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The Application of Hydrodynamic Modelling to Assess the Impact of Supplementary Flow Releases on Coorong Water Levels and Salinities

Model calibration, validation and application

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Executive summary

It has long been known that the salinity regime in the Coorong responds to the volume of water discharged through the barrages. In particular, high volumes of water resulted in relatively low salinities along the 120-km length of the Coorong, whereas low flows resulted in elevated salinities. A hydrodynamic model was developed in 2006 to simulate how the salinity and water levels in the Coorong respond to barrage flows as well as to the other system drivers of rainfall, evaporation rate, wind, sea level variations and flows from the Upper Southeast drainage area (USED). Water level and salinity regimes in the North and South Lagoons of the Coorong have been identified as key determinants of their ecological function.

The hydrodynamic model was originally applied strategically to help gain an understanding of how the Coorong might respond to future conditions of climate change (reduced barrage flows) and to possible sea level rise, but it have also been applied to investigate the efficacy of a number of management options for the Coorong that were aimed at mitigating the very high salinities experienced by the Coorong during the recent drought. These options included dredging the Mouth channel, pumping water from the South Lagoon into the sea, and modifying the drainage works in the Upper Southeast drainage area. More recently, the hydrodynamic model has been used to inform the development of the Murray-Darling Basin Plan by assessing the likely benefits to the Coorong of increased flows in the river system. The Commonwealth Environmental Water Office (CEWO) is charged with buying water from irrigators and releasing it for environmental purposes to the River Murray. The addition of environmental flows to the River Murray has potential benefit to the Coorong also.

Since its inception in 2006, the hydrodynamic model has gone a number of improvements. Its most recent calibration and validation were undertaken in 2009 and did not include measurements obtained in the Coorong in the latter half of the drought which extended from 2002-2010. It is imperative that the model is ‘as good as we can make it’ and this requires it to be recalibrated including recent model modifications and all the more recent measurements for model comparisons. The description of the modifications, its recalibration, and an assessment of model reliability comprise section 2 of this report. Section 3 addresses the issue of how supplemental water provided by the CEWO might be used to optimise the response of the Coorong particularly with regards to preventing the development of excessively high salt concentrations.This section investigates how the barrage flow volume, and the timing and volume of the supplementary flows would interact with one another to determine the salinity and water level regimes in the Coorong. Section 4 of the report considers the response of the Coorong to three possible flow sequences over the coming year specified by the CEWO with and without supplementary flows. These flows are three Annual Exceedence Probability flows (AEP flows) whose likelihood is determined in part by the present water level in reservoirs and by meteorological projections.

Section 2

This section describes the latest model modifications, the revision of forcing data including recent measurements, and an analysis of model reliability. A significant model modification is the alteration of the salinity cell prescription. In the previous model version, salinity cell sizes varied from 5-10 km in length and were based on the locations of historical sampling sites along the Coorong. The updated model utilises 1-km grid cells which coincide with those used in the solution of the flow equations. The model’s representation of the evaporation rate now includes a functional dependence on salinity. At a salinity of 100 g/L the evaporation rate is now reduced by 6% over that at zero salinity, a reduction that becomes progressively larger at higher salinity. In the previous model version, the model assumed that barrage flow rates were proportional to the number of gate openings even though it is well known that the 5 barrages, namely Goolwa, Mundoo, Boundary Creek, Ewe Island, and Tauwitchere, have different gate designs each allowing a different flow rate when open. The MDBA has undertaken an analysis of barrage flows that considers the difference in gate designs and the relative water levels in Lake Alexandrina and in the Coorong. The resulting updated historical barrage flows are utilised in the model recalibration.

The forcing data (wind stress, barrage flows, sea levels, USED flows, evaporation, precipitation) have been extended to the end of August 2012. Wind stress calculations were originally derived from wind speeds and directions measured at Meningie post office. More suitable measurements are now available and used from an anemometer at Pelican Point. Similarly, evaporation and precipitation rates used in the model were originally based on measurements on Hindmarsh Island. These have been replaced in the model by hindcast rates obtained from the SILO database for a site near Parnka Point. The advantages are that they are from a location closer to the centre of the Coorong and that they extend both further back in time and up to the present day.

Modification of the historical barrage flows required revision of the algorithm which describes how the effective Mouth depth evolves with time due to barrage flow scouring and to infilling during low flow times. Model recalibration also involved determining revised values for the depth and width of the channel connecting the North and South Lagoons and the long-lagoon mixing coefficient for salt. With the exception of the long-lagoon mixing coefficient, the recalibrated model parameters are similar to those determined previously. However, the 50% increase in the mixing coefficient arises as a consequence of the change in the cell sizes used in the salinity model.

Model validation is undertaken by comparing salinity measurements obtained since 1963 with simulated salinity. Measured and modelled water levels in the South Lagoon are compared from 1992 to the present. The model is well able to replicate the observed seasonal cycles of salinity and the response of salinity to interannual variation of barrage flows over the observation period. For the North Lagoon, the average error between measured and modelled salinity (the bias) is 3.5 g/L and the standard deviation of the salinity difference is 10.0 g/L. For the South Lagoon the bias and the standard deviation are 0.9 g/L and 12.7 g/L respectively. Both lagoons have a positive bias for the modelled results; that is, modelled salinity is higher on average than measured salinity. However, the degree of agreement between modelled and measured salinity varies somewhat across the salinity range. South Lagoon water levels are well simulated by the model.

Section 3

This section investigates the water levels and salinity outcomes in the Coorong depend on the barrage flow volume, the supplementary flow volume and the timing of the supplementary flows. Simulations are obtained for all combinations of three barrage flow volumes (260, 3180, and 7590 GL/year), for two supplementary flow volumes (750 and 1500 GL/year), and for 12 times of peak supplementary flows. The flow shapes for the barrage flows were held fixed from year to year and based on the MDBA-modelled long-term flow record for barrage flows. The supplementary flows were delivered over a two-month period whose peak timing was allowed to vary through all the months of the year.

Depending on the barrage flow volumes and on the timing of their release, supplementary flows can have a profound impact on the water levels and salinity in the Coorong. Impacts on maximum water level in the two lagoons are largest when these flows are released on top of the barrage flows in winter-spring and when sea levels are seasonally highest. The impact is most significant for the smallest annual barrage flow volumes. When barrage flows are small the Mouth channel tends to infill and become constricted so that any supplementary flows tend~~s~~ to push up water levels more than when the channel is more open. Although impacts of supplementary flows on minimum water levels are fairly minor, supplementary flows released in summer tend to cause an increase in the minimum water level in the South Lagoon at this time of the year.

The supplementary releases have a large impact on the salinity in both lagoons only if they occur when barrage flows are close to zero; that is, during summer and autumn for the medium and large barrage flow volume cases. For the median to large barrage flow volume cases, the winter-spring barrage flows freshen the North Lagoon anyway so any supplementary flow release during this period has a small effect on salinity in the two lagoons. Conversely, supplementary flow releases during months when the barrages are not flowing maintains the North Lagoon in a relatively fresh condition for a greater part of the year with the consequence of significantly reduced maximum salinity in both lagoons. For the smallest annual barrage flow volume, the supplementary flow also has a significant benefit in reducing salinity during the barrage flow time winter-spring. The relative benefits of releasing a supplementary flow volume of 1500 GL/year versus 750 GL/year are modest in terms of reducing salinity.

Section 4

For this analysis, the salinity and water level responses of the Coorong are presented for three possible barrage flow time series for the period October 2012 to June 2013. These responses are compared to the responses obtained using the same base barrage flows supplemented by environmental water provisions. The Murray-Darling Basin Authority (MDBA) models flow projections within the basin throughout the coming year based on the levels of water storage and climate projections at the beginning of the year. The three base flow regimes modelled are the 25, 50, and 90 percentile Annual Exceedence Probability (AEP) flow projections. Under instruction from the CEWO, the MDBA also developed a further three flow sequences which represented the base flow supplemented by an additional environmental flow provision.

The base flows considered which range from 5844 GL/year (AEP25) to 3174 GL/year (AEP90) are mid range flows through the barrages by historical standards. The supplementary flows which mainly enhance barrage flows through the summer low-flow time add an extra 330 to 580 GL to the base flow volumes over a year. The supplementary flows serve to increase water levels in both lagoons above those for the base flows, but the maximum increase is only a few centimetres occurring in summer. The supplementary flows have a more pronounced impact on lagoon salinity with maximum salinity reduced by ~10 g/L in the North Lagoon and ~5g/L in the South Lagoon. All six flow scenarios (3 base and 3 base + supplementary flows) would be expected to prevent the salinity in the South Lagoon from exceeding 100 g/L during the coming year and for salinity in the North Lagoon to remain below 60 g/L. Even considering the likely variability due to variation in meteorological and sea level conditions, it is almost certain that the modelled salinity and levels would not exceed 60 and 100 g/L in the two lagoons.

1 Introduction

It has long been known that the salinity regime in the Coorong responds to the volume of water discharged through the barrages. In particular, high volumes of water result in relatively lower salinities along the 120-km length of the Coorong, whereas low flows resulted in elevated salinities. During the recent drought (2001-2010) in the Murray-Darling Basin, barrage flows were very low allowing salinity in the South Lagoon to exceed 200 g/L in summer. These salinities would have been even higher if a dredging program had not been implemented in the Mouth channel in late 2002. Sea water has a salinity of about 35 g/L and salinity above 100 g/L is toxic to most aquatic organisms even to those that are salt tolerant.

A 1-dimensional hydrodynamic model was developed in 2006 and described by Webster (2007) to simulate how the salinity and water levels in the Coorong respond to the system drivers of barrage flows, rainfall, evaporation rate, wind, sea level variations and flows from the Upper Southeast drainage area (USED). The model was originally developed to investigate the physical response of the Coorong to a series of scenarios including hypothetical decreases in barrage flows as a consequence of climate change, possible changes in mean sea level and a series of management options including Mouth channel dredging and increased flows from the USED. A second Ecological Response Model (ERM), which associated ecological states in the Coorong with salinity and water levels, enabled the assessment of how the ecological condition might change for the different scenarios (Lester et al., 2009). Since then, the model has been applied on a number of occasions both with and without the ERM to examine in detail a series of management options focussed on relieving conditions of high salinity and altered water level in the Coorong that occurred during the recent drought. These options have included the assessment of flow requirements (timing and volume) to achieve salinity targets, pumping the South Lagoon, the effectiveness of dredging the Mouth and Parnka Channel, and the benefits of increased USED flows.

Recently, a project was completed for SA DENWR that aimed to assess whether adverse salinity conditions were likely to occur over the coming year for each of two barrage flow projections developed by the MDBA representing the 50 and 90 percentile Annual Exceedence Probability (AEP) flows. Also simulated were these flows with an environmental flow supplement added during the low-flow time of summer. One aim of the present project for the Commonwealth Environmental Water Office (CEWO) is to extend this work particularly by further investigating the benefits of varying the timing and volume of supplementary flows. Previous modelling has shown that larger flows generally lead to reduced salinity, but the benefit derived from the delivery of a given flow volume also depends on when it is delivered during the year. This investigation focuses on the general case in order to underpin the development of understanding the benefits of such flows. Also included is an analysis of the likely impact of projected flows for the coming year with and without environmental supplements. A scenario approach is adopted to achieve both these investigations and results summarised for salinity and water levels in the North and South Lagoons.

The model was last calibrated and validated at the beginning of 2009. Since then, more measurements of salinity and water level have been obtained in the Coorong. These measurements have run across the time of transition between when barrage flows were virtually zero during the drought to after late 2010 when flows became larger than average. Once the flows increased, Mouth dredging stopped and the Mouth channel dynamics became once again determined by the flow through it. Since the hydrodynamic model will be used to predict the salinity and water level response to a series of flow scenarios for the coming year and beyond, it is essential that its reliability is checked against more recent measurements obtained since the end of the recent drought.

Since its inception the model and the data sets it relies upon for forcing have been revised in important ways. Significant changes to the model include the way that it has been discretised for solving the salinity dynamics and the inclusion of salinity dependence on the evaporation rate. In the absence of a more sophisticated analysis, the original model split the total barrage flow estimated by the MDBA between the different barrages based on the numbers of gates that were open in each. However, in reality the barrages have different gate designs so that the assumption that the flow split is proportional to gate opening is certainly erroneous. Revised barrage flow splits are now available that enable a more accurate representation of the flows through each one. Other changes to the forcing time series include revisions to the evaporation and wind stress time series used to drive the model.

The modifications to the model and to its forcing time series have necessitated the recalibration of the hydrodynamic model. As part of the recalibration process the issue of model validation is revisited including consideration of the Coorong response over the last few years since the end of the drought. The processes of recalibration and revalidation of the model are essential since the model is being used more and more in an operational sense by the CEWO and others where confidence in the reliability of the simulations is paramount.

In the following report, the modifications to the model and the forcing time series are described first followed by model recalibration and validation. This section of the report also addresses the issue of the reliability of model simulation which is essential knowledge when evaluating predictions. The second part of the report considers the relative benefits of the addition of environmental water to barrage flows considering volume and timing of the water delivery. This is undertaken in a strategic sense to underpin the understanding of how barrage flows and environmental flows interact generally. The final section of the report analyses CEWO-specified AEP flows with and without supplemental flows allowing an assessment of the possible benefits of supplemental flows over the coming year.

2 Model development, calibration, and validation

2.1 Model revisions

2.1.1 SALINITY MODEL DISCRETISATION

The hydrodynamic model has two main modules. The flow module solves equations representing the momentum balance and the conservation of water along the Coo~~o~~rong. This component describes how the water moves in response to water level variations and the stress of the wind on the water surface as well as the total water inputs and outputs including evaporation, precipitation, USED flows, and barrage flows. This module is represented on a model grid that extends 102 km from the Murray Mouth to past Salt Creek at the south end of the South Lagoon (

Figure 1. The Coorong, Lower Lakes and Murray Mouth showing the extent of the hydrodynamic model used in the study and the location of water level and meteorological measurements. The equations solved are represented in model 'cells' at 1-km intervals along this length.

The currents and water levels simulated by the base module in the hydrodynamic model were used to drive the second module representing the salinity dynamics where salinity is treated as passive tracer, i.e., it does not affect the momentum balance. The salinity module solved equations for the conservation of the mass of salt in a series of cells along the model domain. Salt is carried between cells by the currents but exchange is also allowed to occur by diffusive mixing. The latter process is intended to represent turbulent mixing and other exchange processes that are not resolved in the model. In the original model, salinity was modelled in 14 cells which extended across groups of between 5 and 10 cells used in the base hydrodynamic module. The revised model uses salinity cells that are 1-km long and that coincide with the cells used in the flow module. The revised representation simplifies the model compared to the original, but it also results in slightly longer calculation times due to an increase in the cell numbers.

