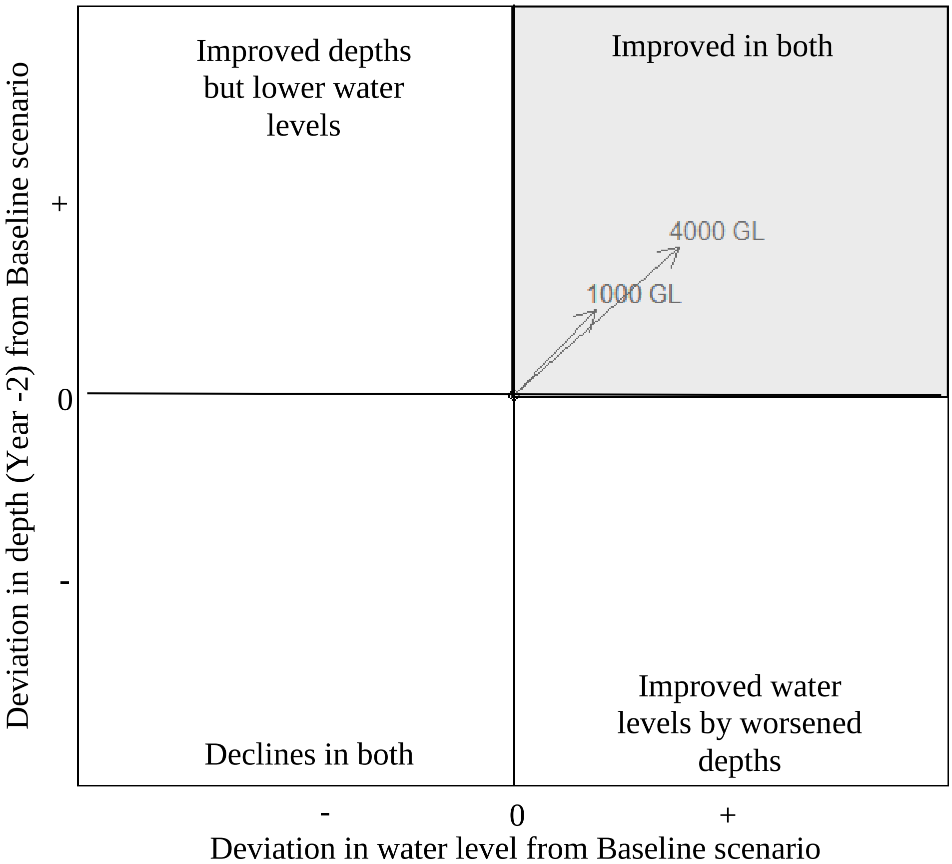

Figure 22: Comparison of the effect of decreasing barrage flow volume scenarios for the North Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline 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 Baseline scenario condition (as shown by the 0,0 origin). Vectors in the top-right quadrant indicate an improvement for both variables (i.e. higher water levels and greater depths). 1000 GL is the low barrage & medium SE flows, medium salinity scenario (Scenario 4), and 4000 GL is the high barrage & medium SE flows, medium salinity scenario (Scenario 5; Table 1)

In contrast, the cumulative impact on South Lagoon hydrodynamics compared to the Baseline scenario varied with the volume of barrage flow delivered (Figure 23). With a lower barrage flow volume of 1000 GL delivered per year, there was deterioration in both maximum salinity (i.e. it was higher) and average water level (i.e. it was lower) compared to baseline conditions of 2000 GL year^{-1} of barrage flow. However, with increased barrage flows (i.e. 4000 GL year^{-1}) there was an improvement in both maximum salinity and average water levels.

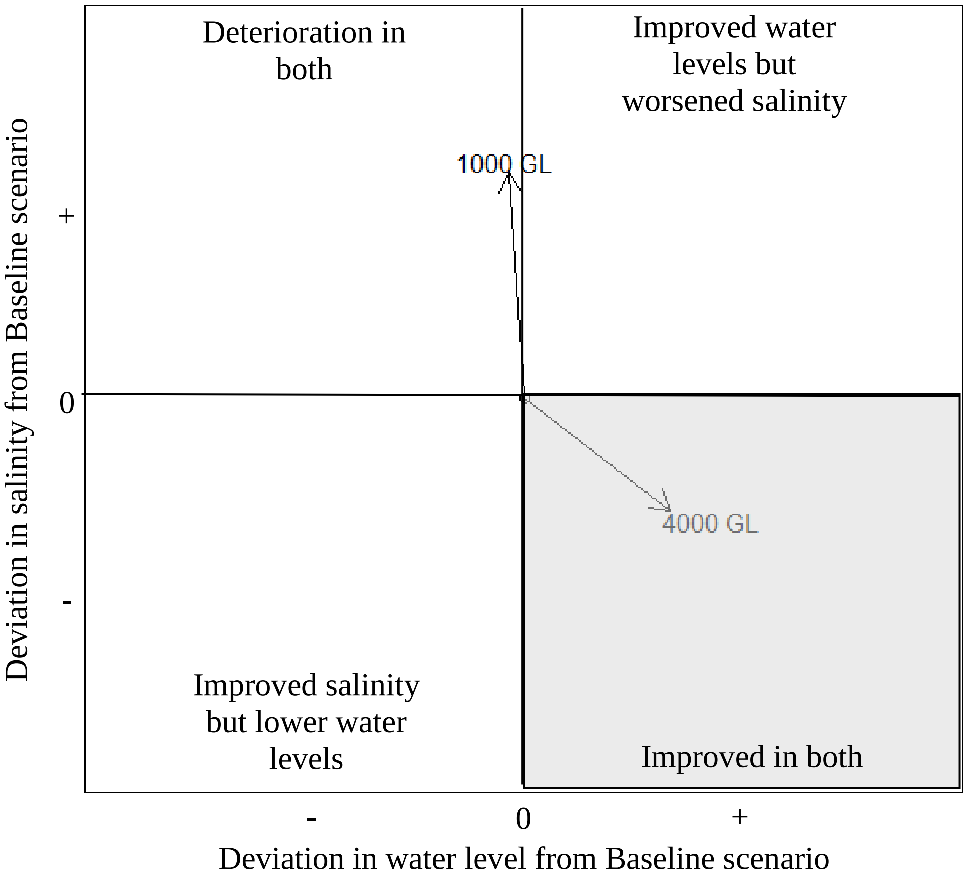

Figure 23: Comparison of the effect of decreasing barrage flow volume scenarios for the South Lagoon
This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Baseline scenario condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant indicate an improvement for both variables (i.e. higher water levels and lower salinities). 1000 GL is the low barrage & medium SE flows, medium salinity scenario (Scenario 4) and 4000 GL is the high barrage & medium SE flows, medium salinity scenario (Scenario 5; Table 1)

Despite improvement in the hydrodynamic drivers under increased barrage flow conditions, there was no deviation in the proportion of ecosystem states between the 4000 GL year^{-1} and the Baseline scenario (i.e. 2000 GL year^{-1}; Figure 24). The reduction of barrage flow to 1000 GL year^{-1} had a small influence on the relative proportions of the ecosystem states. As for USED flows, barrage flows in the range explored had some impact on the ecosystem states of the Coorong. However, even the maximum volume explored here was not sufficient prevent degraded ecosystem states, with 2% of site-years simulated to support degraded ecosystem states even with the addition of 4000 GL year^{-1} of barrage flow. This reflects the importance of the timing of barrage flows, as well as volume, in preventing degraded ecosystem states.

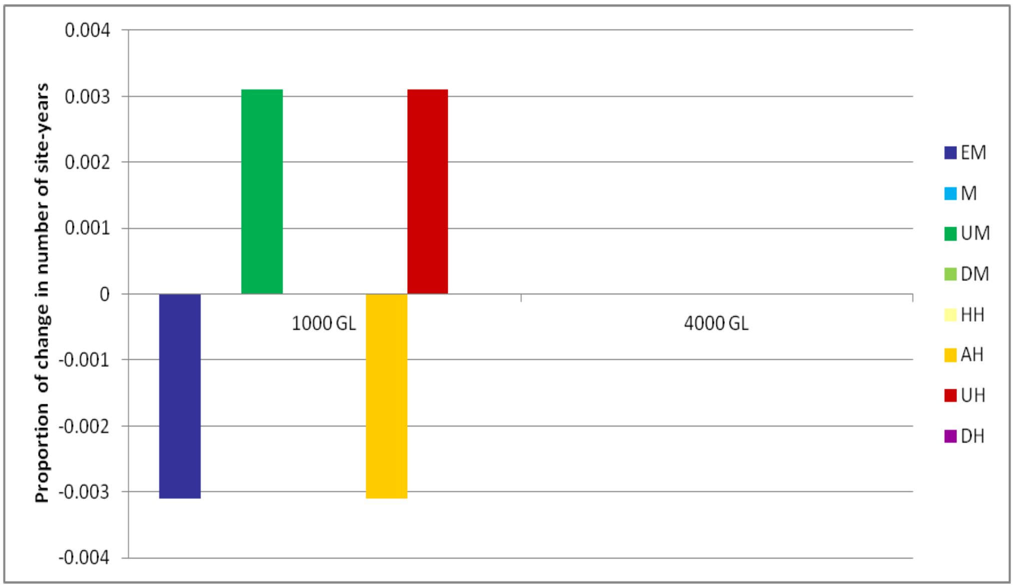

Figure 24: Deviations in the proportion of site-years in each ecosystem state compared to the Baseline scenario for the comparison of decreasing barrage flow volumes Note: 1000 GL is the low barrage & medium SE flows, medium salinity scenario (Scenario 4), 4000 GL is the high barrage & medium SE flows, medium salinity scenario (Scenario 5; Table 1)

3.4.1 Co-variation of barrage and USED flow volumes

By running a large number of scenarios in which barrage flows and USED flows varied together, contour plots demonstrating the impact of co-variation of barrage and USED flows were developed. These plots are shown in Figures 25 to 28 for the average salinity in the North and South Lagoons and the maximum and minimum salinity in the South Lagoon, respectively. All results are shown for a USED salinity of 10 g L^{-1} to illustrate indicative relationships.

The graphs have important common features. All the contours had a negative slope meaning that a particular salinity outcome, say an average salinity of 100 g L^{-1}, could be achieved by a series of pairs of barrage and USED flows in which decreasing barrage flows could be compensated for by increasing USED flows and *vice versa*. Thus, an average salinity of 100 g L^{-1} in the South Lagoon would occur for a barrage flow of about 2000 GL $year^{-1}$ and a USED flow of 10 GL $year^{-1}$ or with a barrage flow of 1000 GL $year^{-1}$ and a USED flow of about 40 GL $year^{-1}$ (Figure 25).

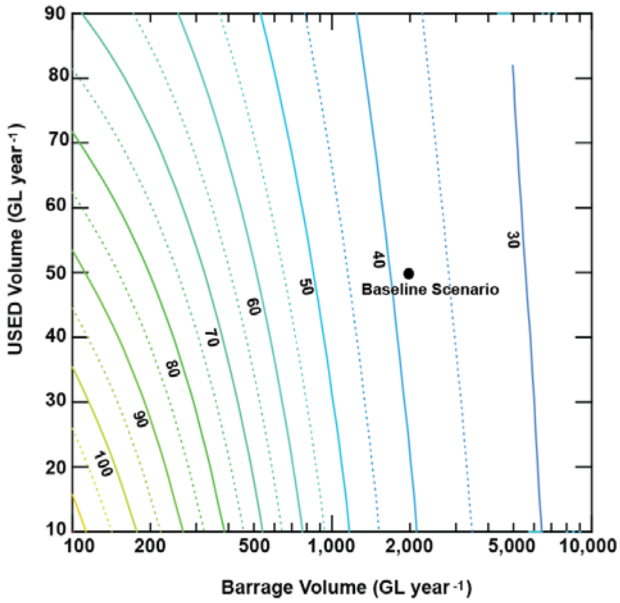

Figure 25: Average salinity in the North Lagoon as a function of USED and barrage flow volumes. USED salinity is fixed at 10 g L^{-1} Note: the x-axis is a log scale

It was also apparent the sensitivity of salinity outcomes changed over the flow ranges on both axes. Thus, at large barrage flows the contour lines become more vertical which reflected a decreasing sensitivity of salinity to variation in USED flows. The salinity contours for the North Lagoon (Figure 25) are much more vertical than those for the South Lagoon (Figure 26) which is consistent with our previous finding that the North Lagoon was less sensitive to variation in USED flows than the South Lagoon (see Research Question 1). As one might also expect, as barrage flows diminished (i.e. on the left hand sides of plots) the contours became less vertical; that is, USED flow volumes increased in importance for achieving a particular salinity statistic whether it be average, minimum, or maximum salinity when barrage flows were small. This pattern was consistent across the maximum average salinity in the South Lagoon (Figure 27) and the minimum average salinity in the same lagoon (Figure 28).

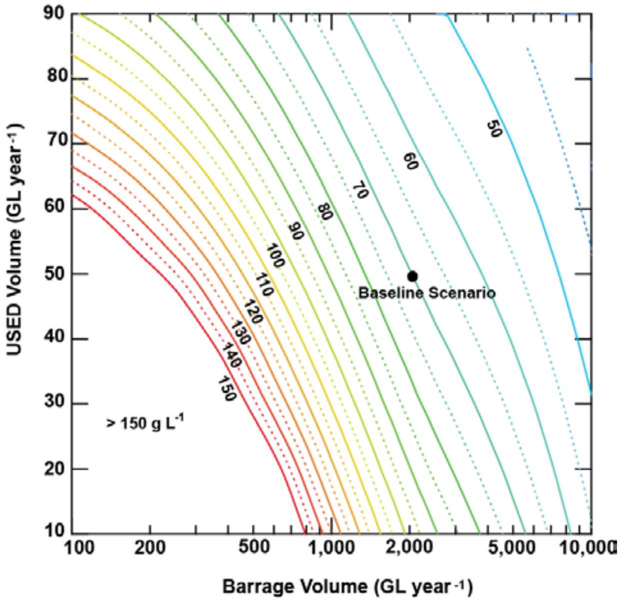

Figure 26: Average salinity in the South Lagoon as a function of USED and barrage flow volumes. USED salinity is fixed at 10 g L^{-1} Note: the x-axis is a log scale

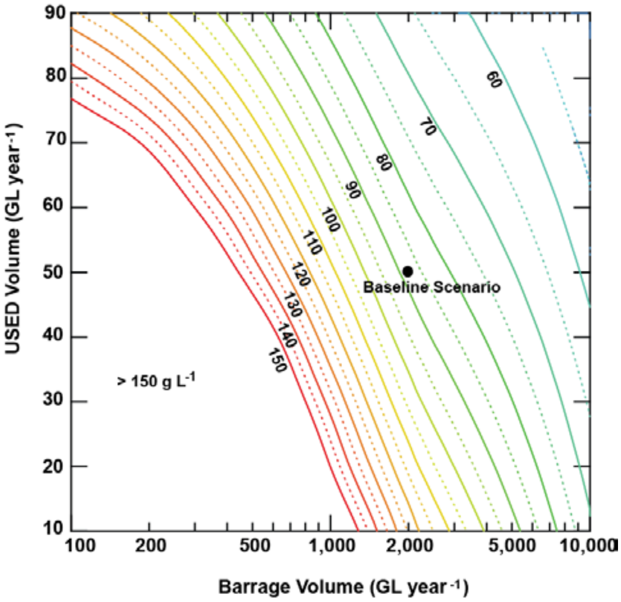

Figure 27: Maximum average salinity in the South Lagoon as a function of USED and barrage flow volumes. USED salinity is fixed at 10 g L^{-1} Note: the x-axis is a log scale

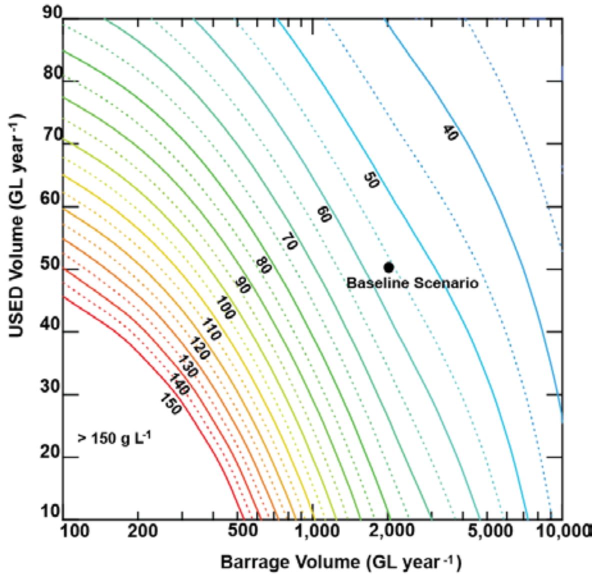

Figure 28: Minimum average salinity in the South Lagoon as a function of USED and barrage flow volumes. USED salinity is fixed at 10 g L^{-1} Note: the x-axis is a log scale

3.5 Research Question 4: Effect of USED salinity

Figures 29 and 30 illustrate the impact of USED salinity on the average seasonal cycle of salinity in the North and South Lagoons. Barrage flow volume was fixed at 2000 GL year^{-1} and USED flow volume at 50 GL year^{-1}. In the North Lagoon, the largest impact of increasing USED salinity from 0 to 15 g L^{-1} appeared at the south end of the lagoon, but even then, the impact on salinity was less than 10 g L^{-1}. The impact on salinity at the north end of the North Lagoon was even smaller (Figure 29). In the South Lagoon, a USED salinity of 15 g L^{-1} increased salinity at all sites at all times of the year by between 10 and 15 g L^{-1} compared to the case of USED salinity of 0 g L^{-1}.

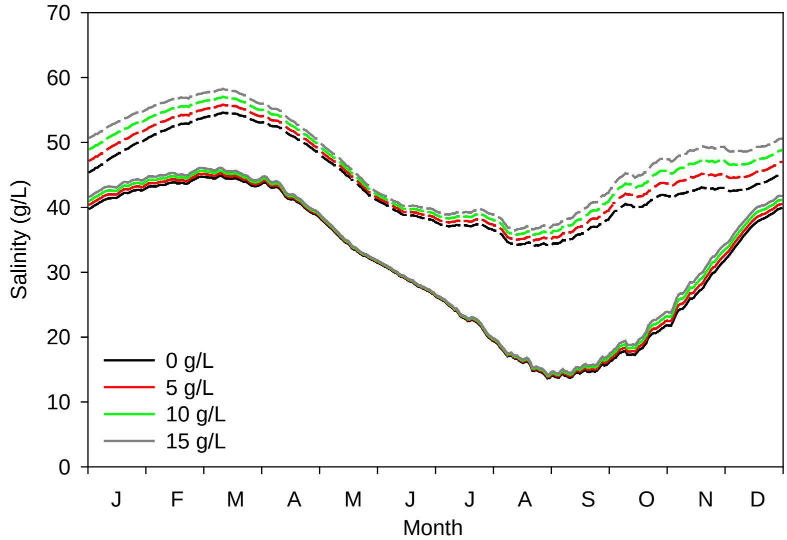

Figure 29: Average yearly cycle of salinity in North Lagoon as a function of USED salinity with barrage flow of 2000 GL year^{-1} and USED flow volume of 50 GL year^{-1} See Figure 10 for additional explanatory detail

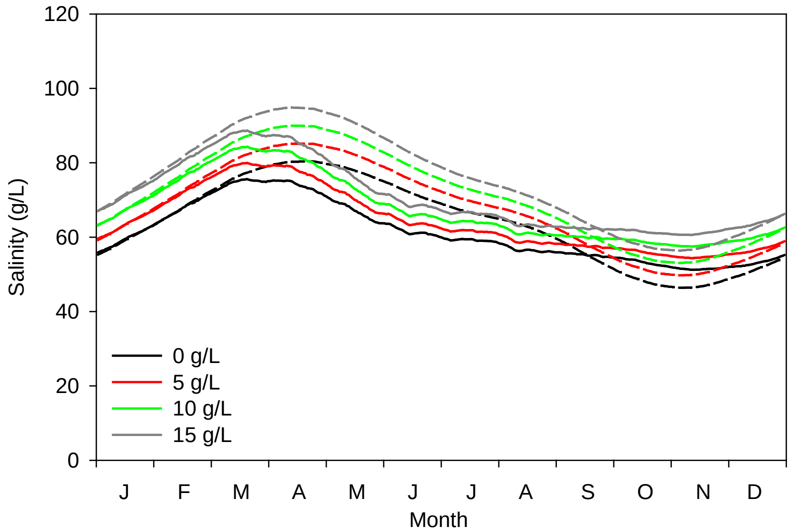

Figure 30: Average yearly cycle of salinity in South Lagoon as a function of USED salinity with barrage flow of 2000 GL year^{-1} and USED flow volume of 50 GL year^{-1} See Figure 11 for additional explanatory detail

3.5.1 Effect of USED salinity under low barrage & medium SE flow conditions

When the effect of USED salinity was investigated under low barrage and medium SE flow conditions, there was little influence on annual range in water levels, depth from two years previous or average water levels (Figure 31). There were small changes in maximum salinity, with median maximum salinity increasing with increased USED salinity. Median maximum salinity increased from 77 g L^{-1} under low

USED salinity conditions, to 80 g L^{-1} under moderate USED salinity conditions, and to 83 g L^{-1} under high USED salinity conditions.

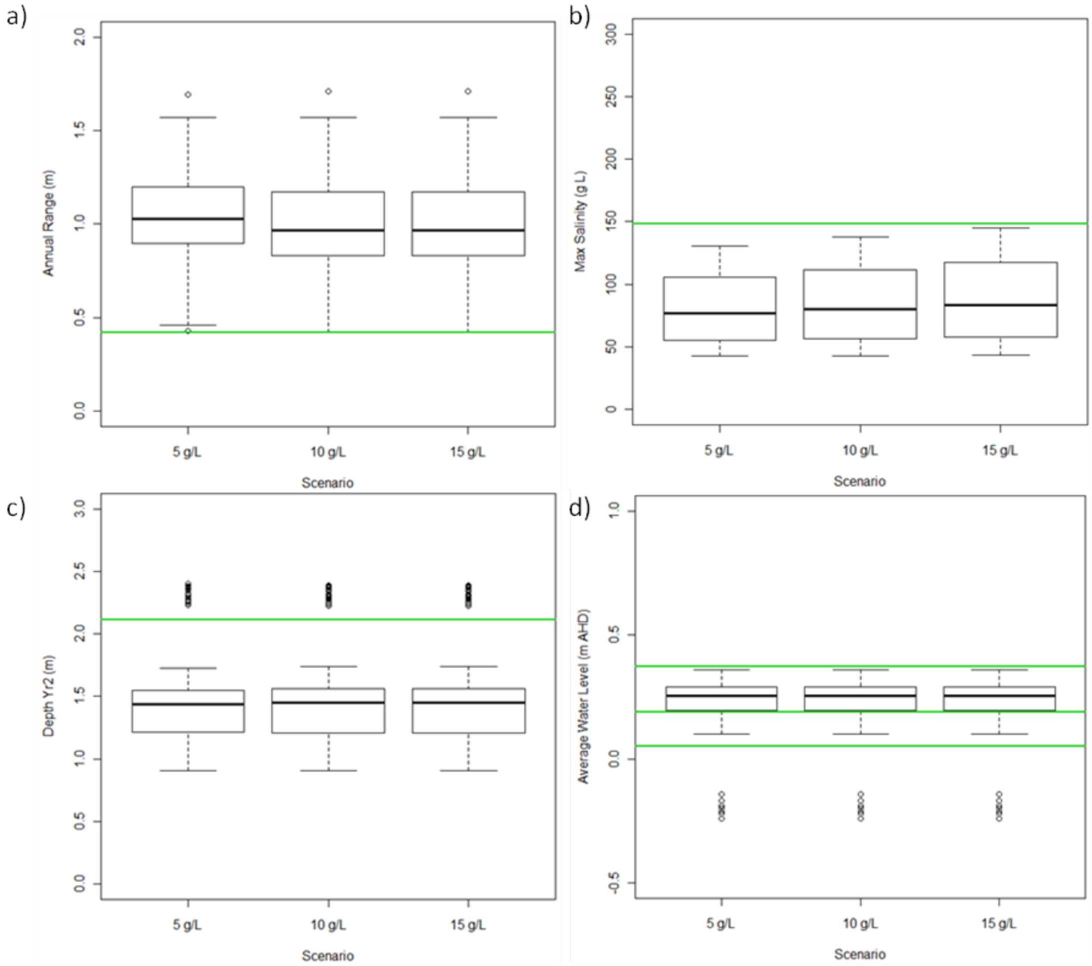

Figure 31: Boxplots showing the distributions of values for each of the variables driving the ecosystem states of the Coorong for the effect of USED salinity scenarios. a) Annual range in water level (m), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Average water level (m AHD) Note: 5 g L^{-1} is the low barrage & medium SE flows, low salinity scenario (Scenario 6), 10 g L^{-1} is the low barrage & medium SE flows, medium salinity scenario (Scenario 4) and 15 g L^{-1} is the low barrage & medium SE flows, high salinity scenario (Scenario 7; Table 1)

There was a small positive cumulative difference in North Lagoon hydrodynamic drivers under moderate USED salinity conditions (i.e. 10 g L^{-1}; Figure 32), largely as a result of the differences in barrage flows in this scenario compared to the Baseline (see Figure 22), rather than as a result of changing USED salinity.

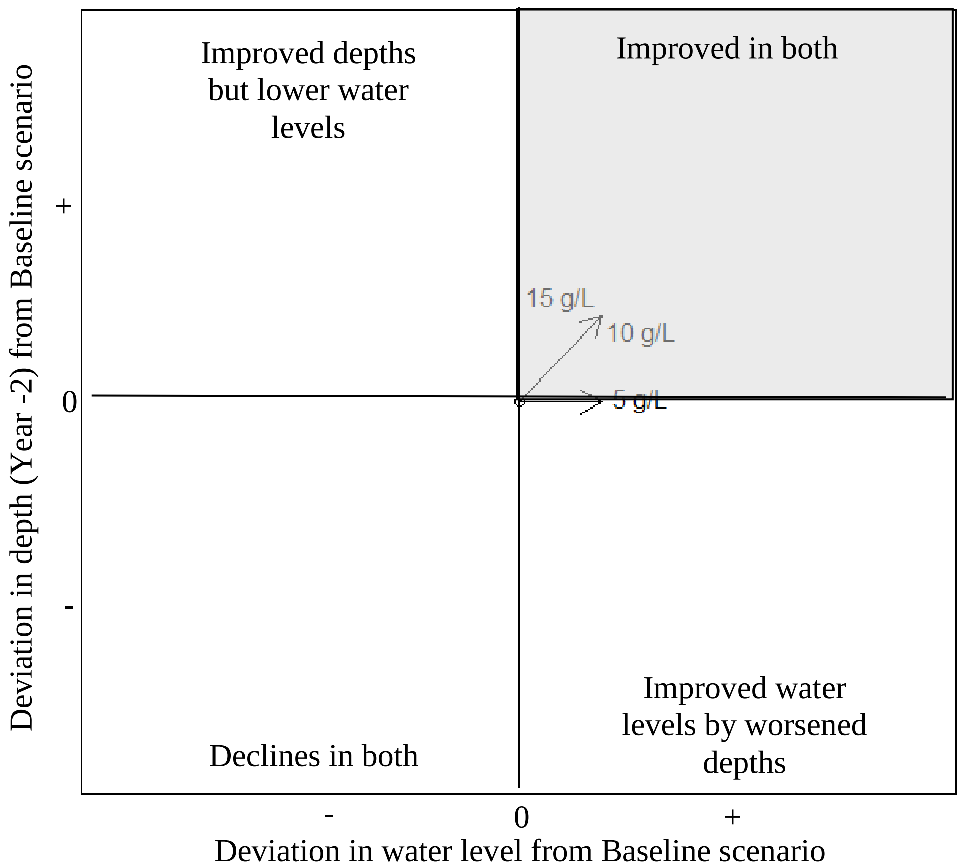

Figure 32: Comparison of the effect of USED salinity for the North Lagoon
This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline scenario with respect to water levels and depths (with depths from two years previously). Length of each vector is proportional to the strength of the deviation from the Baseline scenario condition (as shown by the 0,0 origin). Vectors in the top-right quadrant indicate an improvement for both variables (i.e. higher water levels and greater depths). 5 g L^{-1} is the low barrage & medium SE flows, low salinity scenario (Scenario 6), 10 g L^{-1} is the low barrage & medium SE flows, medium salinity scenario (Scenario 4) and 15 g L^{-1} is the low barrage & medium SE flows, medium salinity scenario (Scenario 7)

The cumulative impact of altered USED salinity on South Lagoon hydrodynamics was negative, with all three scenarios showing deterioration in both maximum salinity and water levels when compared to the Baseline scenario (Figure 33). Again, changes in water level were a result of lower barrage flows in the three scenarios shows, compared to the Baseline scenario. However, the deterioration in maximum salinity increased with increased USED salinity conditions, as shown by the length of the vector shown for each scenario. The relative difference attributable to changes in USED salinity for a change of up to 10 g L^{-1} was approximately equivalent to the change associated with an increase in barrage flows from 1000 to 2000 GL $year^{-1}$.

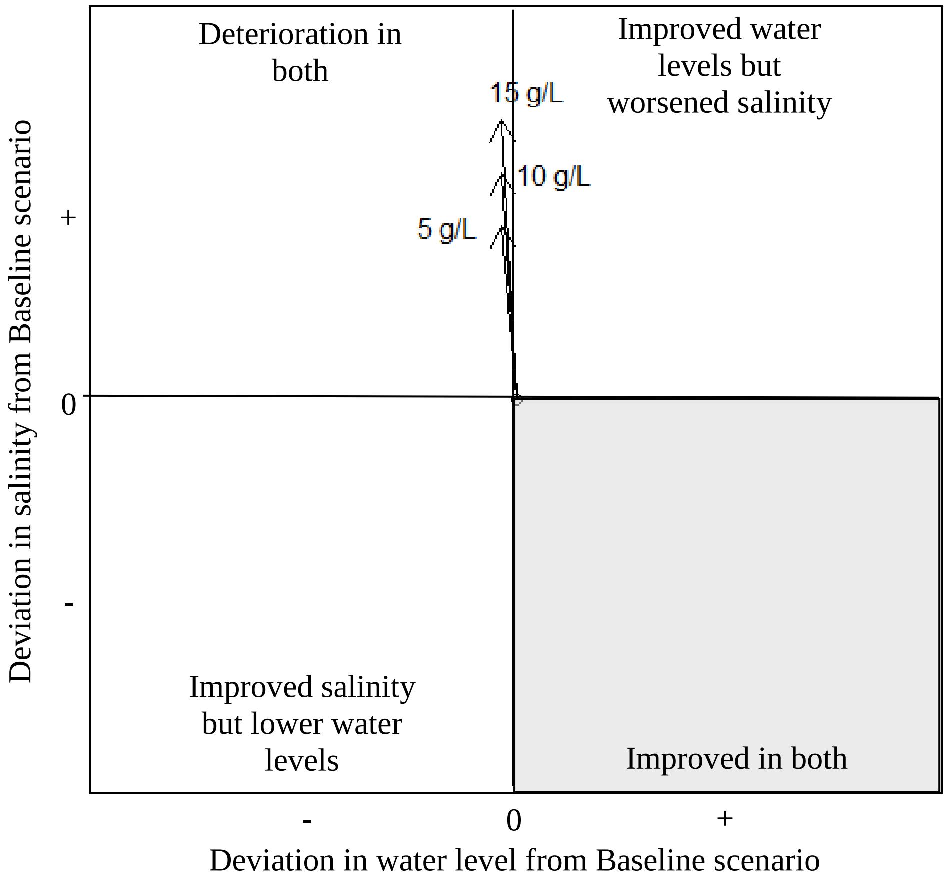

Figure 33: Comparison of the effect of USED salinity for the South Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Baseline scenario condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant indicate an improvement for both variables (i.e. higher water levels and lower salinities). 5 g L^{-1} is the low barrage & medium SE flows, low salinity scenario (Scenario 6), 10 g L^{-1} is the low barrage & medium SE flows, medium salinity scenario (Scenario 4) and 15 g L^{-1} is the low barrage & medium SE flows, medium salinity scenario (Scenario 7)

The effect of increased USED salinity conditions had little effect on the relative proportions of ecosystem states (Figure 34). This meant that each scenario had an almost identical mix of ecosystem states to the Baseline (see Figure 16). Under each scenario, the changes from Estuarine/Marine to Unhealthy Marine and from Average Hypersaline to Unhealthy Hypersaline were very small. This indicates that that increasing USED salinity had some impact on the ecosystem states of the Coorong, but within the salinity range investigated (i.e. up to 15 g L^{-1}) there was no potential to completely eliminate degraded ecosystem states. From all model simulations here, 2% of site-years were simulated to support degraded ecosystem states regardless of USED salinity.

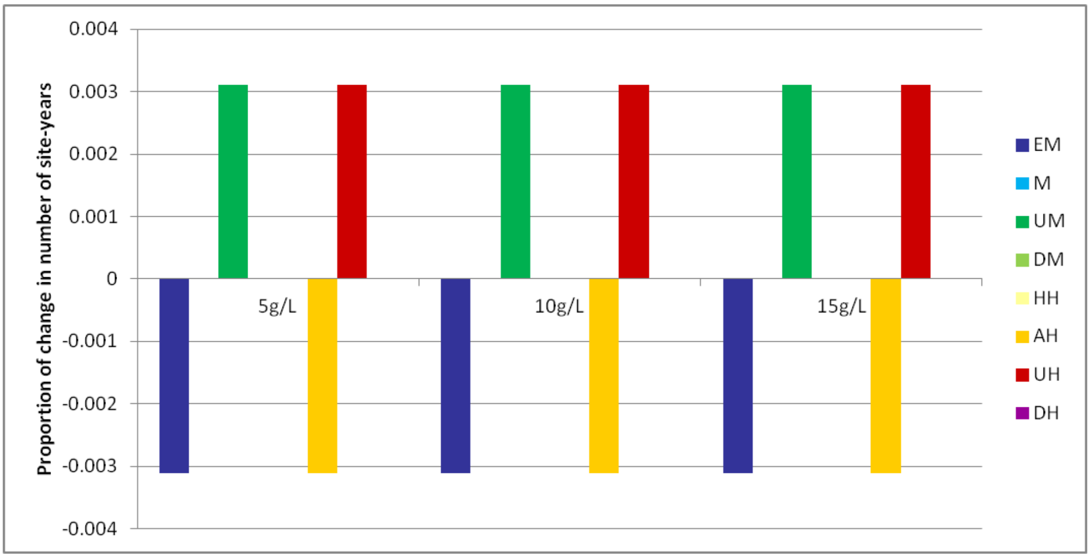

Figure 34: Deviations in the proportion of site-years in each ecosystem state compared to the Baseline scenario for the comparison of USED salinity

Note: 5 g L^{-1} is the low barrage & medium SE flows, low salinity scenario (Scenario 6), 10 g L^{-1} is the low barrage & medium SE flows, medium salinity scenario (Scenario 4) and 15 g L^{-1} is the low barrage & medium SE flows, high salinity scenario (Scenario 7; Table 1)

3.5.2 Effect of USED salinity under medium barrage & low SE flow conditions

When the effects of USED salinity were compared under medium barrage and low SE flow conditions, there was little influence on any of the four hydrodynamic drivers (Figure 35).

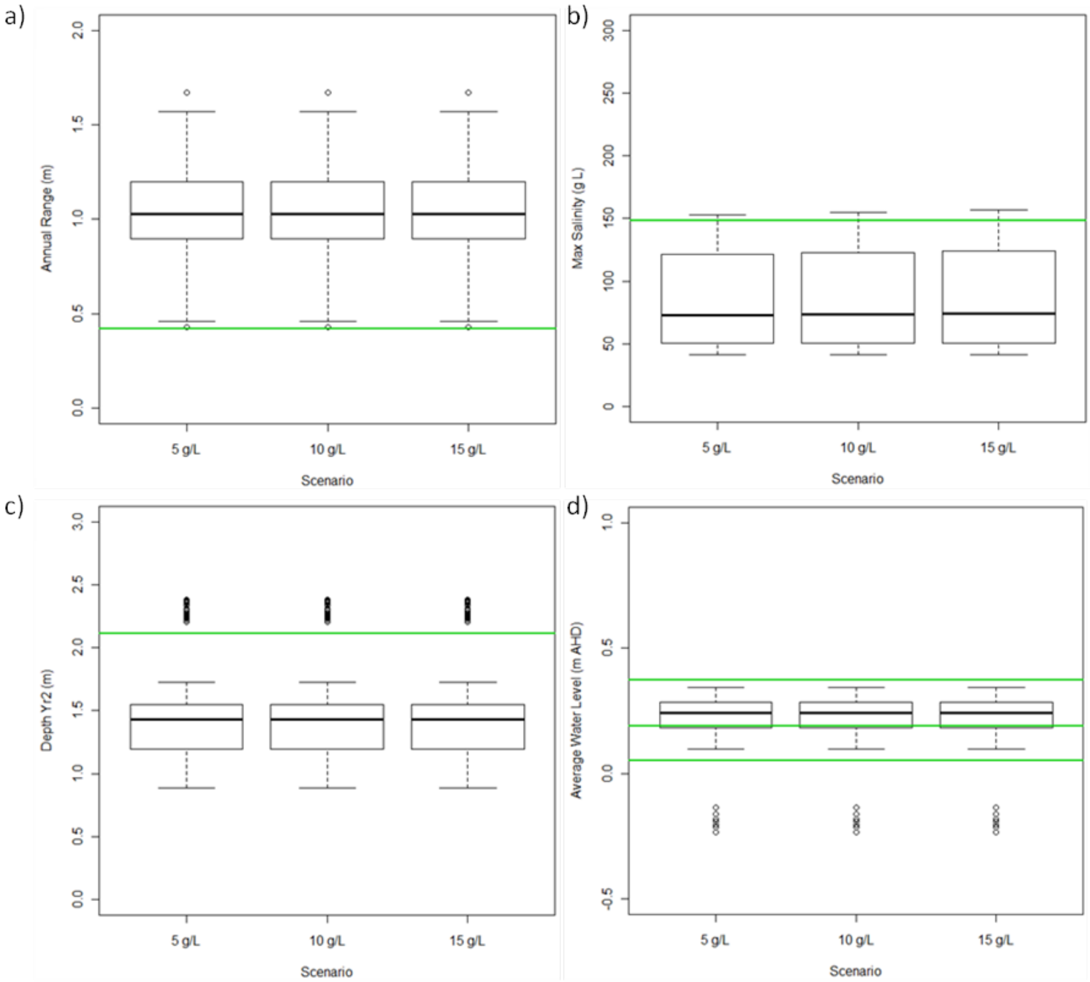

Figure 35: Boxplots showing the distributions of values for each of the variables driving the ecosystem states of the Coorong for the effect USED salinity scenarios. a) Annual range in water level (m), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Average water level (m AHD) Note: 5 g L^{-1} is the medium barrage & low SE flows, low salinity scenario (Scenario 8), 10 g L^{-1} is the medium barrage & low SE flows, medium salinity scenario (Scenario 2) and 15 g L^{-1} is the medium barrage & low SE flows, high salinity scenario (Scenario 9; Table 1)

There was effectively no cumulative difference in North Lagoon hydrodynamic drivers for any of the scenarios considered under medium barrage and low SE flow conditions (Figure 36).

