Hydrodynamic modelling to inform Coorong Infrastructure Investigations Project

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Foreword

The Department for Environment and Water (DEW) is responsible for the management of the State's natural resources, ranging from policy leadership to on-ground delivery in consultation with government, industry and communities.

High-quality science and effective monitoring provides the foundation for the successful management of our environment and natural resources. This is achieved through undertaking appropriate research, investigations, assessments, monitoring and evaluation.

DEW's strong partnerships with educational and research institutions, industries, government agencies, Landscape Boards and the community ensures that there is continual capacity building across the sector, and that the best skills and expertise are used to inform decision making.

John Schutz
CHIEF EXECUTIVE
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Acknowledgements

The Department for Environment and Water (DEW) acknowledges the Traditional Custodians of the lands and waters, current land managers, and all Aboriginal and Torres Strait Islander South Australians. The Department also acknowledges that Aboriginal Nations are the first managers and decision makers of Country and that Country has sustained their culture and economy for thousands of generations. The care, skill and knowledge of Aboriginal Nations has shaped the character of Country across the continent and is seen as an integrated and interdependent cultural landscape.

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

The work undertaken in the Phase 2 Hydrodynamic Modelling informed the Ecological Investigations, and was part of the Coorong Infrastructure Investigations Project.

We thank Roger Ebsary for his input and Ian Teakle for his technical review of this report.

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1 Introduction

The Coorong, Lower Lakes and Murray Mouth (CLLMM) are located at the ocean terminus of the Murray-Darling system, Australia's largest river system. The Lower Lakes (Lake Alexandrina and Lake Albert) are separated from the Coorong by five barrages (Goolwa, Mundoo, Boundary Creek, Ewe Island and Tauwitchere) built in the 1930-40s. Lake Albert is a terminal lake connected to Lake Alexandrina by a narrow channel (the Narrung Narrows), and the Coorong is connected to the Southern Ocean (Encounter Bay) through the Murray Mouth. The CLLMM is listed as a Ramsar Wetland of International Importance, and as such the Australian Government has international obligations to maintain the ecological character of the site.

Drought and consumptive use of the River Murray has led to the ecological decline of the Coorong and Lower Lakes region. With reduced flows from the river, dredging is required to maintain an open Murray Mouth and reduced frequency of high flow events leads to increased salinity and sedimentation in the Coorong.

The scope of the Coorong Investigations Infrastructure Project (CIIP) is to investigate the feasibility of long-term infrastructure options for improving the ecological health of the Coorong. A short list of potential management options was developed through options analysis and community consultation. These were progressed through preliminary hydrodynamic modelling to inform further investigations for the CIIP. This included various dredging and pumping options, as well as connection with Lake Albert and south east catchments. Details of the preliminary modelling are provided in DEW (2021/10).

This report documents the second stage of modelling to inform the CIIP. Of the options that were modelled in stage 1, those that were identified as favorable from the ecological investigations process (DEW, 2021/21) were further refined. High resolution three-year simulations were used to identify the optimal scale of infrastructure options required for the Coorong to achieve a desired state (DEW, 2021), and any management actions required to reduce any trade-offs. Results of these scenarios were evaluated by the CIIP project team, which identified options for progression to long-term simulation monitoring, the results of which are presented here. Outputs from this modelling were provided for the subsequent Ecological Risk Assessment Framework (ERAF) assessment as part of the CIIP Phase 2 Ecological investigations (DEW, in prep).

2 Model schematisation

2.1 Overview

Three hydrodynamic models of the Coorong exist, each developed for a specific purpose, and hence varying in their representation (e.g. resolution) of the system. Stage 1 modelling utilised the original BMT model (BMT, 2019), the origins of which were in detailed representation of a dynamic mouth arrangement (due to sand and sediment movement). A second TUFLOW model was developed in parallel by the University of Western Australia (Collier et al, 2017) with a focus on bio-geochemical modelling. A third model was developed through the HCHB On Ground Works project (BMT, 2021a) with coarser resolution to enable long-term simulations (i.e. 30 years) of the various CIIP options. All three models have been utilised here: the original BMT model as a basis for refining the proposed options, the UWA model to assess dredging alignments, as it is better able to represent the bathymetry through the Parnka narrows; and finally, the rapid model for long-term simulation of the refined options. Details of all three models are provided below.