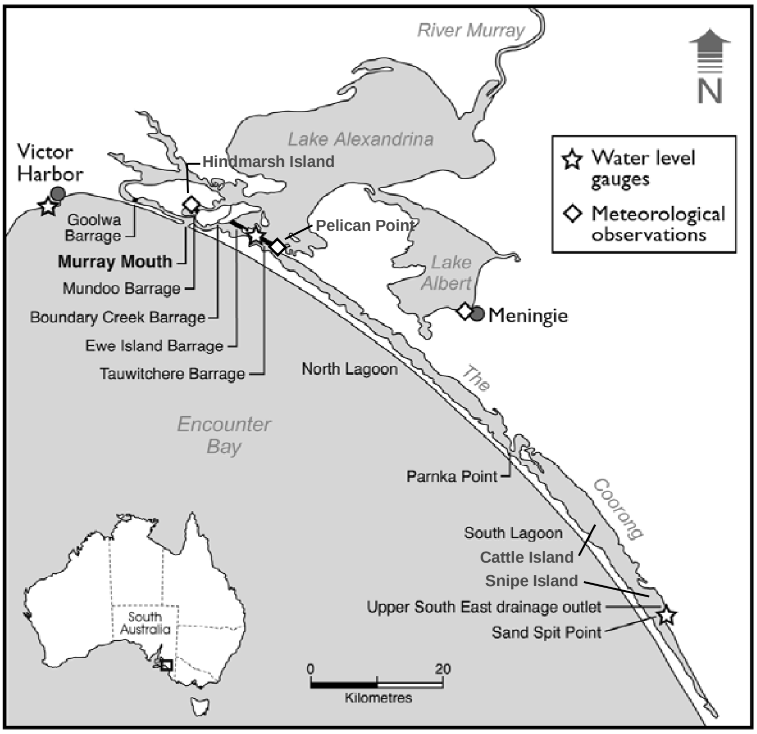

Figure 1. The Coorong, Lower Lakes and Murray Mouth showing the extent of the hydrodynamic model used in the study and the location of water level and meteorological measurements.

2.1.2 EVAPORATION RATE MODIFIED BY SALINITY

Salinity in the South Lagoon particularly can reach levels that are so high that a significant impact on evaporation rate can be expected. In the original model, evaporation rate was assumed to be a fixed multiplier (evaporation factor) of the evaporation rate measured in an evaporation pan on Mundoo Island. The evaporation factor was one of several factors determined from the calibration of the model measured salinity and water level. Being fixed the evaporation factor (= 1.0) did not account for variations in salinity in time or along the length of the Coorong.

In the revised model, the evaporation rate is not determined through model calibration as in the previous version of the model. Rather, a separate evaporation model is developed that is used to develop an evaporation factor that depends explicitly on salinity. Evaporation rate (E) is often represented using a Dalton relationship

$$E = f(U)(e_w - e_a) \qquad (1)$$

in which $f(U)$ is a function of wind speed U, e_a is the vapour pressure in the air at the height of the wind measurement, and e_w is the saturated vapour pressure at the temperature of the water surface (McJannet et al. 2012). Salinity affects evaporation rate by depressing e_w. Suppose, the ratio of the vapour pressure at salinity S to that at zero salinity is β. Measurements of β at salinities typical of hypersaline conditions in the Coorong have been presented by Arons and Kientzler (1954) and Salhotra et al. (1985) (Figure 2). A polynomial fit to these data represents the relationship between S and β as:

$$\beta = 0.9989 - 4.61\times10^{-4} S - 6.51\times10^{-6} S^2 \qquad (2)$$

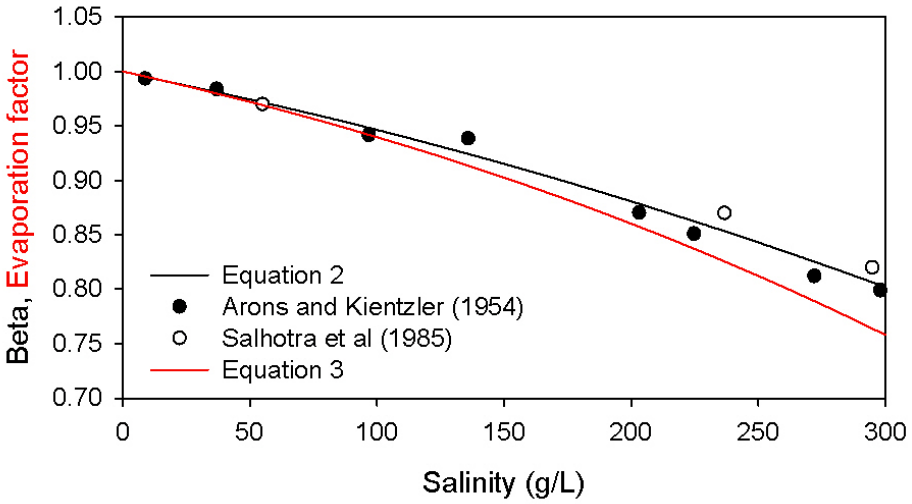

Figure 2.. The ratio of saturated vapour pressure at a prescribed salinity to pressure at zero salinity (β). Also shown is the modelled dependence of Coorong evaporation rate on salinity (compared to zero salinity).

The impact on evaporation rates of a reduced β must also consider its effect on water temperature. In effect, the process of evaporation tends to cool the water column. Consequently, by reducing the evaporation rate, salinity also tends to result in a slightly higher water temperature which in turn enhances the surface vapour pressure. This feedback mechanism mediates the impact of salinity on evaporation rate, but it also means that the estimation of evaporation rate must consider the impact on e_w of a slightly higher water temperature.

As does Salhotra et al. (1985), the evaluation of evaporation rate uses a modification of Penman's combination equation which solves for the energy budget of the water column including solar radiation, longwave thermal emission, cooling by evaporation and sensible heat exchange with the atmosphere (de Bruin, 1982). Data utilised for the application of this approach included measured wind speed, air temperature, relative humidity, and cloud cover measured at Hindmarsh Island as well as downwelling radiation from the SILO database from the same period. The validity of the energy budget approach is demonstrated by the comparison of measured and modelled water temperatures between January 2006 and December 2007 at Parnka Point and at Sand Spit Point (see Figure 3).

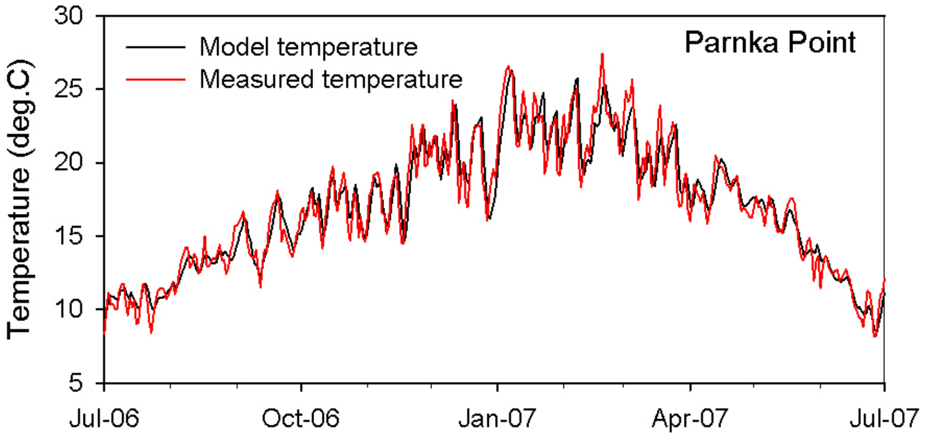

Figure 3. Measured time series of water temperature at Parnka Point compared to water temperature modelled using the energy budget approach.

Using the energy budget approach with forcing data from 2006 and 2007, the evaporation rate can be estimated as a function of salinity. Although a water depth of 1.5 m was chosen for these calculations as being representative of water depths in the main basins of the Coorong, varying the water depth between 1.0 and 2.0 m made approximately 0.5% change in these rates. Figure 2 (red line) shows the dependence of evaporation rate on salinity (compared to zero salinity). This dependence is well represented by the equation:

$$R = 1.0 - 5.01 \times 10^{-4} S - 1.41 \times 10^{-6} S^2 \qquad (3)$$

Over the period, January 2006 to September 2008, modelled evaporation averaged 4.18 mm/day versus 4.11 mm/day estimated from the SILO database for both Hindmarsh Island and Parnka Point. Thus, the ratio of modelled to SILO evaporation rates is 1.02 in both cases so that an estimated evaporation rate is represented as:

$E = 1.02 \times R \times \text{SILO evaporation rate}$. As part of model calibration for the other model parameters (see section 3.2), the factor 1.02 in this evaporation expression was tested by determining the sets of model parameters that provided the best model fits for a range of factors between 0.96 and 1.08. The optimal value of this factor was 1.00 so that the evaporation rate in the revised model is now assumed to be:

$$E = R \times \text{SILO evaporation rate} \qquad (4)$$

This factor is only 2% lower than the 1.02 obtained with the water temperature model. This degree of agreement is considered to be an independent confirmation of the validity of Eq. 4 for estimating the Coorong evaporation rate.

2.2 Forcing data revisions

2.2.1 BARRAGE FLOWS

The barrage flows used in the original model were provided from the MDBA as total monthly flows through all the barrages. The flows through the individual barrages were calculated from the number of gates that were open on each day. The problem with this approach is that there is an inherent assumption that the flow through each gate for all barrages is the same. However, the barrage gates are all of different designs so that the flow through each type will differ even for the same head difference between Lake Alexandrina and the Coorong. Further, for the Goolwa barrage, an open gate may mean that one or two of the stop logs has been removed which will cause further ambiguity for the flow through the Goolwa gates. A second difficulty with this approach is that the daily flow is calculated from the monthly flow volume based on the number of gates open on each day compared to the total number of gate-open days for the month. No account was taken of how water level fluctuations in the Coorong might mediate the daily flows. Thus, it happened on occasion that significant flows through the barrages were calculated even when the water level in the Coorong was as high as the water level in Lake Alexandrina on the other side of the barrage. This situation is physically impossible.

The gate opening information was available for 1982 to 2006 and used to specify the daily flow through each barrage as just described. These were the flows that were used in the original calibration, but the model has been applied many times for scenarios where the flow split is not available. Examples are the scenarios which investigated the effects of climate change on the Coorong salinity and water level response (Lester et al. 2009). These scenarios used barrage flow time series that ran between 1891 and 2007. Other scenarios used hypothetical flow volumes to investigate the consequences of barrage flow volumes in a more strategic fashion (Webster et al. 2009). Where barrage flow splits were not available these were specified as the calculated average split for 1982 to 2007. As a proportion of total barrage flow, these averages were 19% through Ewe Island barrage and 58% through Tauwitchere barrage. The flows through Mundoo and Boundary Creek barrages were small (< 1% combined) and ignored.

In June 2012, the MDBA provided time series of daily barrage flows through each of the 5 barrages for the period January 1985 to April 2012. These flows considered the gate design of the individual barrages, the water levels on either side of the barrages, and the total flow through the barrages. They are considered to represent a significant improvement in the accuracy of these flows and so form the basic barrage flow time series to be used in ongoing applications of the revised hydrodynamic model. Average flows through the barrages between 1985 and 2012 are split as Goolwa (35%), Mundoo (6%), Boundary Creek (1%), Ewe Island (15%), and Tauwitchere (43%). In ongoing hydrodynamic model applications, the Boundary Creek flow is added to the Ewe Island flow and the Mundoo discharge is represented explicitly in the revised model in contrast to its neglect in the original model.

Figure 4 compares the total barrage discharges for model applications pre and post June 2012 for a two-year period as an example. It is apparent that the discharges are comparable in terms of their total volume when averaged over months say, but the discharges used by the model for applications undertaken prior to June 2012 showed a blocky appearance with less variation from day to day. Increases in barrage flows tend to cause water levels to be pushed up along the Coorong due to flow constriction in the Mouth channel and levels fall when barrage flows recede. This variation in water level drives water back and forth between the North and South Lagoon with the consequence that salt exchange is enhanced. Also, it should be remembered that the discharges utilised by the model through the barrages east of the Mouth channel represent a smaller proportion of the total discharge in post June 2012 applications (65%) than they did previously (77%).

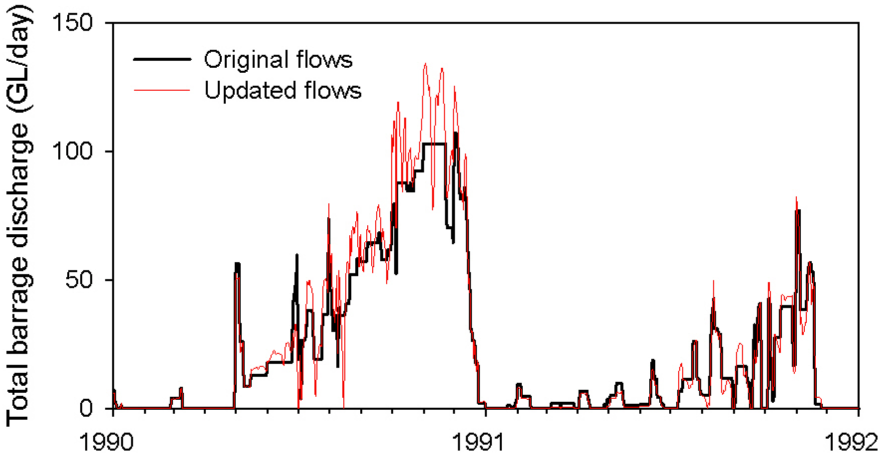

Figure 4. Total barrage discharge used in the original model applications and those assumed for post June 2012 applications.

It has been apparent that for very large barrage flows, the model simulates the water level in the Coorong to reach and exceed 1 m. In reality, such a water level would exceed the water level in Lake Alexandrina and the flow into the Coorong would cease. To prevent this possibility, a maximum barrage flow of 650 m^3 /s (~56 GL/day) was specified to prevent the occurrence of what are clearly unrealistic levels. Between 1963 and 2012, this discharge limit was only reached in 8 years for periods longer than several days (Figure 5). In physical terms, it might be supposed that when actual Coorong water levels were driven up by high barrage discharges, the effective width of the Mouth channel would increase substantially letting out a higher volume of water.

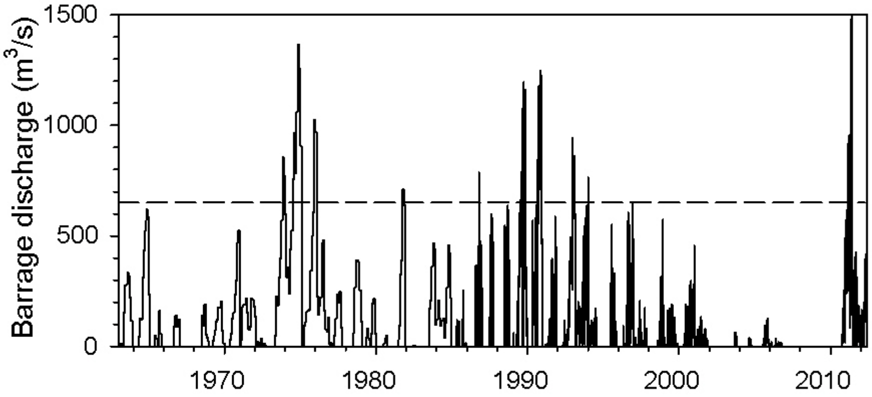

Figure 5. Total discharges through the barrages on the eastern side of the Mouth channel (excluding Goolwa flows). The model's 650 m^3/s upper limit for barrage discharge is indicated.

2.2.2 WIND STRESS

Wind stresses used in the original model application were calculated from measurements of wind speed and direction obtained generally twice a day (9am and 3pm) at the Meningie post office. The model used hourly wind stresses along both lagoons which required the measured time series to be interpolated. Calibration of the wind stresses involved the application of a correction factor to the hourly wind stresses derived from the Meningie measurements in order that the spectra of modelled water level variations matched those measured at Tauwitchere in the North Lagoon and at Sand Spit Point in the South Lagoon (Webster 2007). The time series of wind stresses from Meningie was developed from the measurements up to mid-2008. In order to extend wind stresses to the present time for more recent model application, measurements of wind speed and direction were obtained from a recording anemometer at Pelican Point at the eastern end of the Tauwitchere barrage. These measurements are available at regular sub-hourly time intervals and are much easier to analyse for hourly values of wind stress than those from Meningie. The wind stress calibration factor for the Pelican Point stresses was obtained by matching the wind stress variance calculated over the period January 2007 to July 2008 which is the period of overlap between measurements from the two sites.