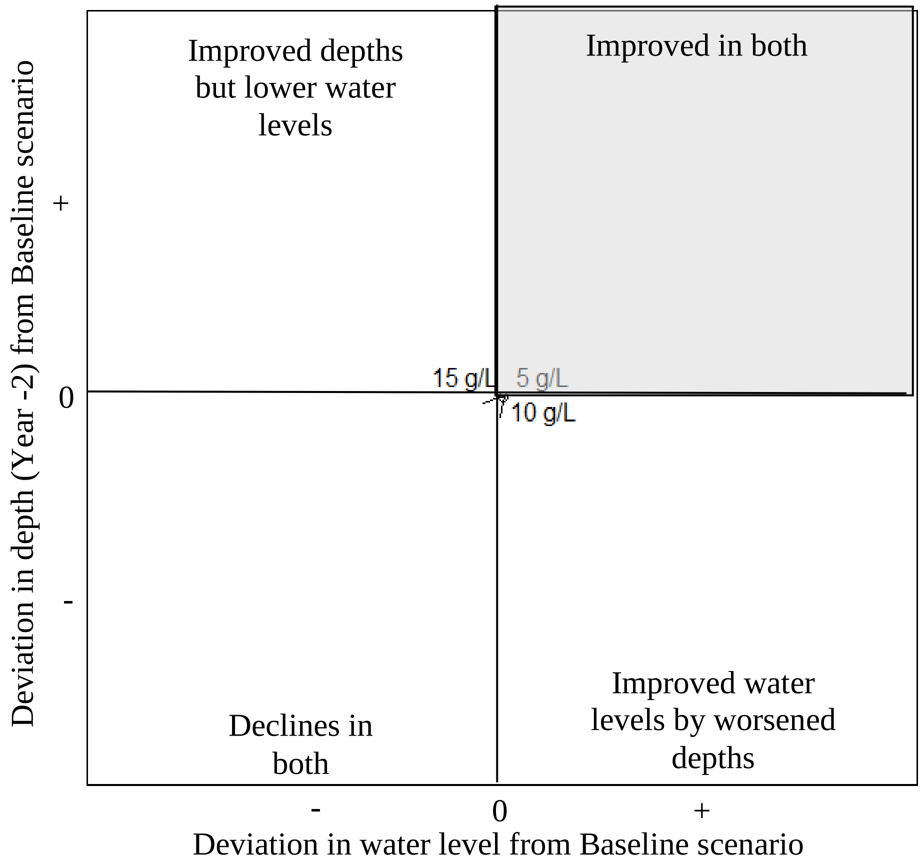

Figure 36: Comparison of the effect of USED salinity for the North Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline 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 Baseline scenario condition (as shown by the 0,0 origin). Vectors in the top-right quadrant indicate an improvement for both variables (i.e. higher water levels and greater depths). 5 g L^{-1} is the medium barrage & low SE flows, low salinity scenario (Scenario 8), 10 g L^{-1} is the medium barrage & low SE flows, medium salinity scenario (Scenario 2) and 15 g L^{-1} is the medium barrage & low SE flows, high salinity scenario (Scenario 9; Table 1)

The cumulative impact on South Lagoon hydrodynamics was more apparent, with deterioration in both maximum salinity and water levels across all three scenarios (Figure 37). This level of deterioration was very similar regardless of the increased USED salinity, with little difference in the size of the vectors across the scenarios.

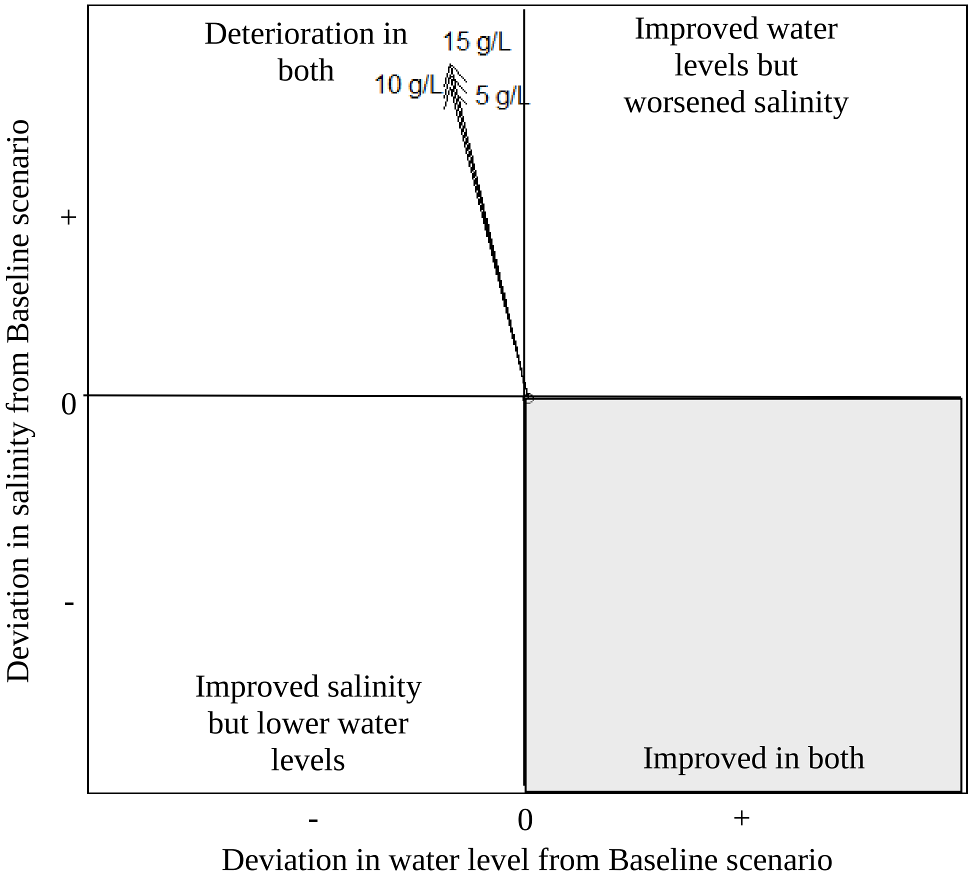

Figure 37: Comparison of the effect of USED salinity for the South Lagoon
This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Baseline scenario condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant indicate an improvement for both variables (i.e. higher water levels and lower salinities). 5 g L^{-1} is the medium barrage & low SE flows, low salinity scenario (Scenario 8), 10 g L^{-1} is the medium barrage & low SE flows, medium salinity scenario (Scenario 2) and 15 g L^{-1} is the medium barrage & low SE flows, high salinity scenario (Scenario 9; Table 1)

There were slight differences in the relative proportions of ecosystem states across the scenarios, when compared to the Baseline scenario (Figure 38). Although these differences were small, the relative change in proportions from the Average Hypersaline ecosystem state to the Degraded Hypersaline state increased with increasing USED salinity. Increasing USED salinities therefore had some impact on the ecosystem states of the Coorong, with small increases in degraded ecosystem states associated with increasing USED salinity.

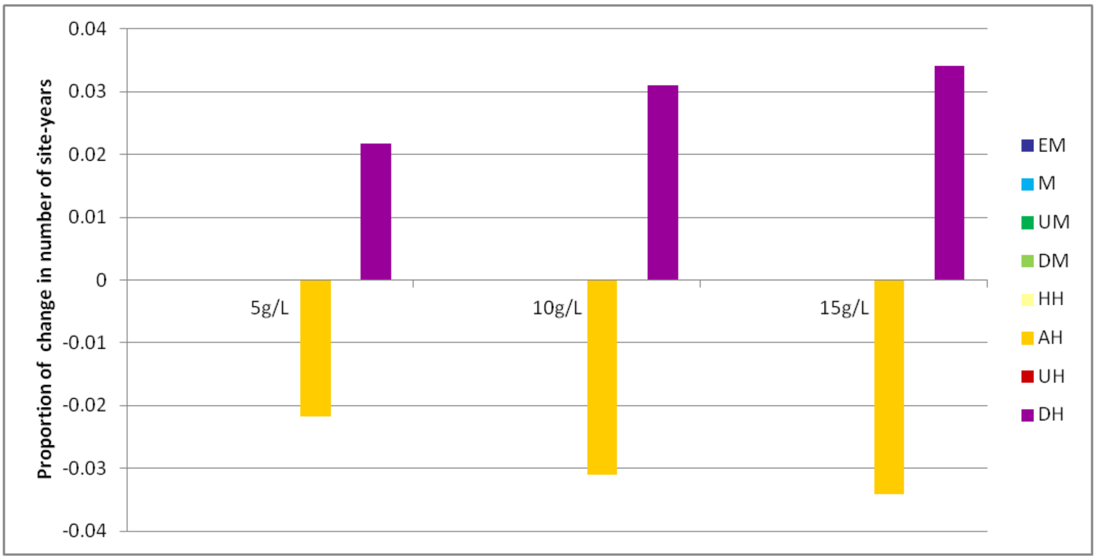

Figure 38: Deviations in the proportion of site-years in each ecosystem state compared to the Baseline scenario for the comparison of USED salinity Note: 5 g L^{-1} is the medium barrage & low SE flows, low salinity scenario (Scenario 8), 10 g L^{-1} is the medium barrage & low SE flows, medium salinity scenario (Scenario 2) and 15 g L^{-1} is the medium barrage & low SE flows, high salinity scenario (Scenario 9; Table 1)

3.5.3 Effect of USED salinity under medium barrage & SE flow conditions

Under medium barrage and SE flow conditions, changing USED salinities had little influence on the hydrodynamic drivers of depth from two years previous and water levels (Figure 39). The driver with the largest change (although also small) was maximum salinity. For median maximum salinity, there was a small increase with increased USED salinity, at 60 g L^{-1}, 62 g L^{-1} and 64 g L^{-1}, under USED salinities of 5 g L^{-1}, 10 g L^{-1} and 15 g L^{1}, respectively.

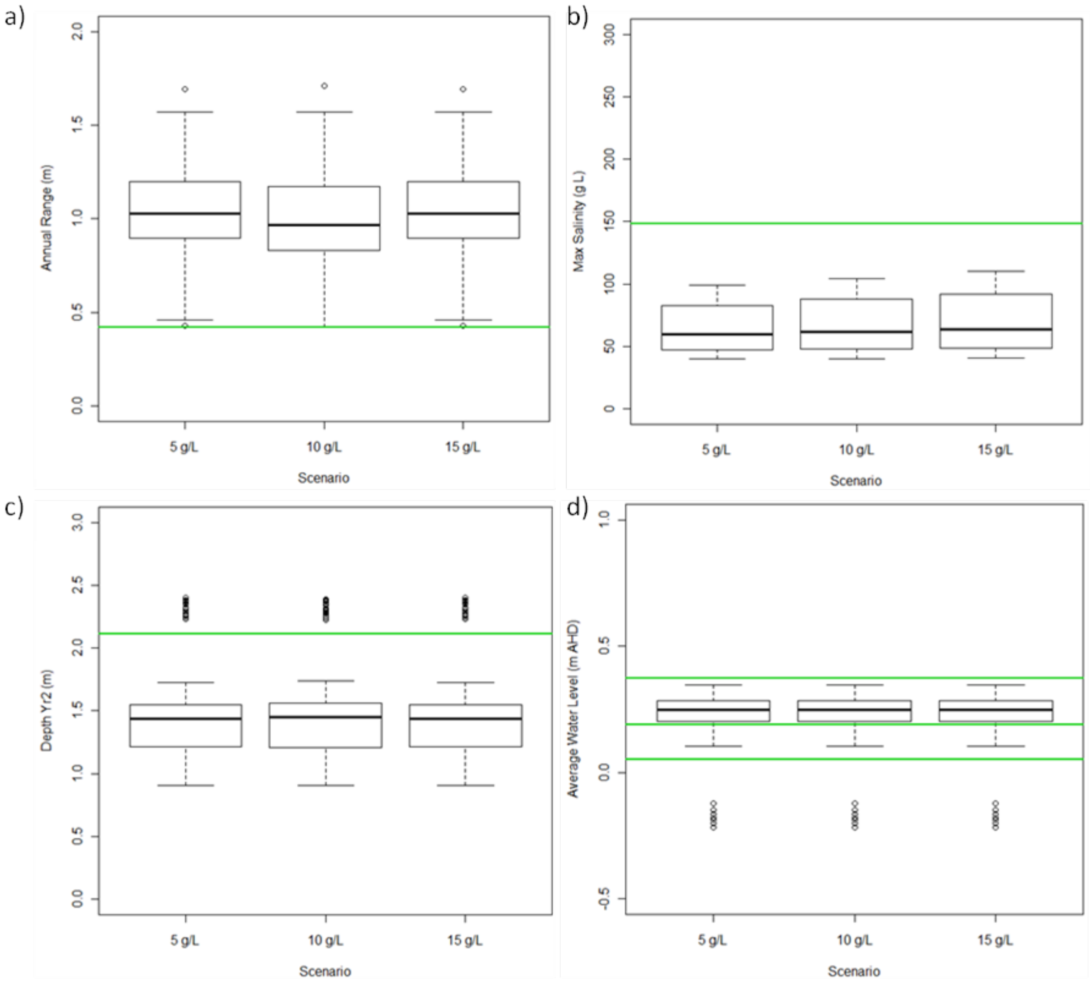

Figure 39: Boxplots showing the distributions of values for each of the variables driving the ecosystem states of the Coorong for the effect of USED salinity scenarios. a) Annual range in water level (m), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Average water level (m AHD)

Note: 5 g L^{-1} is the medium barrage & SE flows, low salinity scenario (Scenario 10), 10 g L^{-1} is the medium barrage & SE flows, medium salinity scenario (Baseline scenario, Scenario 1) and 15 g L^{-1} is the medium barrage & SE flows, high salinity scenario (Scenario 11; Table 1)

There was no cumulative difference in North Lagoon hydrodynamics across the salinity scenarios under medium barrage and SE flows (not shown). The cumulative impact on South Lagoon hydrodynamics was also small (Figure 40). There was an improvement in maximum salinity but no deviation in water levels under high salinity conditions compared to the Baseline scenario (i.e. including a USED salinity of 10 g L^{-1}), as would be expected. Also intuitively, under low USED salinity conditions, there was an improvement in maximum salinity but no deviation in water levels from the Baseline scenario.

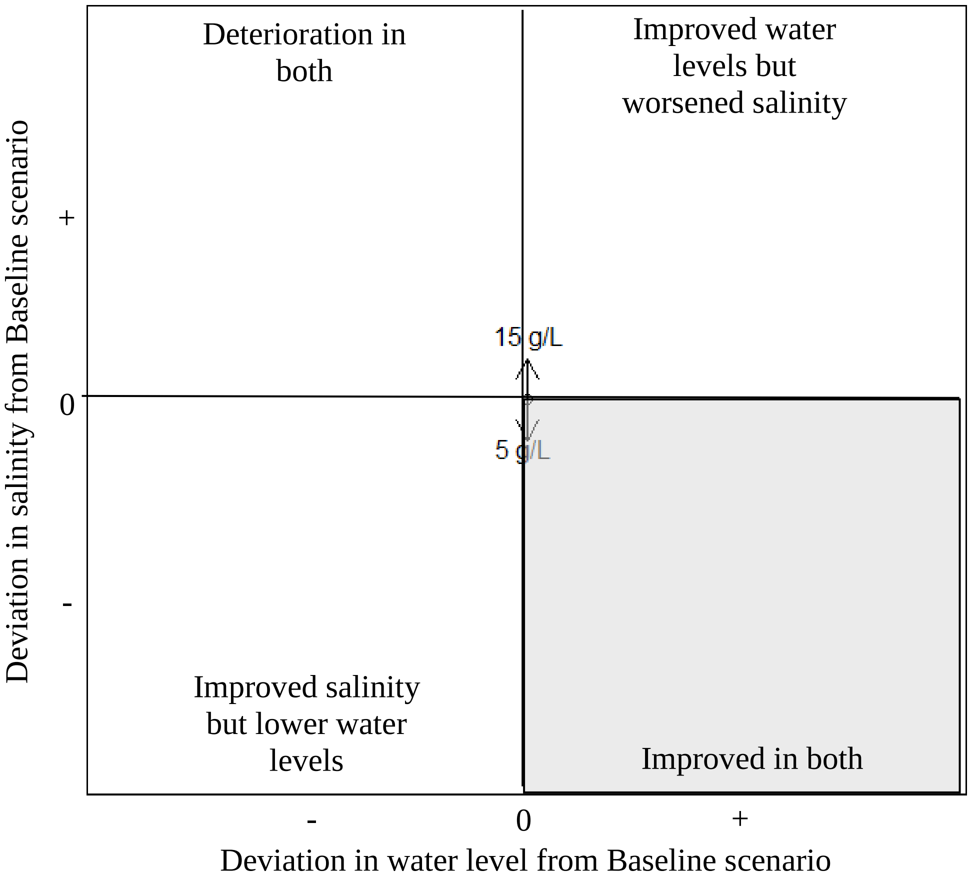

Figure 40: Comparison of the effect of USED salinity for the South Lagoon
This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Baseline scenario condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant indicate an improvement for both variables (i.e. higher water levels and lower salinities). Note: 5 g L^{-1} is the medium barrage & SE flows, low salinity scenario (Scenario 10) and 15 g L^{-1} is the medium barrage & SE flows, high salinity scenario (Scenario 11; Table 1)

None of the scenarios investigated showed differences in the mix of ecosystem states compared to the Baseline scenario.

3.5.4 Effect of USED salinity under medium barrage & high SE flow conditions

When the effects of USED salinity under medium barrage and high SE flow conditions were investigated there was little influence on three of the four hydrodynamic drivers (Figure 41). Maximum salinity was the only driver which showed some change across the three scenarios. There was a slight increase in median maximum salinity with increased USED salinity, at 51 g L^{-1}, 53 g L^{-1} and 56 g L^{-1}, under low, moderate and high salinity conditions, respectively.

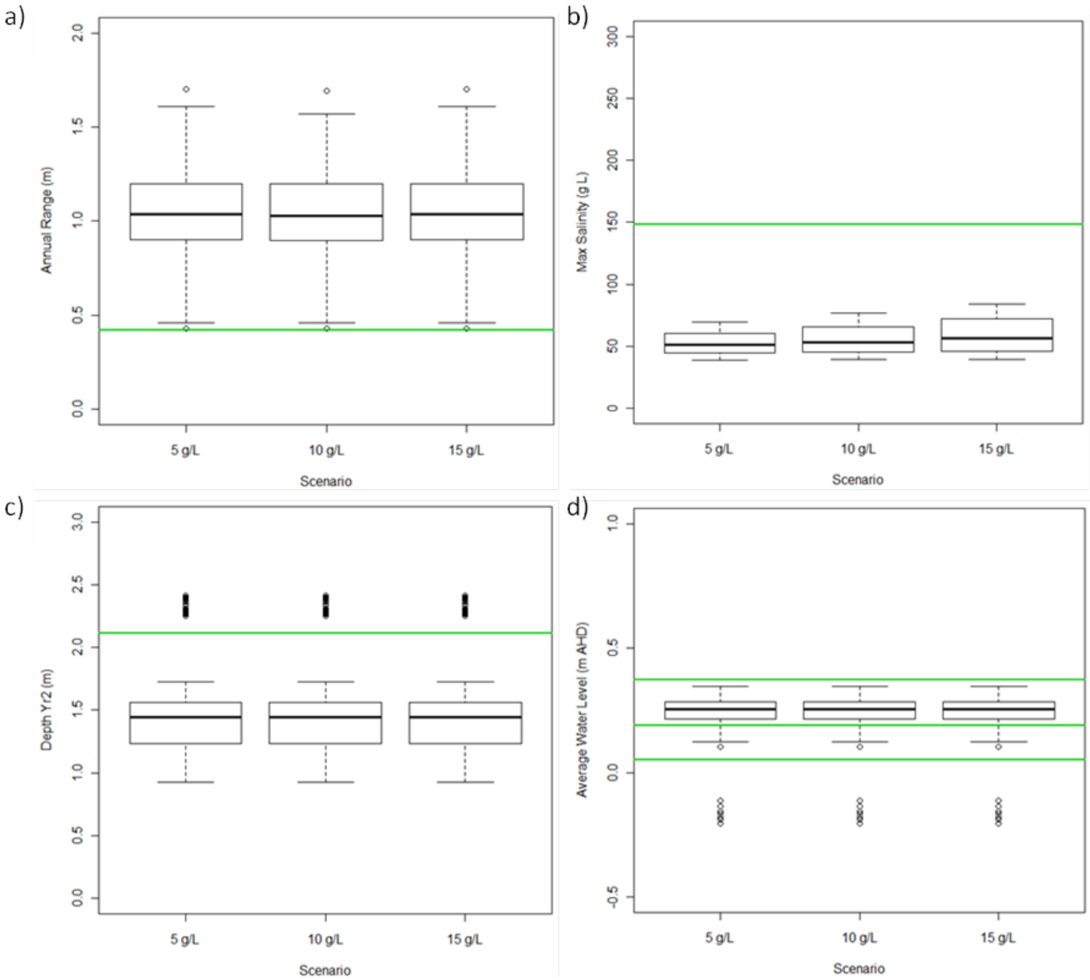

Figure 41: Boxplots showing the distributions of values for each of the variables driving the ecosystem states of the Coorong for the effect USED salinity scenarios. a) Annual range in water level (m), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Average water level (m AHD) Note: 5 g L^{-1} is the medium barrage & high SE flows, low salinity scenario (Scenario 12), 10 g L^{-1} is the medium barrage & high SE flows, medium salinity scenario (Scenario 3) and 15 g L^{-1} is the medium barrage & high SE flows, high salinity scenario (Scenario 13; Table 1).

There were effectively no differences in both North Lagoon hydrodynamic drivers under changing USED salinities (Figure 42).

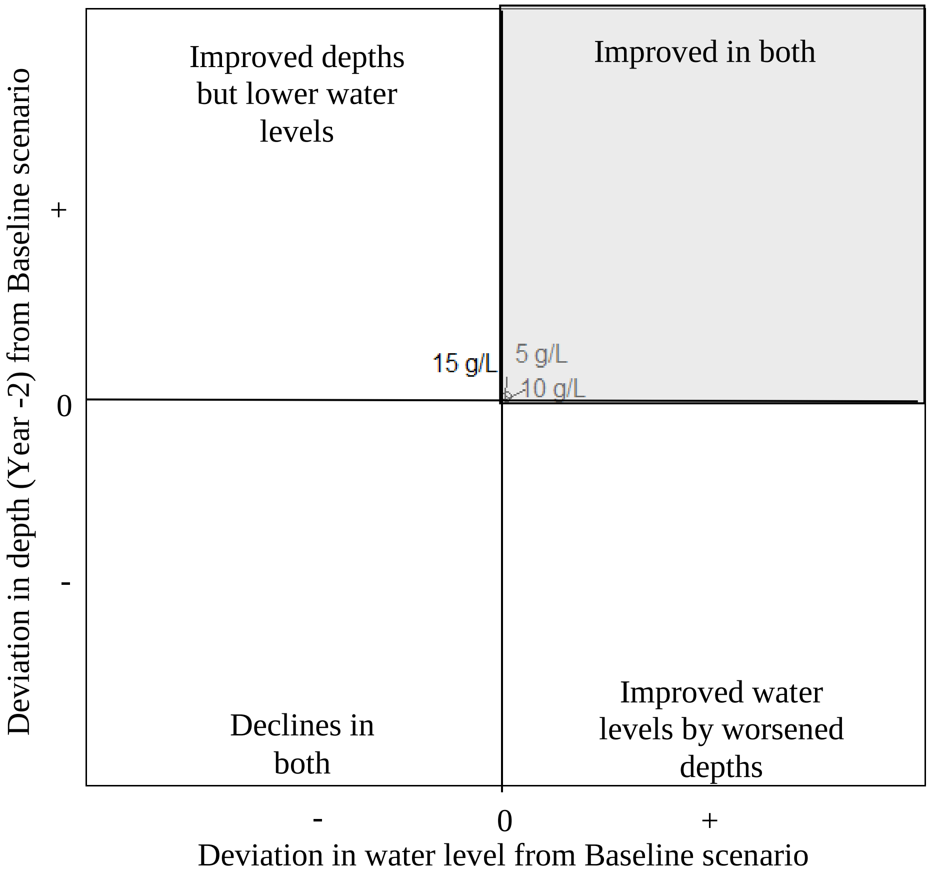

Figure 42: Comparison of the effect of USED salinity for the North Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline 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 Baseline scenario condition (as shown by the 0,0 origin). Vectors in the top-right quadrant indicate an improvement for both variables (i.e. higher water levels and greater depths). Note: 5 g L^{-1} is the medium barrage & high SE flows, low salinity scenario (Scenario 12), 10 g L^{-1} is the medium barrage & high SE flows, medium salinity scenario (Scenario 3) and 15 g L^{-1} is the medium barrage & high SE flows, high salinity scenario (Scenario 13; Table 1).

The cumulative impact on South Lagoon hydrodynamics was larger (Figure 43). There, there was an improvement in both maximum salinity and water level under all three USED salinity scenarios, likely largely as a result of the higher USED flows in these scenarios, compared with the Baseline. This level of improvement was the greatest under low USED salinity conditions and decreased with increased USED salinity conditions, indicating that there was also an impact of USED salinity level.

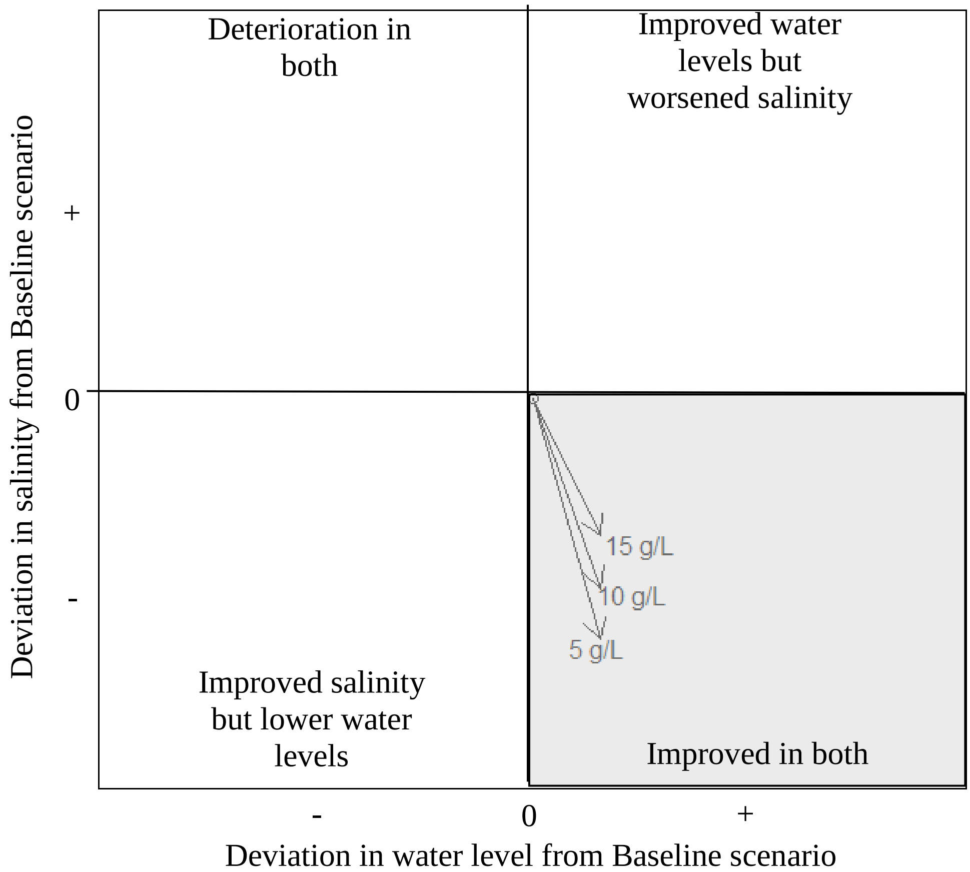

Figure 43: Comparison of the effect of USED salinity for the South Lagoon.
This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Baseline scenario condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant indicate an improvement for both variables (i.e. higher water levels and lower salinities). Note: 5 g L^{-1} is the medium barrage & high SE flows, low salinity scenario (Scenario 12), 10 g L^{-1} is the medium barrage & high SE flows, medium salinity scenario (Scenario 3) and 15 g L^{-1} is the medium barrage & high SE flows, high salinity scenario (Scenario 13; Table 1)

There was no change in the relative proportions of ecosystem states in any of the three USED salinity scenarios when compared to the Baseline scenario, despite the higher USED flow levels and varying salinities compared to the Baseline.

3.5.5 Effect of USED salinity under high barrage & medium SE flow conditions

When the effects of USED salinity under high barrage and medium SE flow conditions were investigated there was little influence evident on three of the four hydrodynamic drivers (Figure 44). Maximum salinity was the only driver which showed some change across the three salinity scenarios. This represented a slight increase in median maximum salinity with increased USED salinity, at 54 g L^{-1}, 56 g L^{-1} and 57 g L^{-1}, under low, moderate and high salinity conditions, respectively.

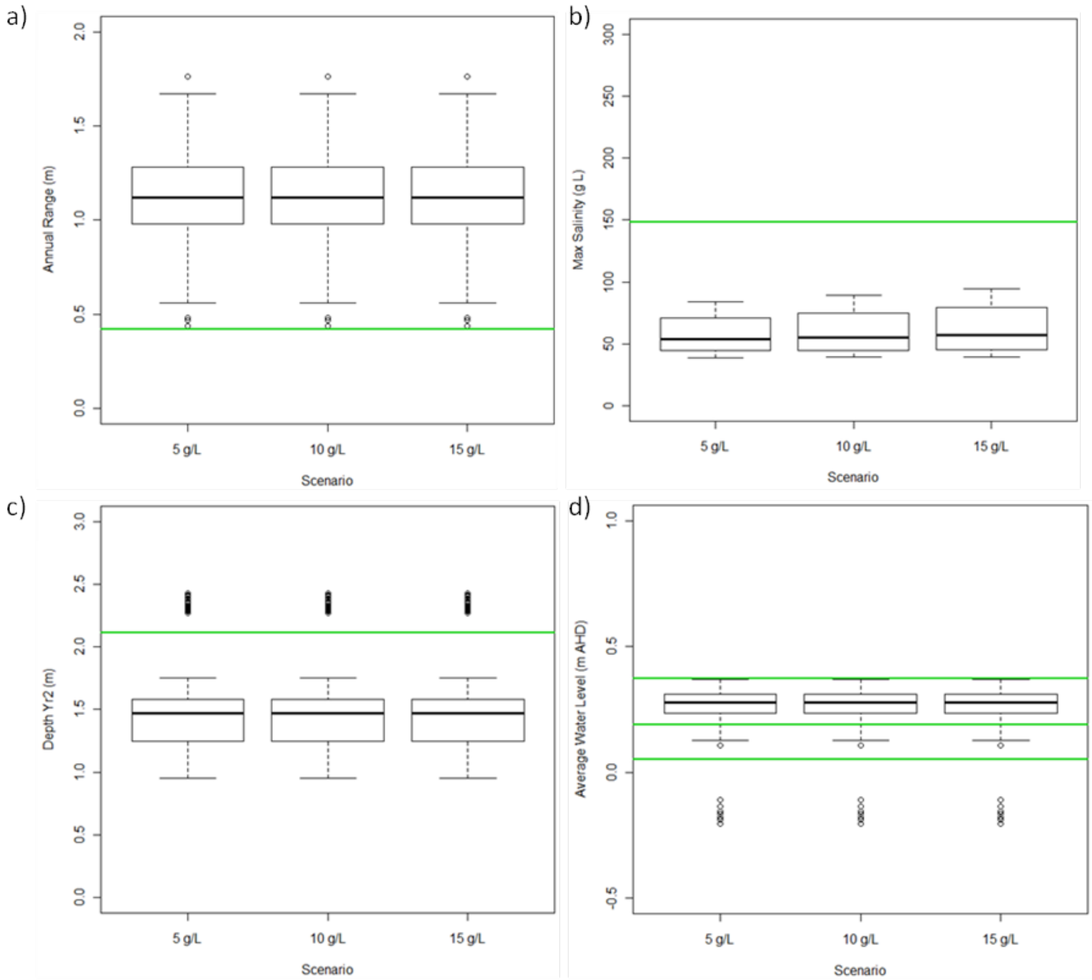

Figure 44: Boxplots showing the distributions of values for each of the variables driving the ecosystem states of the Coorong for the effect of USED salinity scenarios. a) Annual range in water level (m), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Average water level (m AHD) Note: 5 g L^{-1} is the high barrage & medium SE flows, low salinity scenario (Scenario 14), 10 g L^{-1} is the high barrage & medium SE flows, medium salinity scenario (Scenario 5) and 15 g L^{-1} is the high barrage & medium SE flows, high salinity scenario (Scenario 15; Table 1)

There was a positive cumulative difference in North Lagoon hydrodynamic drivers under all USED salinity conditions investigated (Figure 45). This change was as a result of the higher barrage flows for all three scenarios compared to the Baseline. There was no deviation found Baseline scenario associated with the different USED salinity levels.

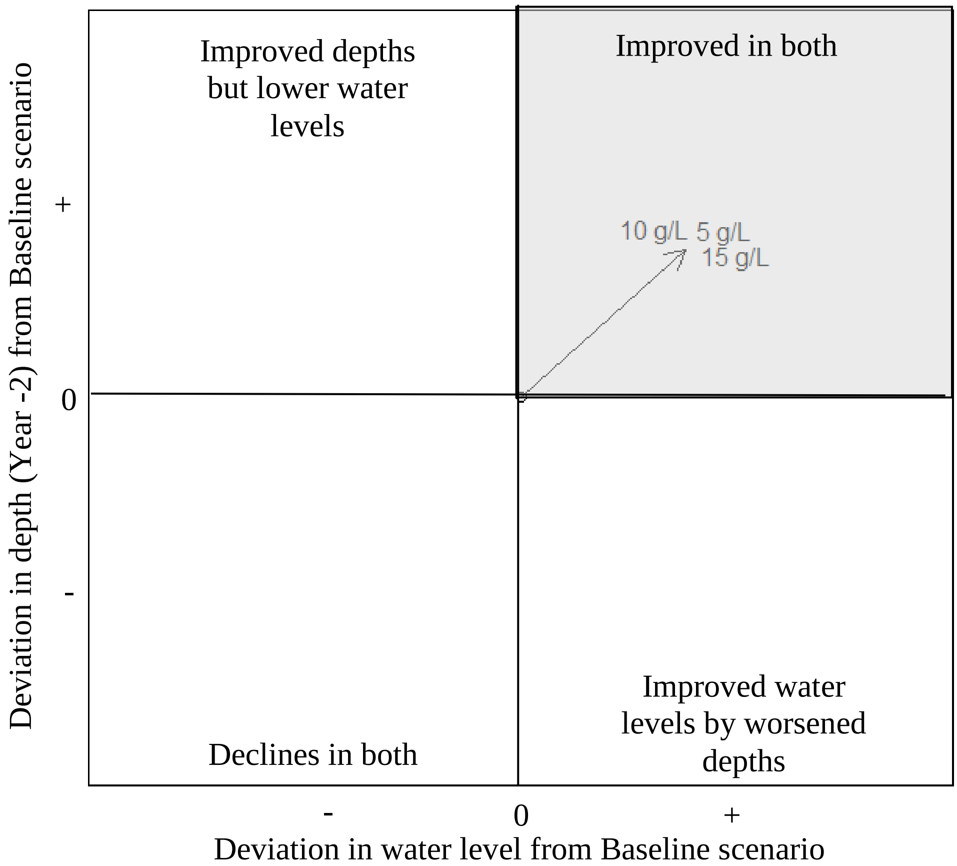

Figure 45: Comparison of the effect of USED salinity for the North Lagoon
This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline scenario with respect to water levels and depths (with depths from two years previously). Length of each vector is proportional to the strength of the deviation from the Baseline scenario condition (as shown by the 0,0 origin). Vectors in the top-right quadrant indicate an improvement for both variables (i.e. higher water levels and greater depths). Note: 5 g L^{-1} is the high barrage & medium SE flows, low salinity scenario (Scenario 14), 10 g L^{-1} is the high barrage & medium SE flows, medium salinity scenario (Scenario 5) and 15 g L^{-1} is the high barrage & medium SE flows, high salinity scenario (Scenario 15; Table 1)

The cumulative impact on South Lagoon hydrodynamics was again positive under all three USED salinity scenarios under high barrage and medium SE flow conditions (Figure 46). There was an improvement in both maximum salinity and water level, with the level of improvement was the greatest under low USED salinity conditions and slightly smaller with increased USED salinity conditions. The cumulative change in water levels can be attributed to the higher barrage flows. The change in maximum salinities however, was as a result of the combination of higher barrage flows and changes in USED salinities.

