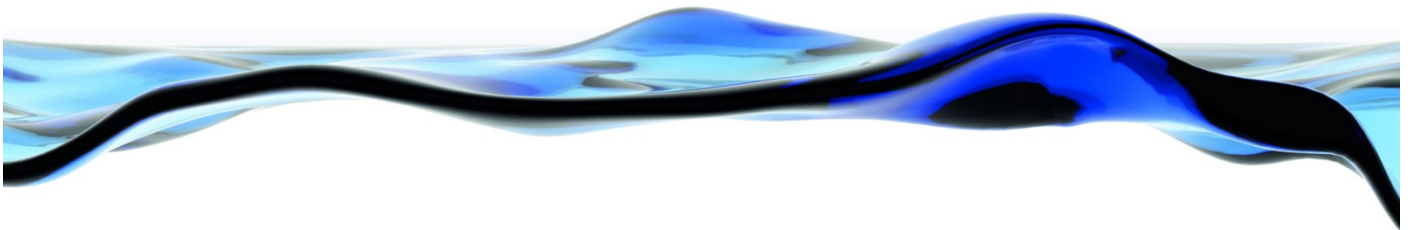


Assessing the impact of volumes proposed under the Draft Basin Plan on the Coorong and Murray Mouth region

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Introduction

The Murray-Darling Basin Authority (MDBA) has selected two Indicator Sites for South Australia in the Basin Planning process (MDBA 2010). One of these was the Coorong, Lower Lakes and Murray Mouth (CLLMM) region at the terminus of the River Murray. The CLLMM region is also one of six identified icon sites for The Living Murray initiative, and is listed as a Wetland of International Importance under the Ramsar Convention (Phillips and Muller 2006).

The Guide to the Proposed Basin Plan included three environmental targets against which to measure ecological condition within the CLLMM region: i) maintenance of a range of healthy estuarine, marine and hypersaline conditions to support key species in the North and South Lagoons of the Coorong; ii) provision of sufficient flows to allow for salt and nutrient export; and iii) provision of a variable lake-level regime to support riparian vegetation communities and prevent the exposure of acidic soils (MDBA 2010). These ecological targets were supported by a set of environmental water requirements (EWRs) that, when met, were assumed to indicate that the underlying targets were also being met (MDBA 2010). EWRs were identified to support populations of the two iconic aquatic macrophytes, *Ruppia tuberosa* and *Ruppia megacarpa*, based on salinity and water-level requirements (MDBA 2010). A salt export target of 2 million tonnes per year and a minimum outflow volume sufficient to maintain an open Murray Mouth were also set (MDBA 2010).

Specific EWRs to support these targets (Appendix A) were:

- a long-term average barrage flow of at least 5100 GL y⁻¹;
- a three-year rolling average barrage flow of greater than 2000 GL y⁻¹ in 95% of years;
- a three-year rolling average barrage flow of greater than 1000 GL y⁻¹ in 100% of years;
- a 10-year rolling average barrage flow of greater than 3200 GL y⁻¹ in 100% of years; and
- a minimum barrage flow of 1000 GL y⁻¹ in 100% of years (MDBA 2010).

In addition, it was also recognized that flows of greater than 5100 GL y⁻¹ were needed on a regular basis, although return frequencies and event magnitudes were not specified (MDBA 2010).

A second set of EWRs was also prepared by Heneker (2010) and Lester *et al.* (2011) and adopted by the SA State Government (Appendix A). This set of EWRs was based on meeting stated salinity targets in Lake Alexandrina. Here, a somewhat different set of average flow volumes were specified, and additional targets relating to high flows were also included (Lester *et al.* 2011). Three nested salinity targets for Lake Alexandrina were included: i) a long-term annual average of 700 µS cm⁻¹ electrical conductivity (EC); ii) a maximum annual average of 1000 µS cm⁻¹ EC to be met in 95% of years; and iii) a maximum annual average of 1500 µS cm⁻¹ EC to be met in 100% of years (Heneker

2010). This nested set of targets was designed to recognise the variability of flows through the region and to cater for occasional low-flow years (Lester *et al.* 2011). For the middle target, a maximum annual average of $1000 \mu\text{S cm}^{-1}$, a three-year minimum flow regime was specified. In a given year, the minimum flow over the barrages should be the maximum of (Heneker 2010):

- 650 GL; or
- 4,000 GL minus flows in the previous year; or
- 6,000 GL minus flows in the previous two years (adjusted for the maximum effect of flows two years ago).

Similar sets of minimum flows were also specified for the remaining salinity targets. Finally, Lester *et al.* (2011) also indicated that high flows of at least 6000 GL and 10 000 GL should recur within the site at least every seven and 10 years, respectively.

The Draft Basin Plan (MDBA 2012) included three options for additional environmental flows. These included returning 2400 GL y^{-1} , 2750 GL y^{-1} (here, approximated as 2800 GL y^{-1}), or 3200 GL y^{-1} . In this report, we investigate the effect of each of those three additional flow volumes on the hydrodynamics and ecological condition, as approximated using ecosystem states, of the Coorong compared baseline and without-development conditions. We also investigate whether any or all of the volumes proposed meet the EWRs specified by MDBA (2010) and Lester *et al.* (2011) (see Appendix A for list of EWRs), and, where they do not, investigate the potential effects of less water.

Methods

Hydrodynamic model

Model description

The Coorong hydrodynamic model (Webster 2010) simulates water movement and levels along the length of the Coorong as these respond to driving forces. Driving forces included in the model were water-level variations in Encounter Bay, wind, barrage inflows, flows at Salt Creek (via the Upper South East Drainage Scheme; Figure 1) and evaporation from the water surface (Webster 2007, 2010). The model domain includes the Murray Mouth to the southern end of the South Lagoon (~ 5 km past Salt Creek; Figure 1) and is divided into 102 cells that are 1 km long each, in which momentum equations describing conservation of mass are solved (Webster 2010). Major channel constructions are resolved independently to represent the effect of the changing shape of the Mouth and the channel connecting the two lagoons past Parnka Point (Webster 2010).

The depth of the Murray Mouth is highly dynamic, increasing during times of significant outflows and tending to infill when flows are very small or zero. In the model, the Mouth channel is assigned a width of 100 m and a length of 1500 m to approximate the dimensions seen in satellite imagery (Webster 2010). Even though the bathymetry of the Mouth channel is highly complex, a single bed elevation is assigned as an approximation. Infilling and scouring by barrage flows of the Mouth channel are represented as changes in the elevation of the channel bed. Dredging, which has been used to maintain Mouth depth in times of low barrage flows, was not included in these simulations. The second constriction that connects the two lagoons, Parnka Channel, is highly complicated and convoluted. The model uses a 100-m wide, 1000-m long approximation of the constriction, rather than attempting to resolve the details of the channel shape. These dimensions are approximately consistent with satellite images of the region. The optimal elevation of Parnka Channel was determined to be -0.19 m AHD through calibration.

The currents, water levels and mixing regimes simulated by the basic hydrodynamic model were used to drive a second module simulating salinity dynamics. Salinity was modelled across 14 cells (Figure 1) that extend across groups of cells used in the basic hydrodynamic model, and the location of each was determined based on historical sampling locations. The salinity module solves equations for the conservation of mass of salt. Salinity of sea water in Encounter Bay was set at 36.7 g L^{-1} , while the inflows from Salt Creek were set at 16.1 g L^{-1} . The latter is the calculated flow-weighted average of salinity in the Salt Creek discharge between 2001 and 2008 (Webster 2010).

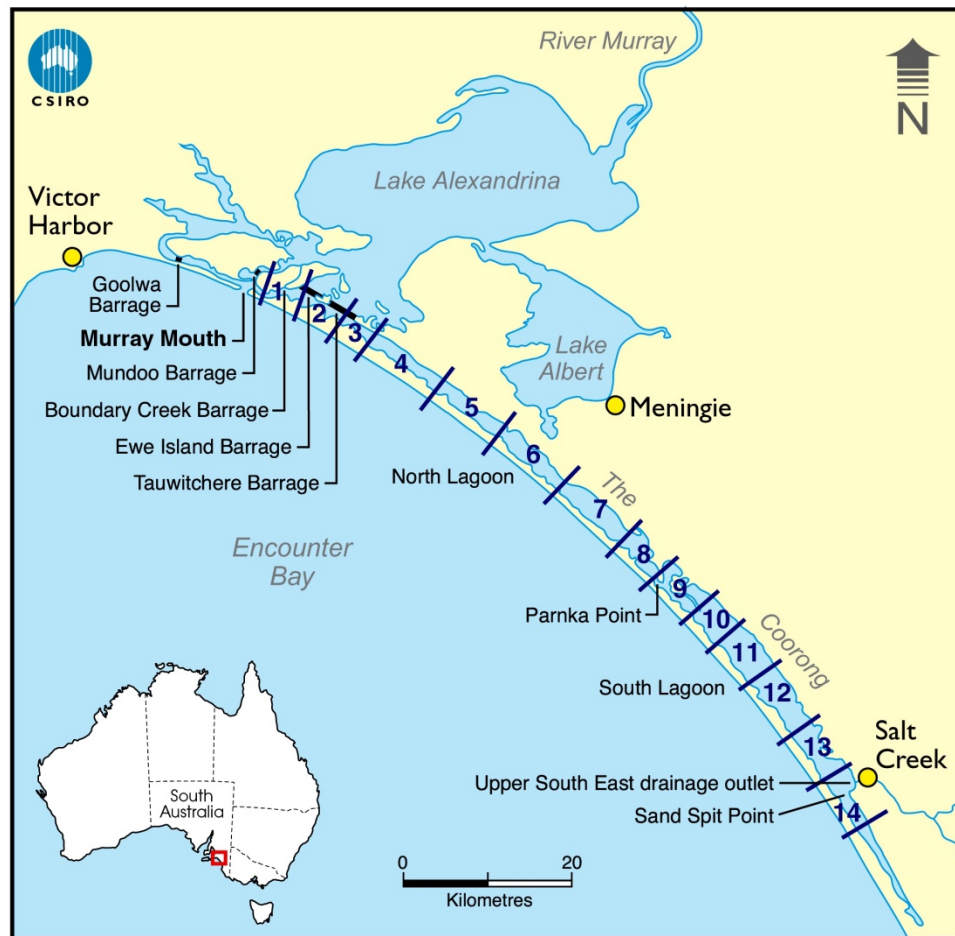


Figure 1. Map of the Coorong showing boundaries of cells used in the salinity module (Webster 2007, 2010)

Model application

This hydrodynamic model was run for five scenarios. These scenarios involved different amounts of environmental flows returned to the river under the Basin Plan. The model was used to simulate water levels and salinity along both lagoons of the Coorong between 1895 and 2009 as this was the length of inflow time series available for the River Murray. Modelled daily barrage flows obtained from MDBA were available for the entire simulation period.