2.2.3 EVAPORATION AND PRECIPITATION

The original model used measured precipitation and pan evaporation from a site on Hindmarsh Island near Mundoo barrage up to the end of 2003. Thereafter, hindcast daily precipitation and evaporation rates were used from the nearest grid point in the SILO database. Comparison between measured and SILO evaporation rates between 1987 and 2003 showed these to be less than 1% different from one another, but SILO precipitation rate was about 5% larger than the measured rate. In the revised model, evaporation and precipitation are both taken from the SILO database from a grid point near Parnka Point which is much closer to the centre of the Coorong. For these data, the hindcast evaporation rate was approximately 1% lower than the measured Hindmarsh evaporation rate, whereas the precipitation rate at Parnka Point for SILO is 20% higher than that measured on Hindmarsh Island for 1987 to 2003.

2.2.4 UPPER SOUTHEAST DISCHARGE AND FLOW SALINITY

Measurements of discharge and flow salinity for the USED discharge through Salt Creek are only available post-2001. In the original model, the daily USED discharge pre 2001 was taken to be the average of measured flows on each day of the year between 2001 and 2008 and the flow salinity was set to ~~be~~ 16.1 g

L^{-1} which was calculated to be the flow-weighted average through this time. In the revised model, discharges prior to 2001 were also set as the daily averages for 2001-2008 as before, but flow salinity was specified as the daily averages for 2001-2008 instead of being a constant (Figure 6). Discharge and salinity measurements are available up to the present time and these are used for the model where available. There have been developments to the drainage system in the USED since 2008 which precluded the use of measurements after this time to infer historical discharges and flow salinity.

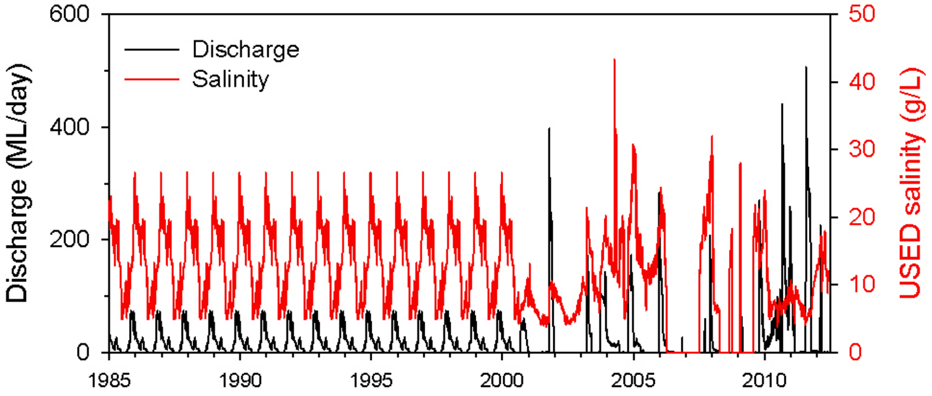

Figure 6. Salt Creek discharge and flow salinity as used in the revised model.

2.2.5 SEA LEVEL MEASUREMENTS

Sea level variations are an important driver of the Coorong dynamics. For the original model, sea level was specified as measured water level at Victor Harbor with a 0.137 m offset factor to account for what appears to be difference in datum between water levels measured within the Coorong and at Victor Harbor. Gaps in the measurement record of several days or less were filled with predicted tides superimposed on a linear interpolation of the daily averaged water level on either side of the gap.

Two large gaps occur in the level measurements for Victor Harbor which needed to be filled if the model is to be applied up to the time of the last salinity profile on 18 April 2012. The first gap extended for 100 days starting in mid-September 2011 and the second started at the beginning of April 2012 and extended for the whole month. The tidal record from Portland in Victoria approximately 400 km to the southeast of the Murray Mouth was used as a basis for filling both these gaps. Analysis of the sub-tidal variations in water level at Portland showed these to be well correlated with those at Victor Harbor although the latter were on average 32% larger than the former and there was also a difference in their mean levels. A surrogate time series of water levels in Encounter Bay for filling the gaps was constructed by adding tidal water level predictions for Victor Harbor to the sub-tidal record from Portland after correcting the Portland record for the difference in the amplitude of the fluctuations at the two sites and adjusting for the difference in average levels. Gaps in the water level records from Tauwitchere and from Sand Spit Point were not filled as these were used for calibration purposes and were not essential for driving the model.

2.3 Model calibration

2.3.1 MOUTH BED ELEVATION

The degree of opening of the Mouth channel governs how oceanic water level variations ranging from tidal to seasonal periods penetrate into the Coorong and cause currents and water level variations along the system. The openness of the Mouth channel changes continuously. Significant barrage flows scour the channel, but when these flows are small, coastal sediment transport processes cause the channel to infill and become more constricted. In view of its importance to the Coorong dynamics, the Mouth openness needs to be simulated for hydrodynamic model applications. The Mouth channel is modelled as a channel of fixed width and length, but whose bed rises and falls in response to scouring or infilling.

In the original model and in the revised model, the elevation of the bed of the Mouth channel ~~are~~ is determined in the same way. In effect, the elevation of the bed in each week is adjusted up or down so that the time series of measured and modelled water levels at Tauwitchere 13 km from the Mouth best match one another at tidal periods (Webster, 2007). The technique ensures that the Mouth openness optimises the observed transmission of the tidal signal into the Coorong from the sea. The time series of 'measured' Mouth bed elevations calculated using this technique is shown in Figure 7.

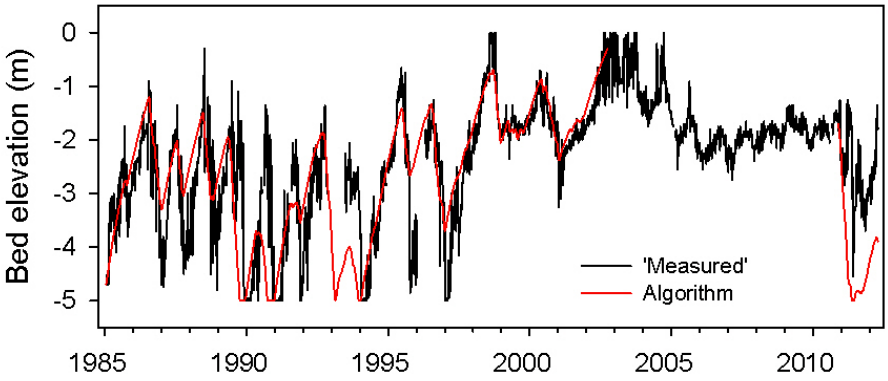

Figure 7. Time series of 'measured' and modelled Mouth bed elevations calculated using Equations 5 to 7.

As in the original model a simple model of Mouth depth versus outflow represents the time rate of change of Mouth elevation as:

$$\frac{dZ_M}{dt} = R_{\text{infill}} - R_{\text{scour}} \qquad (5)$$

where R_{infill} and R_{scour} are the rates of infilling and scouring. With changes in the barrage discharges for the revised model, the equations used to represent R_{infill} and R_{scour} also need to be modified. As previously, these are estimated using a least squares analysis and are found to be:

$$R_{\text{infill}} = 0.0027 \times (1 - 0.6Z_M) \text{ m/day}, \qquad (6)$$

and

$$R_{\text{scour}} = 0.021 |U_M| \text{ m/day when } U_M < 0, \qquad (7)$$

$$R_{\text{scour}} = 0 \text{ when } U_M \geq 0.$$

Here U_M is daily averaged flow velocity into the Coorong through the Mouth channel (in m/s) calculated as the net inflow from the barrages, USED inflow, precipitation less evaporative losses divided by the Mouth cross-sectional area. The previous version of the model used a weighting factor of 1.0 for all bed elevations in the fitting procedure, but the revised version uses a weighting factor that decreases linearly with elevation from 1.0 at $Z_M = 0$ to 0 at $Z_M = -5\text{m}$. Experience of model applications has demonstrated that simulated salinity and water level in the Coorong were much more sensitive to the degree of Mouth openness when the Mouth was relatively constricted so it was judged that these were the times that the algorithm for determining the Mouth bed elevation needed to be most accurate. In any event, the determination of Mouth bed elevation using the method applied becomes less accurate as the Mouth channel deepens because exchange between the Coorong and the sea becomes more and more restricted in the channels leading to the Mouth rather than just in the Mouth channel itself.~~.~~

Figure 7 also compares the Mouth bed elevation determined from the tidal transmission into the Coorong with the elevation calculated using Equations ~~4-6~~5-7. Note that the period between October 2002 and December 2010 was the time when the Mouth was dredged to alleviate the high salinity conditions in the Coorong during the drought. The Mouth algorithm was not fitted or applied during this period. Generally, the Mouth elevation algorithm performs best when these elevations are greater than -3.0 m. Following the elevated barrage flows after the cessation of dredging near the end of 2010, the increased barrage flows caused the measured Mouth elevations to decrease to ~-3.5 m, whereas application of the Mouth algorithm would suggest that the Mouth elevation should decrease to almost -5 m. One might suppose that the 8 years of dredging had modified the region of the Mouth channel in such a way that it did not respond in the same way as it had done previously.

Comment [AL1]: Could this impact over the short term (i.e. <five years)? If so, will this be monitored to continue to test the Mouth algorithm over the short term?
We have not planned to monitor the response at this time, but it is very likely that these Mouth depths will be calculated and compared in the future.

2.3.2 MODEL PARAMETERS

The revised model requires the specification of 5 fitting parameters as before (Webster, 2007). These are the factor to be applied to the measured wind stress to correct for its measurement location (F_{WS}), the factor to be applied to the measured pan evaporation rates to estimate evaporation rate from the Coorong, the bed elevation of the channel near Parnka Point connecting the North and South Lagoons (Z_{PP}), the width of this channel (W_{PP}), and the long-channel mixing coefficient (D_0). For the revised calibration, F_{WS} should not have changed significantly and was not recalibrated. The evaporation factor in the revised model becomes a function of salinity as described in section 2.1.2 in contrast to it being assumed constant in the original model. Nevertheless the validity of the representation of evaporation rate was tested using the following calibration technique and its formulation revised slightly as a consequence as already described.

The parameters Z_{PP}, W_{PP}, and D_0 were calibrated using the same method as previously (Webster, 2007). Calibration utilised salinity measurements obtained at up to 12 sites along the northern shores of the North and South Lagoons and water level measured in the South Lagoon at Sand Spit Point up to September 2008 and at Snipe Island thereafter. Snipe Island is 4 km north of Sand Spit Point. For the original and the revised calibrations, the calibration period commenced in June 1997, but it ended in March 2005 for the original calibration and extended to April 2012 for the revised calibration. For the original calibration, 35 salinity transects were used versus 56 for the recalibration. The salinity measurements used in the calibration were made by the South Australian Department of Environment and Heritage (DEH), by the SA Environmental Protection Agency (EPA), SA Dept. of Water, Land & Biodiversity Conservation (DWBLC), and more recently by the SA Depts. for Water (DfW) and for the Environment and Natural Resources (DENR) (Table 1). The water level measurements were made available by the DfW.

Data source	Data period
Noye (1967)	1963-1967
Krause and Bennett (1976)	1974-1975
Krause and Bennett (unpublished)	1976-1979
Geddes (unpublished)	1981-1985
Owen (1993)	1993
EPA-DEH	1997-2005
DWBLC	2005-2007
DENR, DfW	2008-2012

Table 1. Salinity measurements obtained in the Coorong since 1963.

In previous model applications and in measurements it has been observed that the temporal and spatial variability of salinity is particularly high in certain zones along the Coorong. These zones include the zone between the Mouth and the eastern end of Tauwitchere barrage which is subject to the direct influence of freshwater barrage flows that cause large horizontal gradients and consequently rapid temporal changes in salinity as the winds and tide push this water back and forth. A second zone spans the channel connecting the two Coorong lagoons which is also subject to large short term variability as water sloshes between them. The third zone is the south end of the Coorong within a few kilometres of the USED outflow from Salt Creek. One might expect this flow to cause ~~of~~ a plume of relatively low salinity water that is pushed around by the wind but which gradually mixes into the body of the South Lagoon. Calibration for salinity was undertaken only on measurements obtained between these zones of high variability. In effect, these were measurements obtained between 18 and 50 km from the Mouth and between 67 and 93 km from the Mouth.~~,~~ In total, the numbers of salinity measurements used for calibration were 474 in the North Lagoon and 275 in the South Lagoon.

Hundreds of model simulations were obtained with various combinations of the parameters Z_{PP}, W_{PP}, and D_0. Calibration involved the selection of the particular set of parameters that minimised the 'error' function, δ_T where:

$$\delta_T = \sqrt{\frac{\delta_S^2}{\sigma_S^2} + \frac{\delta_L^2}{\sigma_L^2}} \quad . \qquad (8)$$

Comment [joe001 2]: That's less than 5 different values for each of the 3 parameters. Thus you might specify the actually used range/values of these parameters.
Not as simple as that as there were many iterations of the ranges chosen as well.

Here, δ_S is the RMS deviation between measured and modelled salinity through both lagoons, σ_S is the standard deviation of the salinity measurements, δ_L is the RMS deviation between measured and modelled water level at Sand Spit Point (or Snipe Island), σ_L is the standard deviation of these water level measurements. The optimal values for the recalibration are $Z_{PP} = -0.20\,\mathrm{m}$, $W_{PP} = 99\,\mathrm{m}$, and $D_0 = 87\,\mathrm{m^2s^{-1}}$.

Several modifications to the model were tested to determine if they would improve the agreement between model and measurements. It has been postulated by Webster (2007, 2010) that the large salinity cells used in the original model (up to 10-km long) allowed for an implicit numerical diffusion that would act as a surrogate for long-channel dispersion associated with back and forth currents in the Coorong. For the model, numerical dispersion is proportional to the product of cell length and the amplitude of the flows between cells. Thus, reducing the salinity model discretisation from 5-10 km to 1 km would be expected to reduce the numerical dispersion by these ratios. The impact of the reduction of numerical dispersion on model performance was tested by introducing a mixing coefficient (in addition to D_0) that is proportional to the amplitude of the flow between cells. Co-variation of this extra mixing coefficient along with D_0 suggested that its optimal value (as evaluated by the calculated values of δ_T) was close to zero. Accordingly, such an extra mixing term was not included in the revised model.

Comment [joe001 3]: by the square of it.
I don't think so. As dispersion is proportional to cell length and flows between cells is not really related to cell length

A critical component of the model calibration has been the specification of the width and bed elevation of the constricted channel between the North and South Lagoons (W_{PP}, and Z_{PP}). As with most channels, this channel would be expected to become wider as the water level rises. The possible impact of this effect on model simulations was examined by allowing the representation of the constricted channel to increase its width with water depth. A series of bank slopes were tested with variation in the other fitted model parameters. The benefits of introducing such a scheme were equivocal with a small reduction in δ_T occurred for some model simulations but not for others. With a lack of a clear cut and consistent benefit of introducing a variable channel width, the simplest option of assuming a constant channel width was retained.

2.4 Model validation

2.4.1 VALIDATION 1963-2012

Prior to 1997, a number of other investigators obtained salinity measurements along the Coorong on occasions stretching back to 1963 (Table 1). These measurements are used together with the salinity measurements obtained between 1997 and 2012 to demonstrate the model's validity. Figure 8 compares the range of model simulated salinity within the calibration zones in the North and South Lagoons with the measurements obtained within these zones.