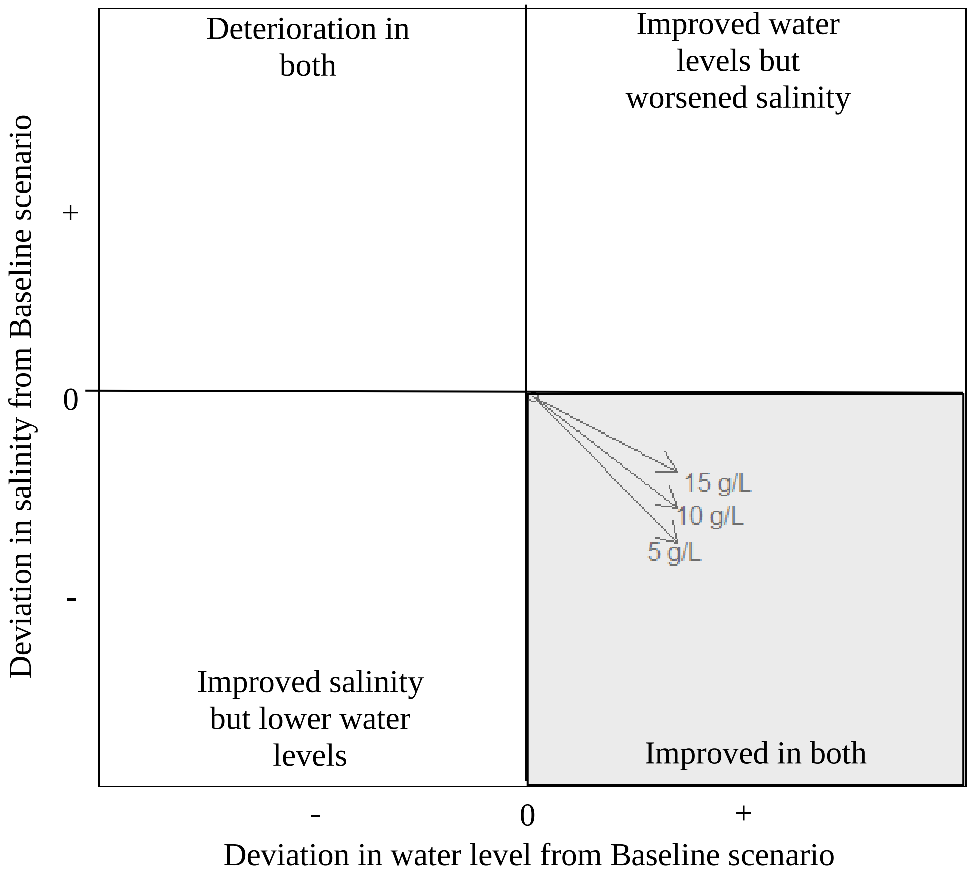

Figure 46: Comparison of the effect of USED salinity for the South Lagoon
This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Baseline scenario condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant indicate an improvement for both variables (i.e. higher water levels and lower salinities). Note: 5 g L^{-1} is the high barrage & medium SE flows, low salinity scenario (Scenario 14), 10 g L^{-1} is the high barrage & medium SE flows, medium salinity scenario (Scenario 5) and 15 g L^{-1} is the high barrage & medium SE flows, high salinity scenario (Scenario 15; Table 1)

There was no change in the relative proportions of ecosystem states in any of the three USED salinity scenarios when compared to the Baseline scenario.

3.6 Research Question 5: Effect of timing & distribution of flows

3.6.1 Effect of shifting barrage & USED flow timing by one standard deviation

The following series of results illustrate the impact of changing the timing and distribution of barrage and USED flows to each be either earlier or later by one standard deviation in the flow distribution individually or in combinations of the two. For barrage flows, one standard deviation was 50 days (i.e. so flows were shifted to either be 50 days earlier or 50 days later) and for USED flows, one standard deviation was 22 days. Shifting the flows in this manner provided an indication of the potential effect of storing water in the USED system and releasing it at different times of the year, or of the potential effects of differences due to altered barrage flow timing either as a result of climate change or changes in river operation.

3.6.1.1 Effect of shifting barrage & USED flow timing under low barrage & medium SE flow conditions

When the effects of shifting the timing and distribution of barrage and USED flows were investigated under low barrage flows and medium SE flow conditions, there were small changes in depth from two years previous and average water levels (Figure 47). Moderate changes in annual ranges in water levels and maximum salinities were also observed. Median annual range in water levels ranged from 0.88 m with a shift of -1 SD in barrage and USED flow timing to 1.12 m with a shift of +1 SD barrage timing and no change in USED flow timing. Median maximum salinity was lowest with a shift of +1 SD in barrage flow timing and no change in USED flow timing, at 57 g L^{-1} and highest with no change in barrage timing and -1 SD shift in USED flow timing, at 82 g L^{-1}. The remainder of scenarios had median salinities which ranged from 73 g L^{-1} (-1 SD barrage timing and no change in USED timing) to 81 g L^{-1} (+1 SD barrage timing and USED timing).

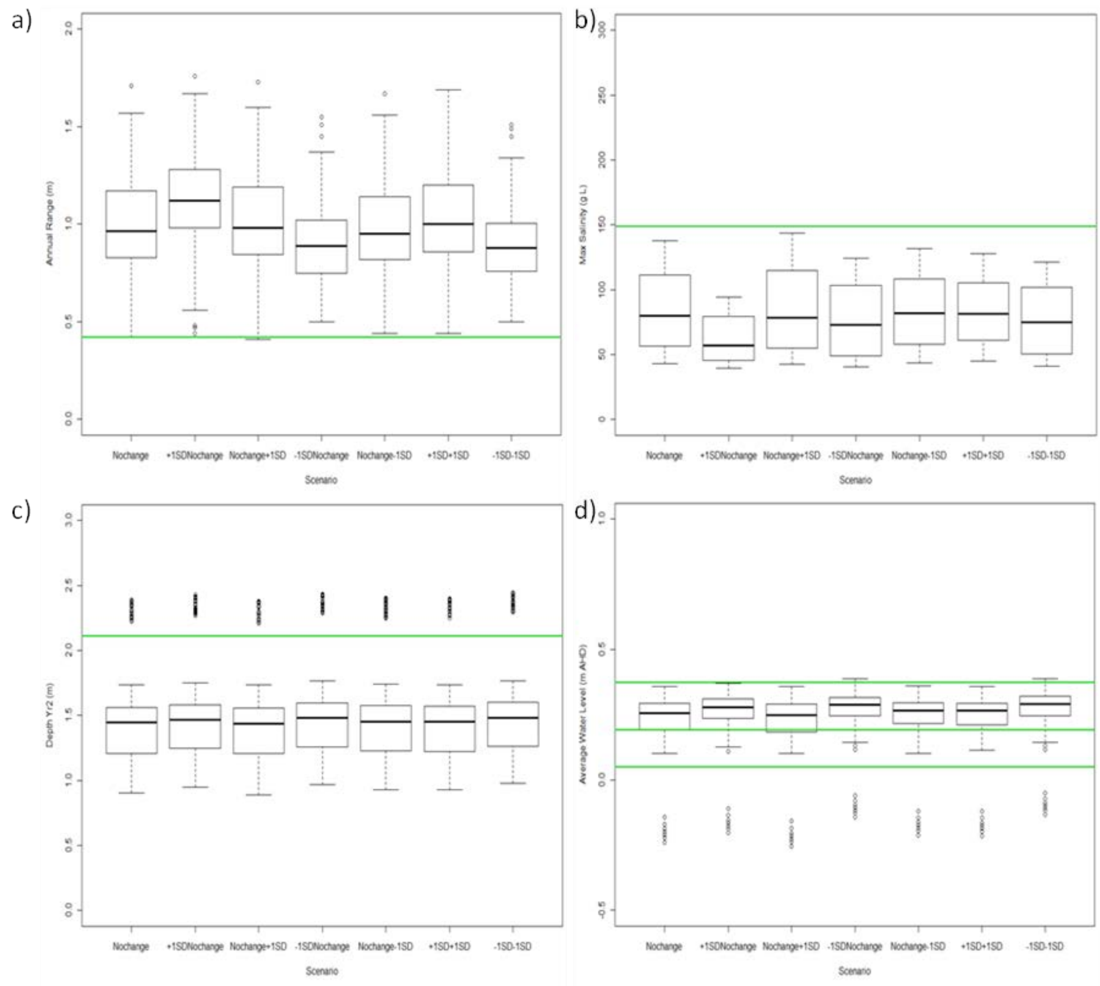

Figure 47: Boxplots showing the distributions of values for each of the variables driving the ecosystem states of the Coorong for the effect of shift in flow timing and distribution. a) Annual range in water level (m), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Average water level (m AHD) Note: Nochange is no change in both barrage and USED timing (Scenario 4), +1SDNochange is a +1SD shift in barrage timing and no change in USED timing (Scenario 16), Nochange+1SD is no change in barrage timing and a +1SD shift in USED timing (Scenario 17), -1SDNochange is a -1SD shift in barrage timing and no change in USED timing (Scenario 18), Nochange-1SD is no change in barrage timing and a -1SD shift in USED timing (Scenario 19), +1SD+1SD is a +1SD shift in barrage and USED timing (Scenario 20), and -1SD-1SD is a -1SD shift in both barrage and USED timing (Scenario 21; Table 1). All scenarios have low barrage flows and medium SE flows with medium SE salinity

There were positive cumulative differences in North Lagoon hydrodynamic drivers for all scenarios shifting the timing of flows under low barrage and medium SE flow conditions compared to the Baseline scenario (Figure 48). Some of this change was associated with the difference in barrage flow volume compared with the Baseline scenario, however, there was also variability associated with changes in timing. The greatest improvements in both average water level and depth from two years previous, when compared to the Baseline scenario, was with both positive and negative 1 SD shifts in barrage timing combined with no change in USED flow timing, and a negative 1 SD shift in both barrage and USED flow timing. Therefore, it appears that the timing of barrage flows had a much larger impact on the hydrodynamic drivers of the North Lagoon than the timing of USED flows, which is unsurprising given their respective locations.

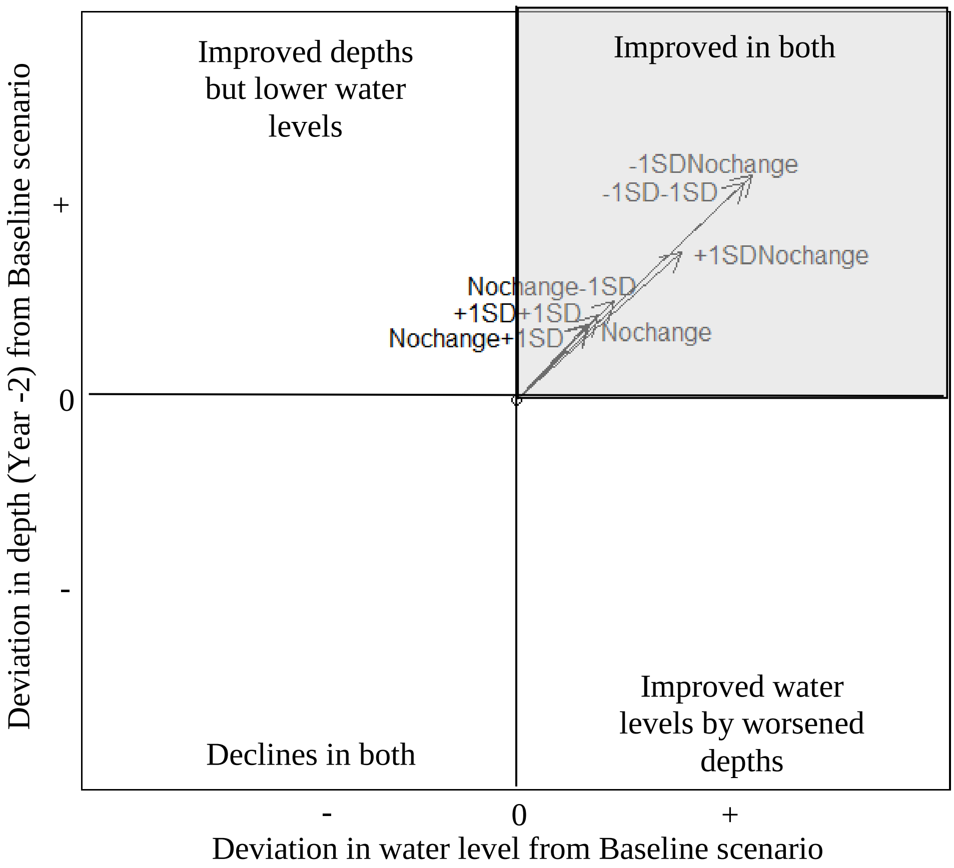

Figure 48: Comparison of the effect of a shift in timing and distribution of flows for the North Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline 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 Baseline scenario condition (as shown by the 0,0 origin). Vectors in the top-right quadrant indicate an improvement for both variables (i.e. higher water levels and greater depths). Note: Nochange is no change in both barrage and USED timing (Scenario 4), +1SDNochange is a +1SD shift in barrage timing and no change in USED timing (Scenario 16), Nochange+1SD is no change in barrage timing and a +1SD shift in USED timing (Scenario 17), -1SDNochange is a -1SD shift in barrage timing and no change in USED timing (Scenario 18), Nochange-1SD is no change in barrage timing and a -1SD shift in USED timing (Scenario 19), +1SD+1SD is a +1SD shift in barrage and USED timing (Scenario 20), and -1SD-1SD is a -1SD shift in both barrage and USED timing (Scenario 21; Table 1). All scenarios have low barrage flows and medium SE flows with medium SE salinity

The cumulative impact on South Lagoon hydrodynamics was more complex (Figure 49). There, there was an improvement in both maximum salinity and average water level when barrage flows had a shift of +1 SD and USED flow timing was not changed, despite the lower barrage flows associated with that scenarios compared to the Baseline (i.e. 1000 compared to 2000 GL year^{-1}) and the distance from the barrages to the South Lagoon.

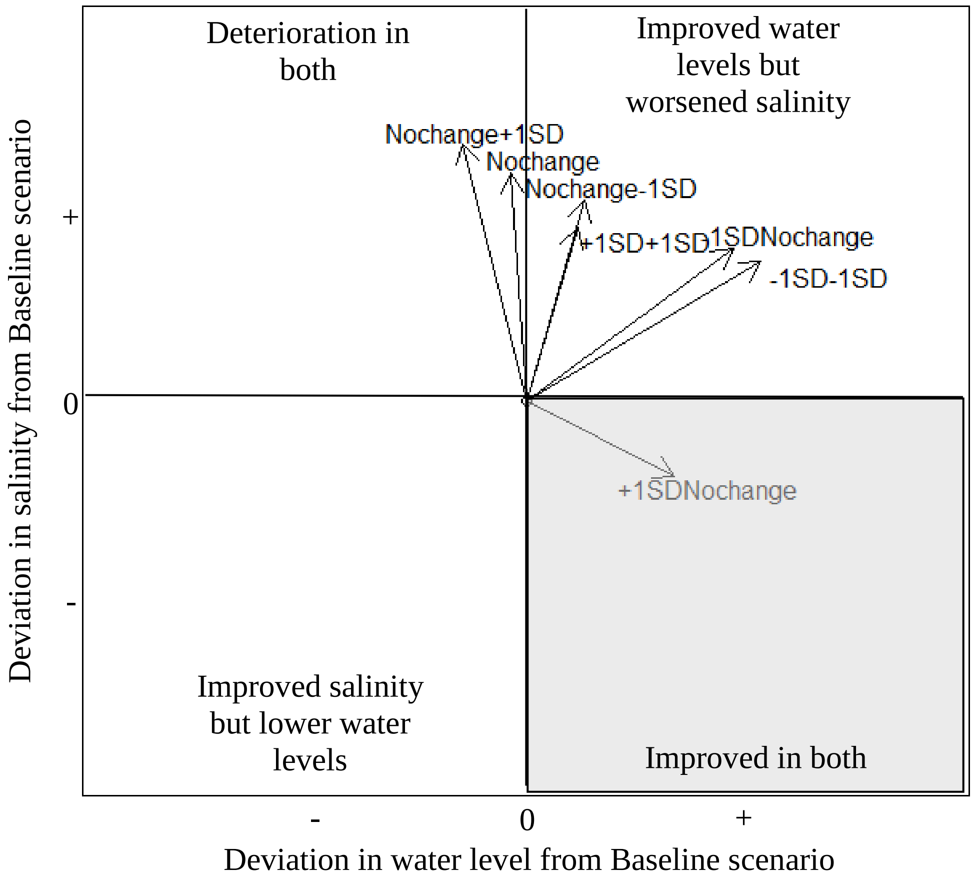

Figure 49: Comparison of the effect of a shift in timing and distribution of flows for the South Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Baseline scenario condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant indicate an improvement for both variables (i.e. higher water levels and lower salinities). Note: Nochange is no change in both barrage and USED timing (Scenario 4), +1SDNochange is a +1SD shift in barrage timing and no change in USED timing (Scenario 16), Nochange+1SD is no change in barrage timing and a +1SD shift in USED timing (Scenario 17), -1SDNochange is a -1SD shift in barrage timing and no change in USED timing (Scenario 18), Nochange-1SD is no change in barrage timing and a -1SD shift in USED timing (Scenario 19), +1SD+1SD is a +1SD shift in barrage and USED timing (Scenario 20), and -1SD-1SD is a -1SD shift in both barrage and USED timing (Scenario 21; Table 1). All scenarios have low barrage flows and medium SE flows with medium SE salinity

Four scenarios showed an improvement in average water level, but a deterioration in maximum salinity. With no change in barrage timing and +1 SD shift in USED timing, and no change in both barrage and USED flow timing, there was deterioration in both average water level and maximum salinity compared to the Baseline. This indicates that delaying USED flows resulted in worse hydrodynamic conditions in the South Lagoon than the historical timing and distribution.

Under low barrage flow and medium USED flow conditions, four of the flow timing scenarios altered the relative proportions of ecosystem states (Figure 50) compared to the Baseline. With no change in either barrage or USED timing or no change in barrage timing with +1 SD shift in USED timing, there were very small (i.e. <1 %) changes from Estuarine/Marine to Unhealthy Marine and from Average Hypersaline to Unhealthy Hypersaline ecosystem states. These shifts were likely to be a result of the low barrage flows compared with the Baseline.

With no change in barrage timing and -1 SD USED timing, or a +1 SD change in both barrage and USED timing, the same change was observed from Estuarine/Marine to Unhealthy Marine ecosystem states but without corresponding changes in the Hypersaline basin states. This indicates that the timing and distribution of both barrage and USED flows had some impact on the ecosystem states of the Coorong and in some cases could compensate for lower barrage flows (i.e. a reduction of 1000 GL year^{-1}). However, in the combinations investigated, the elimination of degraded ecosystem states from the model simulations was not observed, with 2% of site-years simulated to support degraded ecosystem states under all of the timing and distribution scenarios under low barrage and medium SE flow conditions.

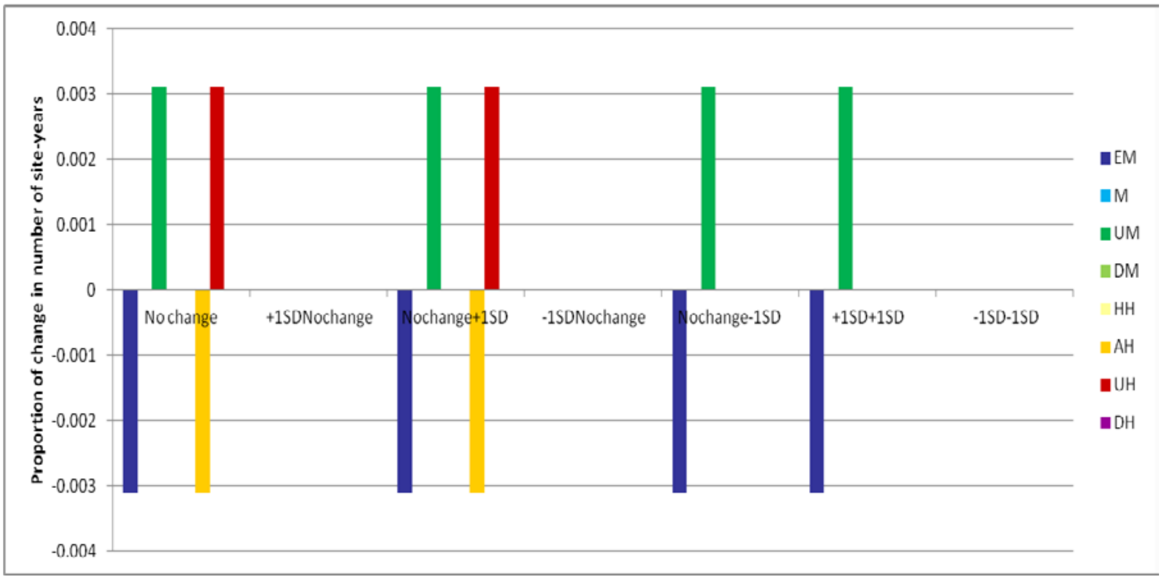

Figure 50: Deviations in the proportion of site-years in each ecosystem state compared to the Baseline scenario for the comparison of USED salinity

Nochange is no change in both barrage and USED timing (Scenario 4), +1SDNochange is a +1SD shift in barrage timing and no change in USED timing (Scenario 16), Nochange+1SD is no change in barrage timing and a +1SD shift in USED timing (Scenario 17), -1SDNochange is a -1SD shift in barrage timing and no change in USED timing (Scenario 18), Nochange-1SD is no change in barrage timing and a -1SD shift in USED timing (Scenario 19), +1SD+1SD is a +1SD shift in barrage and USED timing (Scenario 20), and -1SD-1SD is a -1SD shift in both barrage and USED timing (Scenario 21; Table 1). All scenarios have low barrage flows and medium SE flows with medium SE salinity

3.6.1.2 Effect of shifting barrage & USED flow timing under medium barrage & low SE flow conditions

Under medium barrage and low SE flow conditions, shifts in barrage and USED flow timing had little influence on three of the four hydrodynamic drivers (Figure 51). Changes in median annual range in water level were observed, ranging from 0.91 m with a -1 SD shift in barrage and USED timing, to 1.10 m with a shift of +1 SD in barrage timing and either no change or a +1 SD shift in USED flow timing. Across the remaining drivers, the scenarios which represented shifts of -1 SD in barrage timing and no change in USED timing, and -1 SD in both barrage and USED timing had slightly lower median maximum salinity, and slightly higher depths from two years previous and average water levels when compared to the rest of the scenarios.

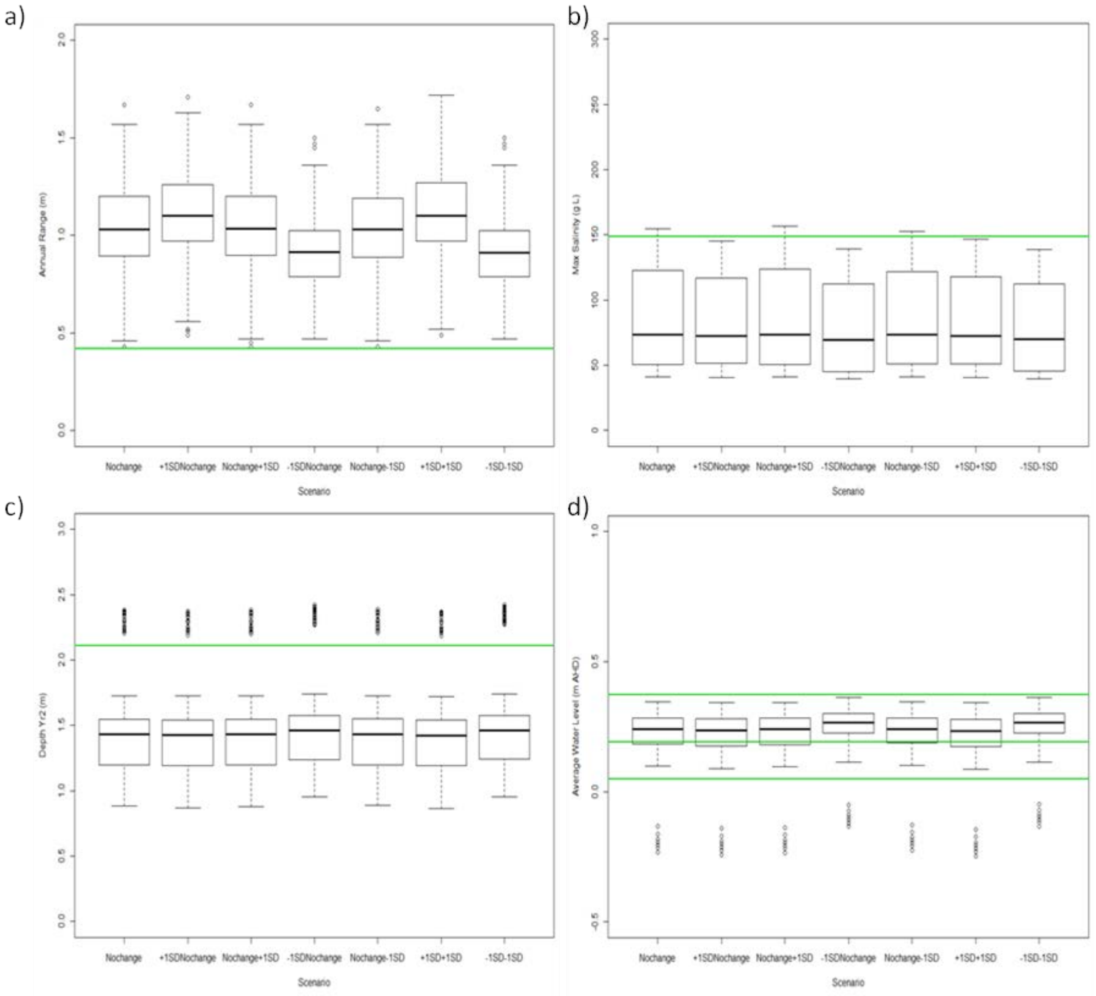

Figure 51: Boxplots showing the distributions of values for each of the variables driving the ecosystem states of the Coorong for the effect of shifting flow timing and distributions scenarios. a) Annual range in water level (m), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Average water level (m AHD) Note: Nochange is no change in both barrage and USED timing (Scenario 2), +1SDNochange is a +1SD shift in barrage timing and no change in USED timing (Scenario 22), Nochange+1SD is no change in barrage timing and a +1SD shift in USED timing (Scenario 23), -1SDNochange is a -1SD shift in barrage timing and no change in USED timing (Scenario 24), Nochange-1SD is no change in barrage timing and a -1SD shift in USED timing (Scenario 25), +1SD+1SD is a +1SD shift in barrage and USED timing (Scenario 26), and -1SD-1SD is a -1SD shift in both barrage and USED timing (Scenario 27; Table 1). All scenarios have medium barrage flows and low SE flows with medium SE salinity

There were positive cumulative differences in North Lagoon hydrodynamics for only two of the timing scenarios under medium barrage flow and low SE flow conditions (Figure 52). These scenarios (i.e. -1 SD shift in barrage timing and no change in USED timing, and -1 SD shift in both barrage and USED timing) represented an improvement in average water levels and depth from two years previous when compared to the Baseline scenario. The remainder of scenarios showed little difference from the Baseline scenario.

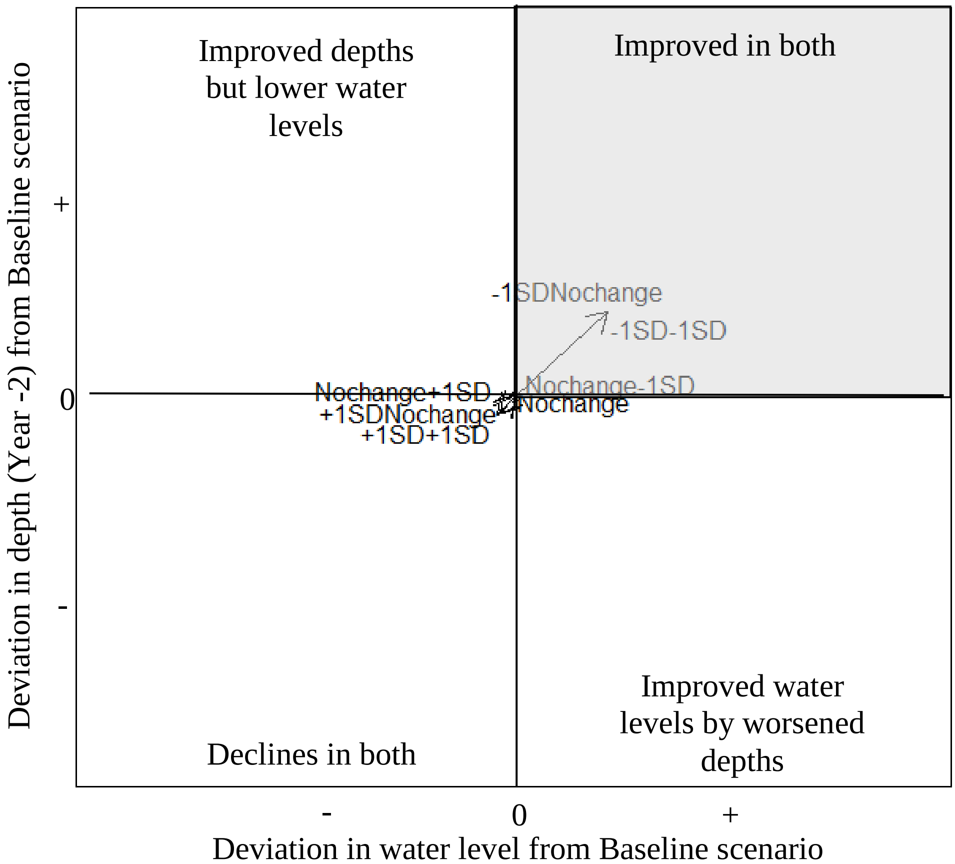

Figure 52: Comparison of the effect of a shift in timing and distribution of flows for the North Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline 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 Baseline scenario condition (as shown by the 0,0 origin). Vectors in the top-right quadrant indicate an improvement for both variables (i.e. higher water levels and greater depths). Note: Nochange is no change in both barrage and USED timing (Scenario 2), +1SDNochange is a +1SD shift in barrage timing and no change in USED timing (Scenario 22), Nochange+1SD is no change in barrage timing and a +1SD shift in USED timing (Scenario 23), -1SDNochange is a -1SD shift in barrage timing and no change in USED timing (Scenario 24), Nochange-1SD is no change in barrage timing and a -1SD shift in USED timing (Scenario 25), +1SD+1SD is a +1SD shift in barrage and USED timing (Scenario 26), and -1SD-1SD is a -1SD shift in both barrage and USED timing (Scenario 27; Table 1). All scenarios have medium barrage flows and low SE flows with medium SE salinity

The cumulative impact on South Lagoon hydrodynamics generally showed deteriorations in both maximum salinities and average water levels compared to the Baseline (Figure 53), consistent with the impact of medium barrage flows and low USED flows compared to the Baseline observed earlier. Such deteriorations were greatest with no change to barrage timing, and no change, a +1 SD or -1 SD shift in USED flow timing. With shifts of -1 SD in barrage timing and either no change or -1 SD shift in USED flow timing there was an improvement in average water level, but a deterioration in maximum salinity when compared to the Baseline scenario. All scenarios involving shifts in barrage flows (i.e. both + 1 SD and -1 SD) resulted in lower salinities compared with the no change scenario, regardless of the timing of USED flows.

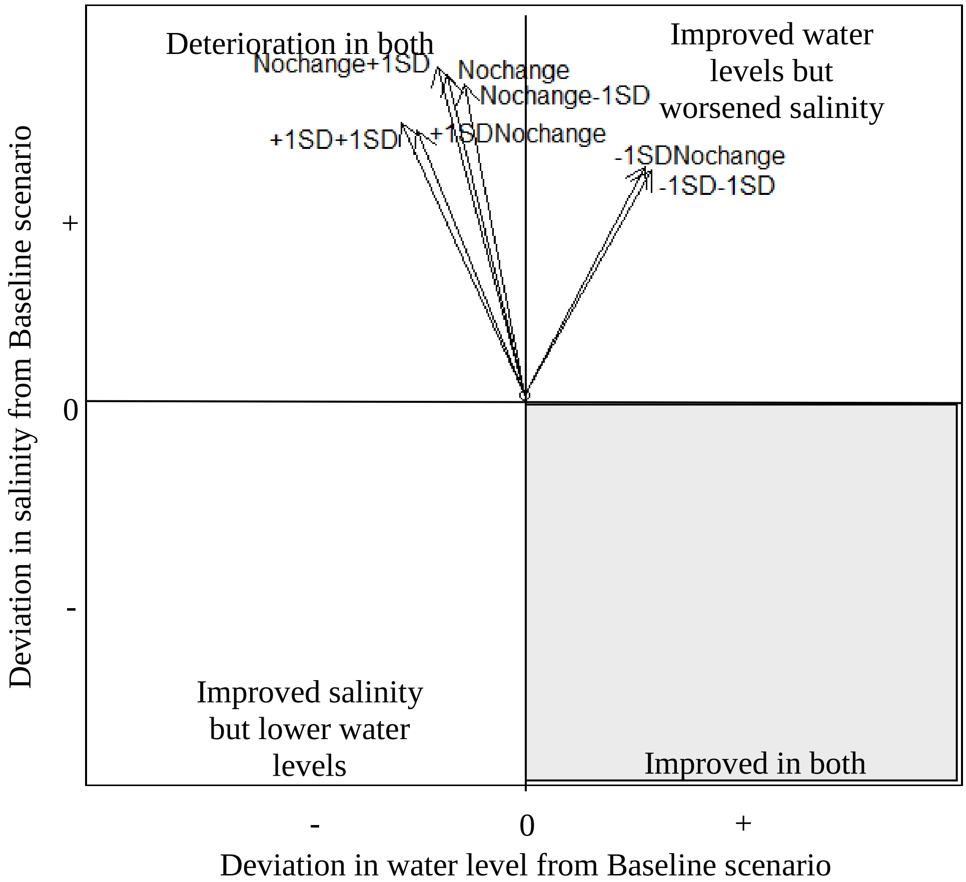

Figure 53: Comparison of the effect of a shift in timing and distribution of flows for the South Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Baseline scenario condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant indicate an improvement for both variables (i.e. higher water levels and lower salinities). Note: Nochange is no change in both barrage and USED timing (Scenario 2), +1SDNochange is a +1SD shift in barrage timing and no change in USED timing (Scenario 22), Nochange+1SD is no change in barrage timing and a +1SD shift in USED timing (Scenario 23), -1SDNochange is a -1SD shift in barrage timing and no change in USED timing (Scenario 24), Nochange-1SD is no change in barrage timing and a -1SD shift in USED timing (Scenario 25), +1SD+1SD is a +1SD shift in barrage and USED timing (Scenario 26), and -1SD-1SD is a -1SD shift in both barrage and USED timing (Scenario 27; Table 1). All scenarios have medium barrage flows and low SE flows with medium SE salinity

Of the seven scenarios investigated, only three showed any alteration to the relative proportions of ecosystem states present compared to the Baseline scenario (Figure 54). The greatest change, although only slight (i.e. <1 % shift from an Average Hypersaline to Degraded Hypersaline state) was with no change in barrage timing and a shift of +1 SD in USED flow timing. A similar alteration of states was observed with no changes in either barrage or USED flow timing, reflecting the difference associated with the lower USED flow volume compared with the Baseline. A smaller change in the same ecosystem state proportions s was found with no change to barrage timing and a shift of +1 SD in USED flow timing. This indicates that shifting the timing of barrage flows may be able to compensate for lower USED flow volumes (i.e. a reduction of 40 GL year^{-1}) but that shifting USED flow timings could not.

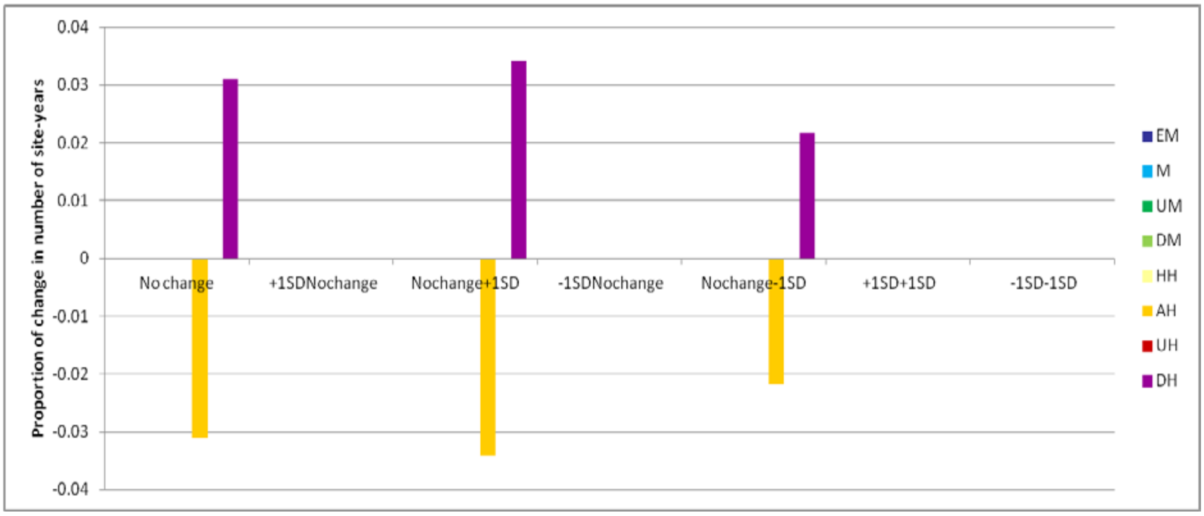

Figure 54: Deviations in the proportion of site-years in each ecosystem state compared to the Baseline scenario for the comparison of a shift in timing and distribution of flows
Nochange is no change in both barrage and USED timing (Scenario 2), +1SDNochange is a +1SD shift in barrage timing and no change in USED timing (Scenario 22), Nochange+1SD is no change in barrage timing and a +1SD shift in USED timing (Scenario 23), -1SDNochange is a -1SD shift in barrage timing and no change in USED timing (Scenario 24), Nochange-1SD is no change in barrage timing and a -1SD shift in USED timing (Scenario 25), +1SD+1SD is a +1SD shift in barrage and USED timing (Scenario 26), and -1SD-1SD is a -1SD shift in both barrage and USED timing (Scenario 27; Table 1). All scenarios have medium barrage flows and low SE flows with medium SE salinity

3.6.1.3 Effect of shifting barrage & USED flow timing under medium barrage & SE flow conditions

When the effects of shifting the timing and distribution of barrage and USED flows were investigated under medium barrage and SE flow conditions, there was little influence on depth from two years previous and average water levels (Figure 55). Changes were observed across the scenarios for annual range in water level. Median annual range was lowest, at 0.93 m for shifts of -1 SD in barrage timing with either no change or a -1 SD shift in USED timing, and was highest with +1 SD shifts in both barrage and USED flow timing, at 1.11 m. Median maximum salinity changed slightly, ranging from 55 g L^{-1} with a shift of -1 SD in barrage timing and no change in USED timing, to 62 g L^{-1} with either no change or +1 SD in barrage timing and a -1 SD or +1 SD shift in USED flow timing.