The barrage flows were provided by MDBA as totals across all the barrages for each day. An analysis of the proportion of flows crossing the main barrages between 1982 and 2007 showed that, on average, 58% of the total flow was released through Tauwichee Barrage and 19% through Ewe Island Barrage (Webster *et al.* 2012). These proportions were applied to the whole of barrage flow time series to obtain estimated daily flows through each of Tauwichee and Ewe Island Barrages. The model did not simulate the flow interaction between Lake Alexandrina and the Coorong that would have occurred prior to the construction of the barrages. One of the scenarios (i.e. Without

Development) attempts to simulate so-called natural flow conditions, without the influence of water resource infrastructure and with no extractions in the Murray-Darling Basin. For this scenario, the barrages were treated simply as if they remained fully open to allow all flows to pass through the Coorong, but disallowed any upstream flow from the Coorong to the Lakes. For all scenarios, the daily Salt Creek inflow was taken to be the average of measured flows on each day of the year between 2001 and 2008.

Scenarios investigated

Scenario analyses were used in order to assess the effect of three proposed sets of river flows, based on work undertaken for the Basin Plan (MDBA 2012), on the hydrodynamics of the Coorong and then on the ecological responses of the Coorong. This allowed the impact of water flows to be objectively assessed under different delivery scenarios (each scenario is outlined below).

The scenarios investigated include:

1. Benchmark conditions (hereafter called 'Baseline')

This scenario included historic climate conditions, current levels of extraction from the Basin (and so current flows over the barrages), and average inflows from Salt Creek. This scenario did not include dredging.

2. Without Development

This scenario included historic climate conditions with no extractions from the Basin and none of the current infrastructure (with the exception of the barrages) and thus represents an upper baseline for the amount of what that could potentially be available within the system at any one time (on average, 11,566 GL y⁻¹).

3. 2400

This scenario was as for the Baseline scenario, but also included additional environmental water returned to the river under the guidelines being developed for the Basin Plan. This scenario returned the lowest of three possible volumes of additional environmental water, using an average of an additional 2400 GL y⁻¹. This scenario represented one possible way in which the Basin Plan could be implemented.

4. 2800

This scenario was as for the Baseline scenario, but also included additional environmental water returned to the river under the guidelines being developed for the Basin Plan. This scenario returned the second of three possible volumes of additional environmental water, using an average of an additional 2800 GL y⁻¹. This scenario represented one possible way in which the Basin Plan could be implemented. Note that the most recent version of the Basin Plan (MDBA 2012) uses a volume of 2750 GL y⁻¹, rather than 2800 GL y⁻¹, but this discrepancy is small and unlikely to influence the findings based on the range of modelling undertaken in this report (*sensu* CSIRO 2012).

5. 3200

This scenario was as for the Baseline scenario, but also included additional environmental water returned to the river under the guidelines being developed for the Basin Plan. This scenario returned the highest of three possible volumes of additional environmental water, using an average of an additional 3200 GL y⁻¹. This scenario represented one possible way in which the Basin Plan could be implemented.

Ecosystem state model

It can be a difficult task to assess ecological condition at an ecosystem scale. There are usually some aspects of an ecosystem that are well understood (e.g. birds and fish) and others that are less so (e.g. microbes, groundwater inputs). For this assessment, the ecological condition of the Coorong was estimated using an ecosystem response model based on the concept of 'ecosystem states'. Unlike the hydrodynamic model described above, the ecosystem states model is not based on a deterministic understanding of how ecosystems behave, but rather on statistical relationships observed in the past. That is, it is not based on equations describing the interactions among each species, their environment, and their competitors and predators. Instead, it is a statistical model, using past relationships identified between the biota that occur within the system at any one point in time and the environmental conditions under which those biota occur (Lester & Fairweather 2011).

The ecosystem states model developed for the Coorong (Lester & Fairweather 2009, 2011) includes eight distinct ecosystem states. The environmental parameters that differentiate amongst the various states included the average daily tidal range, maximum number of days since flow had

crossed the barrages, average water level and salinity at any location, and average depth of water in the previous year. The appearance of average daily tidal range as the first split variable effectively divided the Coorong into two basins, with four possible states within each basin (i.e. tidally-influenced and tidally-independent basins). Additional information on the biota and conditions characterising each of these states can be found in Lester & Fairweather (2009, 2011). The trend of declining biotic richness and the variables for which thresholds were significant (e.g. length of time without barrage flows) show that the states represent a continuum from a healthy ecosystem to a more degraded ecosystem in each basin.

The ecosystem state model uses environmental data as modelled by the hydrodynamic model to predict transitions between the states and hence is a state-and-transition model. By happenstance, all of the parameters identified as driving the ecosystem states of the Coorong could be calculated from the output of the hydrodynamic model. These data were then used to calculate the average annual water levels, depths and salinities as required by the ecosystem state model. By using these parameters as input for the ecosystem state model, we were able to predict the mixture of ecosystem states present in the Coorong each year for the duration of the model run at each of the 14 salinity cells used by the hydrodynamics model. A detailed discussion of the limitations of this model is outside the scope of this research, but those limitations are discussed in detail in Lester and Fairweather (2009, 2011) and we refer the reader there.

Comparison against Environmental Water Requirements (EWRs)

The three flows scenarios developed by MDBA in accordance with MDBA (2012) were compared to the EWRs set by both the MDBA (2010) and Lester *et al.* (2011). Annual barrage flow statistics were calculated for each of the scenarios modelled and the percentage of years in which each EWR was met was calculated. The ability of the each scenario to meet the EWR was determined as a pass or a fail (reported in Table 2), with additional information provided where any scenario did not meet an EWR as it was written (in Table 3). For each year in which EWRs were not met (excluding the allowed failure rate of 5% where relevant), the number of interventions required and the average volume of each to redress the shortfall in barrage flows was calculated (Table 3), thus providing an indication of how far from meeting the target each scenario was.

Assessing the effects of delivering less water than specified by the EWRs

Lester *et al.* (2011) undertook an assessment of the effects of delivering less water than was specified by the EWRs. This analysis investigated each of the three salinity targets identified for Lake Alexandrina (i.e. 700, 1000 and 1500 $\mu\text{S cm}^{-1}$ EC) under historical, median future and dry future climate scenarios. They discovered that there were thresholds in the response of the Coorong to increasingly severe shortages in the amount of water delivered compared to the EWRs. Here, we focus on the thresholds identified under the 1000 $\mu\text{S cm}^{-1}$ EC target for Lake Alexandrina.

Investigating the impact on North and South Lagoon salinities, water levels and the proportion of degraded ecosystem states showed that the discrepancy between barrage flows and EWRs in a single year (i.e. barrage flow volume prescribed by the EWRs minus actual total barrage flow for that year), the cumulative discrepancy in barrage flows across years (i.e. where the discrepancy continued for more than one year), and total barrage flows were the variables that best highlighted differences in salinity, water levels and degraded ecosystem states. These analyses only investigated years in which the EWRs were not met, and so described step-wise degradation within the Coorong.

For both North and South Lagoon water levels, the discrepancy in barrage flow volume in a single year was the key driver. In both, there was a single threshold of 5150 GL. In the North Lagoon, annual average water levels were 0.2 m AHD when this threshold was not exceeded, compared to 0.0 m AHD when it was. In the South Lagoon, annual average water levels were 0.1 m AHD when the threshold was not exceeded, compared to -0.3 m AHD when it was.

Where the EWRs were not met, the cumulative discrepancy in barrage flows was the most important variable describing the impact on salinity in both lagoons (Lester *et al.* 2011). In the North Lagoon, when this cumulative discrepancy was less than 29,288 GL in total (i.e. across multiple years for as many years as the EWRs continue to not be met) and less than 11,202 GL, the average annual salinity was 56.4 g L^{-1} . When the cumulative discrepancy was between 11,202 and 29,288 GL, the average annual North Lagoon salinity was 77.7 g L^{-1} . For cumulative discrepancies above 29,288 GL but below 57,306 GL, annual average North Lagoon salinity was 129.9 g L^{-1} , and for cumulative discrepancies above 57,306 GL, annual average North lagoon salinity was 174.9 g L^{-1} . Note that these include modelled salinities under a dry future climate simulation, so may not be representative of actual future conditions in the region and each is calculated over multiple years, so

more consecutive years over which the EWRs are not met, the more severe the conditions with respect to salinity in the North Lagoon.

For salinity in the South Lagoon, cumulative discrepancy was again the most important variable with average annual salinities of 120.4 g L^{-1} when the first threshold of 20,302 GL was not exceeded, 208.6 g L^{-1} when the second threshold of 36,580 GL was not exceeded, and 316.0 g L^{-1} when the third threshold of 57,306 GL (consistent with that for the North Lagoon) was not exceeded, and 453.2 g L^{-1} when all thresholds were exceeded. The increasing severity of salinities in the South Lagoon indicates that these thresholds are key points that should not be allowed to be crossed.

Finally, the proportion of degraded ecosystem states simulated for the Coorong was associated with thresholds in both cumulative discrepancy and total barrage flow. When the cumulative discrepancy in barrage flows was less than 11,202 GL, the average proportion of degraded states was 0.27. When the threshold in cumulative discrepancy was exceeded, but total barrage flows were greater than 21 GL for the year, the average proportion of degraded states was 0.65. However, if both thresholds were crossed, the average proportion of degraded states was 0.95.

In order to determine the relative severity of the consequences associated with individual scenarios failing to meet the EWRs, the frequency of crossing each of those thresholds in cumulative discrepancy, discrepancy in barrage flows and total barrage flows was calculated for each of the five scenarios investigated.

Results

Assessing the impact of differing additional flow volumes on the Coorong

As previous modelling for the Coorong has shown, there were large differences between the Without Development and Baseline scenarios. In particular, the Without Development scenario had much higher average annual water levels and lower maximum salinities than the Baseline scenario (Figure 2).

Compared to Baseline conditions, flow deliveries of 2400, 2800 and 3200 GL y⁻¹ had little impact on the annual range of water levels, average water levels, and the depth of the water in the Coorong (Figures 2a, c & d). All of the additional flows modelled showed a small increase in the minimum annual range in water levels (0.35 m and 0.41 m for the 2400 and 3200 scenarios, respectively), with only outliers falling below the threshold, but there was little average difference among the three volumes (median values of 0.93, 0.94 and 0.92 m for the 2400, 2800 and 3200 scenarios, respectively). Depth from two years previous did not differ substantially between flow delivery volumes, but showed less variability compared to Baseline (which had lower minimum depths) and Without Development (which had higher maximum and minimum depths) conditions. Average water levels were less variable and median water levels were substantially lower under all flow-delivery conditions (0.31 m AHD for all three flow scenarios), compared to Without Development conditions (0.38 m AHD). Median water levels for all three flow-delivery volumes were higher than that for the Baseline scenario (0.29 m AHD for the Baseline), and minimum water levels were also substantially higher (i.e. 0.12 and 0.13 m AHD for the 2800 and 3200 scenarios, respectively). Only the 2400 scenario had outliers below the minimum threshold for water level (-0.09m AHD was the minimum water level for the 2400 scenario). As for depth from two years previous, there was little difference in median average water levels between flow delivery scenarios (with a difference of 0.07 m between the Without Development [1.54 m AHD] and Baseline [1.47 m AHD] scenarios).