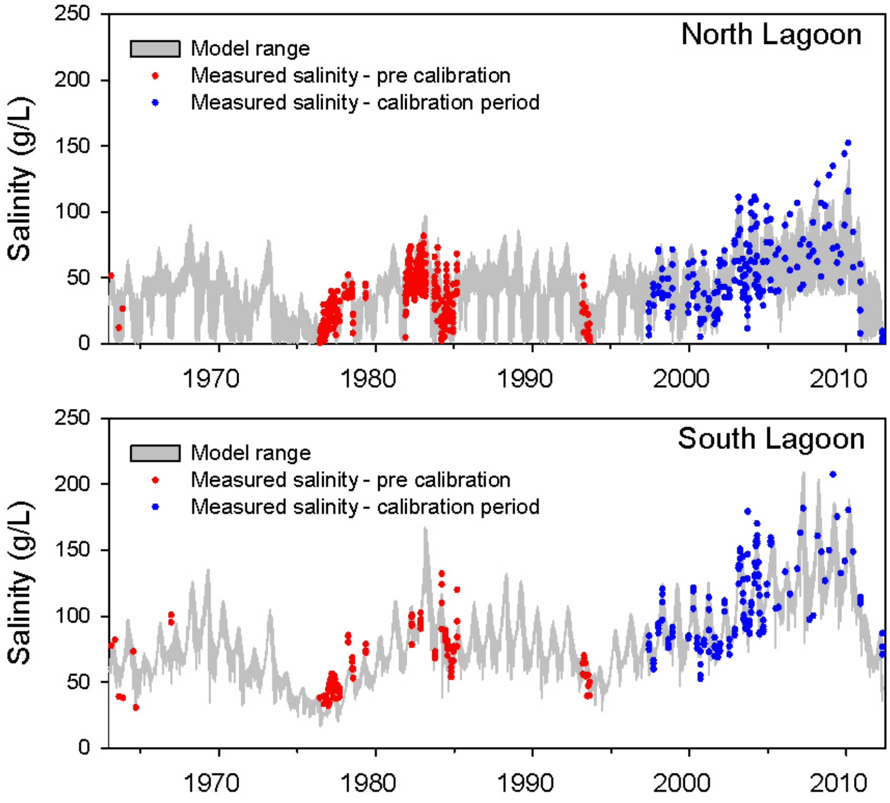

Figure 8. Comparison between measured and modelled salinity in the North and South Lagoon. The grey band represents the range of modelled salinity within the calibration zones in each lagoon.

The model captures the major features in the salinity measurements in both lagoons as these respond to barrage flows. Measured and modelled salinities are relatively low following the relatively high barrage flows of the mid-1970s and the early 1990s (Figure 5). Relatively smaller barrage flows in the mid-1980s and around the turn of the millennium result in both measured and modelled salinity being relatively high during these periods. During the drought beginning in the early 2000s, measured and modelled salinity in the South Lagoon become even higher exceeding 200 g/L at times during the summers. The measurements mostly fall within the modelled ranges both within the calibration period and before it.

Figure 9 shows a second way of comparing measurements and model simulations which plots modelled salinity at the sampling stations against measured salinity at the same time and place. The data points cluster about the 1:1 line. Linear regressions between measured and simulated salinity provide the following relationships:

$$S_{model} = 8.7 + 0.88 \times S_{measured} \text{ for the North Lagoon} \qquad (9a)$$

$$S_{model} = 6.6 + 0.94 \times S_{measured} \text{ for the South Lagoon} \qquad (9b)$$

For the North Lagoon, the average error between measured and modelled salinity (the bias) is 3.5 g/L and the standard deviation of the salinity difference is 10.0 g/L. For the South Lagoon the bias and the standard deviation are 0.9 g/L and 12.7 g/L respectively. Both lagoons have a positive bias for the modelled results, that is, modelled salinity is higher on average than measured salinity. It should be noted that the degree of agreement between modelled and measured salinity varies somewhat across the salinity range. In particular, when salinity in the North Lagoon is below ~25 g/L and the salinity in the South Lagoon is below ~50 g/L, the model tends to underestimate salinity. This happens again for North Lagoon salinity above ~70 g/L and South Lagoon salinity above ~120 g/L. In between~~,~~ these limits, modelled salinity tends to be higher than measured.

Comment [AL4]: This is a key piece of information that will need to be considered and noted when CEW obtain modelled information in future years. Perhaps should be a key point to highlight in recommendations/considerations for CEW in final report.

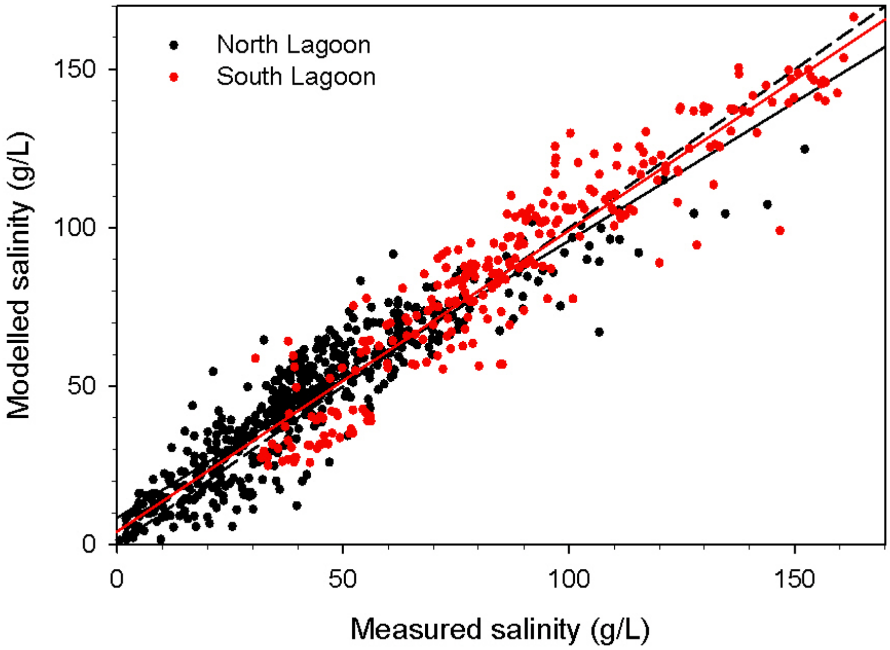

Figure 9. Comparison of measured and modelled salinity within the North and South Lagoon calibration zones for all relevant data since 1963. The dashed line shows the 1:1 relationship. The solid lines show the linear regressions for the North and South Lagoon data taken separately.

To better illustrate the comparison between the time series of water levels in the North Lagoon at Tauwitchere barrage and in the South Lagoon at Sand Spit Point (prior to September 2008) and at Snipe Island thereafter, these levels have been low-pass filtered to remove fluctuations having periods less than 2.5 days. The comparison for the North Lagoon shown in Figure 10 for 1995 also shows the water levels measured at Victor Harbor during this year. Only one year is shown since the detail necessary for comparisons disappears in the 'grass' if longer periods are shown. It is apparent that the low-pass filtered time series for Victor Harbor and those measured and modelled at Tauwitchere barrage all follow one another quite well. Both measured and modelled levels deviate from those at Victor Harbor when the barrage flows are relatively high. On these occasions flows were generally greater than 20,000 ML/day (dashed line in figure).

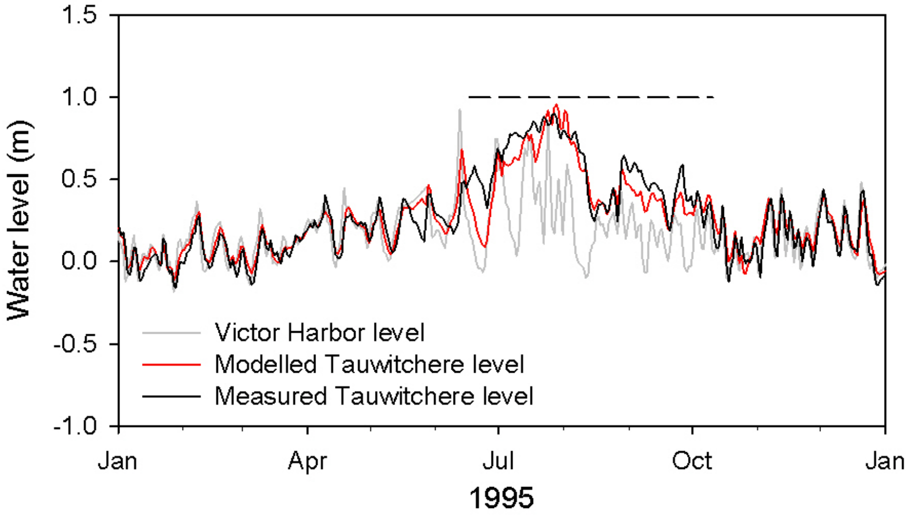

Figure 10. Low-pass filtered water levels measured and modelled at Tauwitchere barrage. Also shown are water levels measured at Victor Harbor and the period (dashed line) when barrage flows were mostly > 20,000 ML/day.

The measured and modelled filtered time series of water levels in the South Lagoon shown in Figure 11 may sometimes differ in detail, but the model well simulates the seasonal cycle of these levels and its interannual variability. For most of the year, rises and falls in water level in the North Lagoon cause the South Lagoon to fill or empty through the channel connecting them. Thus, during these times water levels in the South Lagoon tend to follow those in the North Lagoon. When water levels in the North Lagoon fall below 0 m in early summer typically, the two lagoons become disconnected. Evaporation losses in the South Lagoon are not replaced by flow through the channel connecting the two lagoons causing the water level to fall through summer.

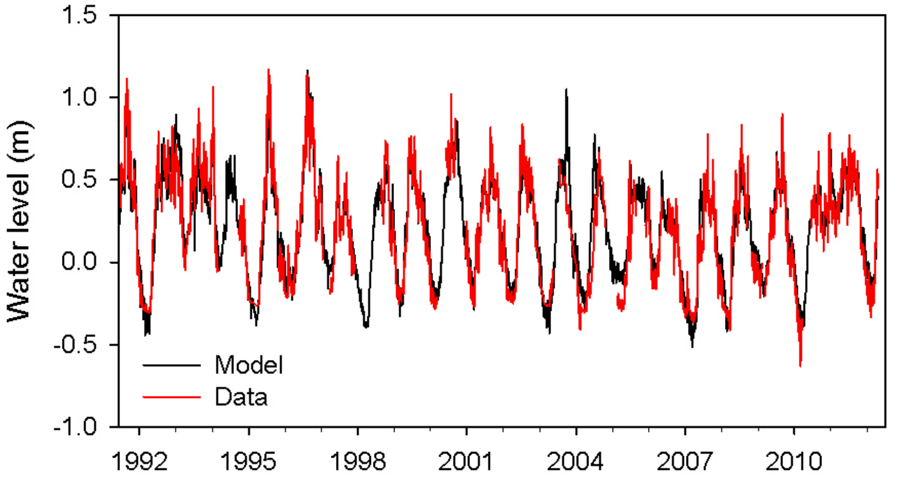

Figure 11. Comparison between measured and modelled water levels for Sand Spit Point pre-September 2008 and for Snipe Island post-September 2008.

Water level variability is thought to be a key driver of the ecological response of the North and South Lagoons. The suitability of mud flats along the sides of the Coorong as habitats for the benthic organisms that form the food supply for wading birds depends on their inundation status. Further, the aquatic macrophyte *Ruppia tuberosa* requires appropriate water level conditions to grow and for its turions to germinate. Accordingly, an important measure of model capability is its ability to simulate the annual water level ranges in both lagoons.

Monthly averaged water levels were calculated for the South Lagoon at Sand Spit Point and the month determined for which the average was greatest. Figure 12 shows the modelled water level averaged for this month plotted against the maximum measured average. Also shown are the average Victor Harbor levels for the same month plotted against the maximum measured average. These maxima effectively represent the time when the barrage flows elevate North Lagoon levels causing the South Lagoon water levels to follow. Compared to the Victor Harbor level, the maximum South Lagoon levels are elevated by between ~0 m and almost 0.6 m. The model simulates the measured behaviour of the yearly South Lagoon maxima at least approximately. The standard deviation of the difference between measured and modelled maxima is 0.08 m with the modelled maxima being 0.06 m lower than measured on average.

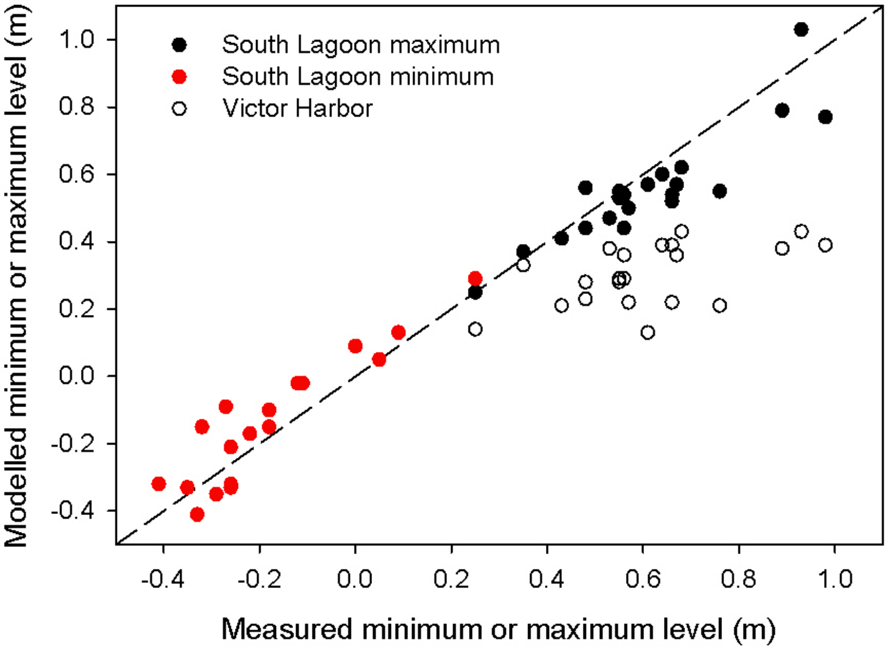

Figure 12. Maximum and minimum yearly monthly averaged water levels (modelled vs. measured) in the South Lagoon. Also shown are the Victor Harbor monthly averaged water levels for the same months as the South Lagoon maxima.

Also shown in Figure 12 are the yearly minimum monthly averaged water levels in the South Lagoon plotted as modelled versus measured. As with the yearly maxima, the measured and modelled minima follow one another approximately. For the minima~~-~~, the standard deviation between the two is also 0.08 m, whereas the modelled minima are 0.04 m higher than those measured on average.

2.4.2 RECENT MODEL COMPARISONS

Due to drought in the Murray-Darling Basin, flows through the barrages were small up to October 2010 when rains in the basin caused barrage discharges to become significantly larger than average over the following year. During the period of drought, dredging of the Mouth channel was required in order to prevent salinity in the Coorong from becoming higher than it eventually became. Following the commencement of the barrage flows in 2010 dredging was terminated and the Mouth channel evolved in response to the flows through it. The most recent comparisons between model and measurement were undertaken for the period up to mid-2008 before the drought ended.

Here, the performance of the model since the beginning of 2008 through the transition from drought to large barrage flows is considered. Figure 7 shows the modelled and measured Mouth channel bed elevations through this period to decrease following the onset of the barrage flows, but the Mouth elevations predicted using Equations 5-7 are significantly lower than those ‘measured’ using the tidal transmission technique. From December 2010 through to April 2012, the modelled bed elevation averaged -4.1 m versus -2.6 m for the ‘measured’ elevation.