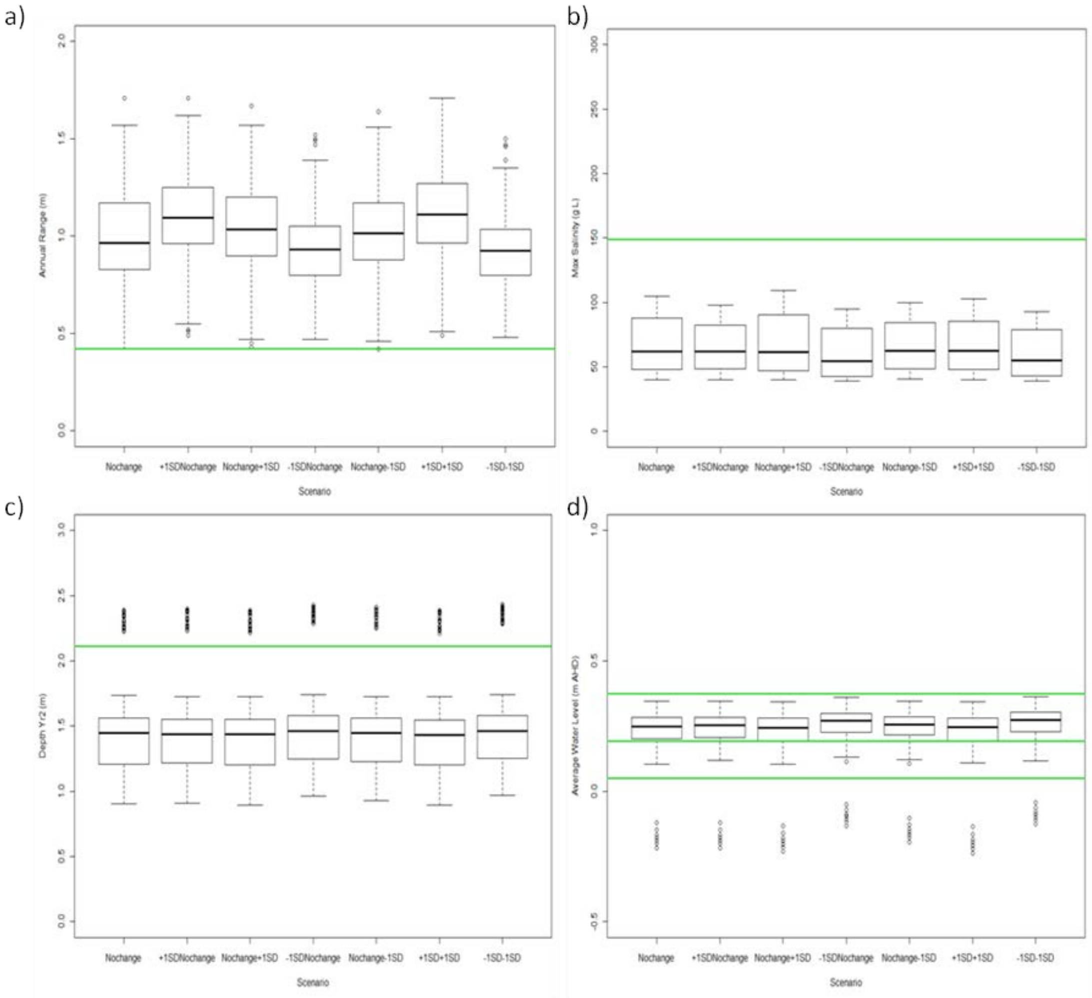

Figure 55: Boxplots showing the distributions of values for each of the variables driving the ecosystem states of the Coorong for the effect of increasing USED flow volume scenarios. a) Annual range in water level (m), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Average water level (m AHD) Note: Nochange is no change in both barrage and USED timing (Baseline scenario, Scenario 1), +1SDNochange is a +1SD shift in barrage timing and no change in USED timing (Scenario 28), Nochange+1SD is no change in barrage timing and a +1SD shift in USED timing (Scenario 29), -1SDNochange is a -1SD shift in barrage timing and no change in USED timing (Scenario 30), Nochange-1SD is no change in barrage timing and a -1SD shift in USED timing (Scenario 31), +1SD+1SD is a +1SD shift in barrage and USED timing (Scenario 32), and -1SD-1SD is a -1SD shift in both barrage and USED timing (Scenario 33; Table 1). All scenarios have medium barrage and SE flows with medium SE salinity

There were positive cumulative differences in North Lagoon hydrodynamic drivers for two of timing scenarios under medium barrage and SE flow conditions (Figure 56). These scenarios included shifts of -1 SD in barrage timing with either no change or a shift of -1 SD in USED flow timing. The remainder of the scenarios had very small deviations in average water level or depth from two years previous compared to the Baseline scenario.

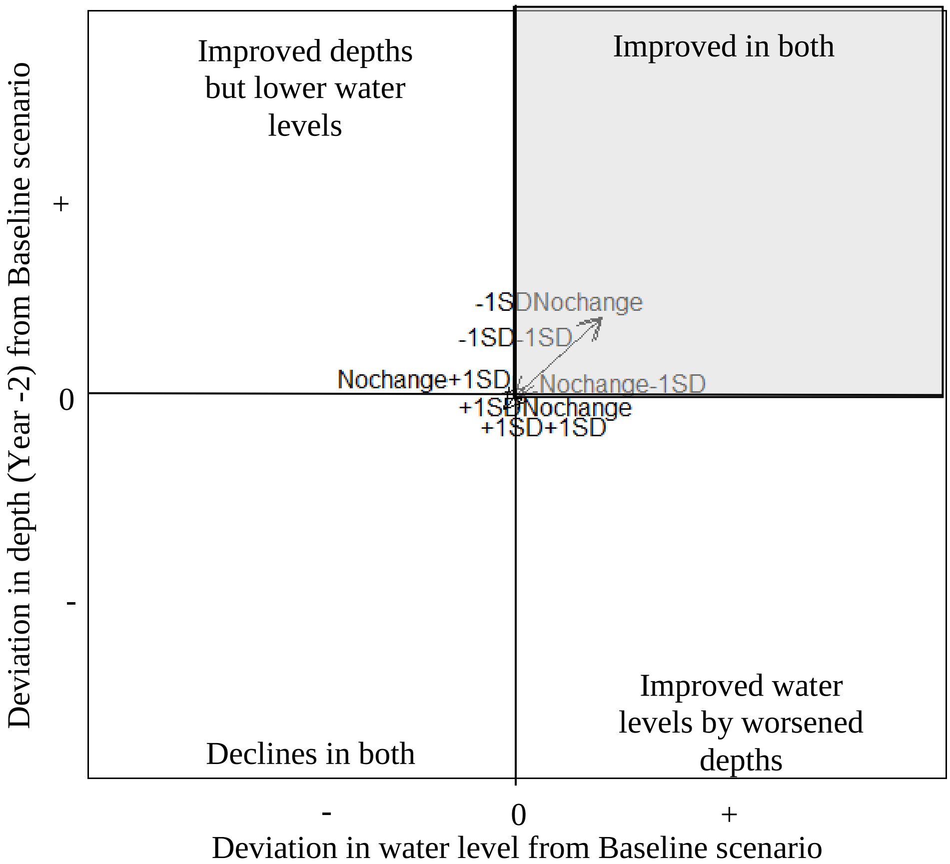

Figure 56: Comparison of the effect of a shift in timing and distribution of flows for the North Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline 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 Baseline scenario condition (as shown by the 0,0 origin). Vectors in the top-right quadrant indicate an improvement for both variables (i.e. higher water levels and greater depths). Note: +1SDNochange is a +1SD shift in barrage timing and no change in USED timing (Scenario 28), Nochange+1SD is no change in barrage timing and a +1SD shift in USED timing (Scenario 29), -1SDNochange is a -1SD shift in barrage timing and no change in USED timing (Scenario 30), Nochange-1SD is no change in barrage timing and a -1SD shift in USED timing (Scenario 31), +1SD+1SD is a +1SD shift in barrage and USED timing (Scenario 32), and -1SD-1SD is a -1SD shift in both barrage and USED timing (Scenario 33; Table 1). All scenarios have medium barrage and SE flows with medium SE salinity

The cumulative impact on South Lagoon hydrodynamics was more complex (Figure 57). In that lagoon, there was an improvement in both maximum salinity and average water level for four of the scenarios. These included combinations of no change, +1 SD and -1 SD in barrage timing with no change and -1 SD in USED timing. The no change and -1 SD scenario is the first of those investigated to date where a shift in only the timing of USED flows resulted in a positive change in hydrodynamics in either the North or South Lagoon (i.e. compared to shifting barrage flow timing or the timing of both).

When there was a shift of +1 SD in both barrage and USED flow timing, an improvement in maximum salinity, but lower average water levels was found. With no change in barrage timing and a shift of +1 SD in USED timing deterioration in both hydrodynamic drivers was observed.

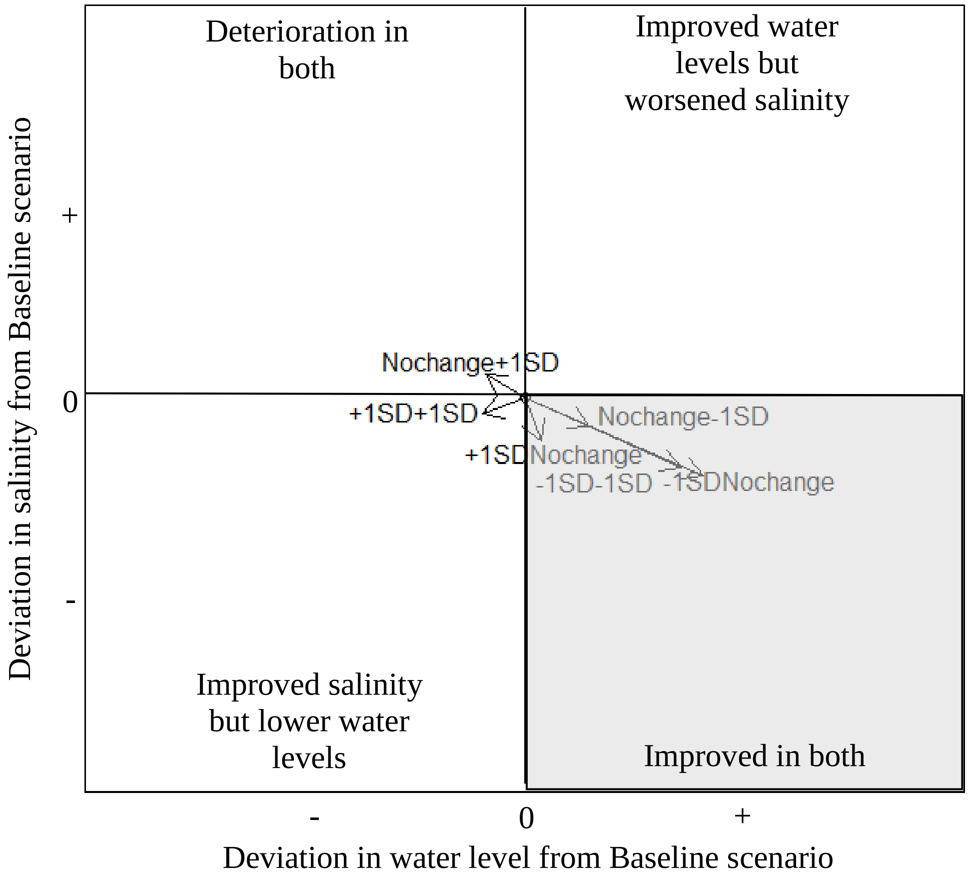

Figure 57: Comparison of the effect of a shift in timing and distribution of flows for the South Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Baseline scenario condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant indicate an improvement for both variables (i.e. higher water levels and lower salinities). Note: +1SDNochange is a +1SD shift in barrage timing and no change in USED timing (Scenario 28), Nochange+1SD is no change in barrage timing and a +1SD shift in USED timing (Scenario 29), -1SDNochange is a -1SD shift in barrage timing and no change in USED timing (Scenario 30), Nochange-1SD is no change in barrage timing and a -1SD shift in USED timing (Scenario 31), +1SD+1SD is a +1SD shift in barrage and USED timing (Scenario 32), and -1SD-1SD is a -1SD shift in both barrage and USED timing (Scenario 33; Table 1)). All scenarios have medium barrage and SE flows with medium SE salinity

Of the seven scenarios under medium barrage and USED conditions, only one showed any deviation in the relative proportion of ecosystem states when compared to the Baseline (Figure 58). This change was observed for the scenario which represented no change in barrage timing and a shift of -1 SD in USED flow timing, but was a relatively small shift (i.e. <1%) from the Average Hypersaline to the Unhealthy Hypersaline ecosystem state. This indicates that the timing and distribution of barrage and SE flows had very little impact on the ecosystem states of the Coorong.

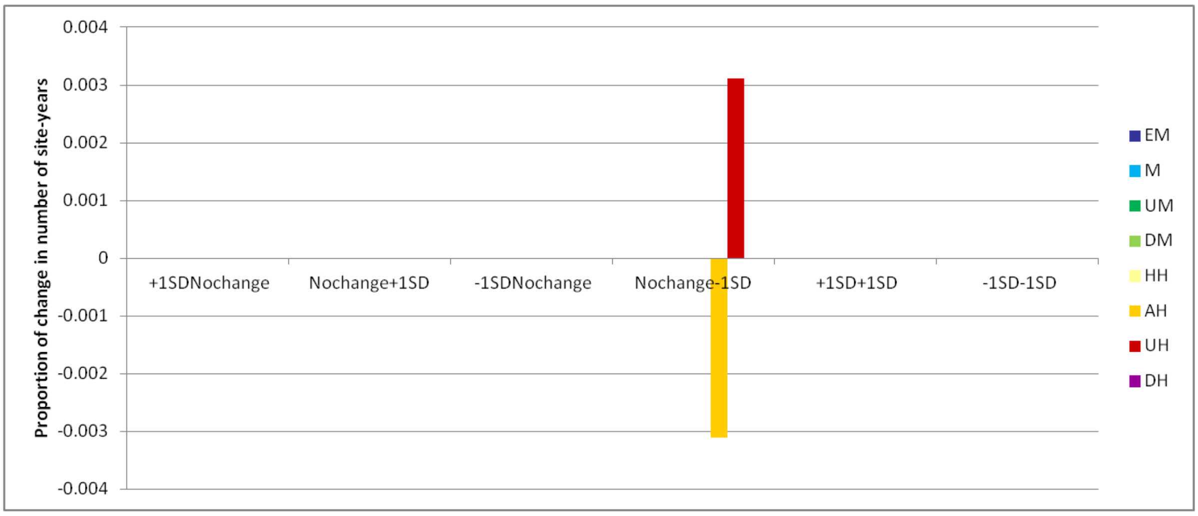

Figure 58: Deviations in the proportion of site-years in each ecosystem state compared to the Baseline scenario for the comparison of a shift in timing and distribution of flows. +1SDNochange is a +1SD shift in barrage timing and no change in USED timing (Scenario 28), Nochange+1SD is no change in barrage timing and a +1SD shift in USED timing (Scenario 29), -1SDNochange is a -1SD shift in barrage timing and no change in USED timing (Scenario 30), Nochange-1SD is no change in barrage timing and a -1SD shift in USED timing (Scenario 31), +1SD+1SD is a +1SD shift in barrage and USED timing (Scenario 32), and -1SD-1SD is a -1SD shift in both barrage and USED timing (Scenario 33; Table 1). All scenarios have medium barrage and SE flows with medium SE salinity

3.6.1.4 Effect of shifting barrage & USED flow timing under medium barrage & high SE flow conditions

There was little influence on depth from two years previous and average water level, when the effects of shifting the timing and distribution of barrage and USED flows were investigated under medium barrage and high SE flow conditions (Figure 59). Slight changes in median annual range in water level and median maximum salinity were observed. Median annual range was lowest at 0.93 m with a shift of -1 SD for both barrage and USED flow timing, and highest at 1.11 m with a shift of +1 SD for both barrage and USED flow timing. Median maximum salinity ranged from 47 g L^{-1} for a shift of -1 SD in barrage timing and no change in USED timing, to 54 g L^{-1} with a shift of +1 SD in both barrage and USED flow timing. The remainder of scenarios had a median maximum salinity of approximately 53 g L^{-1}.

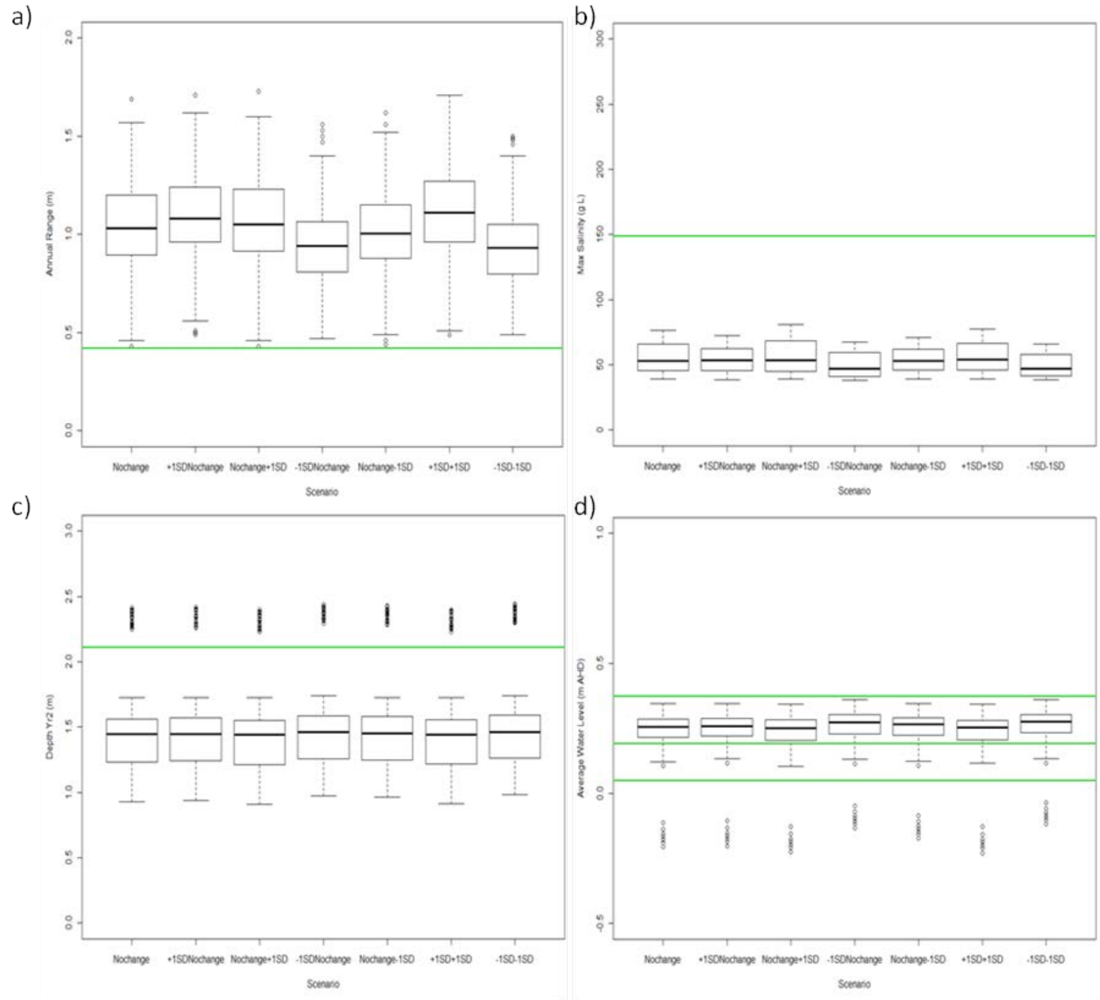

Figure 59: Boxplots showing the distributions of values for each of the variables driving the ecosystem states of the Coorong for the effect of increasing USED flow volume scenarios. a) Annual range in water level (m), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Average water level (m AHD) Note: Nochange is no change in both barrage and USED timing (Scenario 3), +1SDNochange is a +1SD shift in barrage timing and no change in USED timing (Scenario 34), Nochange+1SD is no change in barrage timing and a +1SD shift in USED timing (Scenario 35), -1SDNochange is a -1SD shift in barrage timing and no change in USED timing (Scenario 36), Nochange-1SD is no change in barrage timing and a -1SD shift in USED timing (Scenario 37), +1SD+1SD is a +1SD shift in barrage and USED timing (Scenario 38), and -1SD-1SD is a -1SD shift in both barrage and USED timing (Scenario 39; Table 1). All scenarios have medium barrage and high SE flows with medium SE salinity

There were positive cumulative differences in North Lagoon hydrodynamic drivers for two of the seven scenarios shifting the timing of flows investigated under medium barrage and high SE flow conditions (Figure 60). Those which represented an improvement in both average water level and depth from two years previous had shifts of -1 SD for barrage timing with either no change or a shift of -1 SD in USED flow timing. The remainder of scenarios had very small deviations in North Lagoon hydrodynamics compared to the Baseline scenario.

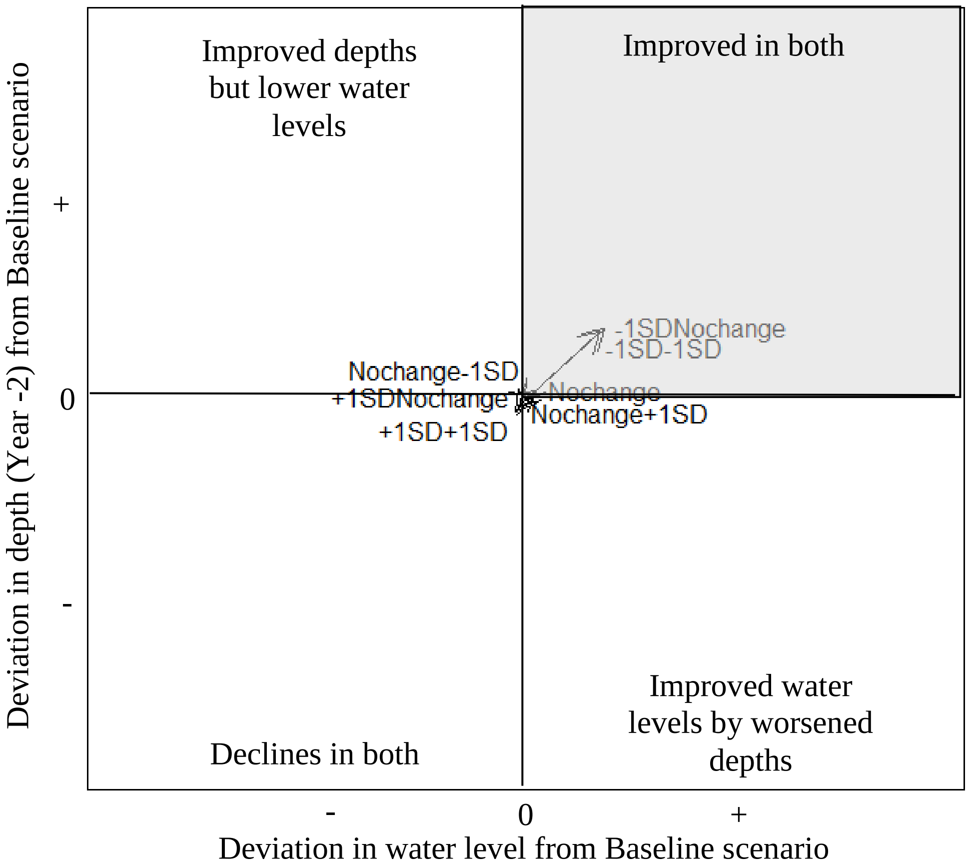

Figure 60: Comparison of the effect of a shift in timing and distribution of flows for the North Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline 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 Baseline scenario condition (as shown by the 0,0 origin). Vectors in the top-right quadrant indicate an improvement for both variables (i.e. higher water levels and greater depths). Note: Nochange is no change in both barrage and USED timing (Scenario 3), +1SDNochange is a +1SD shift in barrage timing and no change in USED timing (Scenario 34), Nochange+1SD is no change in barrage timing and a +1SD shift in USED timing (Scenario 35), -1SDNochange is a -1SD shift in barrage timing and no change in USED timing (Scenario 36), Nochange-1SD is no change in barrage timing and a -1SD shift in USED timing (Scenario 37), +1SD+1SD is a +1SD shift in barrage and USED timing (Scenario 38), and -1SD-1SD is a -1SD shift in both barrage and USED timing (Scenario 39; Table 1).). All scenarios have medium barrage and high SE flows with medium SE salinity

The cumulative impact on South Lagoon hydrodynamics was positive overall, with all scenarios showing an improvement in both maximum salinity and average water level (Figure 61), consistent with the impact of additional flows via the USED system compared with the Baseline scenario. However, additional improvement was greatest improvement was seen with a shift of -1 SD in barrage timing, with either no change or a shift of -1 SD in USED flow timing.

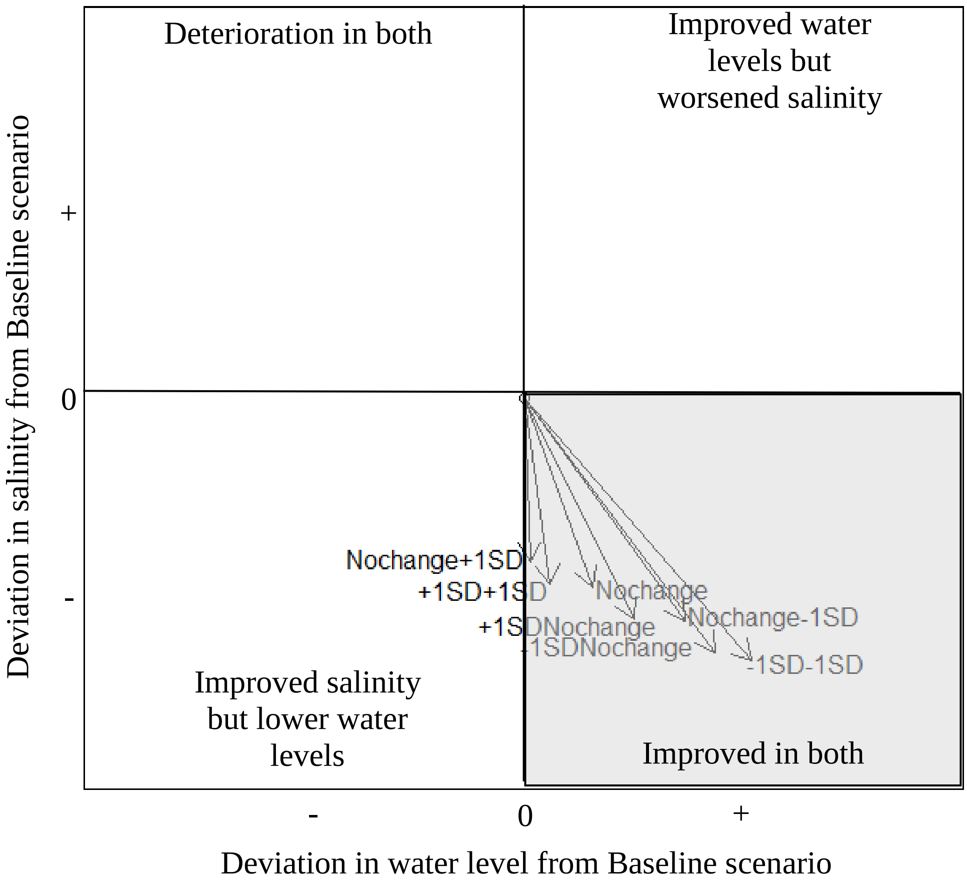

Figure 61: Comparison of the effect of a shift in timing and distribution of flows for the South Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Baseline scenario condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant indicate an improvement for both variables (i.e. higher water levels and lower salinities). Note: Nochange is no change in both barrage and USED timing (Scenario 3), +1SDNochange is a +1SD shift in barrage timing and no change in USED timing (Scenario 34), Nochange+1SD is no change in barrage timing and a +1SD shift in USED timing (Scenario 35), -1SDNochange is a -1SD shift in barrage timing and no change in USED timing (Scenario 36), Nochange-1SD is no change in barrage timing and a -1SD shift in USED timing (Scenario 37), +1SD+1SD is a +1SD shift in barrage and USED timing (Scenario 38), and -1SD-1SD is a -1SD shift in both barrage and USED timing (Scenario 39; Table 1). All scenarios have medium barrage and high SE flows with medium SE salinity

There was no change in the relative proportions of ecosystem states in any of the three USED salinity scenarios when compared to the Baseline scenario.

3.6.1.5 Effect of shifting barrage & USED flow timing under high barrage & medium SE flow conditions

When the effects of shifting the timing and distribution of barrage and USED flows were investigated under high barrage and medium SE flow conditions, there was again little influence on depth from two years previous and average water levels (Figure 62). Slight changes in annual range in water level and maximum salinity were observed. Median annual range in water levels ranged from 0.97 m with a shift of -1 SD in barrage timing, with no change and a shift of -1 SD in USED flow timing, to 1.21 m with a shift of +1 SD in both barrage and USED flow timing. Median maximum salinity ranged from 49 g L^{-1} with a shift of -1 SD in barrage timing, with no change and a shift of -1 SD in USED flow timing, to 56 g L^{-1} with no change in barrage timing and a shift of +1 SD in USED flow timing.

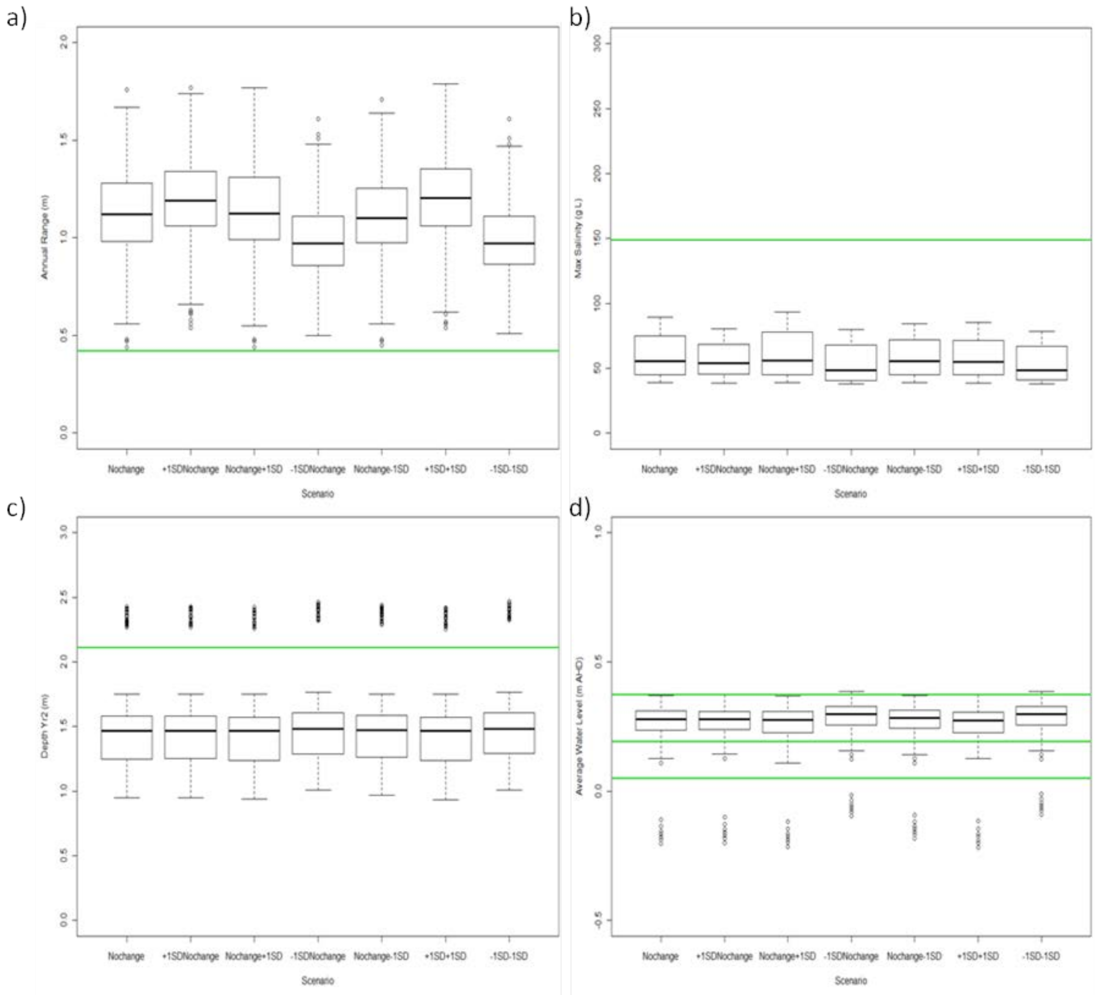

Figure 62: Boxplots showing the distributions of values for each of the variables driving the ecosystem states of the Coorong for the effect of increasing USED flow volume scenarios. a) Annual range in water level (m), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Average water level (m AHD) Note: Nochange is no change in both barrage and USED timing (Scenario 5), +1SDNochange is a +1SD shift in barrage timing and no change in USED timing (Scenario 40), Nochange+1SD is no change in barrage timing and a +1SD shift in USED timing (Scenario 41), -1SDNochange is a -1SD shift in barrage timing and no change in USED timing (Scenario 42), Nochange-1SD is no change in barrage timing and a -1SD shift in USED timing (Scenario 43), +1SD+1SD is a +1SD shift in barrage and USED timing (Scenario 44), and -1SD-1SD is a -1SD shift in both barrage and USED timing (Scenario 45; Table 1). All scenarios have high barrage and medium SE flows with medium SE salinity

There were positive cumulative differences in North Lagoon hydrodynamic drivers for all scenarios shifting the timing of flows under high barrage and medium SE flow conditions (Figure 63), again largely consistent with the barrage flows compared to the Baseline scenario. The greatest additional improvements in both average water level and depth from two years previous compared to the Baseline scenario was with a shift of -1 SD in barrage timing, with either no change or a shift of -1 SD in USED flow timing.

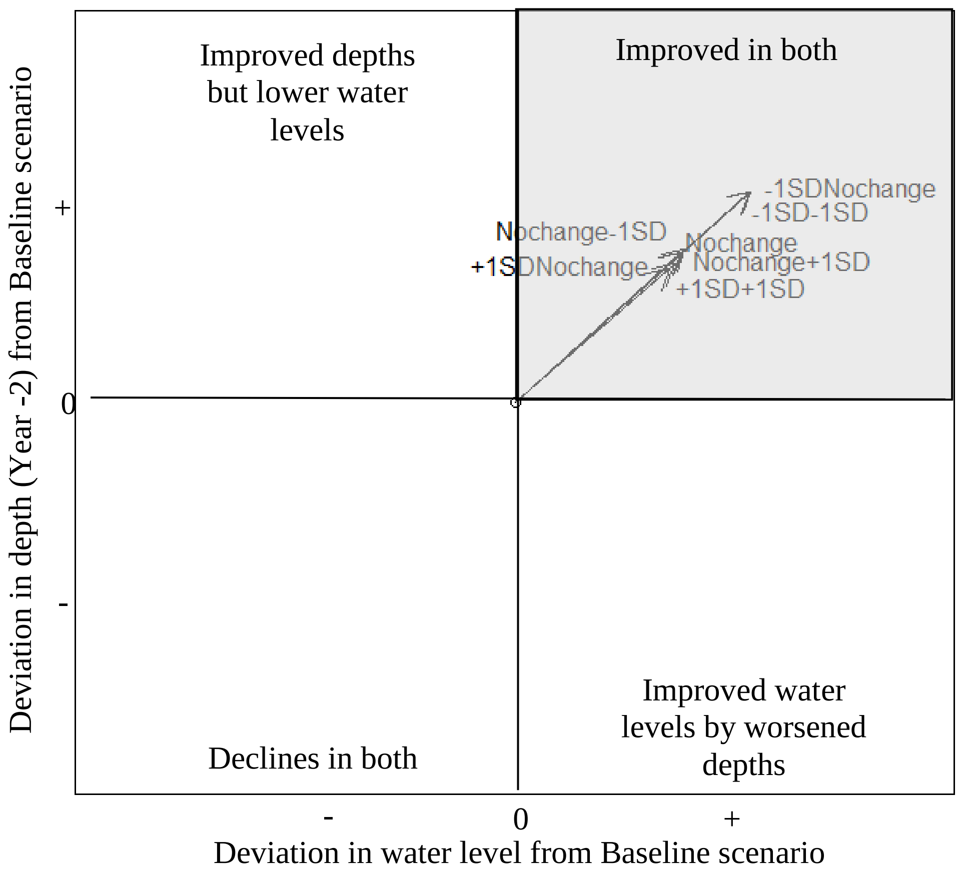

Figure 63: Comparison of the effect of a shift in timing and distribution of flows for the North Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline 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 Baseline scenario condition (as shown by the 0,0 origin). Vectors in the top-right quadrant indicate an improvement for both variables (i.e. higher water levels and greater depths). Note: Nochange is no change in both barrage and USED timing (Scenario 5), +1SDNochange is a +1SD shift in barrage timing and no change in USED timing (Scenario 40), Nochange+1SD is no change in barrage timing and a +1SD shift in USED timing (Scenario 41), -1SDNochange is a -1SD shift in barrage timing and no change in USED timing (Scenario 42), Nochange-1SD is no change in barrage timing and a -1SD shift in USED timing (Scenario 43), +1SD+1SD is a +1SD shift in barrage and USED timing (Scenario 44), and -1SD-1SD is a -1SD shift in both barrage and USED timing (Scenario 45; Table 1).). All scenarios have high barrage and medium SE flows with medium SE salinity

The cumulative impact on South Lagoon hydrodynamics was also positive for all of the scenarios shifting the timing of flows (Figure 64). Like the North Lagoon hydrodynamics, the greatest improvement in both maximum salinity and average water level was observed with a shift of -1 SD in barrage timing, with either no change or a shift of -1 SD in USED flow timing.