Note that biogeochemical modelling was undertaken by BMT (2021b) alongside the work presented here, to assess the performance of the refined infrastructure options on nutrients. Results of this modelling, and the work presented here, were used to inform the Phase 2 Ecological investigations (DEW, in prep*)*.

2.2 Original BMT Model

The preliminary scenario modelling (reference) and further refinement of options utilised the existing two-dimensional TUFLOW hydrodynamic model, with the configuration as outlined in BMT (2019). The model dynamically solves for water level/depth and salinity over the whole Coorong, from the barrages to south of Salt Creek, as seen in Figure 2-1. The sediment transport module included in the original model was not used in this work. This is the same model used in the Phase 1 CIIP hydrodynamic report (DEW, 2021/10).

The model simulates the period 07/05/2013 to 28/01/2016, a period of below average barrage inflows leading to poor flushing and increased salinity in the Coorong South Lagoon, providing a good test case for benefits from infrastructure options. The simulation period is short in the context of response time of the south lagoon to infrastructure changes, and hence has been used only to refine options before commencing the long-term model runs using the model outlined in Section 2.4.

The results of this model are specific to the boundary conditions used, and different conditions will produce different results. Along with the volume and timing of barrage flow, other inputs to the model such as net evaporation, wind and tides, will also influence the results, and can result in changes up to 40 g/L in south lagoon salinity (Lester et al., 2012).

It is expected that the relative comparisons between scenarios would be maintained irrespective of the input conditions, however the magnitude of the differences between scenarios will change. This assumption highlights the importance of testing in long-term simulations, to assess the influence of the different infrastructure options on the Coorong under a range of conditions.

Modifications to the original model are as per those made for stage 1 modelling, and the model validation and discussion on most assumptions and limitations are detailed in DEW (2021/10).