Through this period, salinity was calculated from conductivity measured at a number of locations along the Coorong on 12 occasions. As well as these spot measurements, conductivity recorders were installed at several sites. Time series of salinity were calculated from these measurements for comparison with the modelled salinity at the same location. The results of the comparison between salinity derived from the time series are shown in Figure 13 for the recorders at Pelican Point in the North Lagoon and near Cattle Island near the middle of the South Lagoon. Also, shown are the spot measurements of salinity interpolated to these positions.

For the Pelican Point site, the modelled salinity plots mostly on top of the spot measurements and the recorder measurements. In fact, the measured time series and modelled salinity follow one another ~~is~~ in detail with short term fluctuations in measured salinity largely being reflected in the model. Agreement between simulated and measured salinity at this site would be regarded as very good. Agreement at Cattle Island is not as good. Where they coincide in time, the spot measurements and measured time series are consistent with one another. Modelled salinity tends to be lower than measured salinity especially during the summer of 2009 and after the commencement of the barrage flows in late 2010.

It should be noted that calculation of salinity from conductivity relies on a formula describing the relationship between chlorinity and conductivity based on measurements up to a chlorinity equivalent to a salinity of ~160 g/L. Consequently, the calculation of salinity from conductivity might be expected to become more and more inaccurate as salinity exceeds ~160 g/L . This may represent at least a partial explanation for the difference in peak salinity during the summer of 2009. The difference between measured and modelled salinity during the summer of 2012 is large with measured salinity being significantly higher than modelled salinity. Summertime peaks in salinity in the South Lagoon are typically due to evapoconcentration of salt in the water column when exchange between the two lagoons is limited due to the shallowing of the channel connecting the two lagoons near Parnka Point.

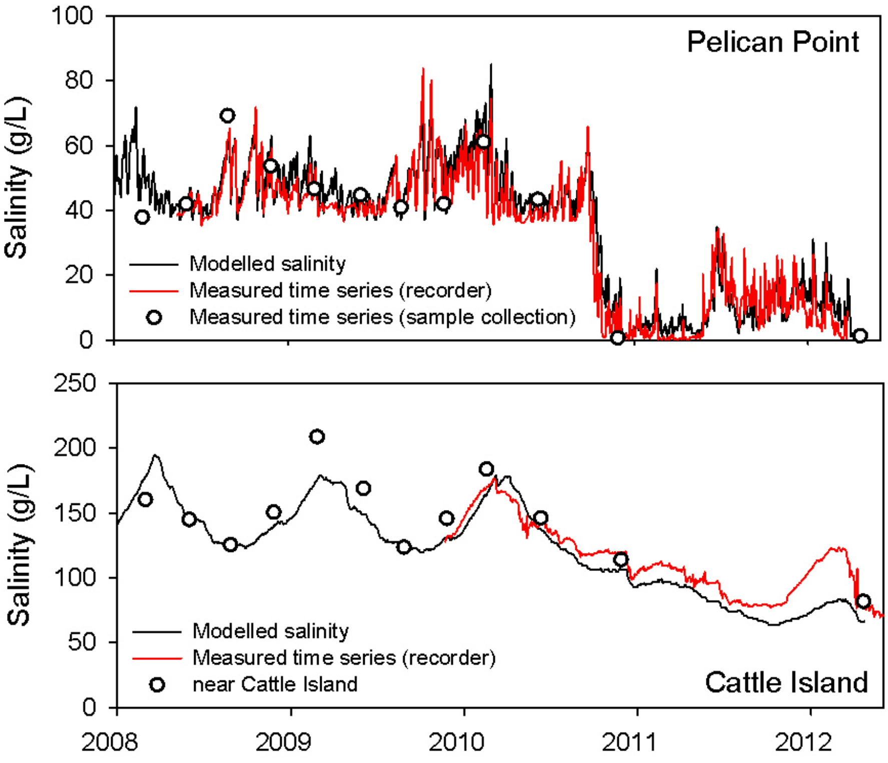

Figure 13. Modelled salinity at Pelican Point and near Cattle Island compared to recorder time series and to spot measurements.

Figure 14 shows measured and modelled water levels at Sand Spit Point since the beginning of 2008. These have been low-pass filtered as in Figure 11. These water levels follow one another reasonably well even down to the detail of short term fluctuations. The comparison between these measured and modelled water levels presents at least a partial explanation for the discrepancy between measured and modelled during the summer of 2012. In particular, for the months November 2011 to February 2012 (dashed line) modelled water levels are consistently higher than those measured. For this period, modelled water level averaged 0.0 m, whereas the average measured was -0.09 m. Since the bed elevation for the channel connecting the two lagoons is -0.20 m, these elevations imply average water depths in the channel of 0.20 m (modelled) versus 0.11 m (measured). The exchange of water between the two lagoons will be much more restricted if the water depth is only 0.11 m compared to what it would be if the water depth was almost twice that. By allowing more active exchange between the lagoons until later in the summer than was the actual case, the model limits the extent of evapoconcentration that is simulated resulting in lower salinity.

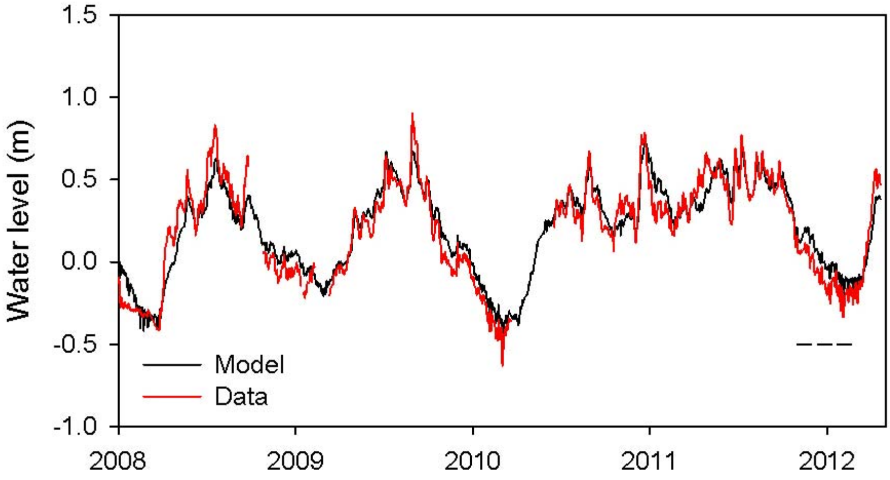

Figure 14. Comparison of measured and modelled low-pass filtered water levels at Sand Spit Point since the beginning of 2008. The dashed line indicates the period 1/11/2011-29/2/2012.

3 Evaluation of the benefits of environmental water delivery – generic case

The following section of the report considers the impacts on the Coorong of the volume and timing of the delivery of supplementary flows for environmental purposes. It aims to inform the Commonwealth Environmental Water Office how barrage flows and the volume and timing of supplementary flows interact in a general way to achieve salinity and water level outcomes in the Coorong.

3.1 Barrage and USED flows

The approach taken here is to investigate the expected impacts on the salinity and water level regimes using a series of scenarios in which the supplementary environmental flow is added to base barrage flows sequences. The simulation used in each scenario extends from 1/1/1985 to 31/12/2010, a period of 26 years. The model simulation starts 5 years earlier than the section of simulation that is analysed to allow for model ‘spin-up’ prior to the commencement of the simulation proper. The sea level and meteorological time series used in the simulations are based on measurements over this time from the tide station at Victor Harbor, from the anemometer at Meningie (and since 2008 at Pelican Point), and evaporation and precipitation hindcasts from Parnka Point. These are the data used in the calibration process described in Section 2 of this report.

The time series of barrage and USED flows both show large interannual variability that obscures the nature of the interactions between them and supplementary flows. To reduce the impact this has on understanding the relationships involved, a synthetic time series of these flows was constructed from the available historical data comprising the annual repetition of a fixed flow sequence of prescribed total annual volume. The flow sequence determined as a form of median flow distribution through each of the 118 years of barrage flows in the MDBA simulation 5520000. For the USED, the median flow distribution was taken from recent modelling undertaken by Montazeri et al. (2011) of flows into the Coorong between 1971 and 2000. For both analyses, the following analysis sequence was applied:

- normalise flows by the total discharge volume for each year
- determine peak time of flow in each year
- determine median time of all peak flows
- adjust timing of flows in each year so that peak flow occurs at median time of all peak flows
- calculate median flows for each day of the year
- develop time series of flows by repeating yearly flow sequence and adjusting amplitude to achieve desired volume

Then, the temporal distribution of these normalised flows with respect to the peak flow time in each year was used in the median calculation rather than the median flow on each day of the year. The resulting yearly flow distributions are shown in Figure 15.

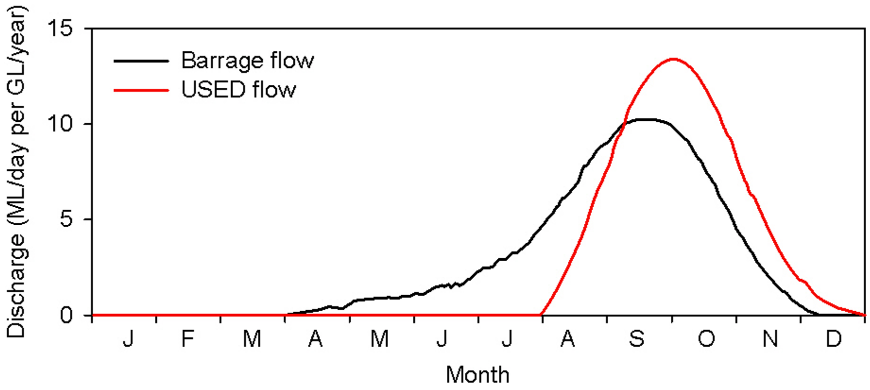

Figure 15. Yearly distribution of barrage and USED flows. Note that daily discharge (ML/day) is obtained by multiplying vertical axis by the annual flow volume in GL. Thus, a barrage discharge of 10 on the above graph represents a daily discharge of 10,000 ML/day if the yearly volume is 1,000 GL.

The times of peak flow are the median times of peak flow in the MDBA and USED flow time series. The actual times of peak flows can vary by several months either before or after from the peak flow times shown in Figure 15. By calculating the flow distributions with respect to the peak flow time rather than the actual day of the year, this analysis results in a composite flow peak that is less spread out and more representative of flow time durations.

Three barrage flow volumes are considered in the analysis. These are the 90, 50 and 25 percentile volumes from 118 years of barrage flows in the MDBA simulation 5520000. These flow volumes are 260, 3180, and 7590 GL/year. Scenarios were also obtained for the zero barrage flow case. The USED drainage system has been undergoing development in recent years in order to increase the flows to the South Lagoon. Flow volumes for 2010 and 2011 were measured to be 29 and 25 GL, respectively, whereas the flow weighted average salinities of these flows are calculated to be 7.4 and 6.7 g/L. For all model scenarios described in the following, the annual USED flow volume are fixed as 25 GL and the salinity of the flow specified as 7 g/L.

The supplementary flow sequences used in the analyses are also idealised. In this case the flow is assumed to have the Gaussian distribution shown in Figure 16. This distribution has a nominal width of 60 days as indicated. The flow volume occurring between ± 30 days of the peak flow is 91% of the total flow volume. Two supplementary environmental water flow volumes are considered; namely 750 and 1500 GL/year. The timing of the peak flow is varied for all flows at monthly increments centred on the beginning of each month.

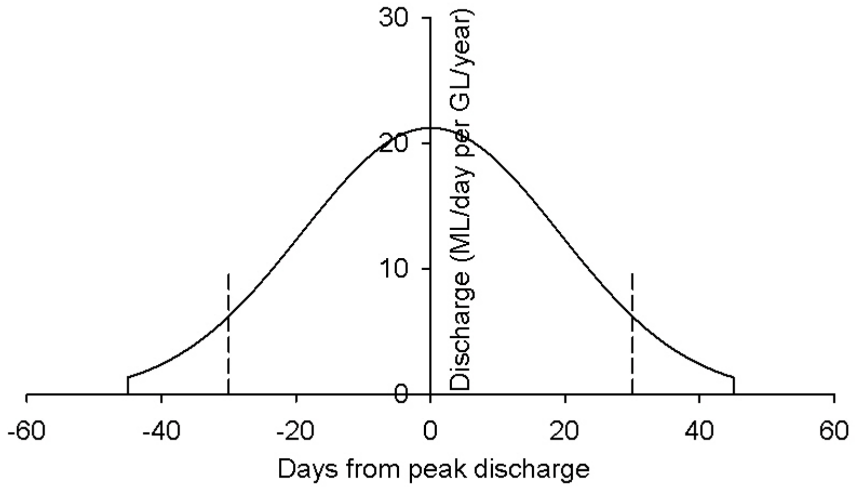

Figure 16. Distribution of supplementary flows around peak discharge. As in Figure 15, daily discharge (ML/day) is obtained by multiplying vertical axis by the annual flow volume in GL. The dashed vertical lines indicate a flow duration of 60 days.

The flow volumes used in the scenarios are all combinations of barrage flows (4 cases including no-flow), supplementary flows (2 cases), and variable timing of the peak (12 cases). For output purposes, salinity and water level are averaged daily over the North and South Lagoon zones described in the calibration/validation section. These lagoon sections are 18-50 km (from the Mouth channel) in the North Lagoon and 67-93 km in the South Lagoon. They are chosen to avoid cells that are directly subject to either barrage or USED flow input where localised impacts may well exceed the impacts on the main lagoon basins. Thus, the averages of the values for these two zones provide a representative assessment of the conditions in each of the respective lagoons.

3.2 Results

To illustrate the salinity and water level response of the model, Figure 17 shows 10 years of the time series of simulated water levels and salinity for the North and South Lagoons without supplementary flows for a barrage flow volume of 3180 GL per year which is the median discharge for the 118 years. Pronounced seasonal cycles of water level and salinity are evident in both lagoons and these are caused by the seasonal cycles of sea level, evaporation and precipitation rates, barrage flows, and USED flows.

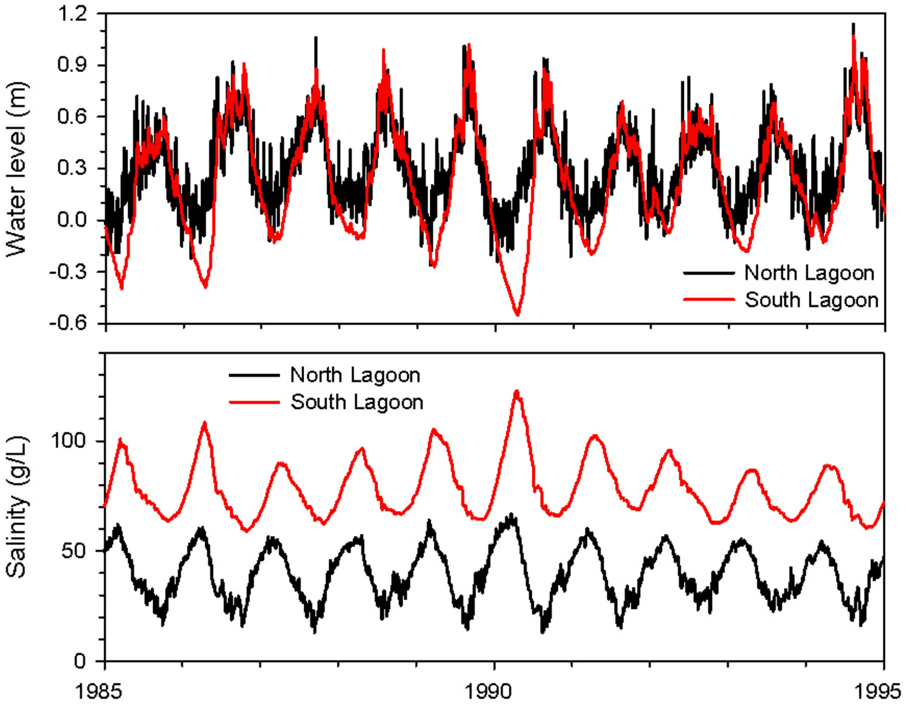

Figure 17. Simulated water levels and salinity in the North and South Lagoons for an annual barrage discharge of 3180 GL.