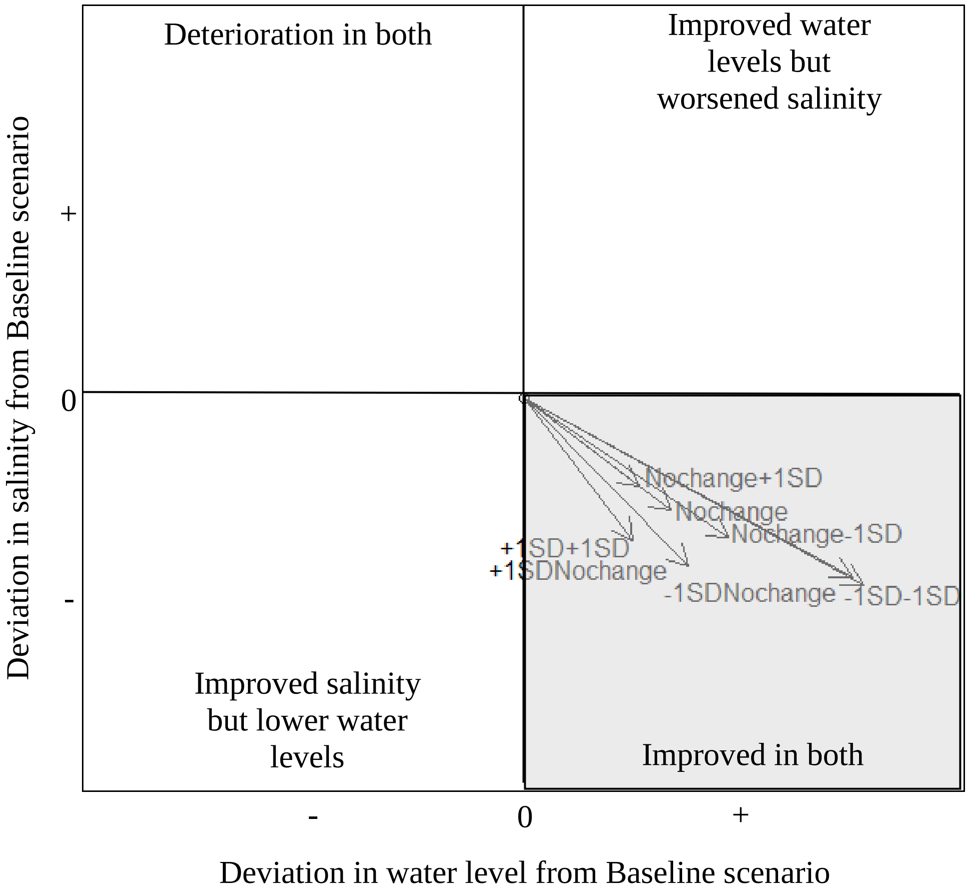

Figure 64: Comparison of the effect of a shift in timing and distribution of flows for the South Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Baseline scenario condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant indicate an improvement for both variables (i.e. higher water levels and lower salinities). Note: Nochange is no change in both barrage and USED timing (Scenario 5), +1SDNochange is a +1SD shift in barrage timing and no change in USED timing (Scenario 40), Nochange+1SD is no change in barrage timing and a +1SD shift in USED timing (Scenario 41), -1SDNochange is a -1SD shift in barrage timing and no change in USED timing (Scenario 42), Nochange-1SD is no change in barrage timing and a -1SD shift in USED timing (Scenario 43), +1SD+1SD is a +1SD shift in barrage and USED timing (Scenario 44), and -1SD-1SD is a -1SD shift in both barrage and USED timing (Scenario 45; Table 1). All scenarios have high barrage and medium SE flows with medium SE salinity

Under high barrage and medium SE flow conditions, four of the seven scenarios altered the relative proportions of ecosystem states when compared to the Baseline (Figure 65). All of those four resulted in a slight shift (i.e. <1%) from the Unhealthy Marine state to the Estuarine/Marine state, and were associated with either a +1 SD or -1 SD shift in the timing of barrage flows, regardless of a shift in USED flows.

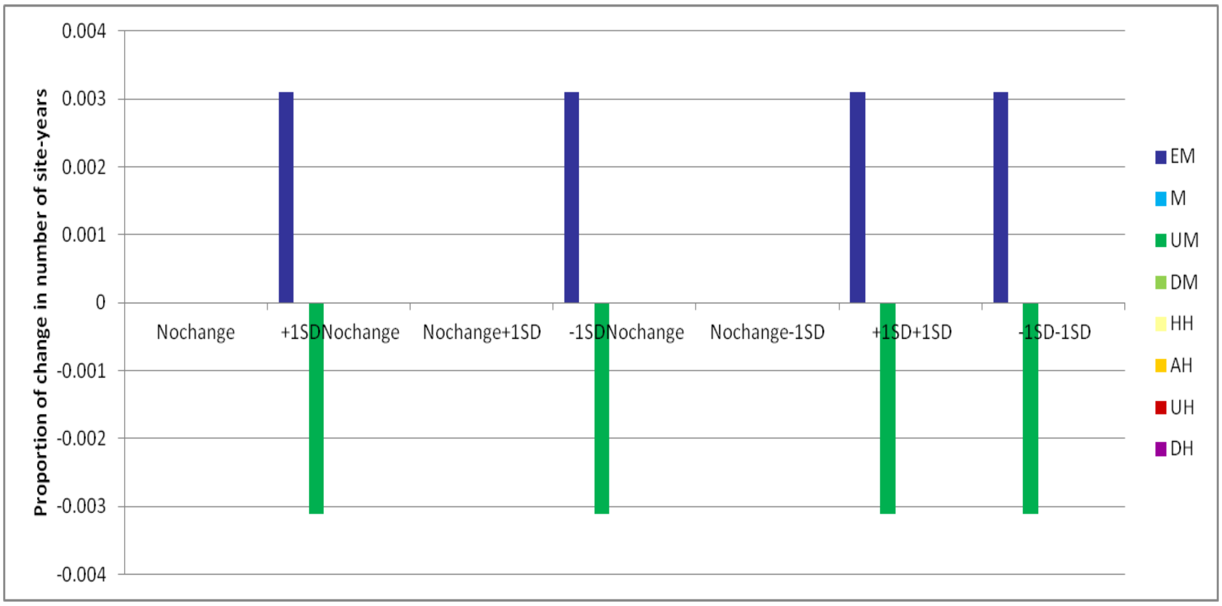

Figure 65: Deviations in the proportion of site-years in each ecosystem state compared to the Baseline scenario for the comparison of a shift in timing and distribution of flows. Nochange is no change in both barrage and USED timing (Scenario 5), +1SDNochange is a +1SD shift in barrage timing and no change in USED timing (Scenario 40), Nochange+1SD is no change in barrage timing and a +1SD shift in USED timing (Scenario 41), -1SDNochange is a -1SD shift in barrage timing and no change in USED timing (Scenario 42), Nochange-1SD is no change in barrage timing and a -1SD shift in USED timing (Scenario 43), +1SD+1SD is a +1SD shift in barrage and USED timing (Scenario 44), and -1SD-1SD is a -1SD shift in both barrage and USED timing (Scenario 45; Table 1). All scenarios have high barrage and medium SE flows with medium SE salinity

3.6.2 Effect of shifting barrage & USED flow timing by two standard deviations

Following from the previous series of results, where the timing and distribution of barrage and USED flows were shifted by 50 and 22 days, respectively, this series of results investigates the effect of shifting flows by a greater amount. Thus, these results show combinations of shifting barrage flows by ±2 SD (i.e. 100 days) and USED flows by ±2 SD (i.e. 44 days).

3.6.2.1 Effect of shifting barrage & USED flow timing (±2 SD) under low barrage & medium SE flow conditions

When the effects of larger shifts in barrage and USED flow timing were investigated under low barrage and medium SE flow conditions, there was little influence on depth from two years previous (Figure 66). Large changes in annual range in water level were observed for scenarios that included a -2 SD shift in barrage flows, regardless of any shift in USED flows, or a +2 SD shift in both barrage and USED flows. Maximum salinity showed small change in median values. Median annual range in water levels ranged from 0.25 m with a shift of +2 SD in USED timing and no change in barrage flows, to 0.33 m with a shift of -2 SD in barrage timing. Median maximum salinity ranged from 77.9 g L^{-1} with a shift of +2 SD in USED timing, to 64.6 g L^{-1} with a shift of -2 SD in barrage flow timing. The absolute maximum salinity recorded differed among scenarios, and was lowest for scenarios involving a -2 SD or a +2 SD shift in barrage flows.

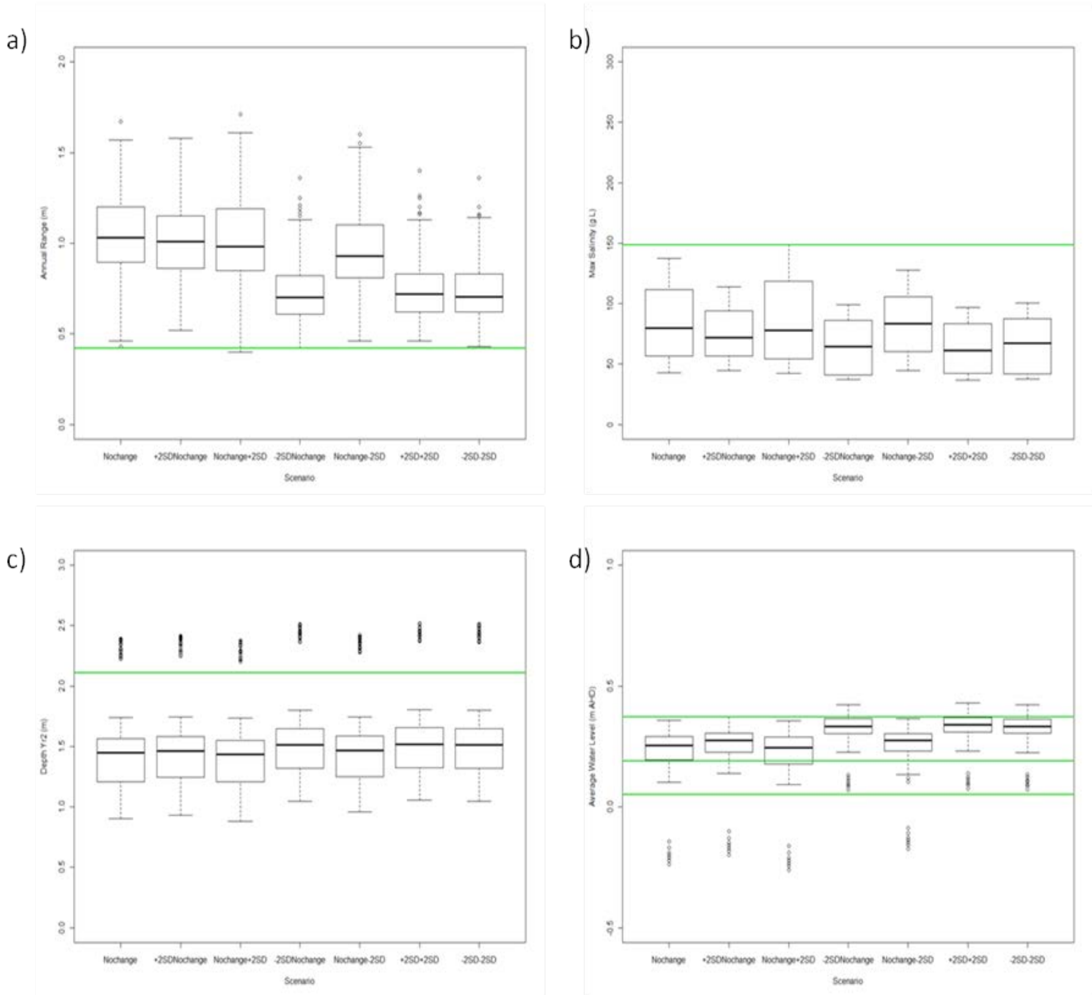

Figure 66: Boxplots showing the distributions of values for each of the variables driving the ecosystem states of the Coorong for the effect of increasing USED flow volume scenarios. a) Annual range in water level (m), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Average water level (m AHD) Note: Nochange is no change in both barrage and USED timing (Scenario 4), +2SDNochange is a +2SD shift in barrage timing and no change in USED timing (Scenario 46), Nochange+2SD is no change in barrage timing and a +2SD shift in USED timing (Scenario 47), -2SDNochange is a -2SD shift in barrage timing and no change in USED timing (Scenario 48), Nochange-2SD is no change in barrage timing and a -2SD shift in USED timing (Scenario 49), +2SD+2SD is a +2SD shift in barrage and USED timing (Scenario 50), and -2SD-2SD is a -2SD shift in both barrage and USED timing (Scenario 51; Table 1). All scenarios have low barrage and medium SE flows with medium SE salinity

The cumulative impact on North Lagoon hydrodynamics was also positive for all of the scenarios shifting the timing of flows (Figure 67), consistent with the effect of changes in barrage flows compared with the Baseline scenario. Very large additional improvements in both maximum depth and water level were observed with a shift of -2 SD in barrage timing or a shift of +2 SD in both barrage and USED flow timing.

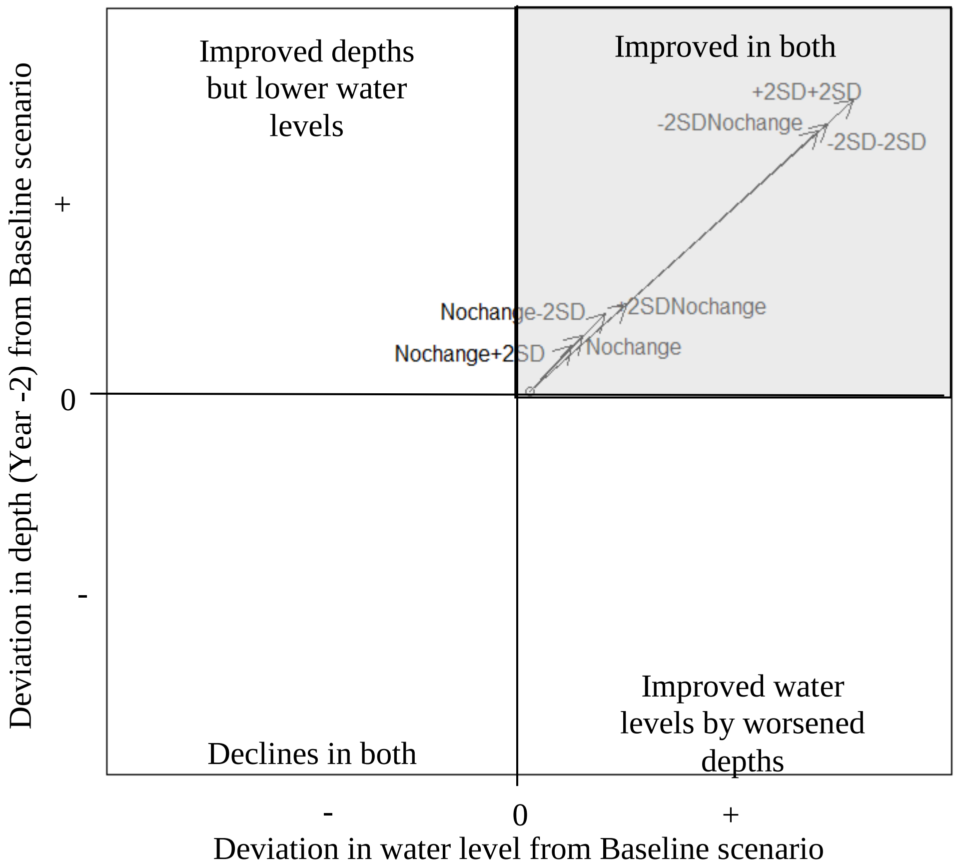

Figure 67: Comparison of the effect of a shift in timing and distribution of flows for the North Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline 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 Baseline scenario condition (as shown by the 0,0 origin). Vectors in the top-right quadrant indicate an improvement for both variables (i.e. higher water levels and greater depths). Note: Nochange is no change in both barrage and USED timing (Scenario 4), +2SDNochange is a +2SD shift in barrage timing and no change in USED timing (Scenario 46), Nochange+1SD is no change in barrage timing and a +2SD shift in USED timing (Scenario 47), -2SDNochange is a -2SD shift in barrage timing and no change in USED timing (Scenario 48), Nochange-2SD is no change in barrage timing and a -2SD shift in USED timing (Scenario 49), +2SD+2SD is a +2SD shift in barrage and USED timing (Scenario 50), and -2SD-2SD is a -2SD shift in both barrage and USED timing (Scenario 51; Table 1). All scenarios have low barrage and medium SE flows with medium SE salinity

Consistent with the effect on hydrodynamics in the North Lagoon, the biggest improvement in South Lagoon hydrodynamics (Figure 68) was observed for shifts of -2 SD in barrage timing or +2 SD in both barrage and USED flow timing scenarios. Most of this change was in the average annual water level. All other scenarios resulted in worse South Lagoon salinities compared to the Baseline scenario, consistent with the lower barrage flows associated with those scenarios.

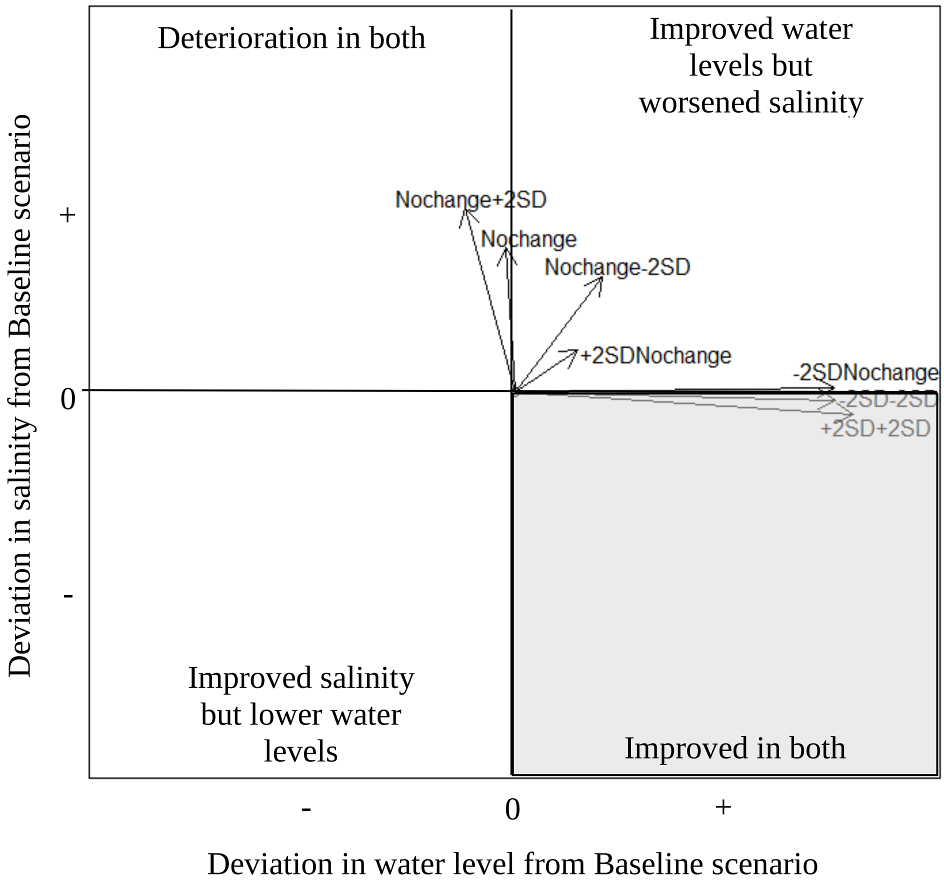

Figure 68: Comparison of the effect of a shift in timing and distribution of flows for the South Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Baseline scenario condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant indicate an improvement for both variables (i.e. higher water levels and lower salinities). Note: Nochange is no change in both barrage and USED timing (Scenario 4), +2SDNochange is a +2SD shift in barrage timing and no change in USED timing (Scenario 46), Nochange+1SD is no change in barrage timing and a +2SD shift in USED timing (Scenario 47), -2SDNochange is a -2SD shift in barrage timing and no change in USED timing (Scenario 48), Nochange-2SD is no change in barrage timing and a -2SD shift in USED timing (Scenario 49), +2SD+2SD is a +2SD shift in barrage and USED timing (Scenario 50), and -2SD-2SD is a -2SD shift in both barrage and USED timing (Scenario 51; Table 1). All scenarios have low barrage and medium SE flows with medium SE salinity

Shifting barrage flows back by 2 SD, or shifting barrage flows and USED flows forward by 2 SD resulted in substantial changes in the mix of ecosystem states simulated (Figure 69). These scenarios showed no degraded ecosystem states in the North Lagoon, in contrast to the other scenarios explored, and resulted in the appearance of the Healthy Hypersaline ecosystem state, which is associated with high flow conditions in the South Lagoon. This suggested an improvement in the ecological conditions of the Coorong. Changes in USED flows in the absence of changes in barrage flows did not produce the same result.

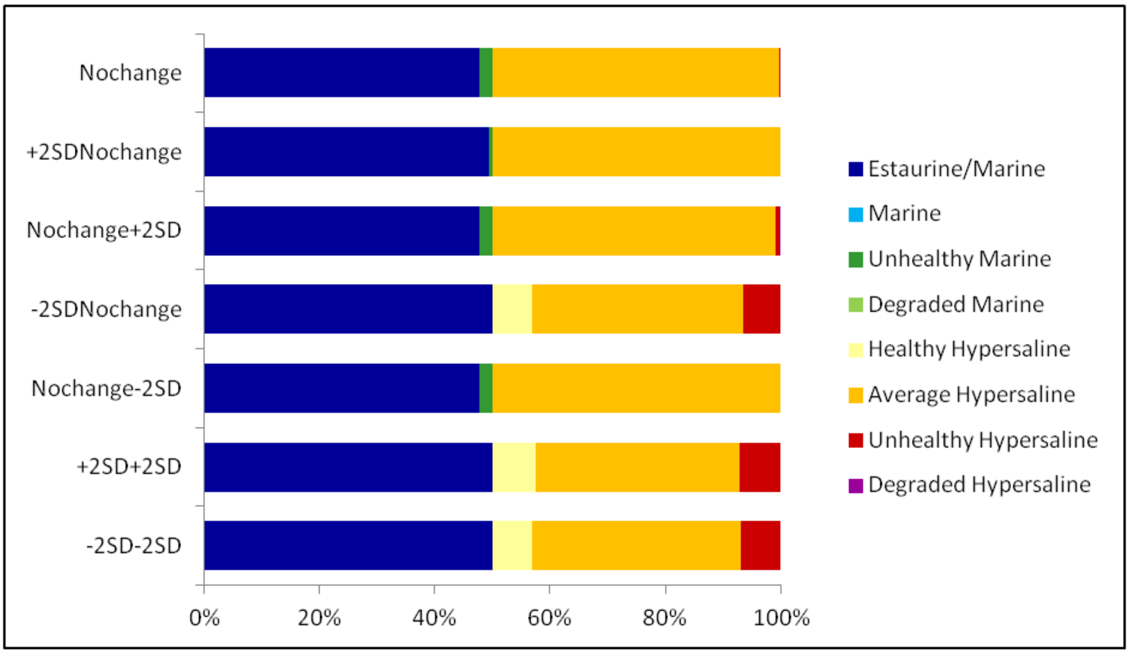

Figure 69: Comparing the proportion of site-years in each ecosystem state for the climate change scenarios Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DM = Degraded Hypersaline. Nochange is no change in both barrage and USED timing (Scenario 4), +2SDNochange is a +2SD shift in barrage timing and no change in USED timing (Scenario 46), Nochange+1SD is no change in barrage timing and a +2SD shift in USED timing (Scenario 47), -2SDNochange is a -2SD shift in barrage timing and no change in USED timing (Scenario 48), Nochange-2SD is no change in barrage timing and a -2SD shift in USED timing (Scenario 49), +2SD+2SD is a +2SD shift in barrage and USED timing (Scenario 50), and -2SD-2SD is a -2SD shift in both barrage and USED timing (Scenario 51; Table 1). All scenarios have low barrage and medium SE flows with medium SE salinity

Under low barrage and medium USED flow conditions, all scenarios shifting the timing of flows altered the relative proportions of ecosystem states compared with the Baseline scenario (Figure 70); consistent with the lower barrage flows included in these scenarios. The greatest changes were seen with -2 SD and +2 SD changes in both barrage and USED flow timing, as well as -2 SD in barrage flow with no change in USED flow timing, which led particularly to changes (i.e. -15%) for Average Hypersaline states. For the same scenarios shifting the timing of flows, the Healthy and Unhealthy Hypersaline ecosystem states increased (i.e. +6%).

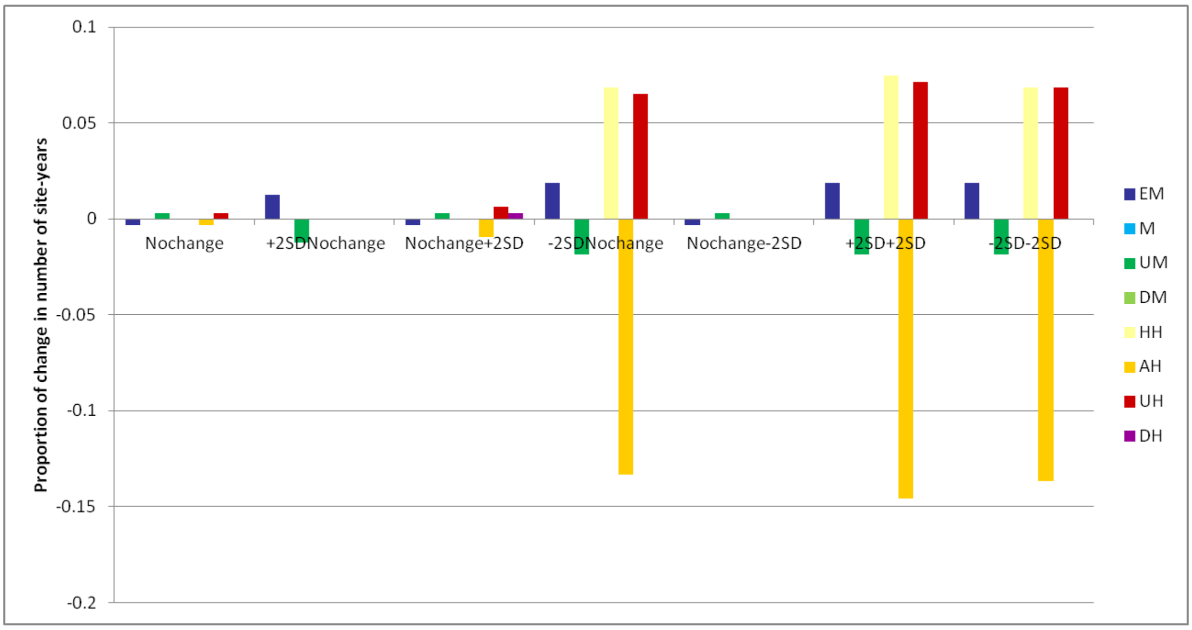

Figure 70: Deviations in the proportion of site-years in each ecosystem state compared to the Baseline scenario for the comparison of a shift in timing and distribution of flows Note: Nochange is no change in both barrage and USED timing (Scenario 4), +2SDNochange is a +2SD shift in barrage timing and no change in USED timing (Scenario 46), Nochange+1SD is no change in barrage timing and a +2SD shift in USED timing (Scenario 47), -2SDNochange is a -2SD shift in barrage timing and no change in USED timing (Scenario 48), Nochange-2SD is no change in barrage timing and a -2SD shift in USED timing (Scenario 49), +2SD+2SD is a +2SD shift in barrage and USED timing (Scenario 50), and -2SD-2SD is a -2SD shift in both barrage and USED timing (Scenario 51; Table 1). All scenarios have low barrage and medium SE flows with medium SE salinity

3.6.2.2 Effect of shifting barrage & USED flow timing (±2 SD) under medium barrage & low SE flow conditions

When the effects of shifting barrage and USED flow timing were investigated under medium barrage and low SE flow conditions, there was little influence on depth from two years previous (Figure 71). Maximum salinity recorded large changes across scenarios. Median maximum salinity ranged from 68 g L^{-1} with a shift of +2 SD in barrage timing and no change in USED flow timing, to 89 g L^{-1} with a shift of -2 SD in both barrage and USED flow timing. Median annual range in water levels ranged from 0.75 m with a shift of -2 SD in barrage timing and no change in USED flow timing, to 1.03 m with a shift of +2 SD in both barrage and USED flow timing.

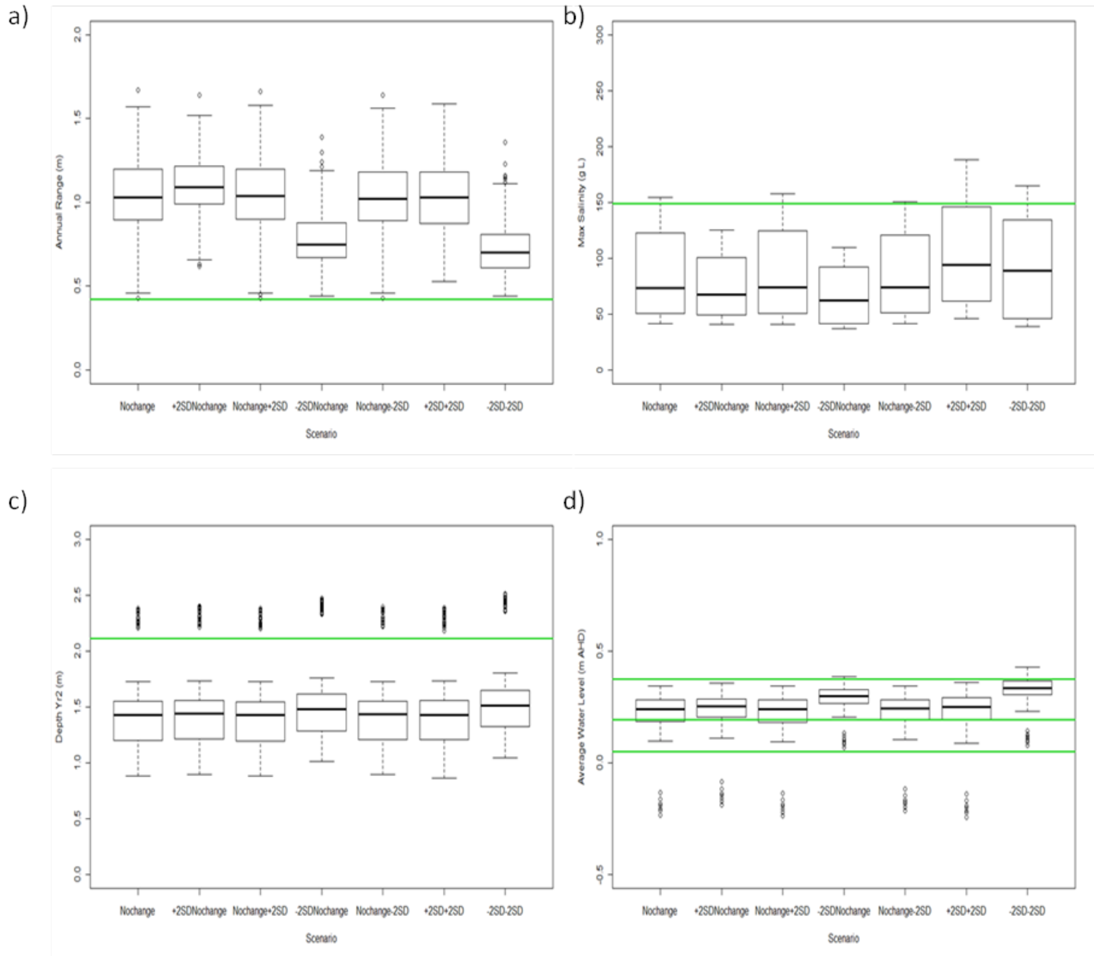

Figure 71: Boxplots showing the distributions of values for each of the variables driving the ecosystem states of the Coorong for the effect of increasing USED flow volume scenarios. a) Annual range in water level (m), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Average water level (m AHD) Note: Nochange is no change in both barrage and USED timing (Scenario 2), +2SDNochange is a +2SD shift in barrage timing and no change in USED timing (Scenario 52), Nochange+2SD is no change in barrage timing and a +2SD shift in USED timing (Scenario 53), -2SDNochange is a -2SD shift in barrage timing and no change in USED timing (Scenario 54), Nochange-2SD is no change in barrage timing and a -2SD shift in USED timing (Scenario 55), +2SD+2SD is a +2SD shift in barrage and USED timing (Scenario 56), and -2SD-2SD is a -2SD shift in both barrage and USED timing (Scenario 57; Table 1). All scenarios have medium barrage and low SE flows with medium SE salinity

The cumulative impact on North Lagoon hydrodynamics was also positive for all of the scenarios involving a shift in barrage flows (Figure 72). The greatest improvement in both depth and water level was observed with a shift of -2 SD in both barrage and USED flow timing. The other scenarios shifting the timing of barrage flows showed modest improvements in both water level and depth, whilst the scenarios shifting only USED flows did not deviate from the from baseline conditions.

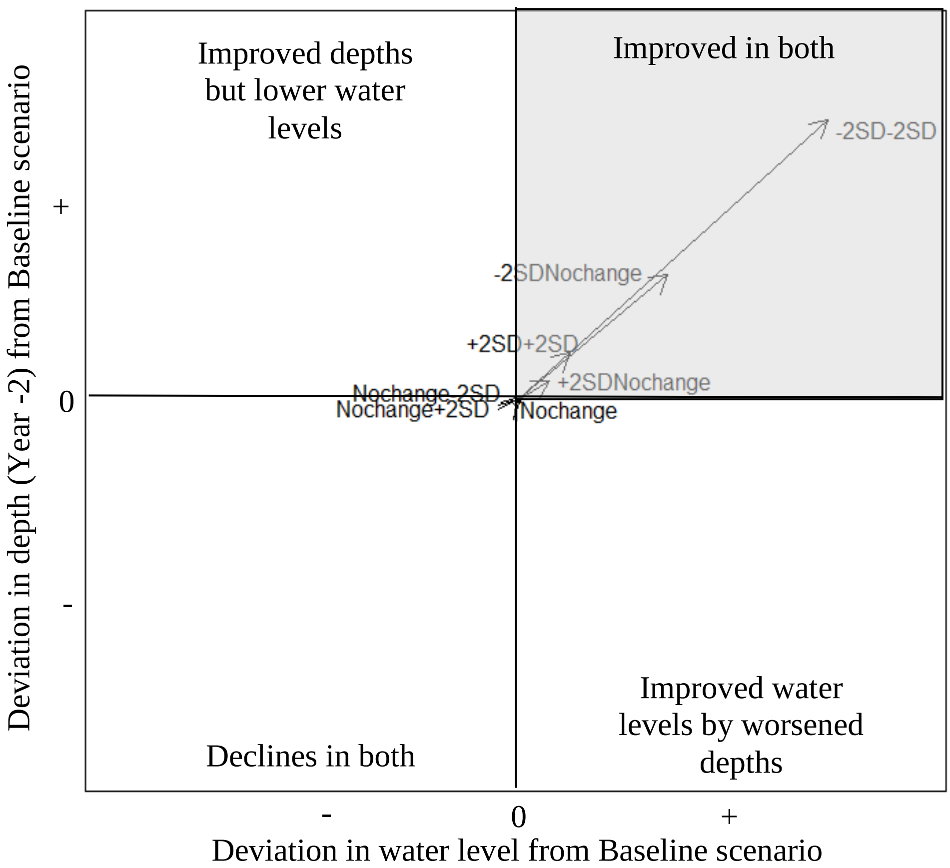

Figure 72: Comparison of the effect of a shift in timing and distribution of flows for the North Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline 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 Baseline scenario condition (as shown by the 0,0 origin). Vectors in the top-right quadrant indicate an improvement for both variables (i.e. higher water levels and greater depths). Note: Nochange is no change in both barrage and USED timing (Scenario 2), +2SDNochange is a +2SD shift in barrage timing and no change in USED timing (Scenario 52), Nochange+2SD is no change in barrage timing and a +2SD shift in USED timing (Scenario 53), -2SDNochange is a -2SD shift in barrage timing and no change in USED timing (Scenario 54), Nochange-2SD is no change in barrage timing and a -2SD shift in USED timing (Scenario 55), +2SD+2SD is a +2SD shift in barrage and USED timing (Scenario 56), and -2SD-2SD is a -2SD shift in both barrage and USED timing (Scenario 57; Table 1). All scenarios have medium barrage and low SE flows with medium SE salinity

No scenario shifting the timing of flows showed improvements in South Lagoon hydrodynamics relative to baseline conditions (Figure 73), but the resultant differences were smaller than those observed for the same barrage and USED flow volumes with no shift in timing. Four scenarios, including no change in both barrage and USED flow timing, no change in USED flow timing but a +2 SD or a -2 SD change in barrage flow timing, and a +2 SD change in both barrage and USED flow timing showed deterioration in both salinity and water level. Both scenarios with a +2 SD or -2 SD change in barrage flow and no change in USED flow, and the -2 SD change in both barrage and USED flow showed improved water levels but worsened salinity. The best outcome overall, relative to the same scenarios with no shifts in flow timing were for the scenarios that shifted barrage flow timing by ±2 SD, with no shifts in USED flow timing.

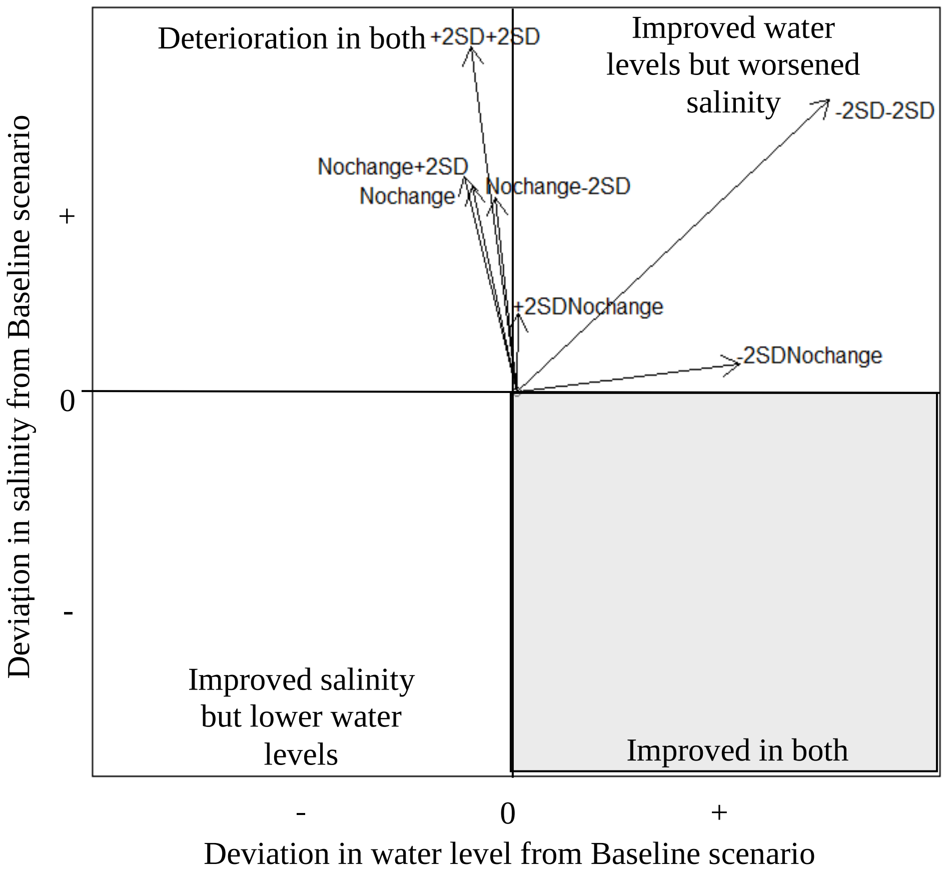

Figure 73: Comparison of the effect of a shift in timing and distribution of flows for the South Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Baseline scenario condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant indicate an improvement for both variables (i.e. higher water levels and lower salinities). Note: Nochange is no change in both barrage and USED timing (Scenario 2), +2SDNochange is a +2SD shift in barrage timing and no change in USED timing (Scenario 52), Nochange+2SD is no change in barrage timing and a +2SD shift in USED timing (Scenario 53), -2SDNochange is a -2SD shift in barrage timing and no change in USED timing (Scenario 54), Nochange-2SD is no change in barrage timing and a -2SD shift in USED timing (Scenario 55), +2SD+2SD is a +2SD shift in barrage and USED timing (Scenario 56), and -2SD-2SD is a -2SD shift in both barrage and USED timing (Scenario 57; Table 1). All scenarios have medium barrage and low SE flows with medium SE salinity

The proportion of site-years classified into the Estuarine/Marine or Average Hypersaline ecosystem state under medium barrage and low USED flow were very similar, except when both barrage and USED flows were shifted by ±2 SD together (Figure 74). Degraded Marine still represented a small proportion (<3%) of site years for each scenario. Under this climate scenario, five scenarios shifting the timing of flows, including no change in either barrage or USED flow, no change in barrage timing with either a ±2 SD change in USED, , and both ±2 SD change in barrage and

USED timing, had site-years classified into Degraded Hypersaline (i.e. ranging from 3 to 20%). Only one scenario, -2 SD change in both barrage release and USED timing had site-years classified into Healthy Hypersaline and Unhealthy Hypersaline (5% each respectively). The appearance of the Degraded Hypersaline ecosystem state, in particular, represents a deterioration in ecological conditions in the Coorong.