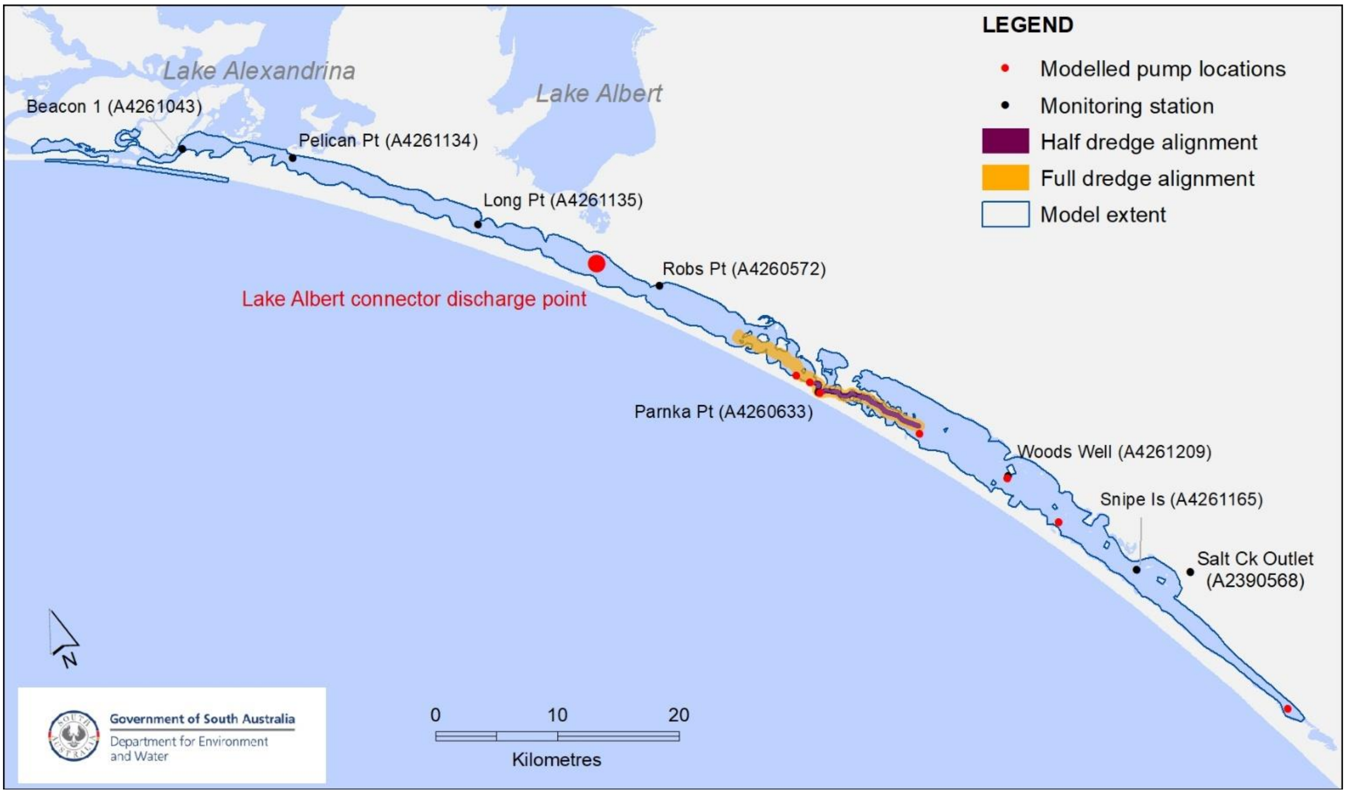

Figure 2-1 Model extent, monitoring stations and location of infrastructure options assessed

2.3 High-resolution model

Further refinement of dredging options through Parnka Narrows was undertaken in the TUFLOW model developed by UWA (Collier et al, 2017) which provides better resolution of the bathymetry at this location. This can be seen in Figure 2-2, where the original BMT model with triangular elements had the potential to create discontinuities between elements when dredging profiles were applied to the model mesh. The high-resolution mesh adopts rectangular elements through this section, providing a better representation of the bathymetry and connectivity in the direction of flow in the constricted region between lagoons.

The model simulates the period 01/05/2013 to 1/01/2016, which is essentially the same period as the original BMT model. It uses the same barrage inflow boundary conditions; however the model is configured to simulate the atmospheric heat exchange, modelling the water temperature and evaporation from water bodies. To do this additional meteorological inputs are required, for the incoming and outgoing heat from the system. These inputs were derived from the Bureau of Meteorology's BARRA dataset[1], and in the case of relative humidity and rainfall, from SILO data.

This model is the same model used in BMT (2021b), albeit without the external water quality model enabled. Performance of the model for hydrodynamic parameters (salinity, water level, water temperature) are provided in BMT (2021b). All scenarios required for comparison have been run in the high-resolution model to ensure consistent comparisons, rather than differences introduced by the differences between the BMT and High resolution model.

[1] More information on the Bureau of Meteorology's Atmospheric high-resolution Regional Reanalysis for Australia (BARRA) dataset is provided at http://www.bom.gov.au/research/projects/reanalysis/