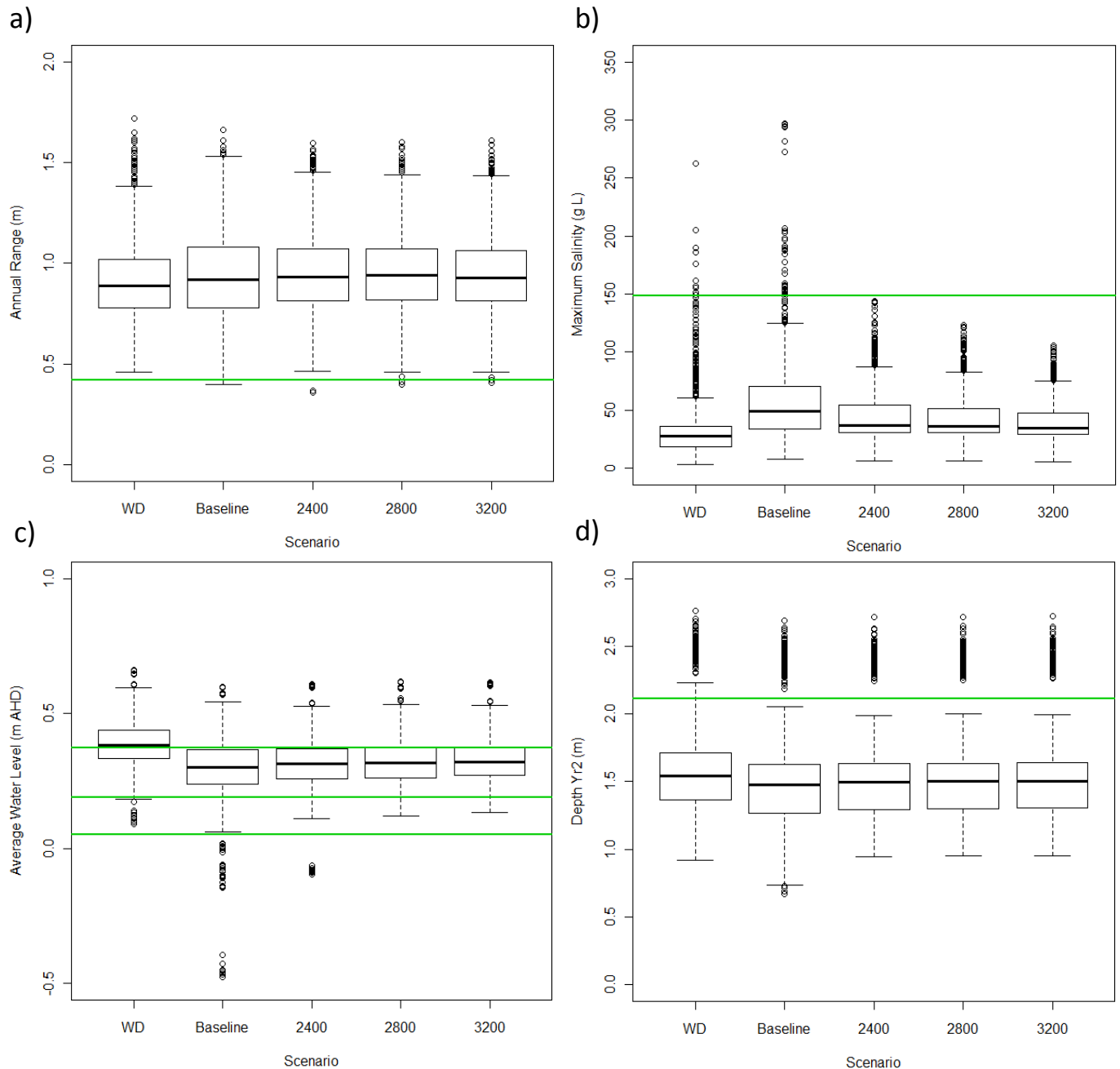


Figure 2: Boxplots showing the comparison between variables driving the ecosystem states of the Coorong for five scenarios a) Annual range in water level (m), b) Maximum salinity (g L⁻¹), c) Average water level (m AHD) and d) Average water depth from two years previous (m) . Information on how to read this figure is presented in Appendix B.1. Thresholds are shown by the green horizontal lines across each boxplot.

The alternative flow delivery volumes did influence maximum salinity, with decreasing maximum salinity occurring with increasing flow volumes, from 144.3 g L⁻¹ with the delivery of an additional 2400 GL y⁻¹, 123.2 g L⁻¹ under the 2800 scenario and 106.0 g L⁻¹ under the 3200 scenario. The lowest

median maximum salinity (28 g L^{-1}) was observed under the Without Development scenario (which also had the smallest interquartile range), compared to all other scenarios. The highest median maximum salinity was under the Baseline scenario (48.9 g L^{-1}). None of the flow volume scenarios crossed the threshold identified in the ecosystem states model, and the interquartile range gradually decreased with increasing flow volume (Figure 2b). Thus the extra volumes showed reduced variability compared with Baseline or Without Development scenarios.

Considering the difference from the Baseline in hydrodynamic drivers of ecosystem states observed under the Without Development scenario compared with all other scenarios, it was unsurprising that the Without Development scenario provided the largest improvement in depth compared to the Baseline scenario (Figure 3). There was also a modest improvement in water depth compared to the Baseline across the three flow volumes as shown by the 2800, 3200 and 3400 scenarios, with a proportional increase in depth with increasing flow volume. Likewise, Without Development showed the largest decrease in annual range compared to the Baseline (i.e. associated with higher minimum flow volumes), with all three flow volumes providing proportional, but modest decreases in annual range with larger flow volumes (Figure 3).

Compared with the Baseline scenario, the Without Development scenario showed the greatest improvement in both salinity and water levels (Figure 4). This was due to higher water levels and lower maximum salinities compared with the other scenarios. The three flow deliveries (including 2400, 2800 and 3400 GL y^{-1}) improved both salinity and water levels proportionally to the increasing flow volumes in each scenario, but not to the same extent as the Without Development scenario (Figure 4).

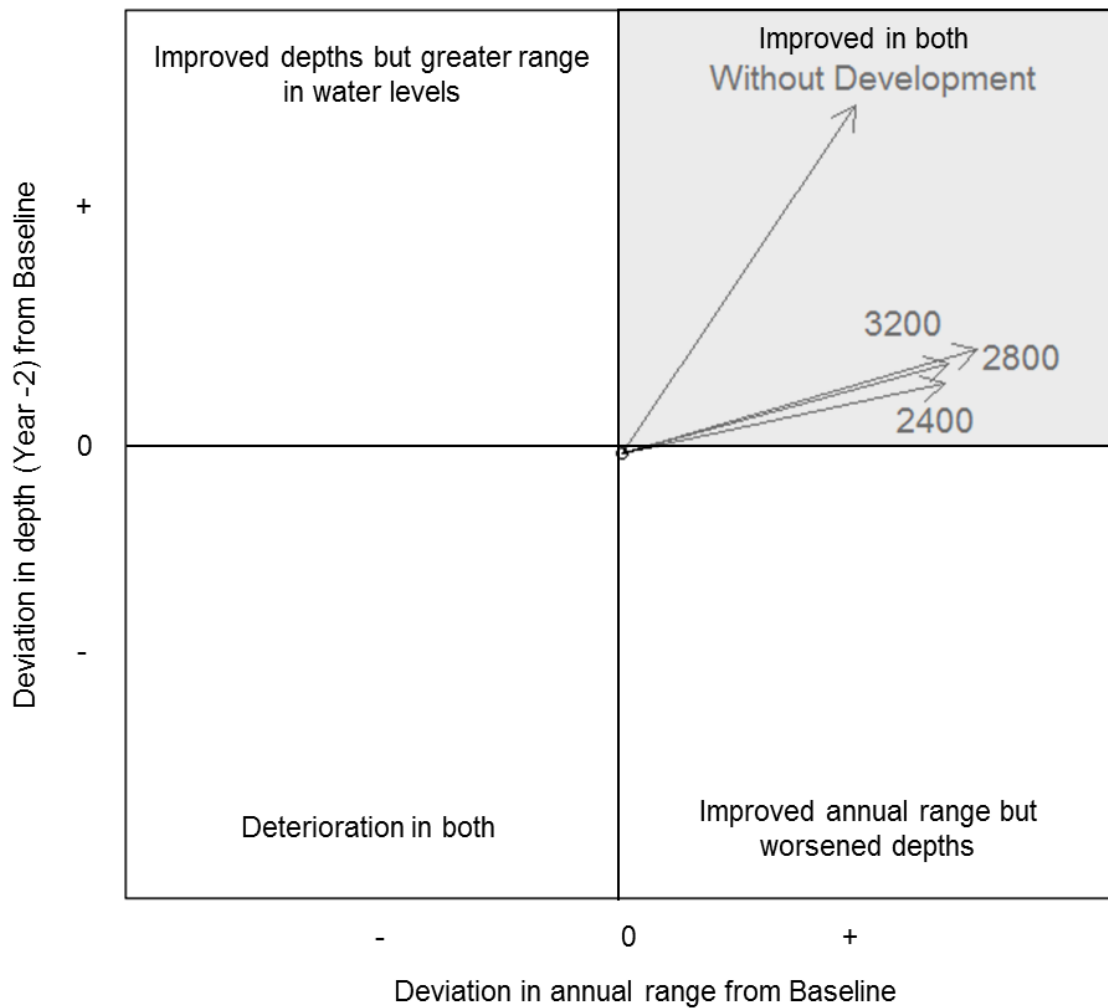


Figure 3: Comparison of the effect of each scenario relative to the Baseline annual range and water depth (two years previous). This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline scenario with respect to annual range and depths (from two years previously). Length of each vector is proportional to the strength of the deviation from the Baseline condition (as shown by the 0,0 origin). Vectors in the top-left quadrant indicate an improvement for both variables (i.e. higher water levels and greater depths). Information on how to read this figure is presented in Appendix B.2.