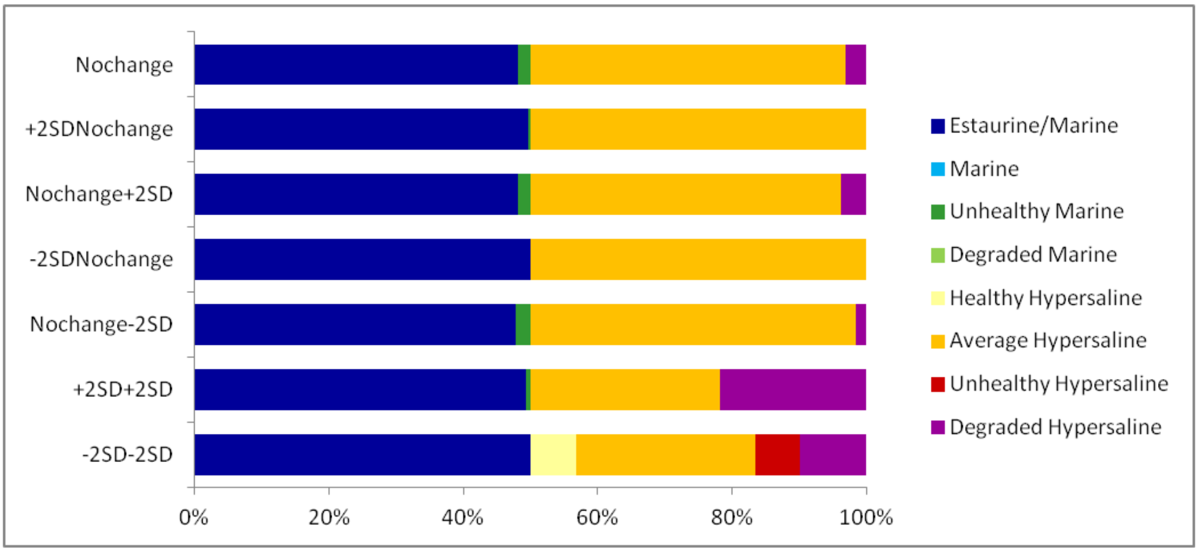

Figure 74: Comparing the proportion of site-years in each ecosystem state for the climate change scenarios Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DM = Degraded Hypersaline. Nochange is no change in both barrage and USED timing (Scenario 2), +2SDNochange is a +2SD shift in barrage timing and no change in USED timing (Scenario 52), Nochange+2SD is no change in barrage timing and a +2SD shift in USED timing (Scenario 53), -2SDNochange is a -2SD shift in barrage timing and no change in USED timing (Scenario 54), Nochange-2SD is no change in barrage timing and a -2SD shift in USED timing (Scenario 55), +2SD+2SD is a +2SD shift in barrage and USED timing (Scenario 56), and -2SD-2SD is a -2SD shift in both barrage and USED timing (Scenario 57; Table 1). All scenarios have medium barrage and low SE flows with medium SE salinity

Under medium barrage flow and low USED flow, all scenarios shifting the timing of flows altered the relative proportions of ecosystem states compared to the Baseline scenario, except for the Nochange scenario (Figure 75). The greatest changes were seen with +2 SD and -2 SD change in both barrage and USED flow timing (much like in Figure 70), which led to changes in the proportion of site-years (i.e. -20%) for Average Hypersaline site-years. For the same shift timing scenarios, the proportion of site-years in the Degraded Hypersaline state increased (i.e. +18% and +7% respectively). The only scenario shifting the timing of flows to show an increase in the proportion of Healthy Hypersaline and Unhealthy Hypersaline site-years was a -2 SD change in both barrage and USED flow.

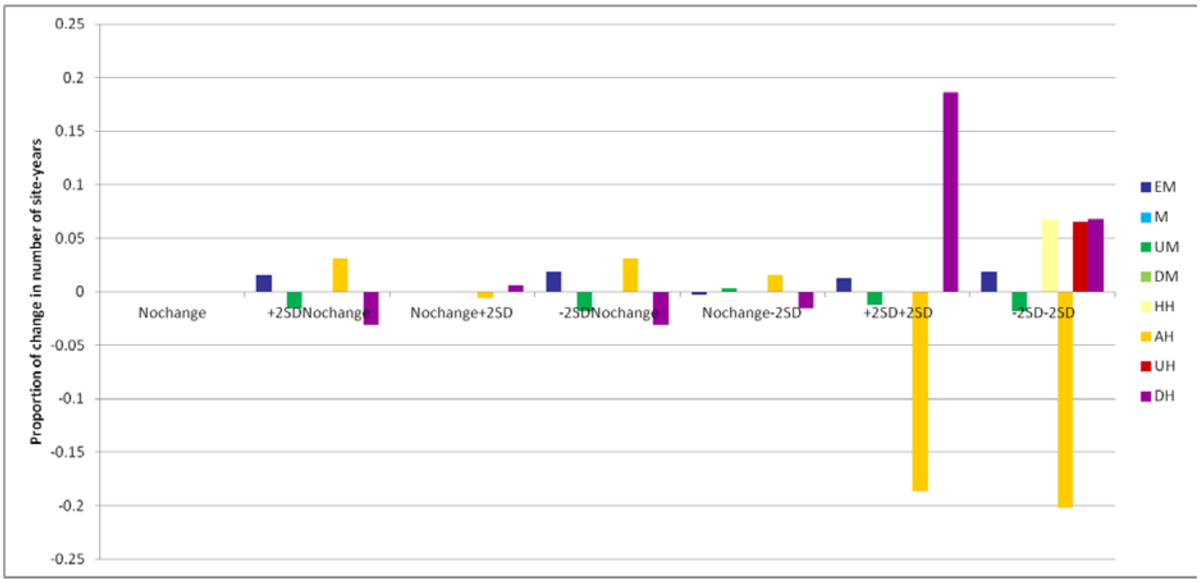

Figure 75: Deviations in the proportion of site-years in each ecosystem state compared to the Baseline scenario for the comparison of a shift in timing and distribution of flows
Note: Nochange is no change in both barrage and USED timing (Scenario 2), +2SDNochange is a +2SD shift in barrage timing and no change in USED timing (Scenario 52), Nochange+2SD is no change in barrage timing and a +2SD shift in USED timing (Scenario 53), -2SDNochange is a -2SD shift in barrage timing and no change in USED timing (Scenario 54), Nochange-2SD is no change in barrage timing and a -2SD shift in USED timing (Scenario 55), +2SD+2SD is a +2SD shift in barrage and USED timing (Scenario 56), and -2SD-2SD is a -2SD shift in both barrage and USED timing (Scenario 57; Table 1). All scenarios have medium barrage and low SE flows with medium SE salinity

3.6.2.3 Effect of shifting barrage & USED flow timing (±2 SD) under medium barrage & SE flow conditions

When the effects of shifting barrage and USED flow timing were investigated under medium barrage and SE flow conditions, there was little influence on depth from two years previous, but all other hydrodynamic drivers showed at least small changes among scenarios (Figure 76). Median annual range in water levels showed the largest differences, ranging from 0.76 m with a shift of -2 SD in barrage timing and no shift in USED timing, to 1.1 m with a shift of +2 SD in barrage and USED flow timing. The same scenarios also showed the largest shifts in average water levels and maximum salinities, although the differences among scenarios were smaller overall.

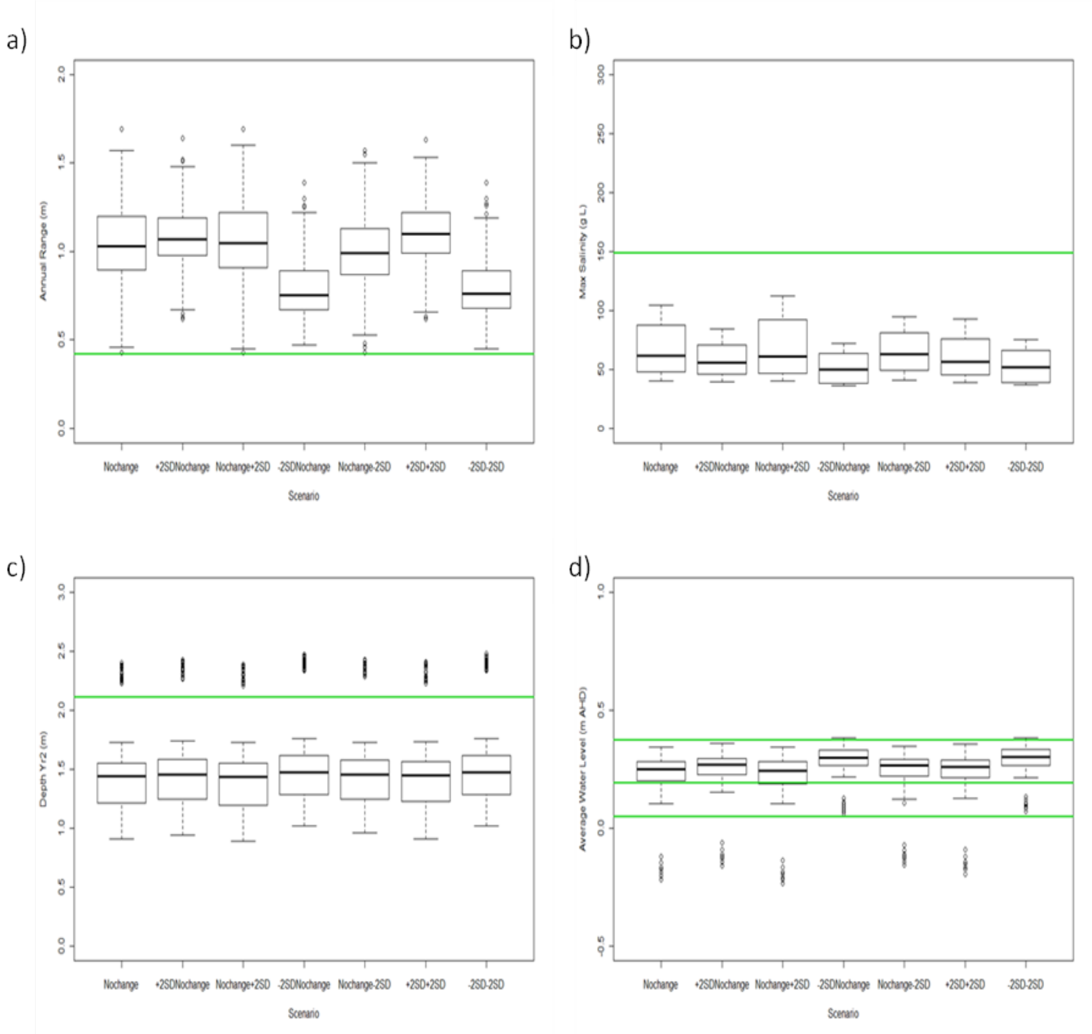

Figure 76: Boxplots showing the distributions of values for each of the variables driving the ecosystem states of the Coorong for the effect of increasing USED flow volume scenarios. a) Annual range in water level (m), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Average water level (m AHD) Note: Nochange is no change in both barrage and USED timing (Baseline, Scenario 1), +2SDNochange is a +2SD shift in barrage timing and no change in USED timing (Scenario 58), Nochange+2SD is no change in barrage timing and a +2SD shift in USED timing (Scenario 59), -2SDNochange is a -2SD shift in barrage timing and no change in USED timing (Scenario 60), Nochange-2SD is no change in barrage timing and a -2SD shift in USED timing (Scenario 61), +2SD+2SD is a +2SD shift in barrage and USED timing (Scenario 62), and -2SD-2SD is a -2SD shift in both barrage and USED timing (Scenario 63; Table 1). All scenarios have medium barrage and SE flows with medium SE salinity

The impact on North Lagoon hydrodynamics was positive compared to the Baseline scenario for four of the seven scenarios shifting the timing of flows (Figure 77). The two scenarios that showed the greatest improvement in depth and water level were a shift of -2 SD in both barrage and USED flow timing and a -2 SD change in barrage flow timing and no change in USED flow timing. All other shift timing scenarios showed only modest improvements away from the Baseline scenario.

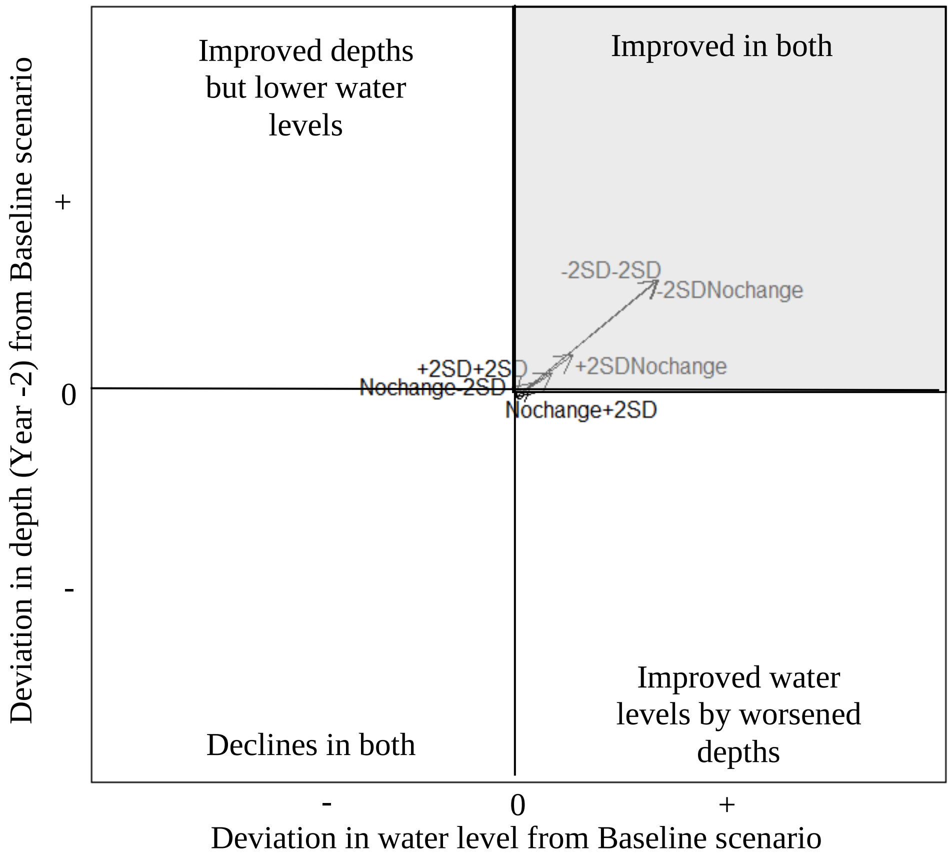

Figure 77: Comparison of the effect of a shift in timing and distribution of flows for the North Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline 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 Baseline scenario condition (as shown by the 0,0 origin). Vectors in the top-right quadrant indicate an improvement for both variables (i.e. higher water levels and greater depths). Note: +2SDNochange is a +2SD shift in barrage timing and no change in USED timing (Scenario 58), Nochange+2SD is no change in barrage timing and a +2SD shift in USED timing (Scenario 59), -2SDNochange is a -2SD shift in barrage timing and no change in USED timing (Scenario 60), Nochange-2SD is no change in barrage timing and a -2SD shift in USED timing (Scenario 61), +2SD+2SD is a +2SD shift in barrage and USED timing (Scenario 62), and -2SD-2SD is a -2SD shift in both barrage and USED timing (Scenario 63; Table 1). All scenarios have medium barrage and SE flows with medium SE salinity

The impact on South Lagoon hydrodynamics was positive for all but one of the seven scenarios shifting the timing of flows (Figure 78). Of the six scenarios to show an improvement, the greatest was observed with a shift of -2 SD in both barrage and USED flow timing and -2 SD change in barrage flow and no change in USED flow timing. The only scenario shifting the timing of flows to show deteriorating conditions in both salinity and water level compared with the Baseline scenario was the scenario involving no change in barrage timing and +2 SD USED flow timing.

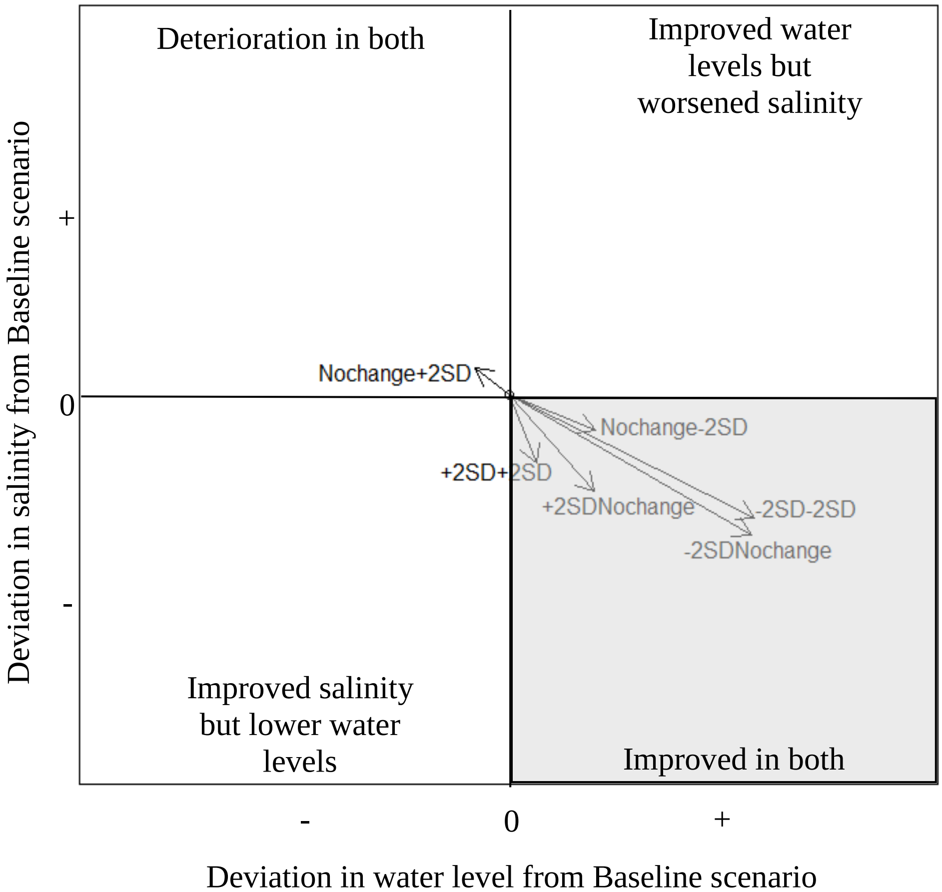

Figure 78: Comparison of the effect of a shift in timing and distribution of flows for the South Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Baseline scenario condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant indicate an improvement for both variables (i.e. higher water levels and lower salinities). Note: +2SDNochange is a +2SD shift in barrage timing and no change in USED timing (Scenario 58), Nochange+2SD is no change in barrage timing and a +2SD shift in USED timing (Scenario 59), -2SDNochange is a -2SD shift in barrage timing and no change in USED timing (Scenario 60), Nochange-2SD is no change in barrage timing and a -2SD shift in USED timing (Scenario 61), +2SD+2SD is a +2SD shift in barrage and USED timing (Scenario 62), and -2SD-2SD is a -2SD shift in both barrage and USED timing (Scenario 63; Table 1). All scenarios have medium barrage and SE flows with medium SE salinity

The proportion of site-years in each ecosystem state under medium barrage and USED flow conditions were very similar (Figure 79). The majority of site-years were classified as either Estuarine/Marine or Average Hypersaline. Scenarios that included either a ±2 SD in barrage flows had no degraded ecosystems states, regardless of the shift in USED flow timing.

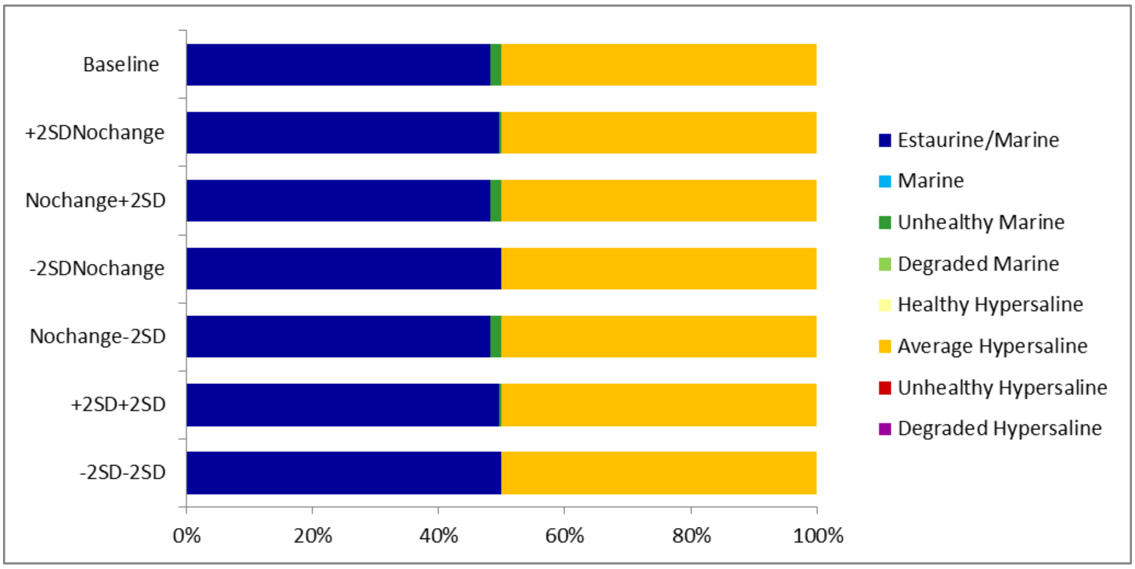

Figure 79: Comparing the proportion of site-years in each ecosystem state for the climate change scenarios

Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DM = Degraded Hypersaline. Baseline scenario is no change in both barrage and USED timing (Scenario 1), +2SDNochange is a +2SD shift in barrage timing and no change in USED timing (Scenario 58), Nochange+2SD is no change in barrage timing and a +2SD shift in USED timing (Scenario 59), -2SDNochange is a -2SD shift in barrage timing and no change in USED timing (Scenario 60), Nochange-2SD is no change in barrage timing and a -2SD shift in USED timing (Scenario 61), +2SD+2SD is a +2SD shift in barrage and USED timing (Scenario 62), and -2SD-2SD is a -2SD shift in both barrage and USED timing (Scenario 63; Table 1). All scenarios have medium barrage and SE flows with medium SE salinity

Under both medium barrage and USED flow conditions, only four scenarios shifting the timing of flows altered the relative proportions (Figure 80) of two ecosystem states, Unhealthy Marine (i.e. -1.5%) and Estuarine/Marine (+1.5%). Those four scenarios included a ±2 SD change in both barrage and USED flow timing, as well as a ±2 SD change in barrage flow with no change in USED flow. No other scenario altered the proportion of ecosystem state site-years.

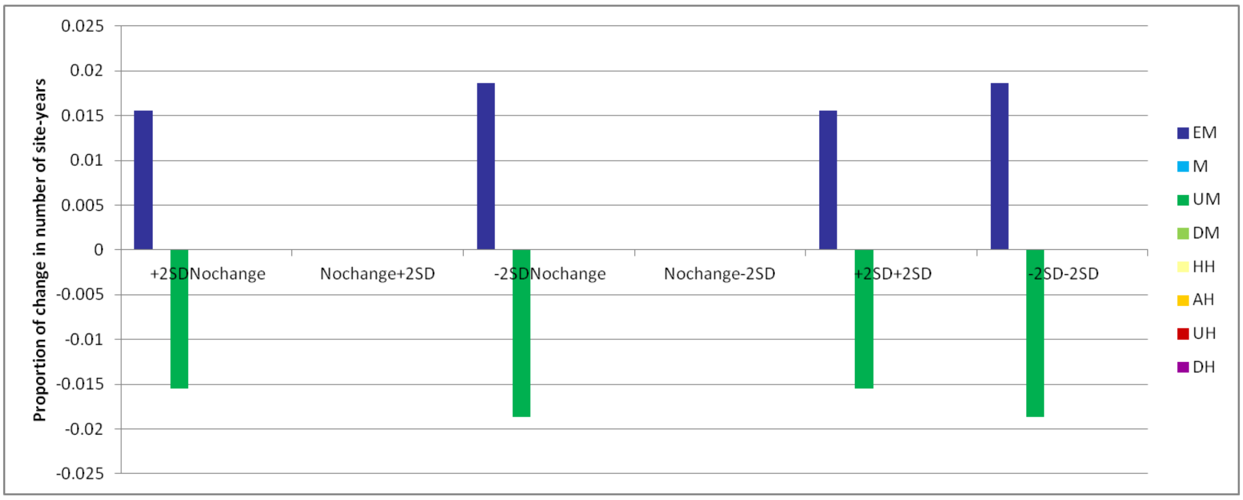

Figure 80: Deviations in the proportion of site-years in each ecosystem state compared to the Baseline scenario for the comparison of a shift in timing and distribution of flows
Note: +2SDNochange is a +2SD shift in barrage timing and no change in USED timing (Scenario 58), Nochange+2SD is no change in barrage timing and a +2SD shift in USED timing (Scenario 59), -2SDNochange is a -2SD shift in barrage timing and no change in USED timing (Scenario 60), Nochange-2SD is no change in barrage timing and a -2SD shift in USED timing (Scenario 61), +2SD+2SD is a +2SD shift in barrage and USED timing (Scenario 62), and -2SD-2SD is a -2SD shift in both barrage and USED timing (Scenario 63; Table 1). All scenarios have medium barrage and SE flows with medium SE salinity

3.6.2.4 Effect of shifting barrage & USED flow timing (±2 SD) under medium barrage & high SE flow conditions

When the effects of shifting barrage and USED flow timing were investigated under medium barrage and high SE flow conditions, there was little influence on depth from two years previous and average water level (Figure 81). Median annual range in water levels ranged from 1.1 m with a shift of +2 SD in barrage and USED timing, to 0.77 m with a shift of -2 SD in barrage and USED flow timing. Median maximum salinity ranged from 54 g L^{-1} with a shift of +2 SD in USED timing and no change to barrage flows, to 40 g L^{-1} with a shift of -2 SD in barrage flow timing and no change to barrage flows.

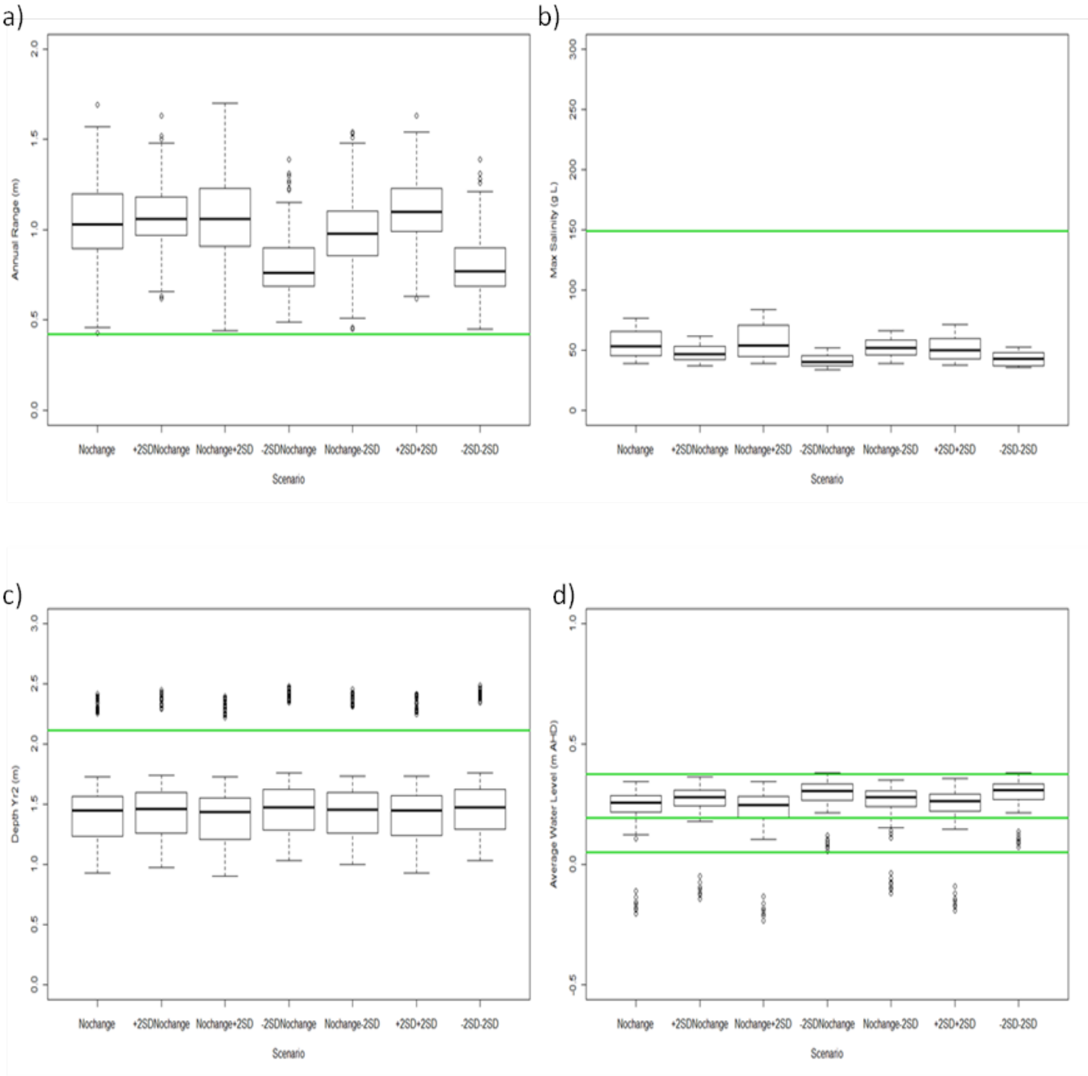

Figure 81: Boxplots showing the distributions of values for each of the variables driving the ecosystem states of the Coorong for the effect of increasing USED flow volume scenarios. a) Annual range in water level (m), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Average water level (m AHD) Note: Nochange is no change in both barrage and USED timing (Scenario 3), +2SDNochange is a +2SD shift in barrage timing and no change in USED timing (Scenario 64), Nochange+2SD is no change in barrage timing and a +2SD shift in USED timing (Scenario 65), -2SDNochange is a -2SD shift in barrage timing and no change in USED timing (Scenario 66), Nochange-2SD is no change in barrage timing and a -2SD shift in USED timing (Scenario 67), +2SD+2SD is a +2SD shift in barrage and USED timing (Scenario 68), and -2SD-2SD is a -2SD shift in both barrage and USED timing (Scenario 69; Table 1). All scenarios have medium barrage and high SE flows with medium SE salinity

The impact on North Lagoon hydrodynamics was positive for all of the seven shift timing scenarios (Figure 82), but the strength of response was overall, quite small, despite the additional water from the USED scheme compared to the Baseline scenario. The scenarios that showed the greatest improvement in both depth and water level were a shift of -2 SD in both barrage and USED flow timing and a -2 SD shift in barrage flows with no change in USED timing. All other scenarios showed only modest improvements or no change from the Baseline scenario.

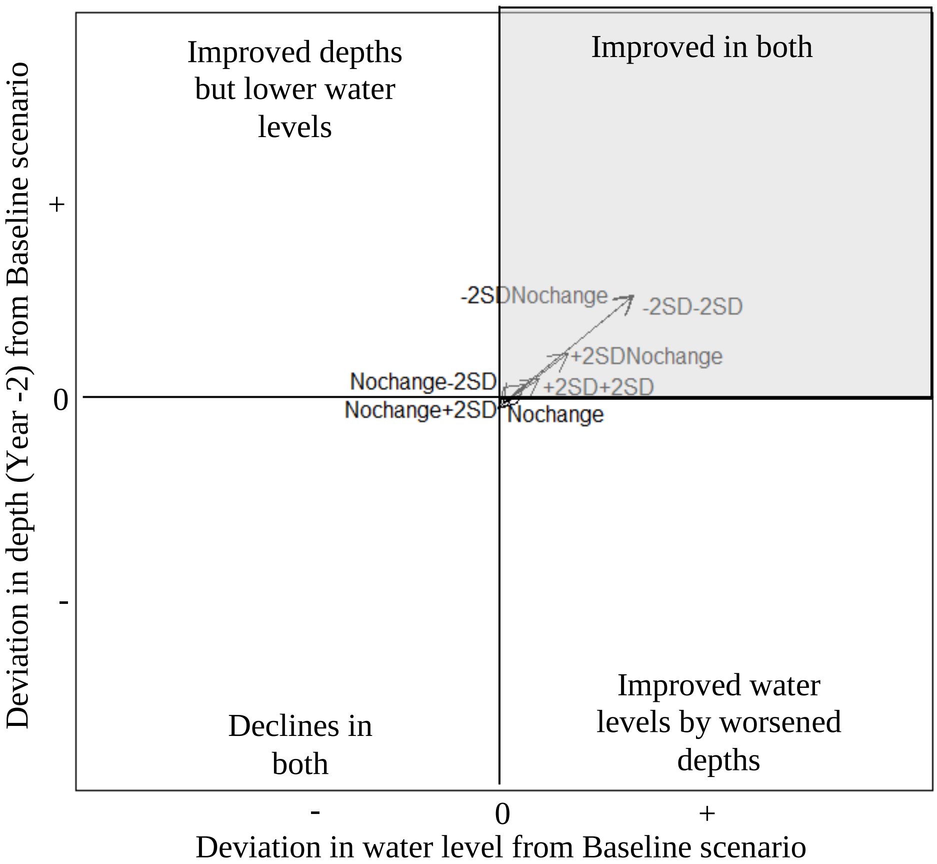

Figure 82: Comparison of the effect of a shift in timing and distribution of flows for the North Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline 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 Baseline scenario condition (as shown by the 0,0 origin). Vectors in the top-right quadrant indicate an improvement for both variables (i.e. higher water levels and greater depths). Note: Nochange is no change in both barrage and USED timing (Scenario 3), +2SDNochange is a +2SD shift in barrage timing and no change in USED timing (Scenario 64), Nochange+2SD is no change in barrage timing and a +2SD shift in USED timing (Scenario 65), -2SDNochange is a -2SD shift in barrage timing and no change in USED timing (Scenario 66), Nochange-2SD is no change in barrage timing and a -2SD shift in USED timing (Scenario 67), +2SD+2SD is a +2SD shift in barrage and USED timing (Scenario 68), and -2SD-2SD is a-2SD shift in both barrage and USED timing (Scenario 69; Table 1). All scenarios have medium barrage and high SE flows with medium SE salinity

Unlike the North Lagoon, all but one of the seven scenarios showed positive hydrodynamic results in the South Lagoon (Figure 83), consistent with the higher USED flows associated with these scenarios. These changes were not larger than those associated with a 1SD shift in the timing of flows. No change in barrage flow with +2 SD in USED flow was the only scenario to show a decline in water levels, and the change was small. A -2 SD in both barrage and USED flows, as well as -2 SD in barrage flow and no change in USED flow showed the strongest improvement in hydrodynamic conditions, but the effect was similar to the corresponding scenarios with a 1 SD shift in flow timing.

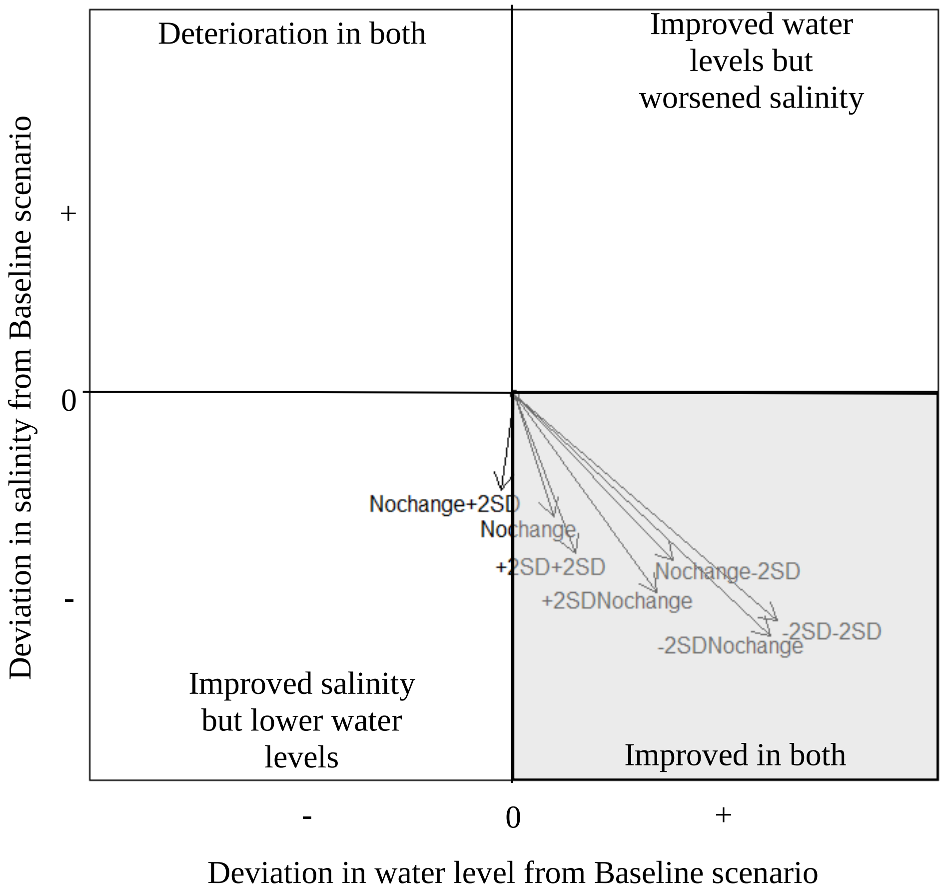

Figure 83: Comparison of the effect of a shift in timing and distribution of flows for the South Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Baseline scenario condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant indicate an improvement for both variables (i.e. higher water levels and lower salinities). Note: Nochange is no change in both barrage and USED timing (Scenario 3), +2SDNochange is a +2SD shift in barrage timing and no change in USED timing (Scenario 64), Nochange+2SD is no change in barrage timing and a +2SD shift in USED timing (Scenario 65), -2SDNochange is a -2SD shift in barrage timing and no change in USED timing (Scenario 66), Nochange-2SD is no change in barrage timing and a -2SD shift in USED timing (Scenario 67), +2SD+2SD is a +2SD shift in barrage and USED timing (Scenario 68), and -2SD-2SD is a -2SD shift in both barrage and USED timing (Scenario 69; Table 1). All scenarios have medium barrage and high SE flows with medium SE salinity

The proportion of site-years classified into each ecosystem state under medium barrage and high USED flow, were very similar (Figure 84). There was little variation between scenarios, where the majority of site-years were classified as either Estuarine/Marine or Average Hypersaline. Scenarios that did not involve a ±2 SD shift in the timing of barrage flows contained some site-years classified into Degraded Marine, but in small proportions (<3%).