In a typical year, sea level shows a maximum in winter and a minimum in summer. For most of the year, North Lagoon water levels reflect those in the sea, but during times of strong barrage flows flow blocking through the Mouth channel can cause lagoon levels to rise significantly above those in the sea. By early summer, sea level and barrage flows have dropped sufficiently that the channel connecting the North and South Lagoons becomes very shallow and flow between the two lagoons becomes severely constricted. Without replenishment from the North Lagoon, summertime evaporation causes the South Lagoon water levels to continue to drop below those in the North Lagoon. When sea levels rise again in autumn, refilling occurs with water from the North Lagoon.

Salinity in the North Lagoon is typically depressed during times of high barrage flows in spring and higher during the rest of the year when salt water is mixed in from the sea through the Mouth channel. In the South Lagoon, salinity tends to be highest near the end of summer when evaporation concentrates the salty water that is there. When water levels rise through autumn, flow from the North Lagoon replenishes the evaporative losses and dilutes the high summertime concentrations in the South Lagoon.

Figure 17 also shows that there is a degree of interannual variation in both the salinity and water level cycles in both lagoons. In the model, this is partly due to interannual variation in meteorological factors including evaporation/precipitation rates and wind strength that impacts on horizontal mixing of water along the lagoons. Interannual variations in the weather systems that cross Australia also cause the seasonal cycle of sea level to vary from year to year causing a significant variation in water exchange along the Coorong and with the sea.

Figure 18 shows how supplementary flows centred on 1 January, 1 April, 1 July and 1 October add to the underlying barrage discharge, whereas Figure 19 illustrates the response of the salinity and water level in the main basins of the North and South Lagoons to these flows. The results shown are simulated using barrage and supplementary flow volumes of 3180 and 750 GL/year, respectively and so represent mid flow conditions. For all plots the results are presented as the median values for each day of the year for the 26 years of simulation. Note that simulations were obtained for supplementary flows centred at the beginning of all 12 months of the year not just the 4 cases presented in Figure 18 and Figure 19.

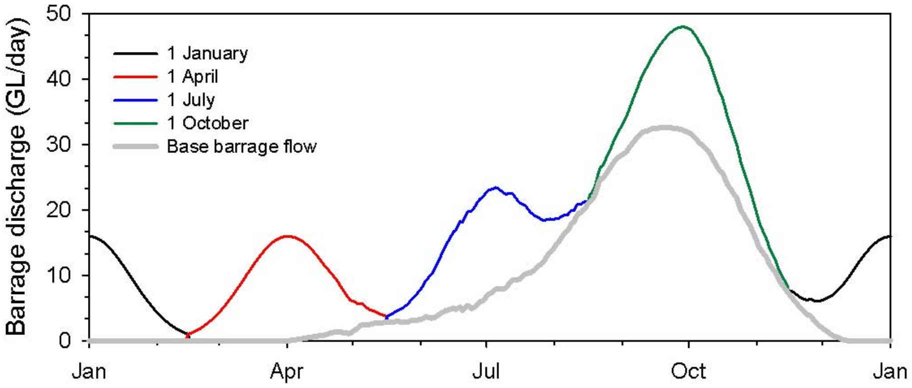

Figure 18. Daily barrage discharges for the cases of 4 supplementary flow releases whose peak discharge occurs on the day indicated. The base barrage flow with no supplement is also shown. The base barrage flow volume is 3180 GL/year and the supplementary flow volume is 750 GL/year.

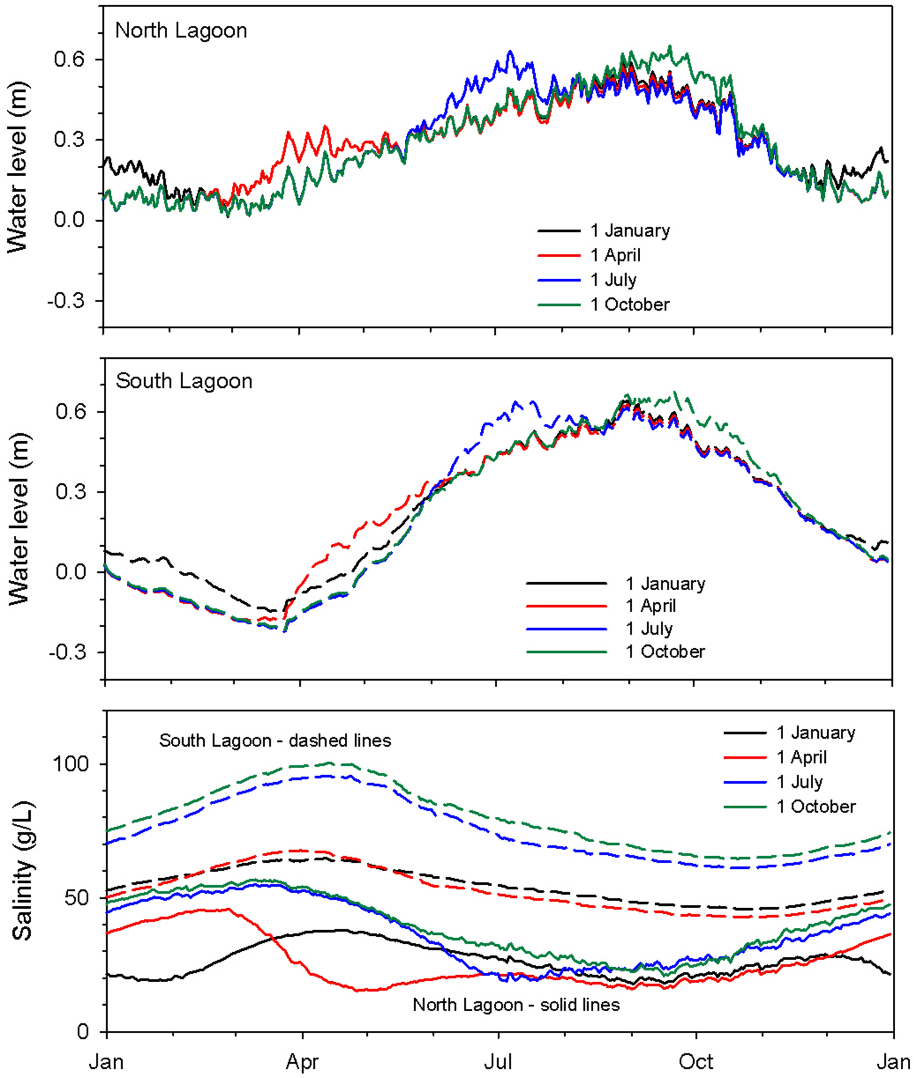

Figure 19. Median daily simulated water level and salinity in the two lagoons for a barrage flow volume of 3180 GL/year and a supplementary flow volume of 750 GL/year.

In the North Lagoon, the supplementary flows act to push up water levels there by ~0.2 m when they occur. In the South Lagoon, the impact of the supplement flows can be seen clearly also. The July and October releases cause water level changes that are similar to those in the North Lagoon, but there are significant differences during the other two flow times. In particular, by pushing up water levels in early summer, the January release delays the separation between the two lagoons caused by seasonally falling water levels. Consequently water levels in the South Lagoon remain higher by ~0.1 m through the whole of summer. The April release causes the two lagoons to reconnect sooner than they would otherwise allowing the South Lagoon to refill a little earlier and more quickly than in the absence of supplementary flows.

The annual cycle of salinity in both lagoons is not affected much by the July and October releases of supplementary flows. The case of zero supplementary flows (not shown) shows salinity in both lagoons that is very similar to that for the October release particularly. As with water levels, the impact on salinity of January and April releases is quite different. Releases centred at the beginning of these two months both show North Lagoon salinity to be significantly depressed during these times although during the winter months salinity is only a little lower than that for the July and October releases. In the South Lagoon, the January and April releases both show salinity to be depressed by ~20 g/L compared to the July, October and zero release cases at all times of the year. The supplementary releases have a large impact on the salinity in both lagoons only if they occur when barrage flows are close to zero.

Comment [AL5]: A key finding for to be drawn out for future CEW delivery in final report.

Figure 20 to Figure 23 show the median maximum and minimum water levels and salinity in the North and South Lagoons. These are the medians of the maximum and minimum levels and salinity modelled across all 26 years of the simulation period. Significant features of these results are listed in the following. These results are obtained from simulations which have the timing of the supplementary flows increased at 1-month increments.

a) Water level – North Lagoon

- higher barrage flows increase the maximum water levels in the North Lagoon with or without supplementary flows
- supplementary flows released at the time of barrage flows and seasonally high sea levels in winter-spring tend to increase the maximum water level, but releases at other times of the year have a much lesser effect.
- the supplementary flow release has its biggest impact on maximum water level for the case of the smallest barrage flows when one would expect the Mouth to be most constricted
- minimum water levels in the North Lagoon are much less affected than maximum water levels by barrage or supplementary flow volumes
- minimum water levels drop slightly with increasing barrage flow volumes due to greater scouring of the Mouth channel which causes less water level hang-up during times of low flows

Comment [AL6]: Key finding for CEW

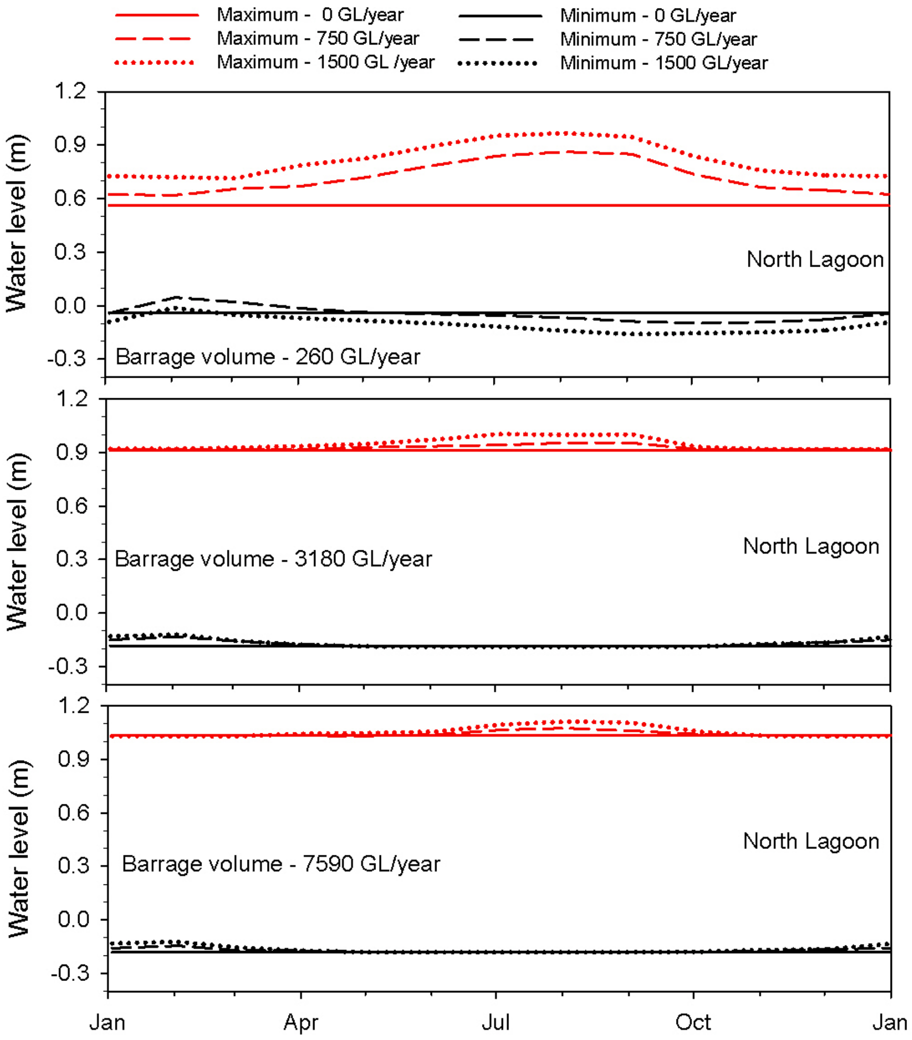

Figure 20. Median maximum and minimum water levels in the North Lagoon for 26 years of simulation. Horizontal axis is time of peak supplementary flow.

b) Water level – South Lagoon

- maximum water levels in the South Lagoon tend to follow those of the North Lagoon with similar dependencies on barrage and supplementary flow volumes and release times
- minimum water levels in the South Lagoon are least when the barrage flow volume is smallest
- summertime supplementary flow releases tend to increase minimum South Lagoon water levels, but release during the rest of the year have minimal impact

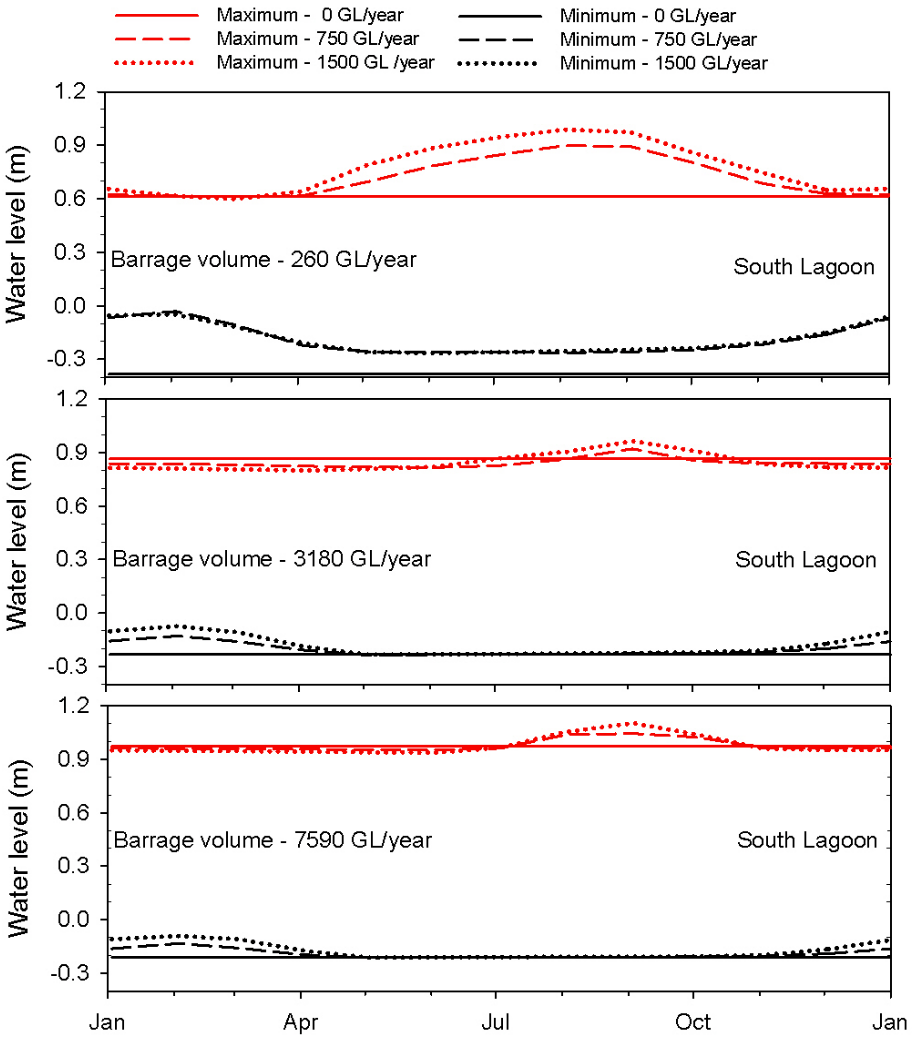

Figure 21. Median maximum and minimum water levels in the South Lagoon for 26 years of simulation. Horizontal axis is time of peak supplementary flow.