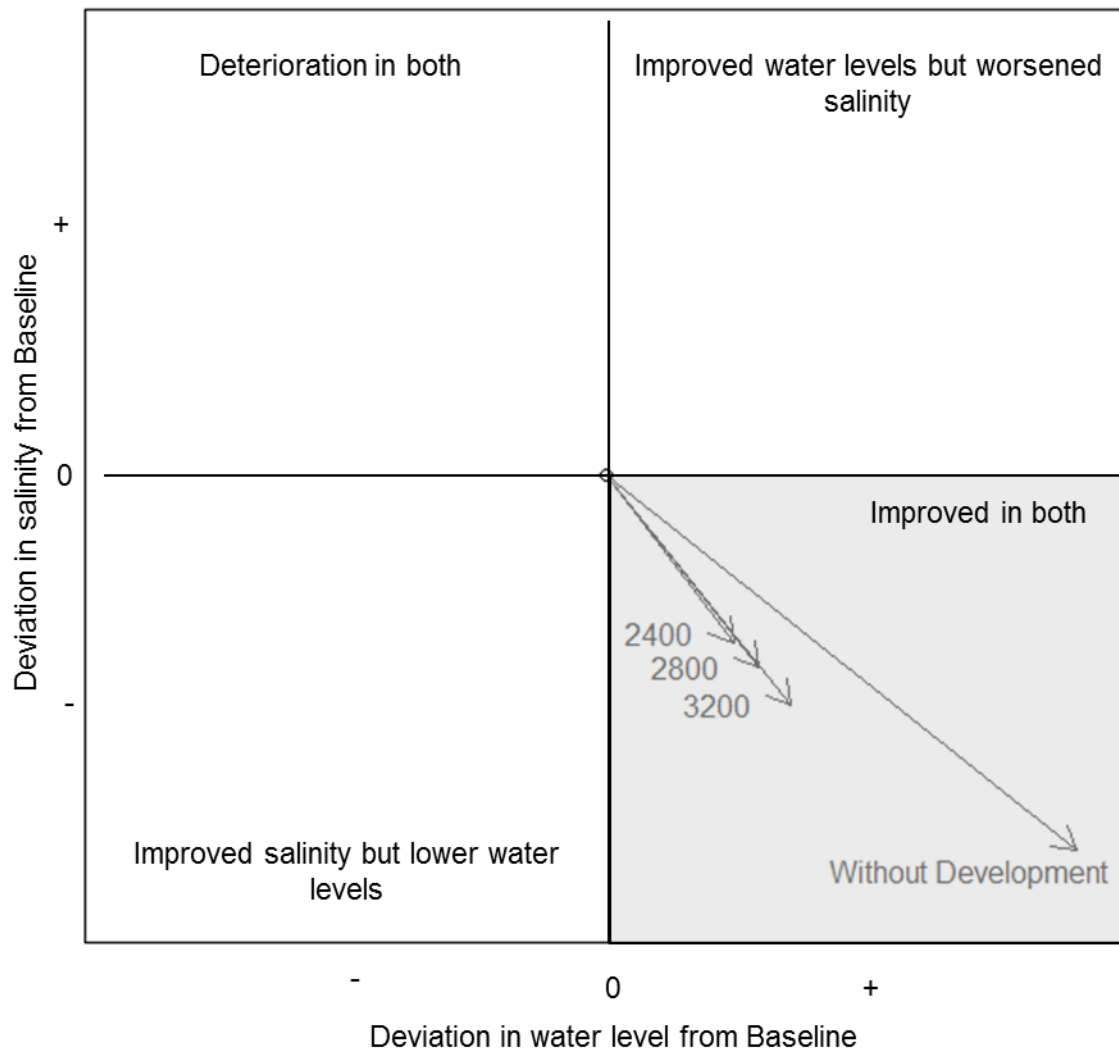


Figure 4: Comparison of the effect of each scenario relative to the Baseline salinity and water levels. This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline scenario with respect to salinity and water level. Length of each vector is proportional to the strength of the deviation from the Baseline 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 greater depths). Information on how to read this figure is presented in Appendix B.2.

The scenarios based on different flow volumes each had a positive influence on the mix of ecosystem states compared with the Baseline scenario (Figure 5). Six of the eight identified ecosystem states occurred within the Baseline scenario, including the Unhealthy Marine and Degraded Hypersaline states. Of these, the Degraded Hypersaline state failed to appear in any other scenario, including the Without Development scenario. The proportion of Unhealthy Marine site-years also decreased gradually with increasing flow volumes, with the 3200 having scenario having fewest Unhealthy Marine site-years of the three flow delivery scenarios, but the overall change was

small. The Without Development scenario had the lowest proportion of Unhealthy Marine site-years overall.

The Without Development scenario had more than twice the proportion of Healthy Hypersaline site-years, as well less than half the proportion of Average Hypersaline site-years, compared to all other scenarios. The Without Development scenario also had the highest proportion of Unhealthy Hypersaline site-years than any other scenario, including the Baseline.

No substantial changes in the proportion of the site-years assigned to each ecosystem state, other than the disappearance of the Degraded Hypersaline state and the effective disappearance of the Unhealthy Marine state, were apparent between flow delivery scenarios (Figure 5). The total number of site-years that fell into each ecosystem state is presented in Table 1, illustrating the trends described above.

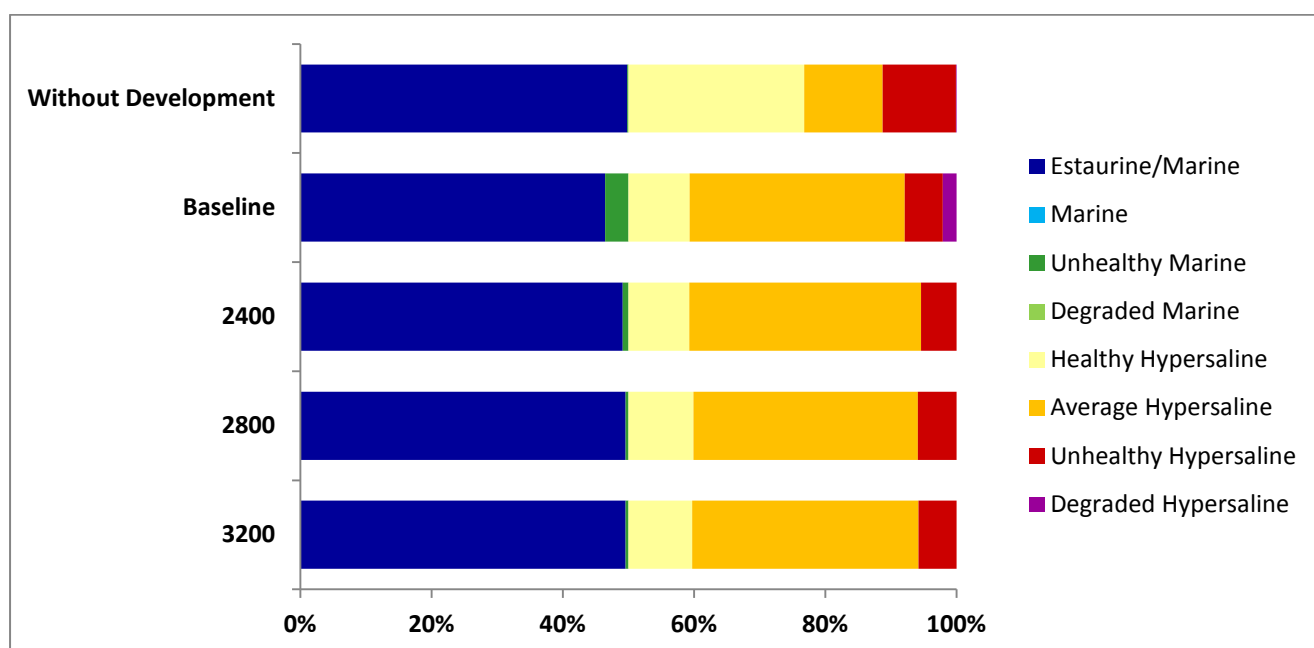


Figure 5: Comparing the proportion of site-years in each ecosystem state

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

Information on how to read this figure is presented in Appendix B.3.

Table 1: The total number of site-years that fell within each ecosystem state across the five

scenarios. The entirety of the model run (113 years and 14 sites) equals 1582 site-years. Each column below sums, however, to only 1568 because the alternate model calculates depth from the previous year and cannot determine ecosystem states for the first year of the model run.

	Scenario				
	Without Development	Baseline	2400	2800	3200
Estuarine Marine	781	728	770	777	777
Marine	0	0	0	0	0
Unhealthy Marine	3	56	14	7	7
Degraded Marine	0	0	0	0	0
Healthy Hypersaline	420	146	145	155	152
Average Hypersaline	187	514	554	536	541
Unhealthy Hypersaline	175	91	85	93	91
Degraded Hypersaline	2	33	0	0	0

The changes in the proportions of site-years in the Healthy Hypersaline, Average Hypersaline, and Unhealthy Hypersaline states between the Without Development scenario and the Baseline scenario is evident in Figure 6. The three flow-delivery scenarios all had similar deviations from the Baseline scenario. Estuarine/Marine, Healthy Hypersaline and Average Hypersaline site-years all increased in incidence between the flow delivery scenarios and the Baseline scenario, while the incidence of Unhealthy Marine and Degraded Hypersaline site-years decreasing proportionally across the increase in flow volumes (Figure 6, Table 1). Additional flows of at least 2800 GL y⁻¹ were necessary to effectively eliminate the Unhealthy Marine state, and to promote the incidence of the Healthy Hypersaline state, but the incidence of the latter did not approximate that observed for the Without Development scenario in any scenario investigating additional environmental flows.

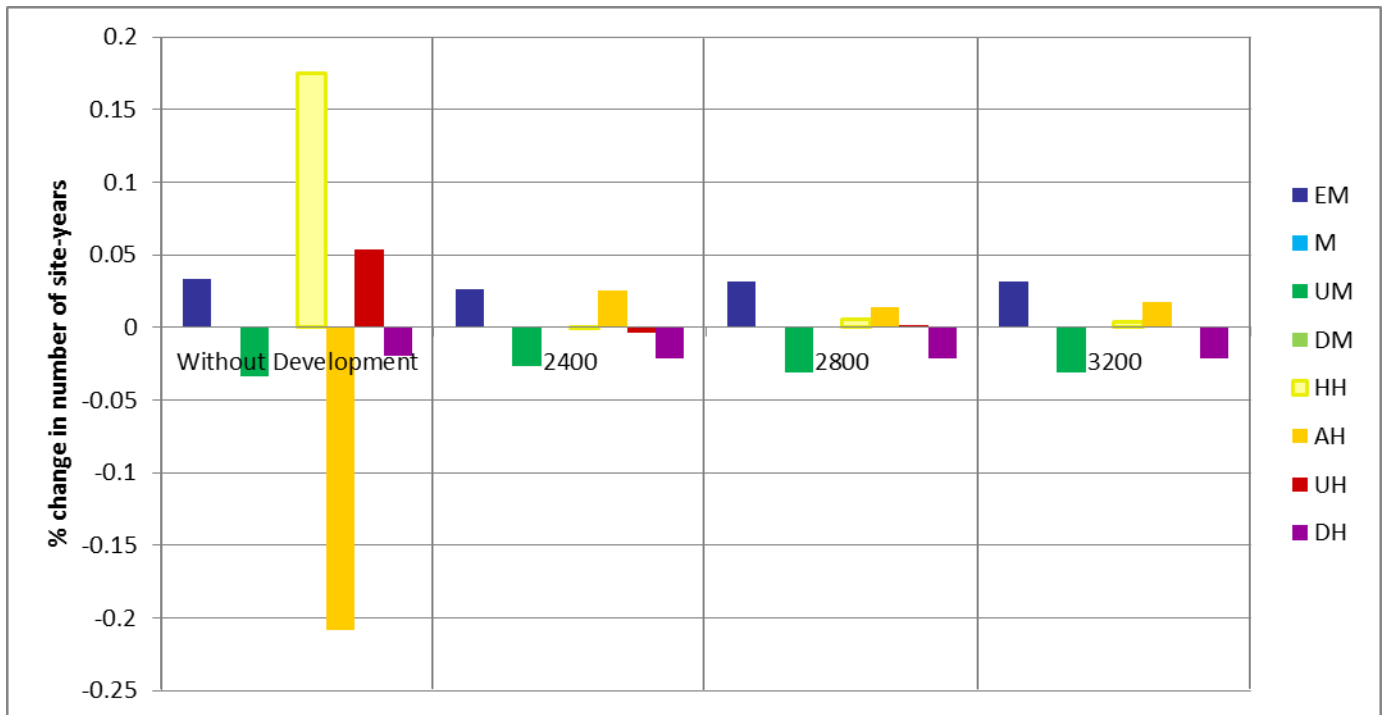


Figure 6: Deviations in the proportion of site-years in each ecosystem state compared to the Baseline scenario

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

Information on how to read this figure is presented in Appendix B.4.