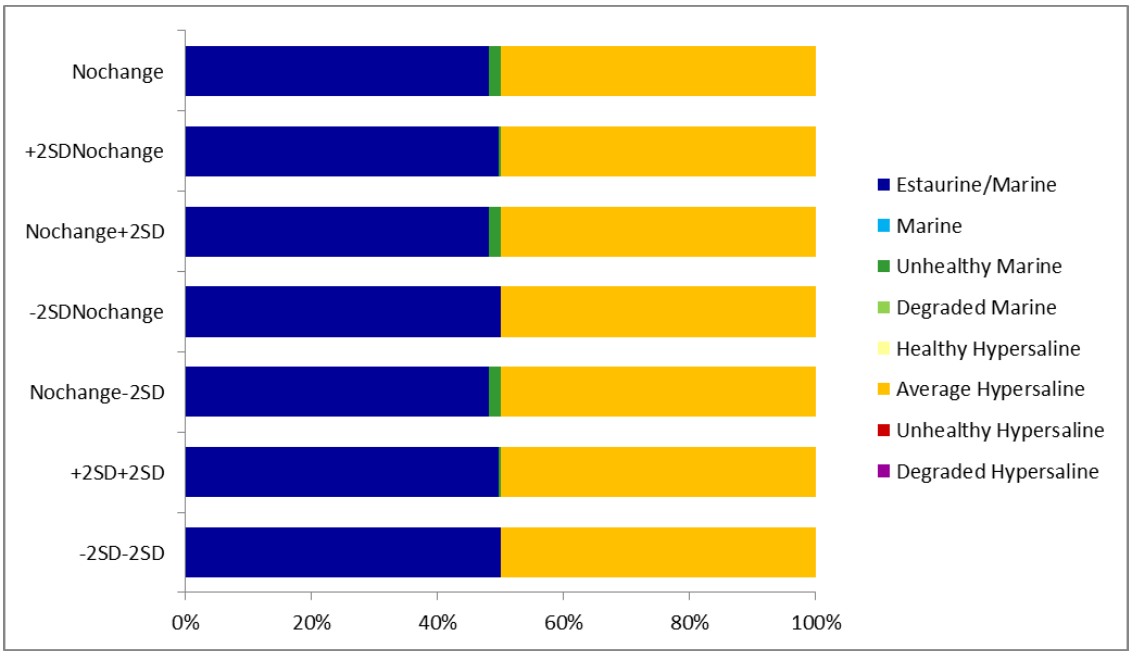

Figure 84: Comparing the proportion of site-years in each ecosystem state for the climate change scenarios

Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DM = Degraded Hypersaline. Baseline scenario is no change in both barrage and USED timing (Scenario 1), Nochange is no change in both barrage and USED timing (Scenario 3), +2SDNochange is a +2SD shift in barrage timing and no change in USED timing (Scenario 64), Nochange+2SD is no change in barrage timing and a +2SD shift in USED timing (Scenario 65), -2SDNochange is a -2SD shift in barrage timing and no change in USED timing (Scenario 66), Nochange-2SD is no change in barrage timing and a -2SD shift in USED timing (Scenario 67), +2SD+2SD is a +2SD shift in barrage and USED timing (Scenario 68), and -2SD-2SD is a -2SD shift in both barrage and USED timing (Scenario 69; Table 1). All scenarios have medium barrage and high SE flows with medium SE salinity

Under medium barrage and high USED flow conditions only four scenarios altered the relative proportions (Figure 85) of two ecosystem states, Unhealthy Marine (i.e. -1.5%) and Estuarine/Marine (+1.5%). Those four scenarios included ±2 SD changes in both barrage and USED flow timing, as well as ±2 SD changes in barrage flow, with no change in USED flow. No other scenario altered the proportion of ecosystem state site-years.

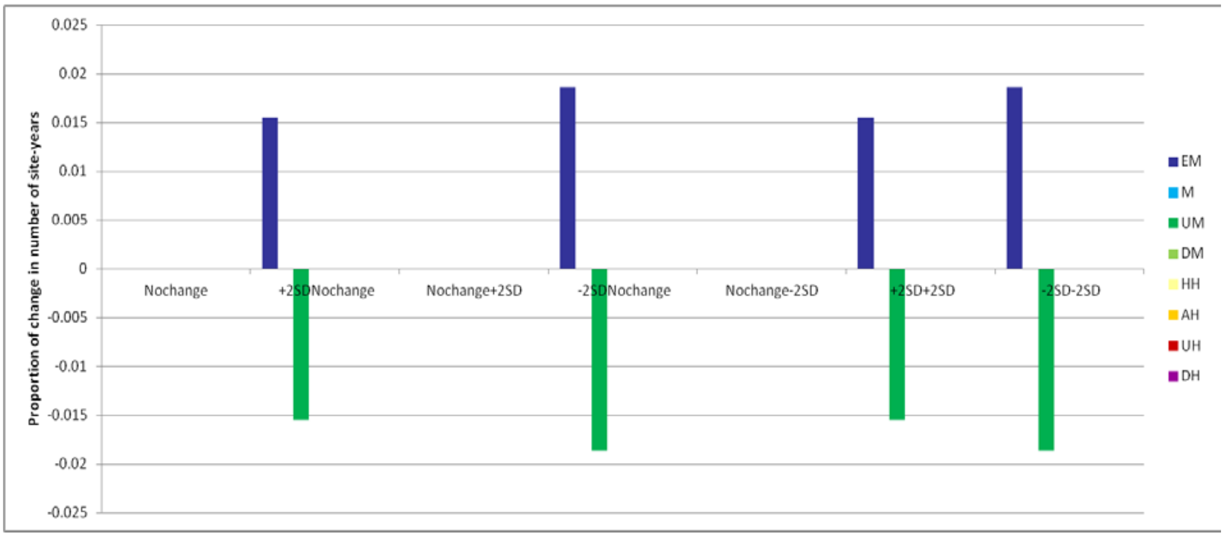

Figure 85: Deviations in the proportion of site-years in each ecosystem state compared to the Baseline scenario for the comparison of a shift in timing and distribution of flows
Note: Nochange is no change in both barrage and USED timing (Scenario 3), +2SDNochange is a +2SD shift in barrage timing and no change in USED timing (Scenario 64), Nochange+2SD is no change in barrage timing and a +2SD shift in USED timing (Scenario 65), -2SDNochange is a -2SD shift in barrage timing and no change in USED timing (Scenario 66), Nochange-2SD is no change in barrage timing and a -2SD shift in USED timing (Scenario 67), +2SD+2SD is a +2SD shift in barrage and USED timing (Scenario 68), and -2SD-2SD is a -2SD shift in both barrage and USED timing (Scenario 69; Table 1). All scenarios have medium barrage and high SE flows with medium SE salinity

3.6.2.5 Effect of shifting barrage & USED flow timing (±2 SD) under high barrage & medium SE flow conditions

When the effects of shifting barrage and USED flow timing were investigated under high barrage and medium SE flow conditions, there was little influence on depth from two years previous and average water level (Figure 86). Median annual range in water levels ranged from 0.80 m with a shift of -2 SD in barrage timing and no change in USED flow timing, to 1.19 m with a shift of +2 SD in both barrage and USED flow timing. Median maximum salinity ranged from 55 g L^{-1} with a shift of -2 SD in USED timing and no shift in barrage flow timing to 44 g L^{-1} with a shift of -2 SD in both barrage and USED flow timing.

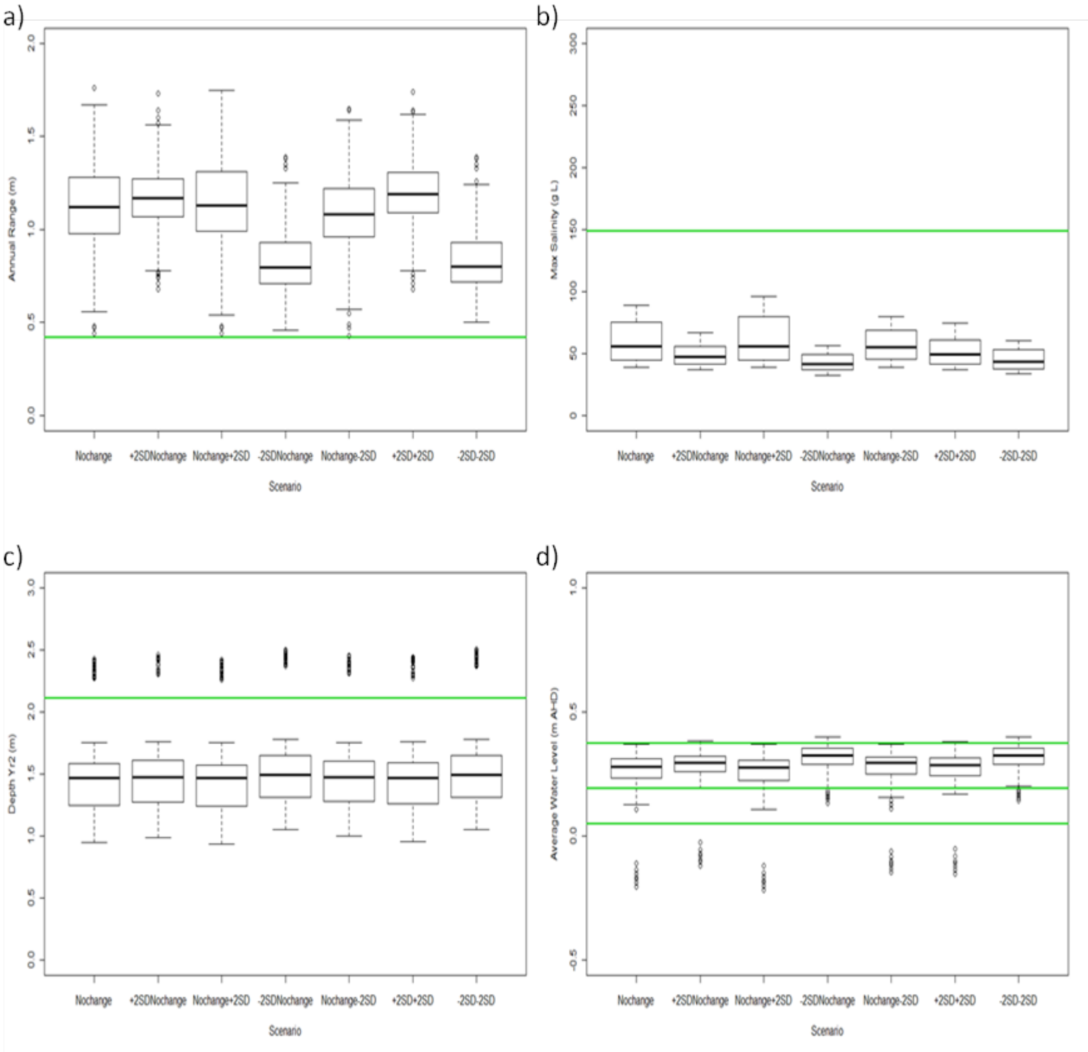

Figure 86: Boxplots showing the distributions of values for each of the variables driving the ecosystem states of the Coorong for the effect of increasing USED flow volume scenarios. a) Annual range in water level (m), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Average water level (m AHD) Note: Nochange is no change in both barrage and USED timing (Scenario 5), +2SDNochange is a +2SD shift in barrage timing and no change in USED timing (Scenario 70), Nochange+2SD is no change in barrage timing and a +2SD shift in USED timing (Scenario 71), -2SDNochange is a -2SD shift in barrage timing and no change in USED timing (Scenario 72), Nochange-2SD is no change in barrage timing and a -2SD shift in USED timing (Scenario 73), +2SD+2SD is a +2SD shift in barrage and USED timing (Scenario 74), and -2SD-2SD is a -2SD shift in both barrage and USED timing (Scenario 75; Table 1). All scenarios have high barrage and medium SE flows with medium SE salinity

The cumulative impact on North Lagoon hydrodynamics was again highly positive for all of the scenarios involving a shift in the timing of flows (Figure 87), consistent with the higher barrage flow volumes included in these scenarios relative to the Baseline. The greatest improvements in both depth and water level was observed with a shift of -2 SD in barrage flow timing, regardless of whether there was a shift in USED flow timing or not. All other scenarios shifting the timing of flows showed modest improvements in both water level and depth.

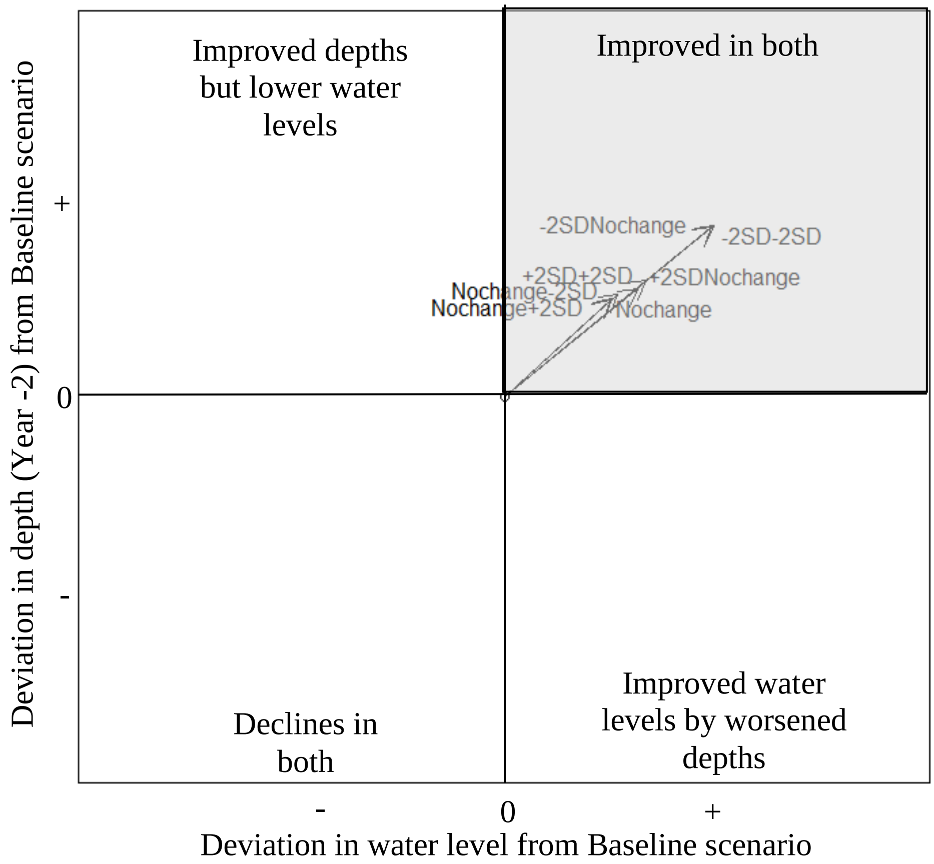

Figure 87: Comparison of the effect of a shift in timing and distribution of flows for the North Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline 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 Baseline scenario condition (as shown by the 0,0 origin). Vectors in the top-right quadrant indicate an improvement for both variables (i.e. higher water levels and greater depths). Note: Nochange is no change in both barrage and USED timing (Scenario 5), +2SDNochange is a +2SD shift in barrage timing and no change in USED timing (Scenario 70), Nochange+2SD is no change in barrage timing and a +2SD shift in USED timing (Scenario 71), -2SDNochange is a -2SD shift in barrage timing and no change in USED timing (Scenario 72), Nochange-2SD is no change in barrage timing and a -2SD shift in USED timing (Scenario 73), +2SD+2SD is a +2SD shift in barrage and USED timing (Scenario 74), and -2SD-2SD is a -2SD shift in both barrage and USED timing (Scenario 75; Table 1). All scenarios have high barrage and medium SE flows with medium SE salinity

The cumulative impact on North Lagoon hydrodynamics was strongly positive for all of the shift timing scenarios (Figure 88), again consistent with the increased barrage flow volumes involved. The largest improvement in both salinity and water level was observed with a shift of -2 SD in barrage flows, regardless of the shift in USED flow timing. All other scenarios showed moderate to strong improvements in both water level and depth in line with scenarios including similar flow volumes but no shifts in flow timing.

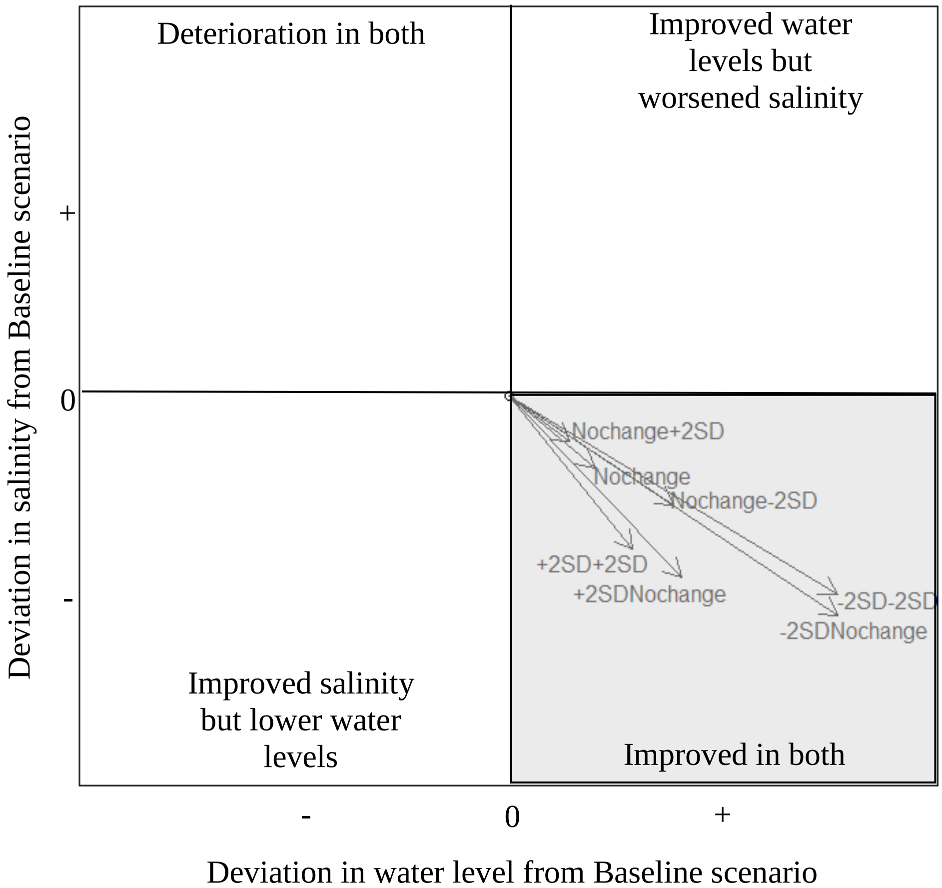

Figure 88: Comparison of the effect of a shift in timing and distribution of flows for the South Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Baseline scenario condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant indicate an improvement for both variables (i.e. higher water levels and lower salinities). Note: Nochange is no change in both barrage and USED timing (Scenario 5), +2SDNochange is a +2SD shift in barrage timing and no change in USED timing (Scenario 70), Nochange+2SD is no change in barrage timing and a +2SD shift in USED timing (Scenario 71), -2SDNochange is a -2SD shift in barrage timing and no change in USED timing (Scenario 72), Nochange-2SD is no change in barrage timing and a -2SD shift in USED timing (Scenario 73), +2SD+2SD is a +2SD shift in barrage and USED timing (Scenario 74), and -2SD-2SD is a -2SD shift in both barrage and USED timing (Scenario 75; Table 1). All scenarios have high barrage and medium SE flows with medium SE salinity

The proportion of site-years classified into each ecosystem state under high barrage and medium USED flow, were very similar, except where there was a -2 SD shift in barrage flow timing (Figure 89). Little variation existed between scenarios, where the majority of site-years were still classified as either Estuarine/Marine or Average Hypersaline, with Degraded Marine still represented in small proportions (<3%) where barrage flows were not shifted. Scenarios involving a -2 SD shift in barrage flows also resulted in site-years being classified as Healthy Hypersaline, a state associated with high flow conditions in the South Lagoon.

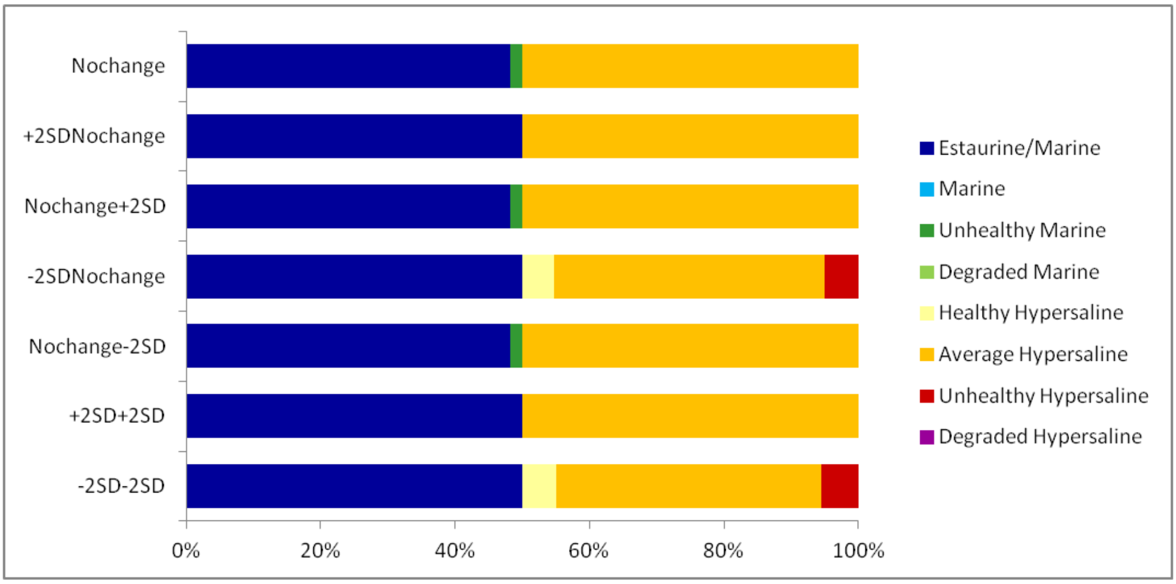

Figure 89: Comparing the proportion of site-years in each ecosystem state for the climate change scenarios Note: EM = Estuarine/Marine, M = Marine, UM = Unhealthy Marine, DM = Degraded Marine, HH = Healthy Hypersaline, AH = Average Hypersaline, UH = Unhealthy Hypersaline, DM = Degraded Hypersaline. Nochange is no change in both barrage and USED timing (Scenario 5), +2SDNochange is a +2SD shift in barrage timing and no change in USED timing (Scenario 70), Nochange+2SD is no change in barrage timing and a +2SD shift in USED timing (Scenario 71), -2SDNochange is a -2SD shift in barrage timing and no change in USED timing (Scenario 72), Nochange-2SD is no change in barrage timing and a -2SD shift in USED timing (Scenario 73), +2SD+2SD is a +2SD shift in barrage and USED timing (Scenario 74), and -2SD-2SD is a -2SD shift in both barrage and USED timing (Scenario 75; Table 1). All scenarios have high barrage and medium SE flows with medium SE salinity

Under low barrage and medium USED flow conditions, four scenarios investigating shifts in the timing of flows altered the relative proportions of ecosystem states compared to the Baseline scenario (Figure 90). The greatest changes were seen with -2 SD shifts to barrage flow, either with or without a corresponding shift in USED flow timing. Then, the proportion of site-years assigned to the Average Hypersaline ecosystem state decreased by -1%. The same two scenarios also saw an increase in Healthy Hypersaline (i.e. +4%) and Unhealthy Hypersaline (+4%) site-years.

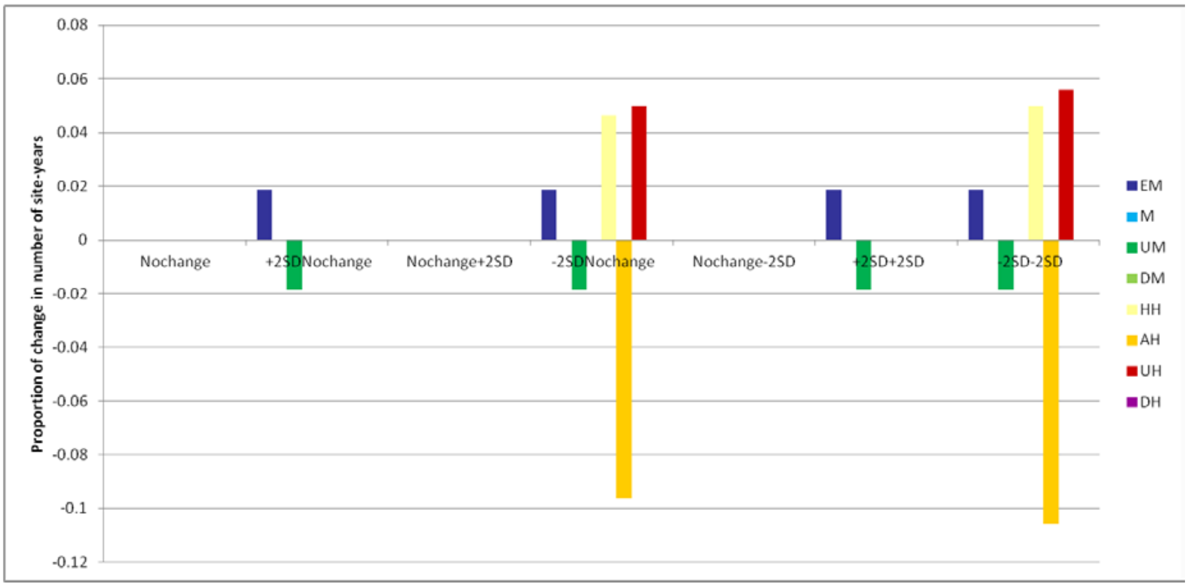

Figure 90: Deviations in the proportion of site-years in each ecosystem state compared to the Baseline scenario for the comparison of a shift in timing and distribution of flows

Note: Nochange is no change in both barrage and USED timing (Scenario 5), +2SDNochange is a +2SD shift in barrage timing and no change in USED timing (Scenario 70), Nochange+2SD is no change in barrage timing and a +2SD shift in USED timing (Scenario 71), -2SDNochange is a -2SD shift in barrage timing and no change in USED timing (Scenario 72), Nochange-2SD is no change in barrage timing and a -2SD shift in USED timing (Scenario 73), +2SD+2SD is a +2SD shift in barrage and USED timing (Scenario 74), and -2SD-2SD is a -2SD shift in both barrage and USED timing (Scenario 75; Table 1). All scenarios have high barrage and medium SE flows with medium SE salinity

3.6.2.6 Co-variation of shifting barrage and USED flow timing and distribution

In order to explore the combined effects of shifting barrage and USED flow timing and distribution, we again ran a large number of scenarios in which the two were varied together. Contour plots, shown in Figures 91 and 92 illustrate the impact of the co-variation of barrage and USED flow timing and distribution on North and South Lagoon average salinities, respectively. All results are shown for a USED salinity of 10 g L^{-1} to illustrate indicative relationships.

The graphs have important common features. When barrage flows have shifted, in almost all combinations of barrage and USED flow volumes, the contour lines were effectively vertical. This indicates that there was no impact of changing USED flow timing if barrage flow timing had already been shifted. This was the case in the North Lagoon (Figure 91). There, under all combinations of barrage and USED flow volumes, if barrage flows were shifted, there would be no impact associated with also shifting USED flow volumes. However, if barrage flows were not shifted, under low barrage flow and/or low USED flow conditions, shifting USED flow timing would result in higher North Lagoon salinities than using the historical timing and distribution (i.e. no shift). When barrage and USED flows were higher, shifting USED flows by one or two standard deviations had some a small beneficial impact on North Lagoon salinities when barrage flows had not been shifted.

A similar pattern was also evident in the South Lagoon (Figure 92), where shifting the timing of barrage flows had a much larger impact on average salinity than shifting USED flow timings. The contours in Figure 92 were not, however, always vertical, so there was a small effect of shifting the timing of USED flows too, although in most instances, any shift resulted in higher salinities, indicating a detrimental result. The magnitude of change in the South Lagoon as a result of shifts in the timing of either set of flows was larger overall than those that occurred in the North Lagoon (i.e. up to 20 g L^{-1} difference in the South Lagoon compared with up to 8 g L^{-1} in the North Lagoon).

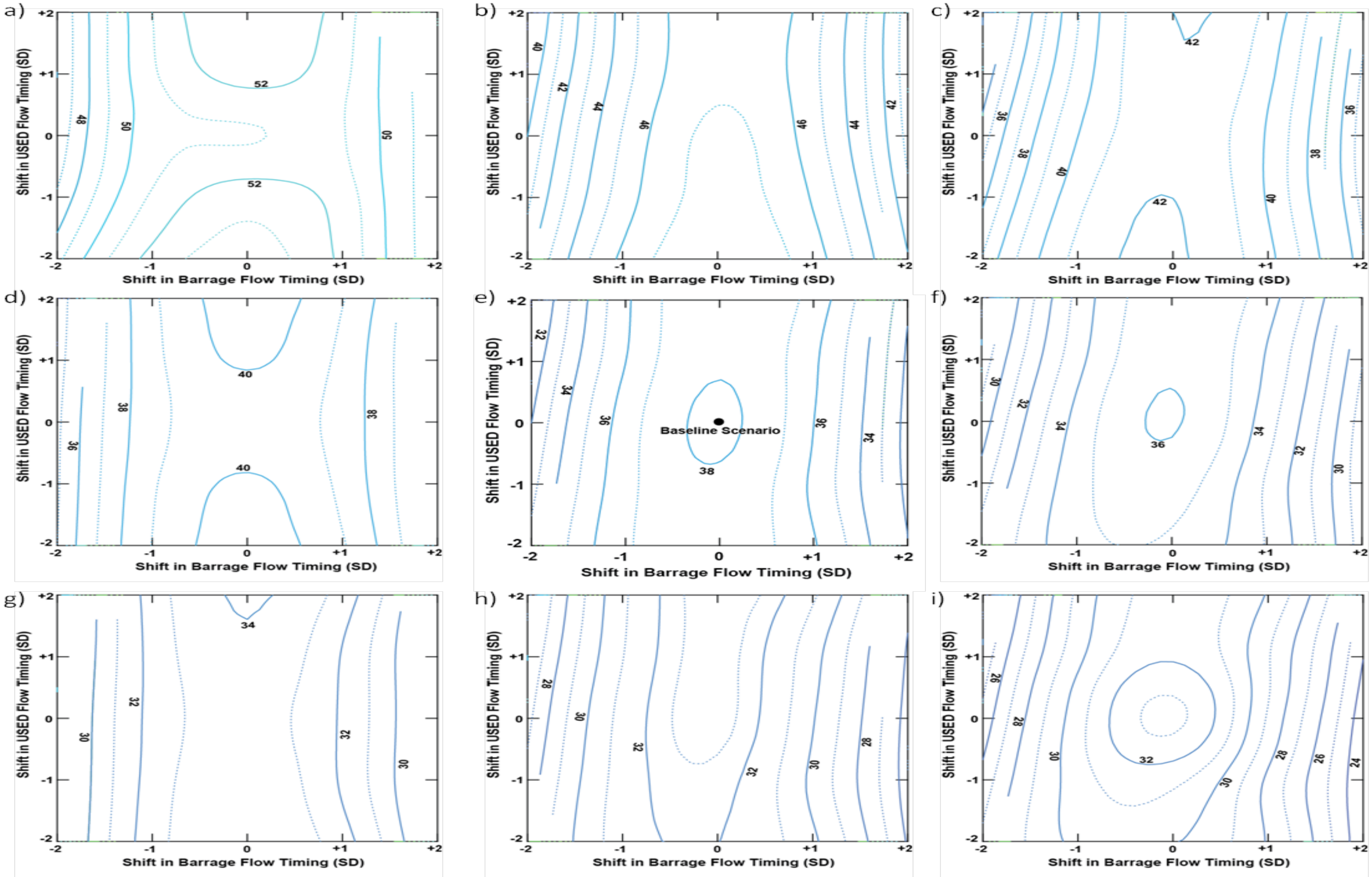

Figure 91: Average salinity in the North Lagoon as a function of a shift in timing of barrage & USED flows. USED salinity is fixed at 10 g L^{-1}. a) under low barrage & USED flow conditions, b) low barrage & medium USED flows, c) low barrage & high USED flows, d) medium barrage & low USED flows, e) medium barrage & USED flows, f) medium barrage & high USED flows, g) high barrage & low USED flows, h) high barrage & medium flows, and i) high barrage & high USED flow conditions

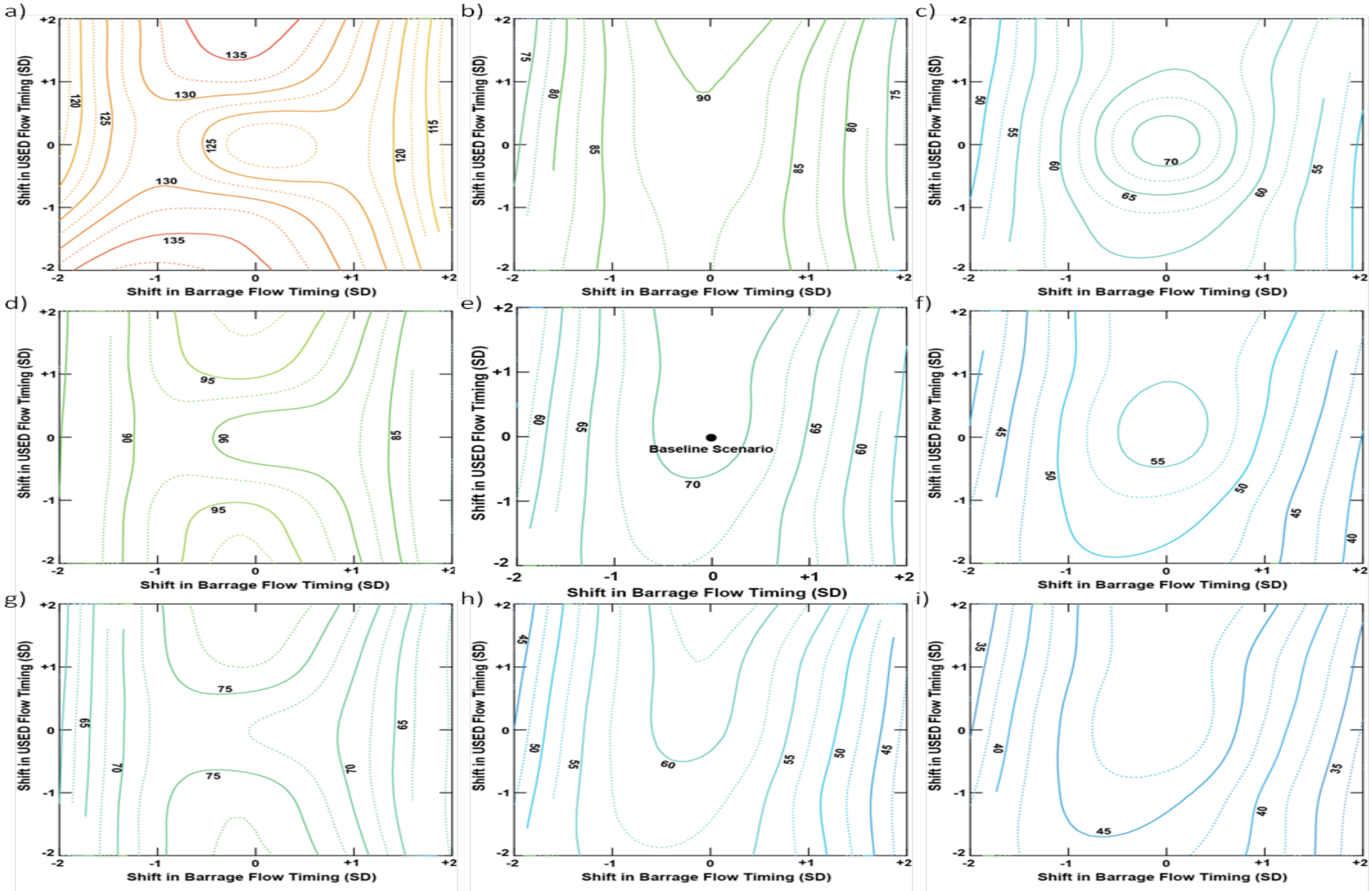

Figure 92: Average salinity in the South Lagoon as a function of a shift in timing of barrage & USED flows. USED salinity is fixed at 10 g L^{-1} a) under low barrage & USED flow conditions, b) low barrage & medium USED flows, c) low barrage & high USED flows, d) medium barrage & low USED flows, e) medium barrage & USED flows, f) medium barrage & high USED flows, g) high barrage & low USED flows, h) high barrage & medium flows, and i) high barrage & high USED flow conditions

3.7 Research Question 6: Effect on Lakes ecosystems

One of the purposes of this investigation was to investigate the potential for altering the relative contribution of freshwater flows from the USED system and the River Murray via the barrages. However, the USED scheme flows into the southern end of the Coorong, via Salt Creek, and does not pass through the Lower Lakes, which are also intended to be supported by previously-described environmental water requirements (Lester et al. 2011). Thus, changing the relative inputs from the two sources may result in an adverse outcome for Lakes ecosystems that would not benefit from additional USED water.

In order to explore this possibility, an ecosystem model for the Lakes was used. This model includes a possible 10 ecosystem states, some of which are defined by their location (i.e. distance to the nearest freshwater source). That means that, regardless of the conditions, the model will always place them in the same ecosystem state. This is obviously a limitation of this model, and is a result of a lack of data regarding some potentially-important drivers of ecological condition, including tributary flows.