c) Salinity – North Lagoon

- maximum salinity in the North Lagoon decreases from ~130 g/L for the smallest barrage flow volume to less than 60 g/L for the largest.
- supplementary flow release in summer causes the largest reduction in maximum salinity and release in winter-spring causes the smallest
- for the two larger barrage flows, supplementary flow release in July-October has little effect on maximum salinity in the North Lagoon
- minimum salinity for the lowest barrage flow volume is reduced by ~20-40 g/L from its minimum of ~50 g/L with no supplementary flow
- minimum salinity for the two larger flow volumes is less reduced by supplementary flow

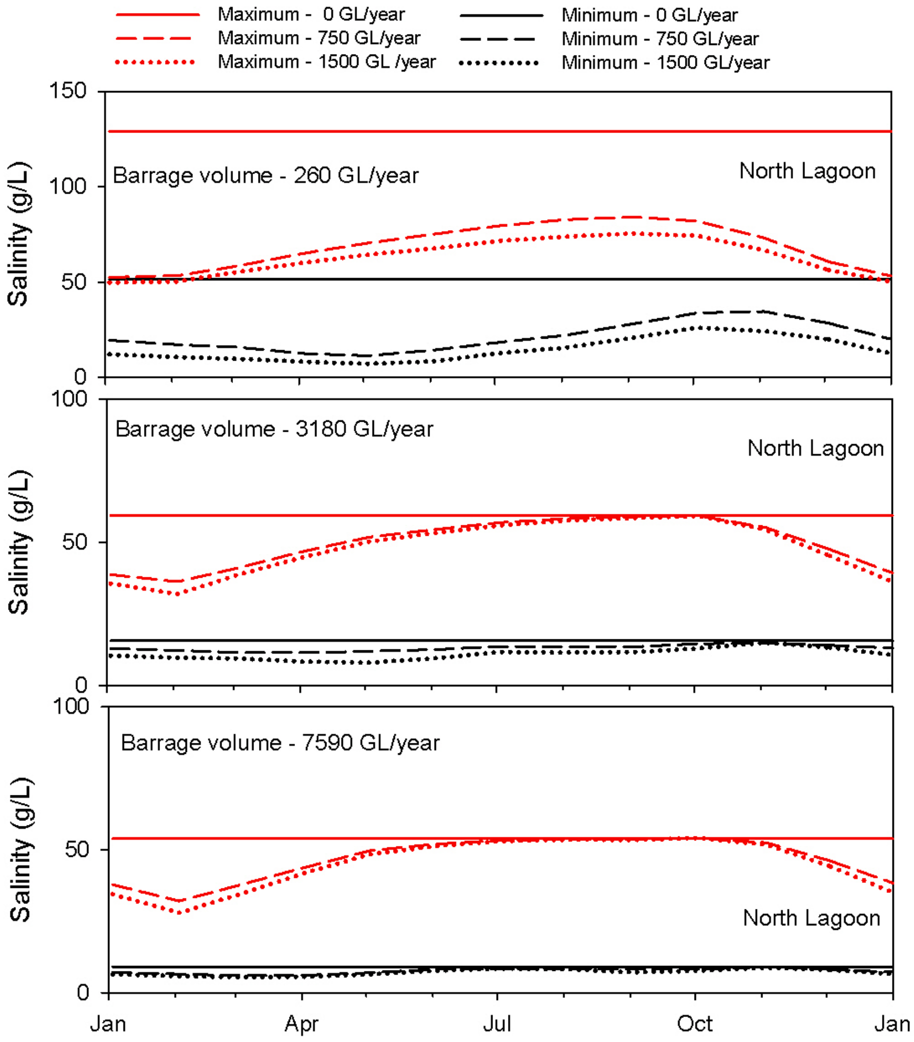

Figure 22. Median maximum and minimum salinity in the North Lagoon for 26 years of simulation. Horizontal axis is time of peak supplementary flow.

d) Salinity - South Lagoon

- maximum salinity in the South Lagoon decreases from ~240 g/L for the smallest barrage flow volume to less than 90 g/L for the largest.
- supplementary flow release in summer causes the largest reduction in maximum salinity and release in winter-spring causes the smallest
- for the two larger barrage flows, supplementary flow release in July-October has little effect on maximum salinity in the South Lagoon
- minimum salinity for the lowest barrage flow volume is reduced by ~60-90 g/L from its minimum of ~150 g/L with no supplementary flow
- minimum salinity for the two larger flow volumes is less reduced by supplementary flow
- the impact of a 750 GL supplementary release volume versus the 1500 GL supplementary release volume are similar to one another

Comment [joe001 7]: 1500G L suppl. flow reduces salinity further by 20 g/L. I would say by 5 g/L.

Comment [AL8]: Although the impact of these flows are similar, is the impact of supplementary flows (whether 750 or 1500) significant? In relation to the second point above, is there a difference between 1500GL and 750 GL in Summer? Depends on what is meant by significant in ecological terms I suppose. In computational terms, the salinity is difference is certainly significant.

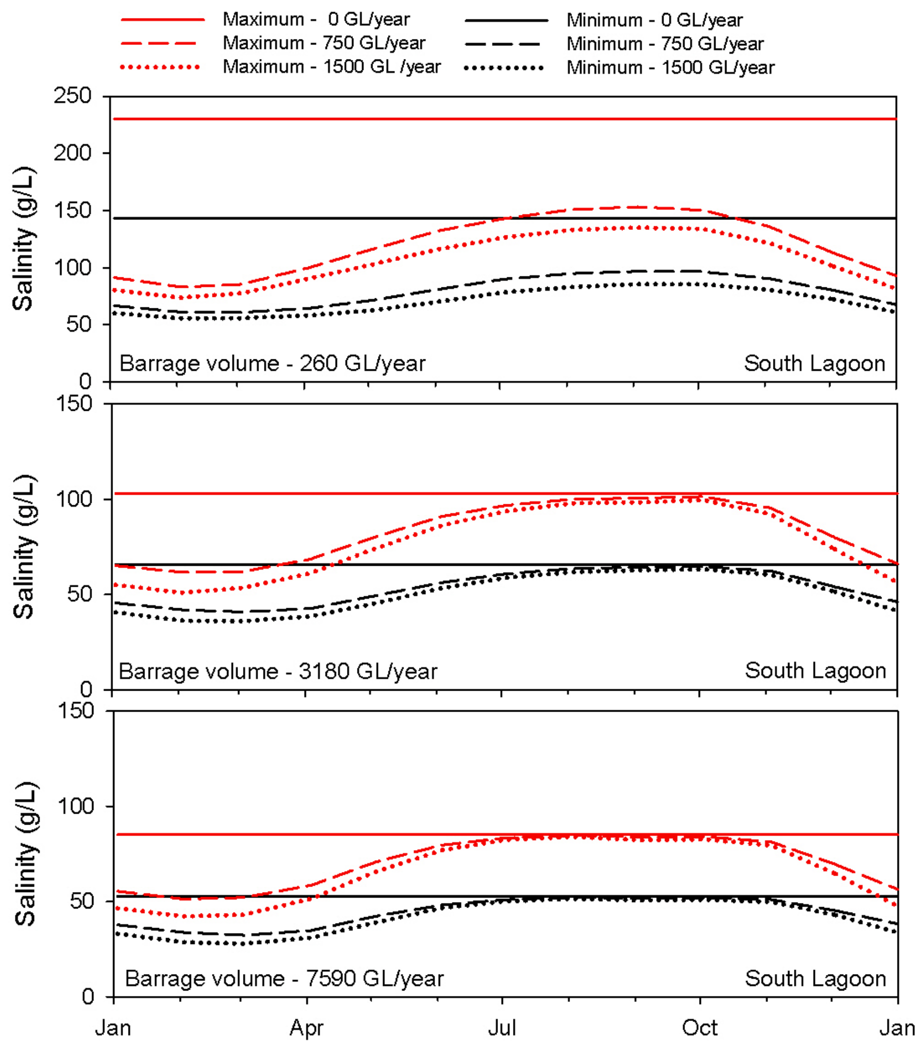

Figure 23. Median maximum and minimum salinity in the South Lagoon for 26 years of simulation. Horizontal axis is time of peak supplementary flow

3.3 Conclusions Section 3

Depending on the barrage flow volumes and on the timing of their release supplementary flows can have a profound impact on the water levels and salinity in the Coorong. Impacts on maximum water level in the two lagoons are largest when these flows are released on top of the barrage flows in winter-spring and when sea levels are seasonally highest. The impact is most significant for the smallest annual total barrage flow volumes. When barrage flows are small the Mouth channel tends to infill and become constricted so that any supplementary flows tend~~s~~ to push up water levels more than when the channel is more open. Although impacts of supplementary flows on minimum water levels are fairly minor, supplementary flows released in summer tend to cause an increase in the minimum water level in the South Lagoon at this time of the year. By increasing water levels in the North Lagoon at his time, the seasonal disconnect between the two lagoons is delayed or minimised so that summertime evaporative losses can be replenished.

The impacts of supplementary flows on salinity in both lagoons can be profound. These flows do have the effect of altering water levels and causing water to flow from one part of the Coorong to another especially between the two lagoons, but the main effect of these flows is to freshen the North Lagoon. Water flowing along the two lagoons to replenish evaporative losses carries less salt so less salinity build-up occurs. For the median to large barrage flow volume cases, the winter-spring barrage flows freshen the North Lagoon anyway so any supplementary flow release during this period has a small effect on salinity in the two lagoons. Conversely, supplementary flow releases during months when the barrages are not flowing maintains the North Lagoon in a relatively fresh condition for a greater part of the year with the consequence of significantly reduced maximum salinity in both lagoons. The relative benefits of releasing a supplementary flow volume of 1500 GL/year versus 750 GL/year are modest in terms of reducing salinity.

4 Impact of supplementary barrage flows 2012-2013

This section considers what salinity and water level response might be achieved over the coming year given a series of flow projections based on possible water availability in the Murray-Darling Basin. For this analysis, the salinity and water level responses of the Coorong are presented for three projections of barrage flow time series for the period October 2012 to June 2013. These responses are compared to the responses obtained using the same base barrage flows supplemented by environmental water provisions.

4.1 Barrage and USED flows

The Murray-Darling Basin Authority (MDBA) models flow projections within the basin throughout the coming year based on the levels of water storage and climate projections at the beginning of the year. The three base flow regimes modelled are the 25, 50 and 90 percentile Annual Exceedence Probability (AEP) flow projections. Under instruction from the CEWO, the MDBA also developed a further 3 flow sequences which represented the base flow supplemented by an additional environmental flow provision. The time series of total barrage flows are shown in Figure 24 for the 6 sequences used in the simulations. The volumes of these flows delivered between 1/7/2012 and 30/6/2013 for the 6 scenarios are listed in Table 2. Note that the percentile flow volumes are quite different from those assumed in section 3. The AEP flow percentiles are based on the likelihood of particular flow volumes for the coming year based on the present conditions in the reservoirs in the catchment whereas the percentiles used in section 3 refer to the frequency distribution of annual barrage flow volumes over 118 years.

The barrage flows were provided as total flows through all the barrages on both sides of the Mouth channel, but the split between flows past the Goolwa barrage and the others has a significant effect on the simulated salinity and water level. For the simulations the ratios of the flow through each barrage to the total discharge was assumed fixed at Goolwa (23%), Mundoo (26%) Boundary Creek + Ewe Island (16%), and Tauwitchere (35%). These were the ratios of the flows through the barrages between 1 May 2011 and 30 April 2012 derived from an analysis by the MDBA of water levels in Lake Alexandrina and barrage gate openings. The flow from the USED for the year was assumed to have a volume of 25 GL and a salinity of 7 g/L. These were values representative of measured flow and salinity through Salt Creek in the last two years (see section 3.1). The shape of the USED flow distribution is shown in Figure 15.

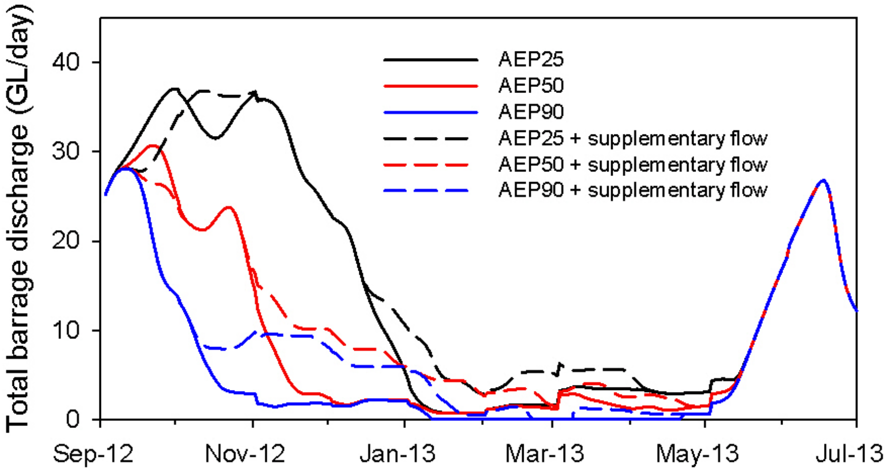

Figure 24. Barrage flows used in the 6 scenarios.

Scenario	Total barrage flow (GL/year)
AEP 25%-ile	5844
AEP 25%-ile + eflow	6177
AEP 50%-ile	4106
AEP 50%-ile + eflow	4634
AEP 90%-ile	3174
AEP 90%-ile + eflow	3756
USED flow	25

Table 2. Average daily flows through barrages for the 6 scenarios and USED flow.

The base flow scenarios shown in Figure 24 all have low flows through mid summer and early autumn (January to April). The 50 and 90 percentile flow cases show reduced flows starting in November 2012, whereas flows in the 25 percentile case do not diminish to close to zero until early January. The principal impact of the environmental flow supplement is to delay the reduction in flows for all three scenarios to mid-January or later. Summertime flows are also elevated over what they are for the base cases.

4.2 Model application

The model was applied in two stages. The first stage starting on 18 April 2012 ran to 28 August 2012. For this stage all the barrage flow were assumed to be those estimated by the MDBA as those that actually occurred. For this stage all the forcing time series namely wind stresses, precipitation rate, evaporation rate, and seal levels at Victor Harbor were specified as measured for this period. At the commencement of the simulation on 18 April 2012, the initial water levels and salinities are assumed to be those measured on this day. Water samples were collected along the Coorong on 18 April 2012 and analysed for their salt concentrations. Initial water level in the North Lagoon was that measured at Tauwitchere barrage, whereas the initial South Lagoon water level was assumed to be the measured Snipe Island level. The hydrodynamic model was applied to assess Mouth bed elevations that best described the measured transmission of tidal variations through the period leading up to 18 April, 2012. This analysis suggested that the best estimated bed elevation on 18 April, 2012 was -2.93 m so that this was used as the initial bed elevation in the simulations.