Comparison against EWRs

The Without Development and one Basin Plan scenario, with an additional flow of 3200 GL y^{-1} , met all eight relevant MDBA and SA Government EWRs, whereas the Baseline scenario, using the historical delivery profile of water, failed to meet any EWR (Table 2). The remaining two Basin Plan scenarios (including the additional flow volumes of 2400 and 2800 GL y^{-1}) met only 3 and 4, respectively, of the EWRs investigated (Table 3) and therefore represented improvements on the Baseline scenario. The 2400 scenario met the fewest (3 out of 8) EWRs, and failed to meet the MDBA EWR of 2000 GL y^{-1} as a rolling average over 3 years in 95% of years, which was met by both the 2800 and 3200 scenarios. An increase in additional flow volume from 2400 to 2800 GL y^{-1} resulted in one additional EWR being met (4 out of 8), the MDBA EWR of 2000 GL y^{-1} as a rolling average over 3 years in 95% of years (Table 3).

The EWRs of a long-term average barrage flow volume of at least 5100 GL y⁻¹, an absolute minimum of 650 GL in 95% of years, and high flows of more than 6000 and 10,000 GL at least every 3 and 7 years, respectively, were met in every scenario except the Baseline. Overall minimum flow volumes to be achieved in 95% and 100% of years were not met under three out of five scenarios, with only the Without Development and 3200 scenarios meeting those EWRs (Table 2). The MDBA EWRs of achieving at least 1000 GL y⁻¹ as a 3-year rolling average and a salt-export target of 3200 GL y⁻¹ as a 10-year rolling average were also only met by the Without Development and the 3200 scenarios.

Although there was almost no improvement in the number of additional EWRs that were met by additional environmental water allocations between 2400 and 2800 GL yr⁻¹ (Figure 7), the increase in flow volume did result in fewer instances of failure, and smaller amounts of water required to redress the deficit (Table 3). For example, in order to meet the MDBA EWR of 3200 GL y⁻¹ as a 10-year rolling average for salt export, the 2400 scenario required an average of 257 GL of additional water on two occasions. The 2800 scenario only fell short for that EWR on one occasion, with an additional 219 GL required. This pattern of decreasing numbers of, and smaller, interventions required to meet each target held for all EWRs.

Whilst the addition of 400 GL y⁻¹ between the 2400 and 2800 scenarios resulted in only one additional EWR being met, a further increase of 400 GL y⁻¹ between the 2800 and 3200 GL yr⁻¹ scenarios met all 8 EWRs (Table 2). While the volume of additional water is instrumental to increasing the number of EWRs that are met (Figure 7), the method of flow delivery is also a driver of the number of EWRs that are met, with the pattern of flow delivery modelled by the 3200 scenario optimised to meet each target. Should the actual delivery pattern for flows not match that modelled here, the number of EWRs that are met may fall, as there is very little redundancy in the current flow sequence. That is, while the EWRs are met, they are not necessarily met by much and relatively small changes in the pattern of flow delivery may risk ecological degradation in times of low flow and this will need to be managed carefully.

Table 2. Capacity of the Basin Plan scenarios to meet environmental water requirements (EWRs) for the CLLMM region (Appendix A). ‘✓’ indicates the EWR was met by the monthly model. ‘✗’ indicates the EWR was not met by the monthly model. ‘NA’ is not assessed, due to insufficient detail in the specification of the EWR (high flows).

Target	Scenario				
	WD	Baseline	2400 GL	2800 GL	3200 GL
<i>MDBA EWRs</i>					
5100 GL y ⁻¹ long-term average	✓	✗	✓	✓	✓
2000 GL y ⁻¹ rolling average over 3 years in 95% of years	✓	✗	✗	✓	✓
1000 GL y ⁻¹ rolling average over 3 years	✓	✗	✗	✗	✓
High flow requirements (exact volumes not specified, see below)	NA	NA	NA	NA	NA
3200 GL y ⁻¹ 10-year rolling average for salt export	✓	✗	✗	✗	✓
% success in meeting MDBA EWRs (of the 4 that could be assessed)	100	0	25	50	100
<i>SA Government EWRs</i>					
SA minimum flow (max of three previous targets) in 95% of years	✓	✗	✗	✗	✓
SA minimum flow (max of three previous targets) in 100% of years	✓	✗	✗	✗	✓
6000 GL y ⁻¹ with at least a 1:3 year frequency	✓	✗	✓	✓	✓
10000 GL y ⁻¹ with at least a 1:7 year frequency	✓	✗	✓	✓	✓
% success in meeting SA EWRs (of the 4 independent EWRs)	100	0	50	50	100

Table 3. Capacity of the Basin Plan scenarios to meet environmental water requirements (EWRs) for the CLLMM region including the number of interventions required to meet each EWR and then the average size of each intervention in terms of the amount of water needing to be added. '✓' indicates the EWR was met, and a '-' indicates that no additional water was required (i.e. because the EWR was met). Figures show the number of occasions on which the EWR was not met (or '✗' if that is not sensible because of the form of the EWR) and then the average volume of additional water (GL) required to achieve the EWR is given as a number. 'NA' is not assessed, either due to insufficient detail in the specification of the EWR (high flows) or an inability to assess the EWR from barrage flow data (Lakes evaporation).

Target	Scenario								
	WD	Baseline		2400 GL		2800 GL		3200 GL	
	# occasions		Added volume (GL)	# occasions	Added volume (GL)	# occasions	Added volume (GL)	# occasions	Added volume (GL)
MDBA EWRs									
5100 GL y ⁻¹ long-term average	✓	✗	282	✓	-	✓	-	✓	-
2000 GL y ⁻¹ rolling average over 3 y in 95% y	✓	19	675	3	597	✓	-	✓	-
1000 GL y ⁻¹ rolling average over 3 y	✓	7	293	1	384	1	321	✓	
High flow requirements (exact volumes not specified)	NA	NA	NA	NA	NA	NA	NA	NA	NA
3200 GL y ⁻¹ 10-y rolling average for salt export	✓	26	702	2	257	1	219	✓	-
Success rate	4/4	0/3		1/4		2/4		4/4	
SA Government EWRs									
SA minimum flow in 95% y	✓	26	1990	2	3313	2	3233	✓	-
SA minimum flow in 100% y	✓	14	708	3	631	3	535	✓	-
6000 GL y ⁻¹ at least a 1:3 y	✓	4	606	✓	-	✓	-	✓	-
10000 GL y ⁻¹ at least a 1:7 y	✓	3	127	✓	-	✓	-	✓	-
Success rate	4/4	0/4		2/4		2/4		4/4	

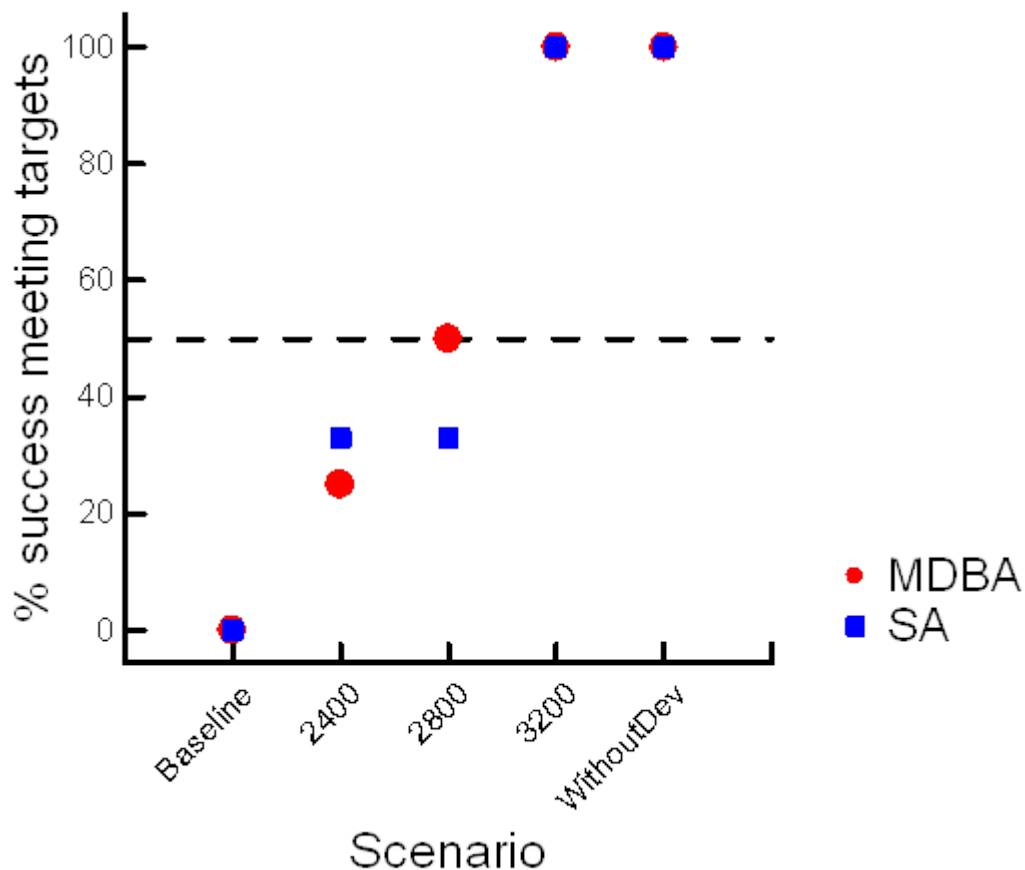


Figure 7: A visualisation of each scenario's percentage success of meeting MDBA and SA Government EWRs, increasing in flow volume from left to right. The dotted line represents meeting 50% of either MDBA or SA Government EWRs.

Assessing the effects of delivering less water than specified by the EWRs

The amount by which a scenario fails to meet an EWR, by providing less water than specified, has an impact on the severity of the ecological degradation that could be expected. As outlined above, a number of thresholds were identified that indicated increasingly severe consequences in terms of average annual water levels, average annual salinity and the proportion of degraded ecosystem states simulated in the North and South Lagoons. These thresholds were identified for the discrepancy in barrage flow volume in a single year compared to the EWR ('Discrepancy'), the cumulative discrepancy over multiple years, where the EWRs were not met in consecutive years ('Cumulative Discrepancy') and the total barrage flow volume.