Despite these limitations, we attempted to analyse scenarios investigating different barrage flow volumes and timing to identify any impact on Lakes ecosystems, as simulated with the Lakes ecosystem state model.

All scenarios modelled using the Lakes ecosystem state model showed the same distribution of ecosystem states (Figure 93). This may be as a result of the smaller impact that timing of flows have on the hydrodynamics of the Lakes (Heneker 2010), or may be as a result of the limitations of the model. We recommend caution when interpreting these results, as the lack of sensitivity may be an artefact of the model, rather than a realistic representation of the likely ecological impact.

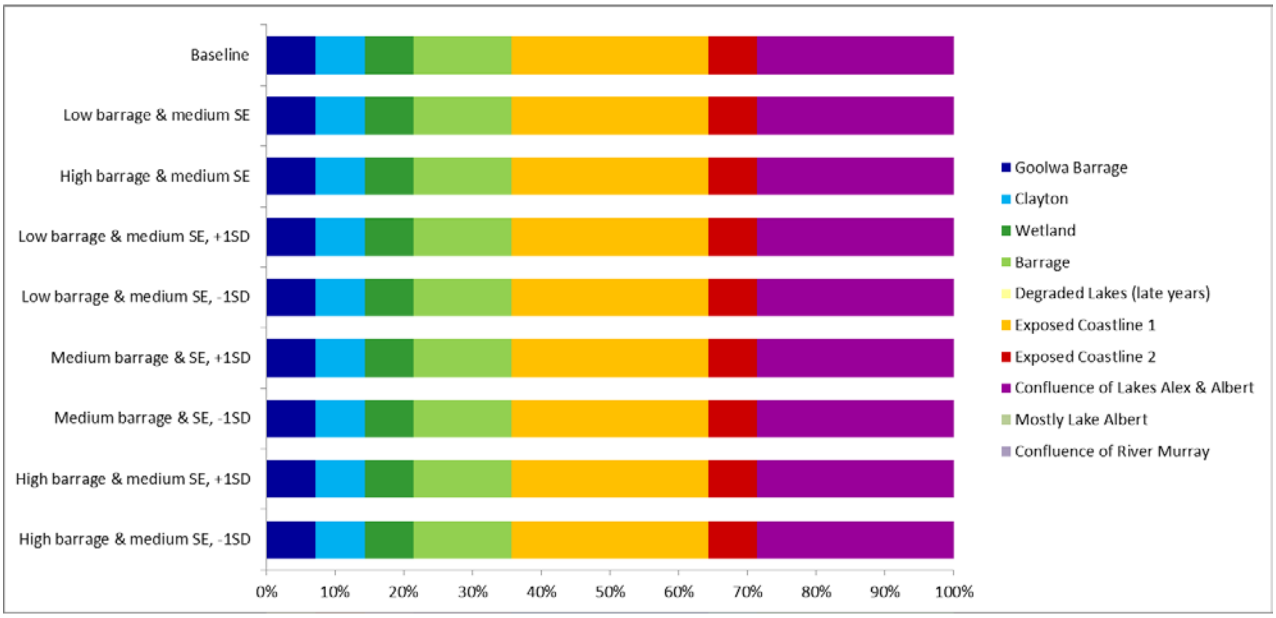

Figure 93: Comparing the proportion of site-years in each ecosystem state for the climate change scenarios Note: Baseline is medium barrage and SE flows (Scenario 1), Low barrage & medium SE is low barrage & medium SE flows (Scenario 4), High barrage & medium SE is high barrage & medium SE flows (Scenario 5), Low barrage & medium SE, +1SD is low barrage & medium SE flows, and a shift in barrage flow timing of +1SD (Scenario 16), Low barrage & medium SE, -1SD is low barrage & medium SE flows, and a shift in barrage flow timing of -1SD (Scenario 18), Medium barrage & SE is medium barrage & SE flows, and a shift in barrage flow timing of +1SD (Scenario 28), Medium barrage & SE, -1SD is medium barrage & SE flows, and a shift in barrage timing of -1SD (Scenario 30), High barrage & medium SE, +1SD is high barrage & medium SE flows, and a shift in barrage timing of +1SD (Scenario 40), and High barrage & medium SE, -1SD is high barrage & medium SE flows, and a shift in barrage timing of -1SD (Scenario 42)

4 Discussion

This investigation was designed to provide a comprehensive set of results that would enable readers to isolate the impact of different factors on the hydrodynamics of the Coorong, including any benefits that might accrue from implementation of an expanded USED scheme. These factors included local climatic conditions, such as wind, rainfall, evaporation and nearby sea levels in Encounter Bay, the timing of flows from the River Murray via the barrages and from the USED scheme, and the salinity of water flowing from the USED scheme. Approaching the investigation in this way allows for extrapolation to other scenarios within the limits explored here. That means that the impact of different combinations of those factors that were not explicitly explored here can be estimated from these results.

In order to isolate each factor effectively, the scenarios included in the report use a series of repeating sequences of barrage and USED flows for each year, with only weather conditions (i.e. wind, rainfall, evaporation and sea levels) varying among years. That is, for each scenarios, the same volume of water is delivered year-on-year from both the barrages and the USED scheme (although barrage flows are not equal to USED flows). This allows us to separate the differences in salinity, water levels and ecosystem states simulated as a result in variation in weather from the effect of barrage flow volume, USED flow volume, the timing of both flows and USED salinity.

4.1 General hydrologic observations

In general, Coorong hydrodynamics showed distinct seasonal cycles of salinity and water levels in both lagoons. This was as a result of the natural seasonal pattern in barrage and USED flows and seasonality in weather patterns (e.g. evaporation and local sea level both vary seasonally). In particular, water levels and salinities in the North Lagoon appeared to be largely driven by local sea level, showing a strong seasonal pattern. South Lagoon salinities and water levels were largely driven by the timing of hydrologic disconnection between the North and South Lagoons (i.e. when water levels are relatively low, there is ineffective mixing between the two Lagoons at Parnka Channel). When the timing of that disconnection was delayed, either due to unseasonably high summer sea levels or substantial barrage flows, the South Lagoon had lower salinities and higher water levels than typically occurs.

Both barrage flows and USED flows had an impact on salinities and water levels along the length of the Coorong, rather than having only localised impacts at the point of discharge.

4.2 Effect of climate variability

A substantial level of variability was evident in Coorong hydrodynamics as a result of changes in local climatic conditions from year to year. This pattern was exacerbated in times of low flows, but was always present to some degree. Under Baseline conditions (i.e. barrage flows of 2000 GL year^{-1}, USED flows of 50 GL year^{-1} and USED salinity of 10 g L^{-1}), a range of up to 40 g L^{-1} was observed in simulations simply as a result of weather variability. This was despite barrage flows and USED flows remaining constant from year to year. Furthermore, maximum, minimum and average conditions (e.g. salinities) responded differently to climatic variability, so the effects were not uniform across different measures of water level and salinity.

This finding has significant implications for management. It means that it is not possible to be precise in estimating the effect of a given volume of environmental water, for example. For any given volume, there will always be a range of possible outcomes, associated with the weather conditions that occur prior to and at the time of delivery. Local sea level in particular affects the amount of change in hydrodynamics associated with a given freshwater flow, and this is not able to be easily predicted in advance. However, these findings do enable the precise estimation of a confidence interval associated with a given flow volume. This should provide greater certainty for managers in the outcomes of environmental and other freshwater flows to the Coorong. By using an approach including a confidence interval, managers can be sure that conditions will fall within a range of values for salinity or water level, rather than predicting an exact response that is not subsequently realised.

This finding also highlights the need to include a buffer around any thresholds set for environmental purposes. For example, a threshold of 117 g L^{-1} has been set for annual average South Lagoon salinity to avoid degraded ecosystem states in the Coorong (Fairweather and Lester 2010). Understanding that there may be up to 40 g L^{-1} variability in annual average South Lagoon salinity due to year-to-year differences in weather, as well as spatial and temporal variability at smaller scales, suggests that a somewhat conservative approach should be taken to avoid crossing that threshold in case of a severe-weather year. This may mean that management intervention is required earlier than would be the case if there was no climatic variability.

4.3 Effect of changes in USED flows

USED flow volumes have more impact on Coorong salinities than Coorong water levels. The greatest influence occurs in the southern part of the North Lagoon and in the South Lagoon, with the degree of influence varying with the volume discharged. In the South Lagoon, salinity levels were approximately 50 g L^{-1} lower when 90 GL $year^{-1}$ was discharged via the USED scheme than when 10 GL $year^{-1}$ was discharged. In contrast, there was little impact on water levels, regardless of the volume discharged.

Similarly, maximum salinity was the only hydrodynamic driver of ecosystem states affected by USED flow volumes, with depth from two years previous, average water level and annual range in water levels largely unaffected. The drivers of ecosystem states (i.e. maximum salinity, annual range in water levels, depth from 2 years previous and average water level) were used as these have been shown to have the greatest impact on the ecological condition of the Coorong from a suite of 230 variables that were assessed (Lester and Fairweather 2011). In addition, these variables cover a range of factors that are intuitively likely to influence Coorong ecosystems including the most extreme salinity (i.e. maximum salinity), seasonal differences in water levels (i.e. annual range in water levels) and water heights (i.e. depth and water level). Thus, we have analysed what we consider to be the most meaningful variables (i.e. based on previous analyses designed to identify those variables; Lester and Fairweather 2011) using the hydrodynamic model for the Coorong, and have then subsequently linked those effects to any changes in ecosystem state using the ecosystem state model for the Coorong.

Increasing volumes of USED water tended to decrease the median maximum salinity in the Coorong, but also reduced the range of salinity values, by effectively preventing the highest salinities that are most likely to cause ecological damage in the Coorong. Thus, there is some positive benefit to additional fresh water entering the Coorong via the USED scheme. As the majority of USED flows under historical timing occur prior to the seasonal hydrologic disconnection between the two lagoons, there is little overall impact on average water levels or annual ranges in water levels, as flows from Salt Creek would be offset with flows to and from the North Lagoon.

However, very little impact was observed on the ecosystem states of the Coorong as a result of increasing flow volume from the USED scheme, at least in the range explored here (i.e. 10 to 90 GL year^{-1}). There was a small reduction in degraded ecosystem states with either 50 or 90 GL year^{-1} compared with 10 GL year^{-1} from the USED scheme, but even the larger flow volumes were not sufficient to eliminate degraded ecosystem states from the Coorong. Furthermore, none of the scenarios investigated altered the incidence of the Healthy Hypersaline state, which is thought to be associated with high flow conditions in the South Lagoon, and thus represents an important part of the conditions needed to sustain a healthy estuarine system in the long term. Thus, additional flows from the USED scheme alone are not sufficient to support the ecology of the South Lagoon.

4.4 Effect of changes in barrage flows

Changes in barrage flow volumes affected both salinities and water levels along the length of the Coorong. North Lagoon salinities responded quickly and consistently to barrage flows, with bigger flows resulting in proportionally lower salinities. The same was true in the South Lagoon, with declines in salinity of more than 50 g L^{-1} as a result of a change in barrage flows from 1000 GL year^{-1} to 8000 GL year^{-1}.

A seasonal pattern was evident in the response in water levels, consistent with the timing of barrage flows. Between March and October, there were large increases in water level in both lagoons as a result of increases in barrage flows, but over summer, very little difference was observed. No barrage flows were simulated to occur over those months, based on historical flow distributions, but no residual impact in water level was observed either (i.e. there was no lag in the decline in water levels). The pattern of changes in water level in the North Lagoon with increasing barrage flow volumes was somewhat counterintuitive. Under some conditions, smaller flow volumes resulted in higher water levels in that lagoon than occurred under higher flow conditions. This finding is a function of the interaction between the effect that increasing flow volumes have on water levels and on Mouth openness (Webster et al. 2012). The same interaction was not observed in the South Lagoon, where bigger flows consistently resulted in higher water levels.

When considering the hydrodynamic drivers of ecosystem states, maximum salinity was again the most influenced by barrage flow volume, although there were also changes in the annual range in water levels. The South Lagoon showed the biggest cumulative changes compared to the Baseline scenario, again with maximum salinity the main contributor. The deterioration in maximum salinity associated with an annual barrage flow of 1000 GL compared with 2000 GL was marked, indicating that conditions may deteriorate quickly flows fall below levels recommended as an environmental water requirement in the region. This deterioration was reflected in a very small increase in degraded ecosystem states.

4.5 Co-variation in barrage and USED flow volumes

Both barrage and USED flows were found to influence the salinity and water levels in the Coorong. Barrage flows had the greater impact, but USED flows tended to increase in importance when barrage flows were low. There were pairs of barrage and USED flow volumes that would result in the same salinity outcome, indicating that some adjustment in the volumes delivered from different sources may be possible, at least with respect to North and South Lagoon salinity outcomes.

4.6 Effect of changes in USED salinity

There was no impact on water levels, depth or the annual range in water level in either lagoon as a result of changes in USED salinity. Altering the relatively quality of USED inflows resulted in small changes in the maximum salinity experienced in the South Lagoon, with cumulative changes from the Baseline scenario apparent that were proportional to the increasing salt concentration of USED flows. The magnitude of those changes in South Lagoon maximum salinity as a result of changed USED salinities was of approximately the same magnitude as the change in maximum salinity associated with a shift from 1000 to 2000 GL year^{-1} in barrage flows. This finding suggests that higher quality flows from the USED system may be able to offset some hydrodynamic impacts of low barrage flows, depending on the timing and distribution of flows from both sources.

There were, however, few differences in ecosystem states associated with changing USED salinities. Changes were only apparent under medium barrage flows and low USED flows, when there were small increases in the proportion of degraded states associated with higher USED salinities. All other combinations of barrage and USED flows resulted in the same mix of ecosystem states, suggesting that any of the USED salinities investigated may result in similar ecological outcomes for the Coorong.

4.7 Effect of changes in timing and distribution of flows

Shifting the timing and distribution of barrage flows had a much larger impact on conditions in the Coorong than shifting the timing and distribution of USED flows. Interestingly, shifts both forward and backward in the timing of barrage flows had positive effects on Coorong hydrodynamics (i.e. lower salinities and higher water levels), regardless of the timing of USED flows. Annual ranges in water levels and maximum salinities were the two drivers of ecosystem states that were consistently influenced by changes in timing. Smaller annual ranges, associated with higher minimum water levels, and lower maximum salinities were observed for shifts in barrage flow timing of 50 or 100 days, either forward and/or backwater, with small variations associated with the volume of barrage and USED flows considered.

Shifting the timing of barrage flows also had some impact on the mix of ecosystem states, with lower incidences of degraded ecosystem states associated with altered barrage flow timing, particularly of 100 days in either direction. Delaying USED flows by 22 days had some positive impact on annual range in water level when barrage flows were low and USED flows were moderate, assuming barrage flow timing did not change. There was no corresponding benefit for maximum salinity though, and this pattern was not consistently observed for different combinations of barrage and USED flow volume. There was very little impact of shifting the timing of USED flows on ecosystem states.

Thus, in general, shifts in barrage timing, either forward or backwards, tended to improve at least some hydrodynamics in the Coorong. Presumably, this is because these shifts minimise the length of time that the North and South Lagoons are effectively disconnected. For shifts of 100 days, there were also positive changes in the mix of ecosystem states that were less apparent for shifts of 50 days. The patterns are most pronounced for barrage flows, suggesting that changing the timing of flows may be a strategy that could be employed in low-flow years to offset the impacts of dry conditions. There was less effect, and some detrimental impacts, associated with shifting flow timing for larger barrage flow volumes, particularly when these shifts were combined with shifts in USED flow volume (although this pattern was not consistent for all combinations of barrage and USED flow volumes).

Shifts forwards for USED flows (i.e. with flows then occurring later in the season) tended to result in a deterioration in Coorong conditions, particularly in the South Lagoon, where salinities were higher and water levels lower. This may be because the historical timing already delays the onset of hydrologic disconnection between the two lagoons and the shorter period of time that these flows are shifted compared with the move in barrage flow volumes (i.e. 22 or 44 days compared with 50 or 100 days, respectively) is insufficient to compensate otherwise. Even when positive results were observed, this was almost always in conjunction with a corresponding shift in barrage flows that was observed to result in a similar improvement without any shift in USED flow timing. This suggests that, in those instances, any improvement must be considered to be as a result of the shift in barrage flow timing, rather than the combination of the two. Thus, based on this investigation, there appears to be little benefit associated with delaying the timing of USED flows, potentially affecting the utility of any storage capacity in that system.

4.8 Co-variation in barrage and USED flow timings

Investigating the co-variation in barrage and USED flow timings showed clearly the relative impact of shifting barrage flow timing, compared with shifting USED flow timing. In both lagoons, any impact on average salinity was almost exclusively a result of shifts in barrage flow timing. Only when barrage flows were not shifted was any impact of shifting USED flows observed, and often shifting USED flows resulted in higher average salinities. This indicates that the historical distribution of USED flow timing and distribution should be used as a guide for the management of any expansion to the USED scheme.

4.9 Impact on the Lower Lakes

One of the dangers associated with adjusting barrage flow volumes as a result of higher flows being available from the USED system is that the USED system discharges directly into the Coorong without passing through the Lower Lakes. Thus, any impact of low flows on Lakes ecosystems would not be ameliorated by higher USED flows. Here, we applied the Lakes ecosystem states model for the first time to investigate whether there was any potential impact. No differences were identified in the likely mix of ecosystem states in the Lakes, associated with different flow volumes or shifts in the timing of flows. This finding may be a result of a lack of sensitivity in the model, rather than a true reflection of the impact on Lakes ecosystems.

The Lakes ecosystem states model did not perform as well as the Coorong model, in that not all drivers of differences in ecology could be modelled, due to a lack of data on flows from Currency Creek and Finniss River. Therefore, we urge caution in drawing conclusions from this work, and refer the reader to Heneker (2010) which outlines the hydrodynamic impact of lower flow volumes (i.e. 1000 GL year^{-1} compared to 2000 and 4000 GL year^{-1}). We also strongly recommend that any trade-offs that may occur in average annual barrage flow volumes do not compromise the minimum flow rules set for environmental flows for the CLLMM region (Lester et al. 2011).

4.10 Summary of findings

In summary, this investigation has found:

- Conditions in the Coorong vary seasonally with local weather and the pattern of flows both from the River Murray and the USED scheme.
- Flows from the barrages and the USED scheme both affected salinities along the entire length of the Coorong, not just at the point of discharge.
- Hydrodynamics including salinity varied substantially as a result of variations in local weather conditions. This means that a confidence interval is needed when indicating the likely impact of any freshwater flows to the Coorong, and that a precautionary buffer should always be used to avoid ecological degradation.
- USED flows influenced Coorong salinities much more than water levels, and had the most impact in the South Lagoon, with higher flows cutting off the highest salinities that were likely to cause ecological degradation
- The highest USED flow volumes considered here were insufficient to prevent the occurrence of degraded ecosystem states, or to trigger the state that is thought to be associated with high flows, so were not found sufficient to replace the role of River Murray flows in supporting healthy Coorong ecosystems
- Increasing barrage flow volumes resulted in decreasing Coorong salinities, but there was a seasonal response in water levels. Barrage flows less than 2000 GL year^{-1} resulted in substantially higher maximum salinities than larger flows.

- Both barrage and USED flow volumes affected the salinities and water levels in the Coorong, but USED flow volumes had a larger impact in times of low barrage flows.
- The range of salinities investigated here to represent the quality of USED inflows had very little impact on the hydrodynamics or ecosystem states simulated for the Coorong.
- Shifting the timing of barrage flows could have a positive impact on Coorong hydrodynamics and ecosystem states.
- Shifting USED flows away from the historical timing, however, rarely resulted in positive impacts, instead usually leading to deteriorations in hydrodynamic conditions and sometimes also ecosystem states.
- The historical USED flow timing and distribution should be used as a guide for the future delivery of flows to the Coorong via Salt Creek.
- Any changes to River Murray flows arising from the increased availability of flows via the USED scheme should continue to meet minimum environmental flow requirements set for the region as a whole.

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6 Appendices

Appendix A – 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.

A.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 A.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. There is no one order in which the boxes could be presented which would allow all comparisons to be easily made. In order to assist the reader, we have included a set of symbols above the first box plot in each panel, showing the similarities between the scenarios (Figure A.1). We have identified the boxes that share a climate, flow path, maximum daily diversion or other intervention, for example. This will allow the reader to easily identify which boxes are of interest to the specific comparison they are interested in exploring.

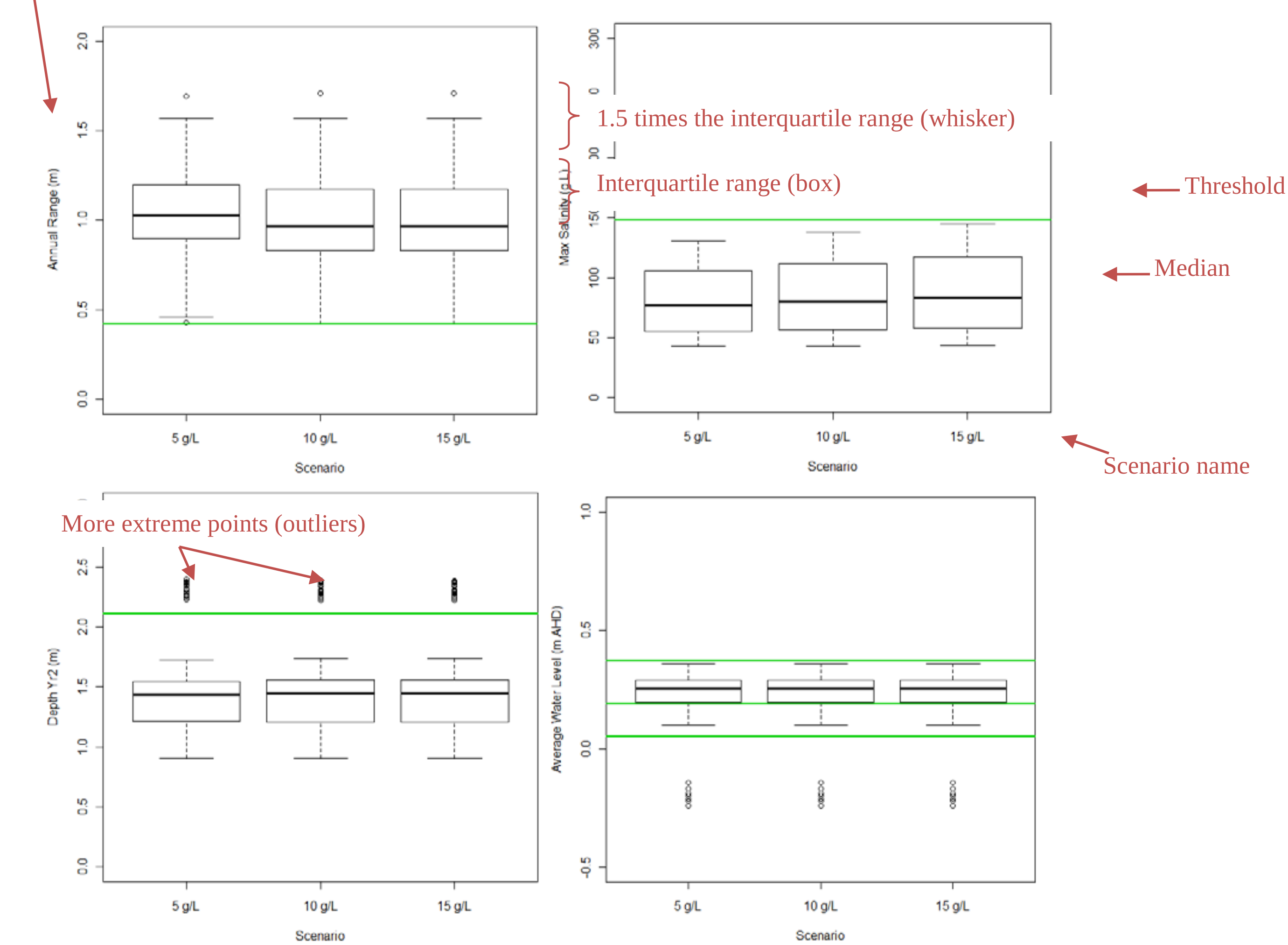

Figure A.1: Example of boxplots from the climate change scenarios, highlighting points to note in red a) Annual range in water level (m), b) Maximum salinity (g L^{-1}), c) Average water depth from two years previous (m), and d) Average water level (m AHD)

A.2 Deviations from Baseline scenario

The second output displaying the hydrodynamic results of the various scenarios compares the deviances of values for key variables from the values obtained in the Baseline scenario (Figure A.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 Baseline scenario. That is, scenarios that fall on the lines had a zero sum deviation compared with the Baseline 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 North Lagoon (Figure A.2). Here, an increase in water level and an increase in depth could be considered an improvement, compared with the Baseline. Thus, scenarios where the vector ends in the upper-right quadrant (which is shaded grey) 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 A.3). As for Figure A.2, scenarios falling on the horizontal and vertical lines indicate no deviation from the Baseline 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 upper-left) showed a deterioration with respect to both variables.

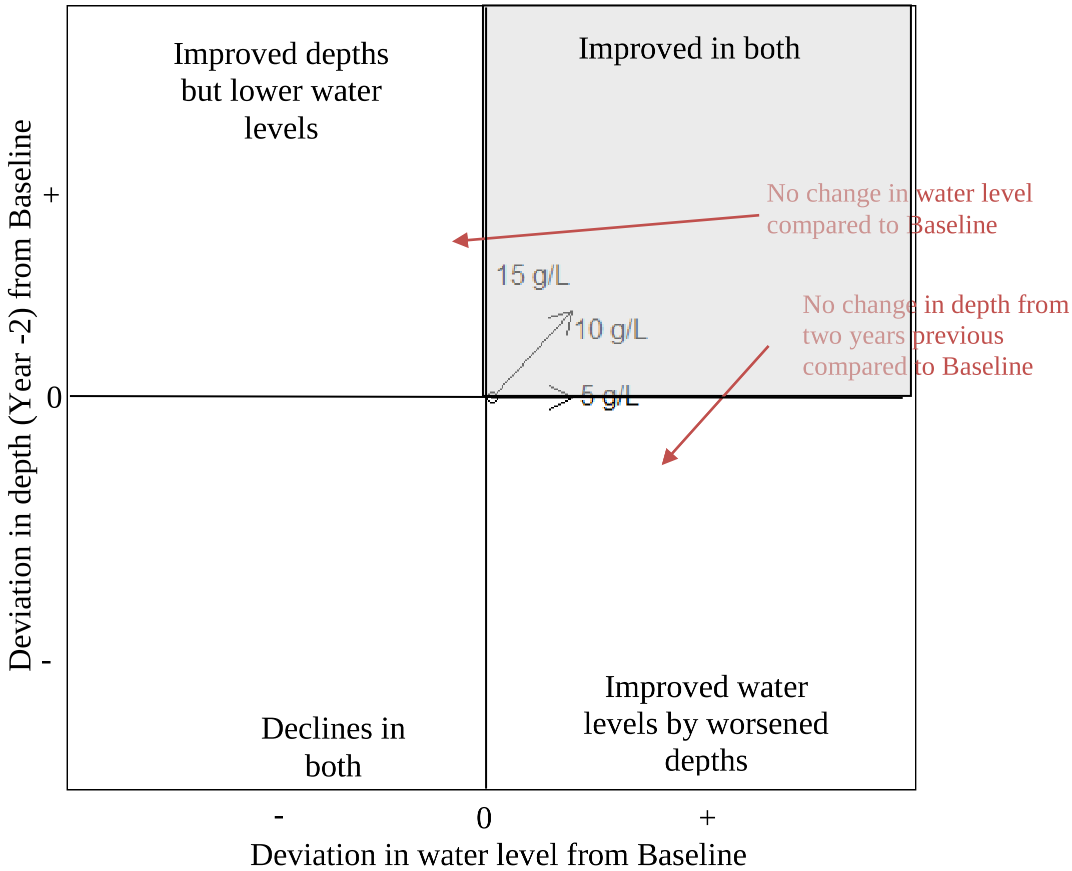

Figure A.2: Example of comparison of climate change scenarios to the Baseline scenario for key variables, highlighting points to note in red

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline 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 Baseline scenario condition (as shown by the 0,0 origin). Vectors in the top-right quadrant indicate an improvement for both variables (i.e. higher water levels and greater depths). 5 g L^{-1} is the low barrage & medium SE flows, low salinity scenario (Scenario 6), 10 g L^{-1} is the low barrage & medium SE flows, medium salinity scenario (Scenario 4) and 15 g L^{-1} is the low barrage & medium SE flows, medium salinity scenario (Scenario 7)

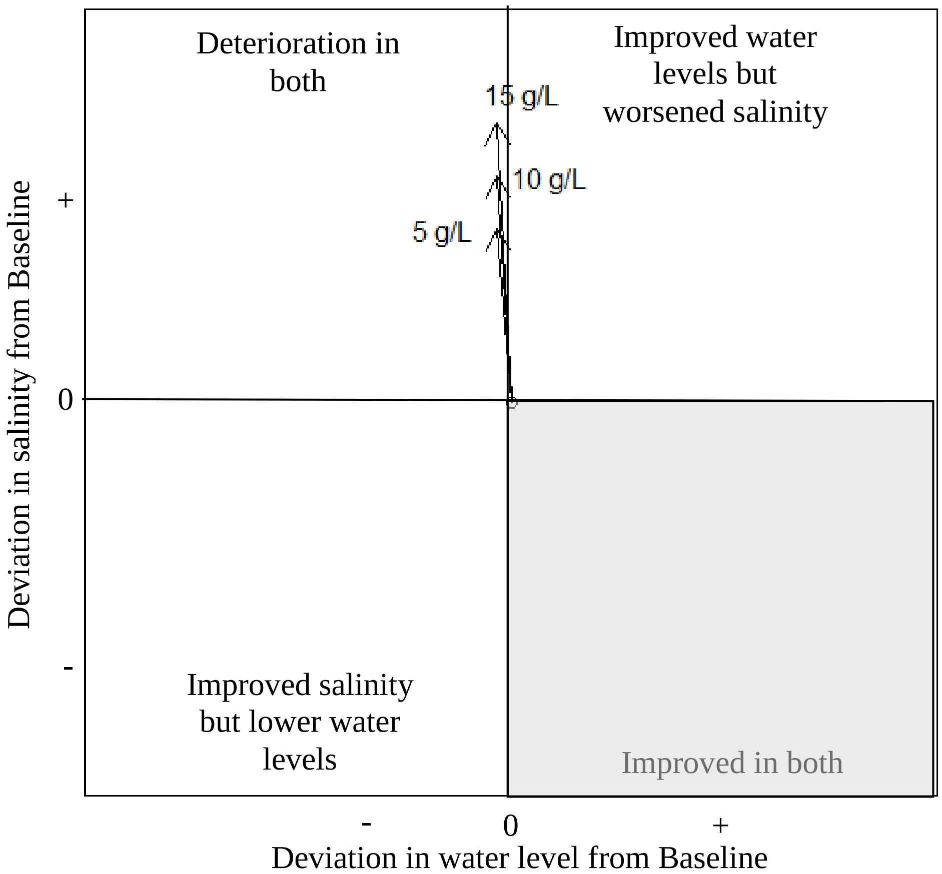

Figure A.3: Example of comparison of the effect of climate change scenarios relative to the Baseline for the South Lagoon

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline scenario with respect to water levels and salinity. Length of each vector is proportional to the strength of the deviation from the Baseline scenario condition (as shown by the 0,0 origin). Vectors in the bottom-right quadrant indicate an improvement for both variables (i.e. higher water levels and lower salinities). 5 g L^{-1} is the low barrage & medium SE flows, low salinity scenario (Scenario 6), 10 g L^{-1} is the low barrage & medium SE flows, medium salinity scenario (Scenario 4) and 15 g L^{-1} is the low barrage & medium SE flows, medium salinity scenario (Scenario 7)

A.3 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 A.4). 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 (114 years). Note that not all states are seen in every scenario. Also the number of colours is not an indicator of ‘diversity’ because the usually less-common colours represent degraded states (not necessarily a good thing).

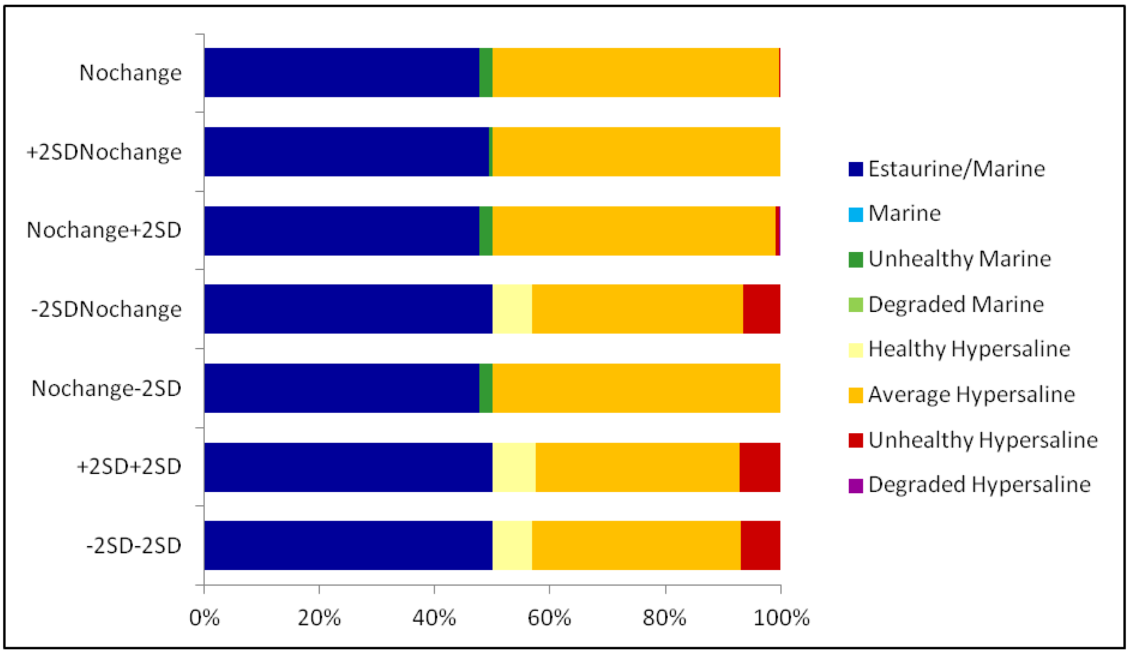

Figure A.4: Comparing the proportion of site-years in each ecosystem state for the climate change scenarios

Note: Nochange is no change in both barrage and USED timing (Scenario 4), +2SDNochange is a +2SD shift in barrage timing and no change in USED timing (Scenario 46), Nochange+1SD is no change in barrage timing and a +2SD shift in USED timing (Scenario 47),-2SDNochange is a -2SD shift in barrage timing and no change in USED timing (Scenario 48), Nochange-2SD is no change in barrage timing and a -2SD shift in USED timing (Scenario 49), +2SD+2SD is a +2SD shift in barrage and USED timing (Scenario 50), and -2SD-2SD is a -2SD shift in both barrage and USED timing (Scenario 51; Table 1). All scenarios have low barrage and medium SE flows with medium SE salinity

A.4 Comparing the deviation in the proportion of site-years in each ecosystem state compared to the Baseline scenario

Figure A.5 illustrates the percent change in the number of site-years predicted to be in each ecosystem state compared to the Baseline scenario. Increases in the incidence of an ecosystem state are shown as a positive change (i.e. above the x-axis), while decreases in frequency are shown as a negative change (i.e. below the x-axis). The terms positive and negative are used in a mathematical sense and are not pejorative (i.e. do not imply improvement or deterioration, which will vary depending on the ecosystem state in question). A legend with abbreviated ecosystem state names is given, with a key below the figure explaining each of the abbreviations. Colour-coding is consistent with Figure A.4.

The display of multiple scenarios along the x-axis allows the relative changes associated with different scenarios to be compared. For example, in Figure A.5, the

5 g L^{-1} scenario had a smaller decline in the incidence of the Estuarine/Marine state and an increase in the incidence of the Unhealthy Marine state compared to the Baseline scenario.

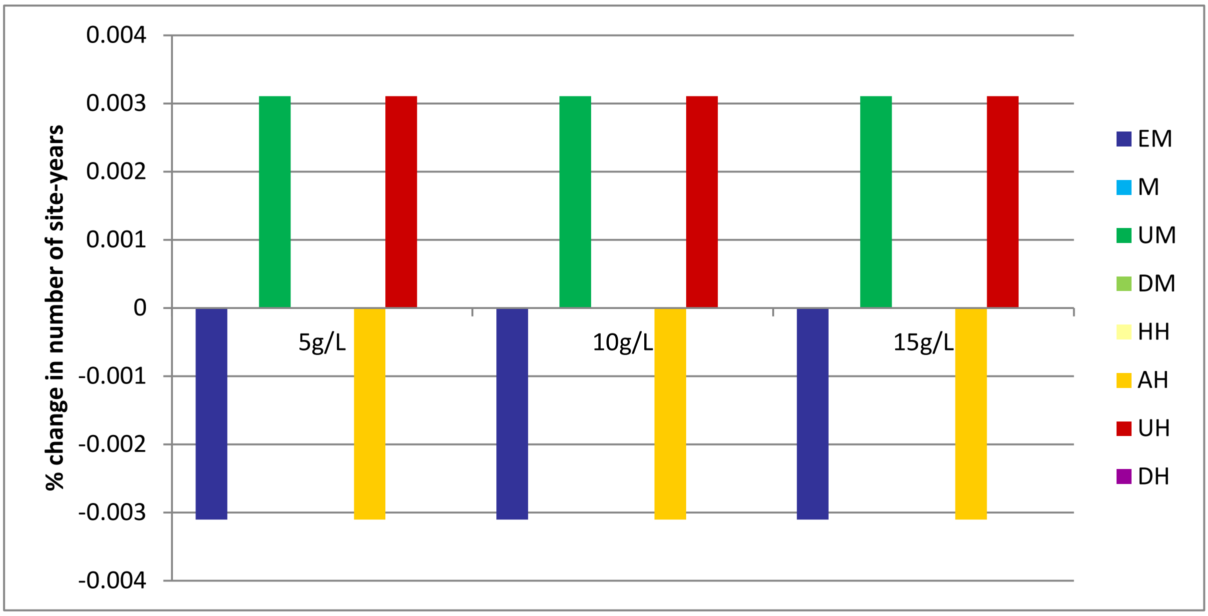

Figure A.5: Example of the deviations in the proportion of site-years in each ecosystem state compared to the Baseline scenario for the comparison of USED salinity under low barrage flow volumes and medium SE flow volumes

Note: 5 g L^{-1} is the low barrage & medium SE flows, low salinity scenario, 10 g L^{-1} is the low barrage & medium SE flows, medium salinity scenario and 15 g L^{-1} is the low barrage & medium SE flows, high salinity.