The second simulation stage commenced on 29 August 2012 and continued to 30 June 2013. The first simulation was used to estimate the salinity concentrations and water levels along the Coorong as initial conditions on the second stage start date. For the second stage, the 6 barrage flow projections were used. Each flow scenario comprised 30 simulations. Each simulation was undertaken using consecutive years of forcing data from between 1982 and 2012. Thus, the first simulation used measured Victor Harbor water level, wind stress, evaporation and precipitation from 29 August 1982 to 30 June 1983, whereas the second simulation used the forcing data from 29 August 1983 to 30 June 1984, and so on. Thus, on each day of the year, there were 30 simulated water levels and salinities for each model cell. As described in the previous section, the results for each simulation on each day were averaged over two sections representing the North and South Lagoons (18-50km and 67-93km from the Mouth) chosen to avoid cells that are directly subject to either barrage or USED flow input. Mostly, the results presented in the following are the salinity and levels in both lagoons calculated as the medians of the 30 simulations.

4.3 Results

Figure 25 shows the simulated median water levels in the North and South lagoons for the 6 scenarios modelled (3 base + 3 base with supplementary flows). As is typically the case, Coorong water levels are seasonally high during winter and spring due to the seasonally high sea levels in winter and the influence of barrage flows which push water levels up in spring (see Figure 17 for example). Water levels in the North Lagoon are lowest towards the end of summer when barrage flows have ceased and sea level is near its seasonal minimum. Water level in the South lagoon and South Lagoon continues to drop for another month or so due to evaporation.

The impacts of varying the base flow volumes are fairly subtle. One can see though that for the first few months the water level drops more quickly for the AEP90 scenario than it does for the AEP25 scenario. As Figure 24 shows significant AEP25 flows are maintained until December 2012, but these flows diminish 2 months earlier for the AEP90 scenario. Water levels in the South Lagoon during summer are higher for the AEP25 case than for the AEP90 case as one would expect considering that flows for the former case extend into the beginning of summer for the AEP25 case thereby maintaining the connection between the two lagoons for longer, but have terminated well before then for the AEP90 case. Minimum summertime water levels for the AEP25, AEP50, and AEP90 scenarios are -0.16, -0.19, and -0.21, respectively. The impact of supplementary flows for water levels in both lagoons is small. These flows reduce the depression of South Lagoons between January to April by only 3-4 cm for the three base flow cases.

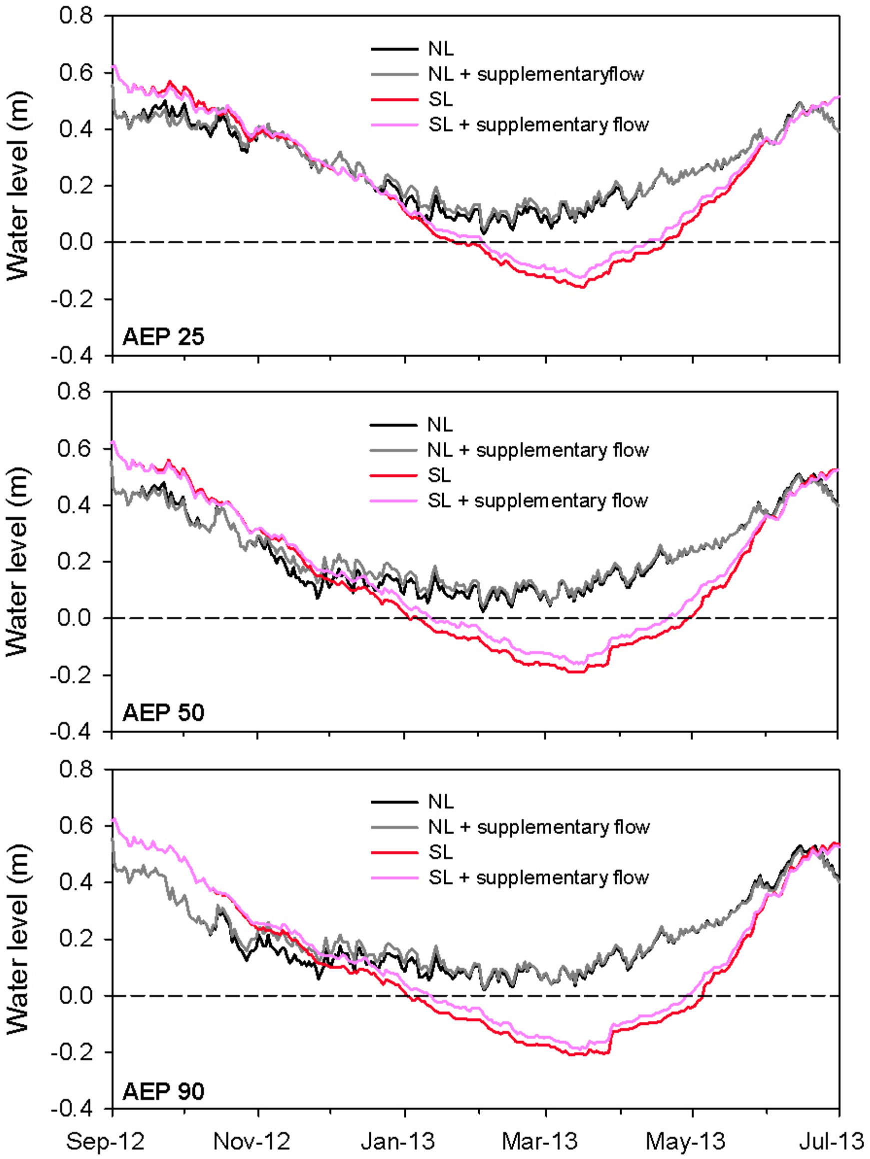

Figure 25. Simulated median water levels in the North and South Lagoons for the three base flow and base flow + supplementary flow scenarios.

The impact of variation in the base flow and of the addition of supplementary flows on salinity in the North and South Lagoons is shown in Figure 26. Overall, salinity in both lagoons becomes progressively lower in both lagoons as the base flow is increased from AEP90 to AEP25. Peak salinity in the North Lagoon is 39, 45, and 53 g/L for AEP25, AEP50, and AEP90, respectively. The impact of the addition of the supplementary flows is to reduce these peak salinities to 29, 33, and 43 g/L respectively; that is, by about 10 g/L. North Lagoon peak salinities occur in late summer and early autumn. Peak salinities occur in autumn in the South Lagoon for all the cases considered. As for the North Lagoon, the peak salinity in the South Lagoon diminishes as the flow volume is increased. For the AEP25, AEP50, and AEP90 scenarios, peak salinity is 77, 82, and 87 g/L, but these reduce to 74, 77, and 80 g/L with the addition of supplementary flows. .

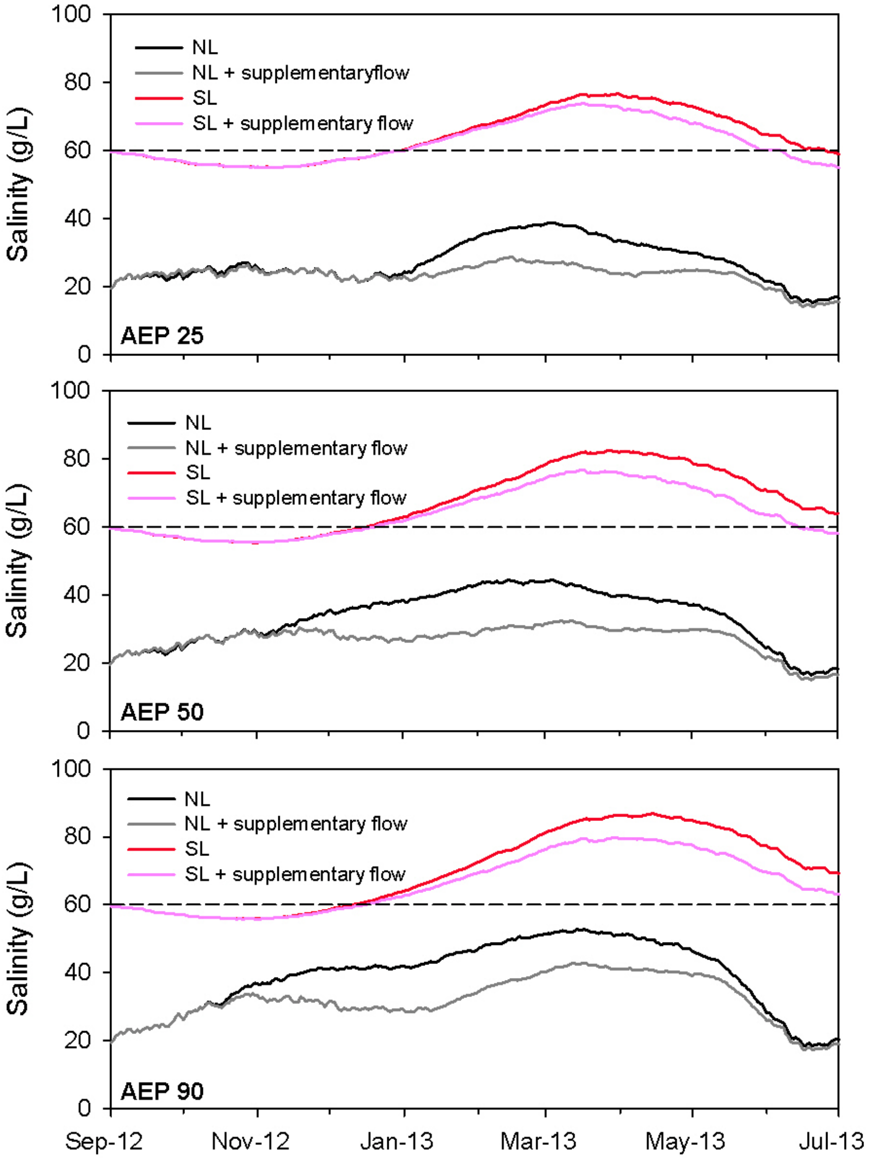

Figure 26. Simulated median salinity in the North and South Lagoons for the three base flow and base flow + supplementary flow scenarios. A salinity of 60 g/L is plotted for reference purposes.

It is recognised that simulated water levels and salinities in the Coorong vary significantly from year to year in response to interannual variations in the meteorological forcing and sea level. This is illustrated in Figure 27 where identical inflows were simulated from year to year, but the actual historical sequences of meteorological and sea level forcing are assumed in the model. To demonstrate the impact of interannual meteorological and sea level variability on simulations, the scenario comprising the AEP50 + supplementary flow is considered. Figure 27 shows the ranges of lagoon-averaged salinity and water level simulated in the Coorong using the 30 weather and water level sequences for this scenario. South Lagoon salinity showed a pronounced seasonal cycle for all meteorological sequences. The North Lagoon did not exhibit quite such a well defined seasonal salinity cycle. Salinity in the South Lagoon varied by up to about 8 g/L greater than or less than the median, whereas salinity in the North Lagoon showed variation around the median of about 6 g/L. Water level in the South Lagoon also showed a well defined seasonal cycle in all years with lowest level occurring in summer due to the lack of barrage flows then, to seasonally low sea level, and to evaporative water loss from the lagoon. In the South Lagoon the range of water level above and below the median averaged 0.2 m, whereas in the North Lagoon.

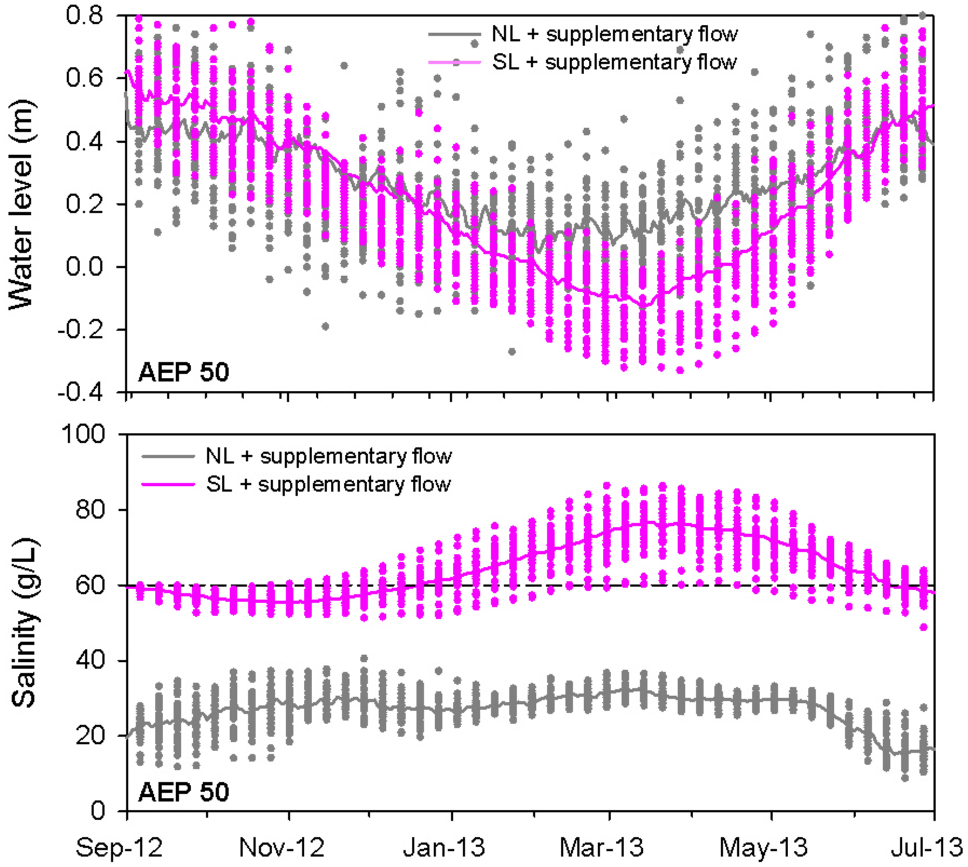

Figure 27. Simulated water levels and salinity in the North and South Lagoons for AEP50 + supplementary flows. The dots represent the results from the 30 individual simulations whereas the solid lines are the medians of all these simulations.

4.4 Conclusions Section 4

The purpose of this analysis has been to assess how a series of likely barrage flows over the coming year will impact salinities and water levels in the North and South Lagoons of the Coorong and how the addition of supplementary flows would affect these impacts. Six Annual Exceedence Probability scenarios are considered representing 25, 50, and 90 percentile exceedence flow sequences each with and without supplementary environmental flows. All 6 flow scenarios would be expected to prevent the salinity in the South Lagoon from exceeding 100 g/L during this time and for salinity in the North Lagoon to remain below 60 g/L. Even considering the likely variability due to variation in meteorological and sea level conditions, it is almost certain that the modelled salinity and levels would not exceed the 60 and 100 g/L in the two lagoons.

The base flows considered which range from 5844 GL/year (AEP25) to 3174 GL/year (AEP90) are mid range flows through the barrages by historical standards. A flow volume of 3174 GL/year is close to the median of the annual barrage discharges over the long term (118 years), whereas, the 5844 GL/year is close to the 30 percentile long-term annual flow volume. The supplementary flows serve to increase water levels in both lagoons, but the maximum increase is only a few centimetres occurring in summer. The supplementary flows have a more pronounced impact on lagoon salinity with maximum salinity reduced by ~10 g/L in the North Lagoon and ~5g/L in the South Lagoon. .

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