Five thresholds were identified that indicated increasingly severe consequences in the cumulative discrepancy in barrage flows compared to the EWRs (Table 4). The three most severe thresholds (i.e. 57,306, 36,580 and 29,288 GL) were not exceeded by any scenario including the Baseline (Table 4, Figure 8a). The other two thresholds for the cumulative discrepancy in barrage flows (of 20,302

and 11,202 GL) were only exceeded by the Baseline scenario, indicating that any of the volumes of additional flows considered under the Basin Plan would be sufficient to prevent the level of degradation associated with those thresholds. Neither the Without Development nor any of the Basin Plan scenarios exceeded the threshold in any year. Exceeding the threshold of 11,202 GL for the cumulative discrepancy in barrage flow volume compared with the EWRs was associated with average annual salinities in the North Lagoon of at least 77.7 g L⁻¹, indicating that estuarine conditions had been lost and that the tolerances of many Coorong taxa were likely to have been exceeded. The same threshold was also associated with the occurrence of an average of more than 28% of degraded ecosystem states, indicating that ecological degradation was occurring over at least 28% of the region. The delivery of additional volumes in the magnitude considered by the Basin Plan should be sufficient to avert that level of impact (although some damage was still likely as a result of failing to meet the EWRs).

Table 4: The percentage of years where each scenario failed to meet the effect of less-water thresholds. For the Cumulative Discrepancy and Discrepancy thresholds, the percentage of years which fell over each threshold is reported, while the percentage of years that fell under the Total Barrage Flow threshold is also presented, in line with the interpretation of 'failing' to meet each threshold. A dash symbol indicates a zero value (i.e. that threshold was not crossed by the scenario in question).

Threshold	Scenario				
	WD	Baseline	2400	2800	3200
<i>Cumulative Discrepancy</i>					
11,202 GL	-	6%	-	-	-
20,302 GL	-	1%	-	-	-
29,288 GL	-	-	-	-	-
36,580 GL	-	-	-	-	-
57,306 GL	-	-	-	-	-
<i>Discrepancy</i>					
5150 GL	-	1%	-	-	-
<i>Total Barrage Flow</i>					
21 GL	-	1%	-	-	-

The threshold for the discrepancy in flow volume compared with the EWRs in a single year (5150 GL) was only exceeded by the Baseline scenario (Table 4, Figure 8b). That threshold was associated with very low water levels in both the North and South Lagoons.

The final threshold, of a total barrage flow in any one year of less than 21 GL in any one year was not reached by the Baseline scenario. Thus, under the Baseline scenario, barrage flows were lower than 21 GL in 1% of years. This threshold is associated with the occurrence of an average of 95% of site-

years in degraded ecosystem states, indicating almost uniform degradation in the Coorong. Additional flows of either at least 2400 GL y^{-1} should be sufficient to avert that occurrence.

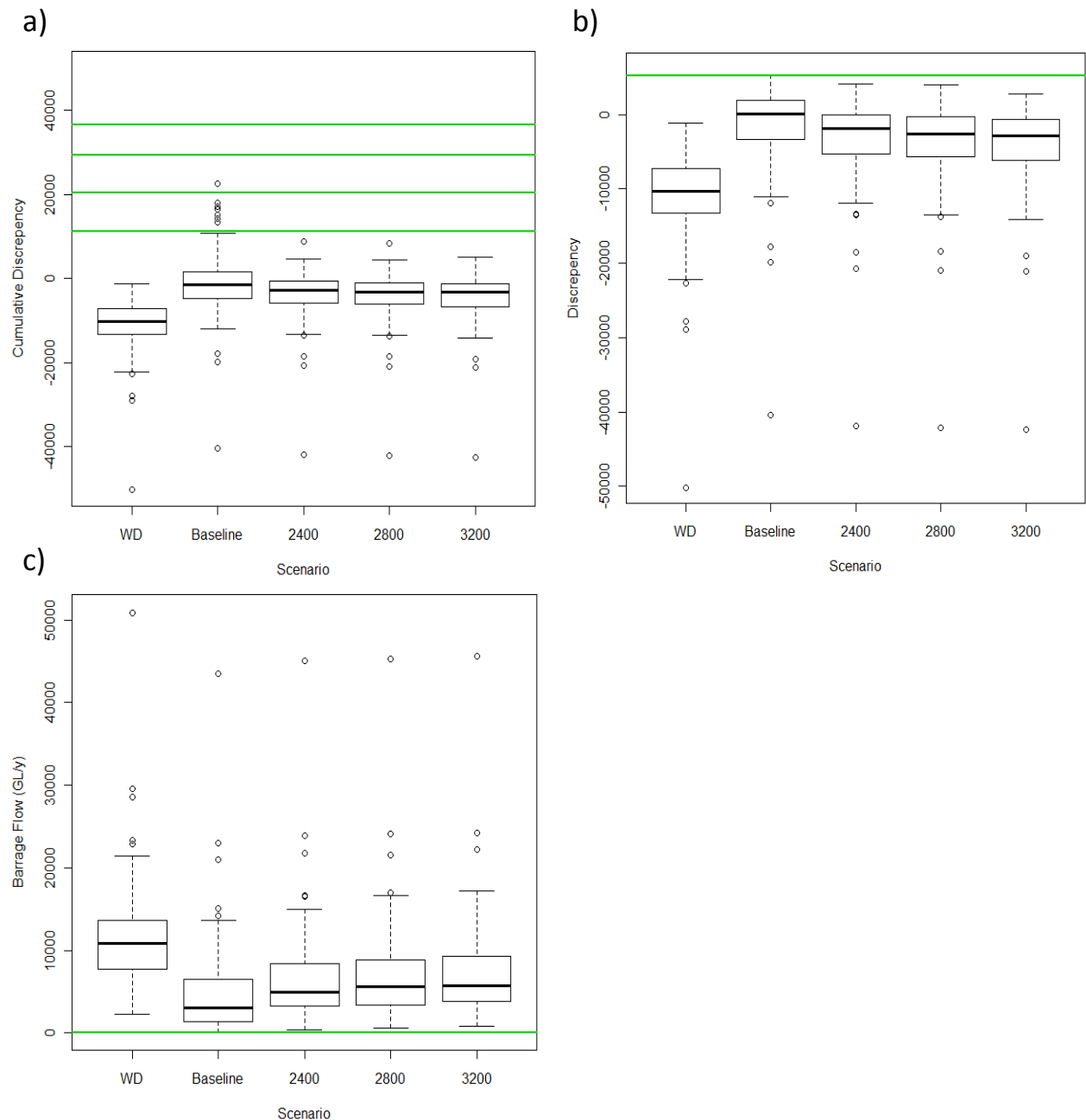


Figure 8: Boxplots showing the comparison between barrage flow, discrepancy and cumulative discrepancy for five scenarios under the 1000EC rule a) Cumulative Discrepancy (GL), b) Discrepancy (GL) and c) Barrage flow (GL). Information on how to read this type of figure is presented in Appendix B.1. Thresholds are shown by the green horizontal lines across each boxplot.

Discussion

This report investigated the effect of three proposed sets of river flows on the hydrodynamics and ecosystem states of the Coorong, based on work undertaken for the Basin Plan (MDBA 2012). The three sets of river flows represented different volumes of additional environmental water to be provided by the Murray-Darling Basin Plan. The volumes considered here were an additional 2400, 2800 and 3200 GL y^{-1} , respectively. These were compared with a scenario representing current river operations as a baseline, and the possible flows likely without any water resources infrastructure or extractions in the Basin.

The biggest difference for Coorong hydrodynamics associated with returning higher volumes of environmental water under the Basin Plan was in the maximum salinity observed in the Coorong. All three flow-delivery scenarios fell below the threshold set for maximum salinity, but increasing the amount of water proportionally increased the margin by which the threshold was not crossed. There were few differences in the average depth, annual range in water level or average annual water levels, but the 2400 scenario showed more extreme outliers (e.g. occasionally very low water levels) than either the 2800 or 3200 scenarios. When considering the cumulative difference of the scenarios compared to the baseline, the biggest difference was observed in the South Lagoon, where there were incremental increases in water levels and decreases in maximum salinities associated with increasing the additional volume of water delivered from 2400 to 3200.

Very few differences were observed in the proportion of site-years assigned to each of the ecosystem states across the three water-delivery scenarios. There was, however, a general trend for fewer site-years in degraded ecosystem states with increasing volumes of additional water, but the improvement was slight under the modelled flow-delivery regime, particularly when compared with the Without Development scenario.

The ability of each of the scenarios to meet the EWRs set by the MDBA and by the South Australian Government was investigated. There was little difference in the number of EWRs that were met under the 2400 and 2800 scenarios; increasing the average additional flow volume delivered between these two scenarios resulted in only one additional EWR being met (see Figure 7). In contrast, a subsequent increase in flow volume of 400 GL y^{-1} between the 2800 and 3200 scenarios meant that an additional 4 EWRs were met. Additional flows also reduced the frequency and severity of failure of the EWRs that were still not met, with fewer and smaller interventions required

to meet each target as the additional flow volume increased from 2400 to 2800, before sufficient water was added to meet each of the EWRs under the 3200 scenario.

The pattern through time of flow delivery will have a large impact on the relative success of any volume of additional water at meeting the specified EWRs. For those EWRs that were not met, there was a general trend for increasing volumes of flow to fail to meet the EWRs on fewer occasions and by smaller volumes of water. The relative in the number EWRs that were met across the 2400, 2800 and 3200 scenarios with incremental increases in flow volumes (i.e. of 400 GL y⁻¹ for each scenario) highlights the importance of flow-delivery timing to meeting the EWRs specified for the Coorong. The overall volume of water provided, however large, will be insufficient to support the ecological condition of the Coorong unless it is provided in an appropriate manner. For the Coorong, this means that there should be few years of very low flows, particularly in sequence. Having higher levels of additional flow coming to the system provides a greater chance that EWRs will be met, as there is likely to be greater flexibility in the method of flow delivery possible, given the constraints in the system. Thus, as the volumes of additional flows were reduced for the Coorong, the risk of failing to provide that water in an appropriate manner increases, resulting in increased risk of ecological damage in the region.

The value of providing additional environmental water even in volumes lower than the EWRs was also apparent when the effects of delivering less water were examined for each scenario. The four undesirable flow thresholds associated with increasingly severe degradation in the Coorong that were crossed by the Baseline scenario (see Table 4) were never crossed by any of the scenarios investigating the effects of additional water that may be delivered under the Basin Plan. This means that the consequences of delivering less water were somewhat lower when additional water of at least 2400 GL y⁻¹ was delivered.

Based on these findings, all three scenarios exploring additional flow volumes to be provided under the Basin Plan were an improvement over Baseline conditions, but none replicated Without Development conditions. Higher volumes of additional water resulted in lower maximum salinities and higher minimum water levels, but there were few differences in the mix of ecosystem states across the three scenarios. Fewer site-years were allocated to degraded ecosystem states with increasing volumes, but the changes were small. There were increases in the number of EWRs that were met with increasing flow volumes, and only the 3200 scenario was sufficient to meet all targets. All Basin Plan scenarios provided sufficient water to avoid the worst consequences of delivering less water than specified by the EWRs.

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Appendix A: EWRs included in this report

This appendix provides a brief summary of the EWRs that have been included within this report.

MDBA EWRs

- Long-term barrage flow average of at least 5,100 GL y⁻¹
- Rolling 3-year average barrage flow greater than 2,000 GL y⁻¹ in 95% of years
- Rolling 3-year average barrage flow greater than 1,000 GL y⁻¹ in 100% of years
- Maintain at least proportion of years with high flows (5,100-10,000 GL y⁻¹) experiences under current arrangements
- Rolling 10-year average barrage flow of greater than 3,200 GL y⁻¹

SA Government EWRs

- Maximum flow over barrages should be the maximum of:
 - o 3150 GL; or
 - o 8000 GL minus flows in the previous year; or
 - o 12 000 GL minus flows in the previous two years (adjusted for the maximum effect of flows two years ago).
- Minimum flow over barrages should be the maximum of:
 - o 650 GL;
 - o 4000 GL minus flows in the previous year; or
 - o 6000 GL minus flows in the previous two years (adjusted for the maximum effect of flows two years ago).
- High flows of 6000 GL y⁻¹ maintained at their current frequency of every 3 years
- High flows of 10 000 GL y⁻¹ maintained at their current frequency of every 7 years

Appendix B: How to read these figures

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.

B.1 Boxplots

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

In a boxplot, the interquartile range is represented by a box (Figure B.1). That is, the limits of the box show the range for which the variable in question falls for 50% of the time. The whiskers on the box show an interval which is 1.5 times the interquartile range, and more extreme values (outliers) are represented by points. Finally, the median is represented by a line through the box at the relevant height. Thresholds are shown by the green horizontal lines across each boxplot. Boxplots are presented that compare each group of scenarios, in line with the research questions (Figure B.1). There is no one order in which the boxes could be presented that would allow all comparisons to be easily made.

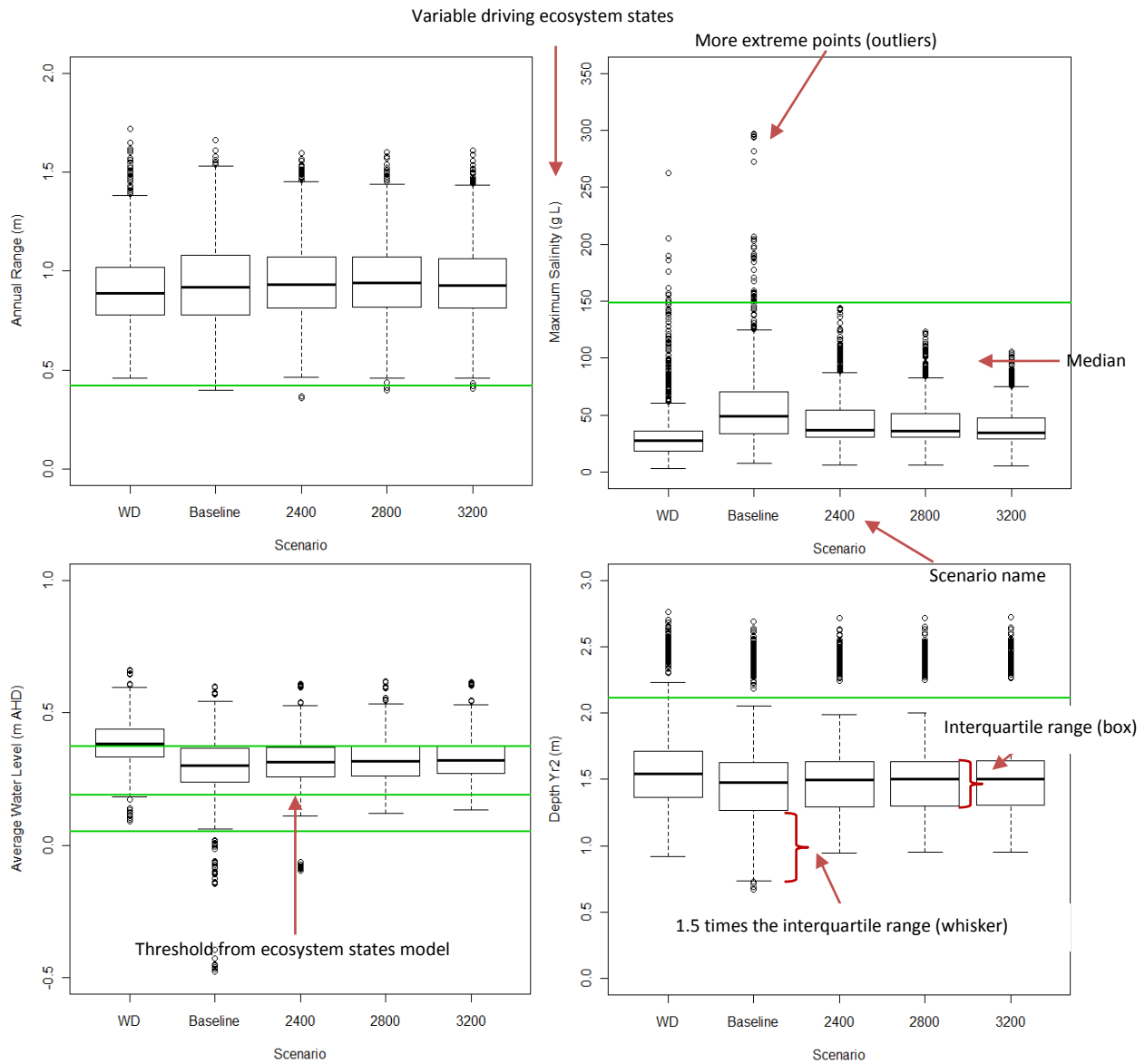


Figure B.1. Example of boxplots, highlighting points to note in red

a) Average water level (m AHD), b) Maximum salinity (g L⁻¹), c) Average water depth from two years previous (m) and d) Annual range in water level (m).

B.2 Deviations from the 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 (Figures B.2). This was divided into two figures, one for the two key variables in the marine (or northern) basin (i.e. annual range and depth from two years previous) (Figure B.2a), and one for two key variables in the hypersaline (or southern) basin model (i.e. water level and salinity) (Figure B.2b).

In these figures, 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 figure for the North Lagoon plots the sum of deviations for annual range and depths without flow for site-years in the North Lagoon (Figure B.2a). Here, an increase in annual ranges and an increase in depth could be considered an improvement, compared with the Baseline. Thus, scenarios where the vector ends in the upper-left quadrant (which is shaded grey) represent an improvement on both variables. Scenarios with vectors ending in the opposite quadrant (the bottom-right) represent relative deterioration relative to both variables. The other two quadrants are an improvement for one variable but not the other.

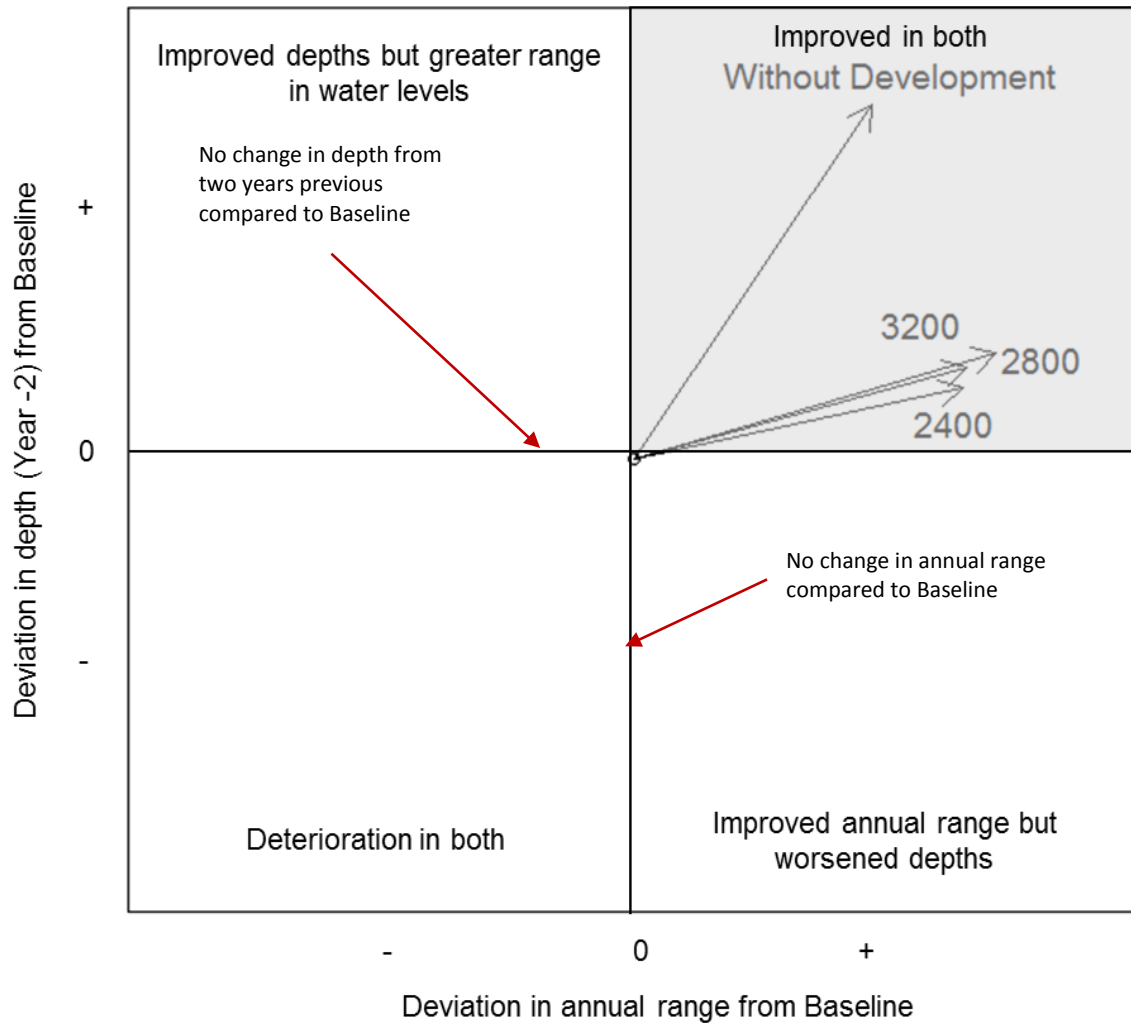


Figure B.2a. Example of comparison of each of the scenarios to the Baseline scenario for key variables in the North Lagoon, highlighting points to note in red

This figure shows a vector for each scenario indicating the magnitude and direction of change from the Baseline scenario with respect to annual ranges and depths (with depths from two years previously). Length of each vector is proportional to the strength of the deviation from the Baseline condition (as shown by the 0,0 origin). Vectors in the top-left quadrant indicate an improvement for both variables (i.e. higher annual ranges and greater depths).

The second figure plots the sum of deviations for salinity and water level in the South Lagoon (Figure B.2b). As for Figure B.2a, scenarios falling on the horizontal and vertical lines indicate no deviation from the Baseline scenario for the variable in question. In this case, a decrease in salinity and an increase in water level constitute an improvement. This corresponds to the bottom-right quadrant. Scenarios falling in the opposite quadrant (i.e. the upper-left) showed deterioration with respect to both variables.

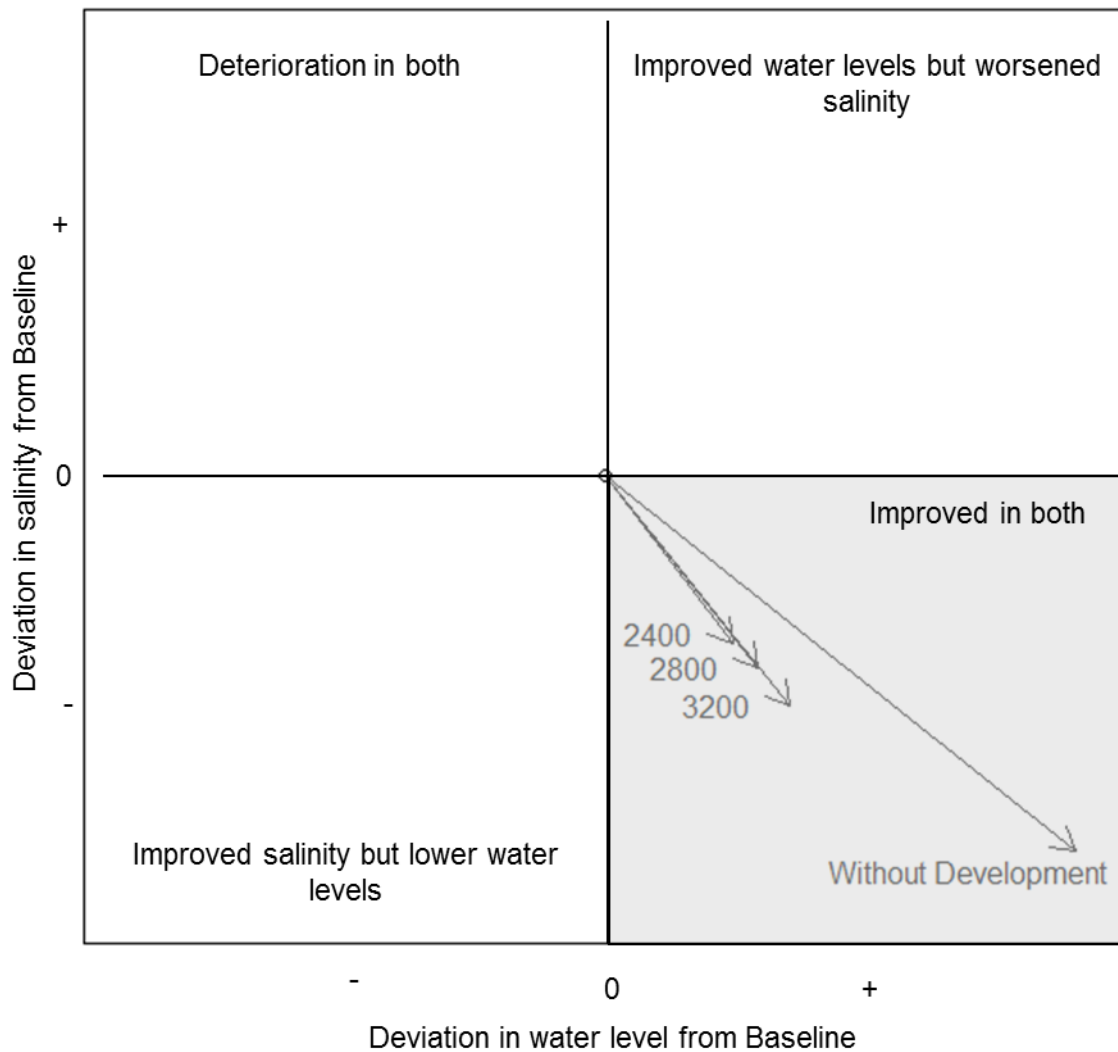


Figure B.2b. Example of comparison of the effect of each of the scenarios relative to Baseline scenario for the South Lagoon

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 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).

B.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 B.3). 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 all 1568 site-years per run that were found in each ecosystem state, across the entirety of the model run (113 years) and 14 sites. The entirety of the model run (113 years and 14 sites) equals 1582 site-years. Proportions were determined on 1568 site-years however, because the alternate model calculates depth from the previous year and cannot determine ecosystem states for the first year of the model run. 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).

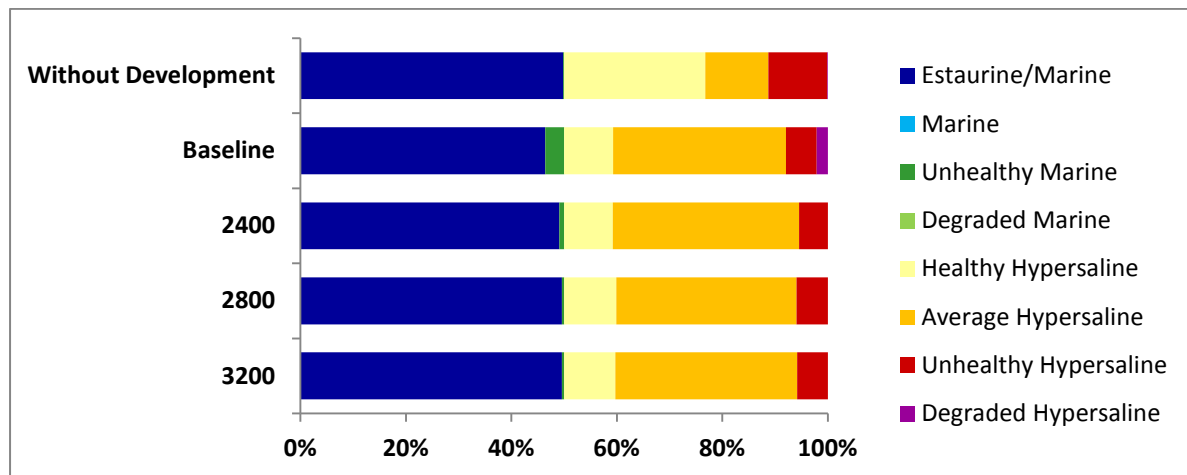


Figure B.3. Example of comparing the proportion of site-years in each ecosystem state for the scenarios

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

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

Figure B.4 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 B.3. The display of multiple scenarios along the x-axis allows the relative changes associated with different scenarios to be compared.

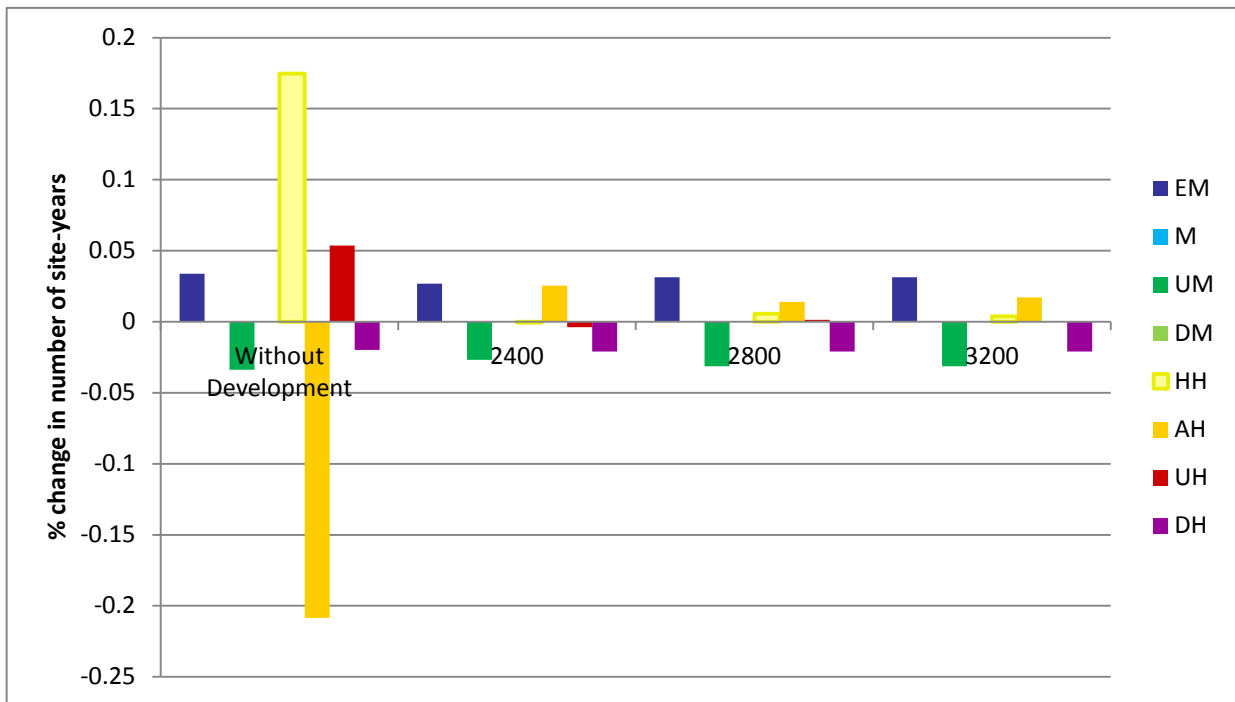
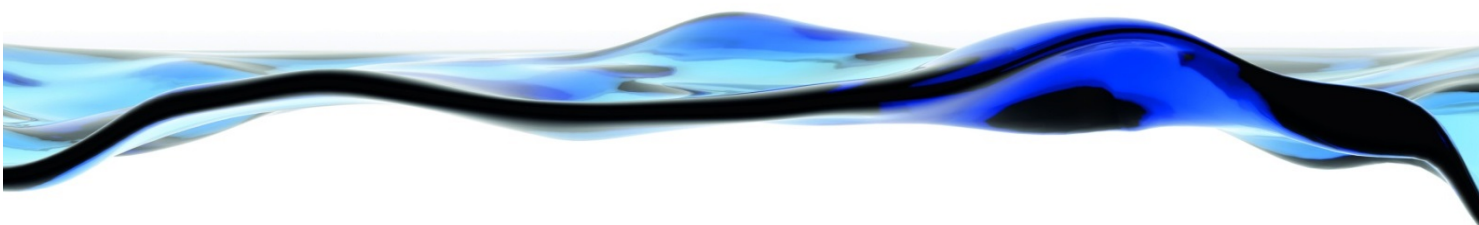


Figure B.4. Example of the deviations in the proportion of site-years in each ecosystem state compared to the Baseline scenario.

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



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