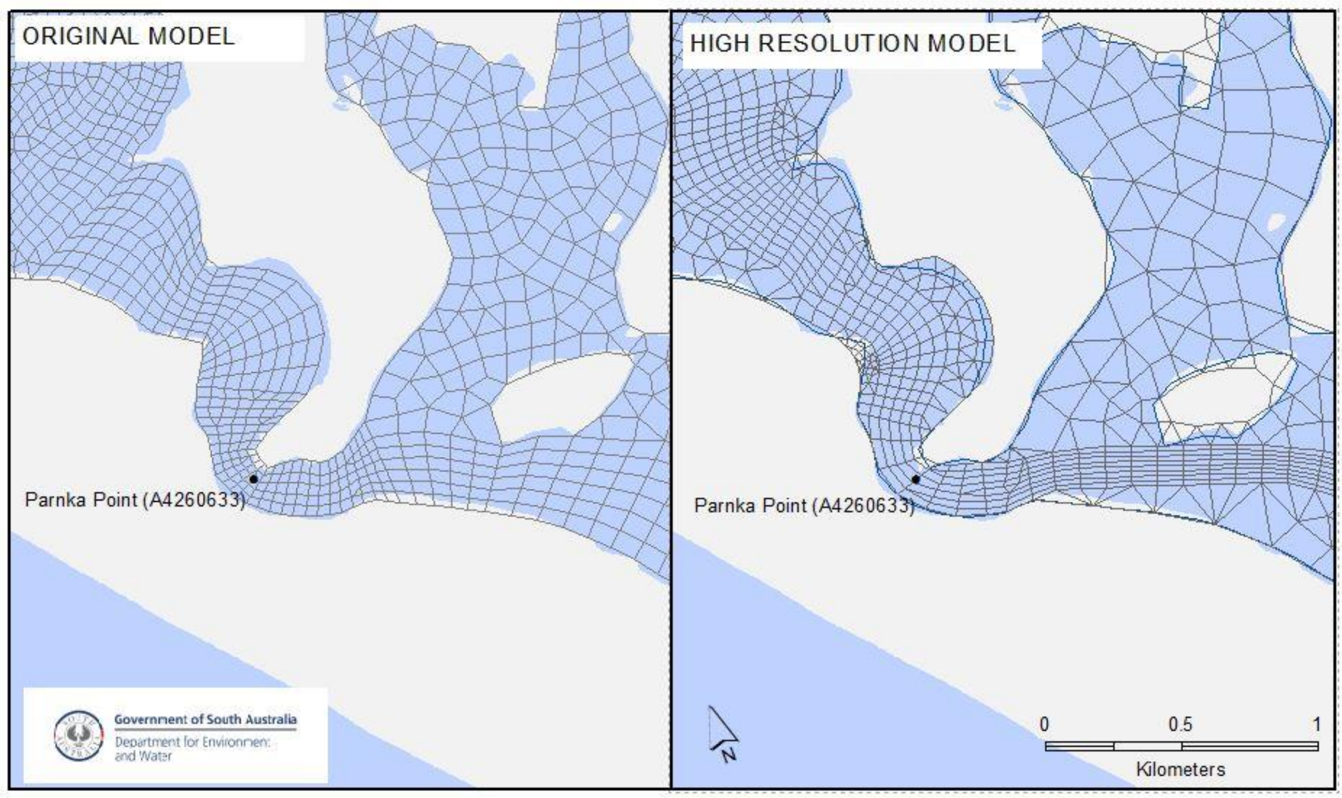

Figure 2-2 Representation of Parnka Narrows in the original and high resolution models. Note the narrower rectangles to the east of Parnka Point in the high resolution model, which allow for a more detailed representation of a dredging alignment

2.4 Rapid (long term) model

BMT (2021a) outlines the development of a 'rapid' TUFLOW FV model capable of running longer term simulations in shorter time frames. This work included:

1. The development of additional operational functionality within the TUFLOW FV software to schematise the Murray Mouth opening/closing dynamics with a morphological update structure.
2. The development and calibration/validation of the rapid 2D model that captures broad-scale trends in water levels and salinities and can simulate long-term scenarios quickly.

The rapid model has a coarser mesh than the original BMT TUFLOW model with 2,202 nodes compared to 48,968 nodes in the original model used in DEW (2021). The coarser mesh results in a run time ratio in the order of 1:25,000, meaning simulations in the order of 100 years long can be undertaken in slightly over one day. Following the initial model development, additional calibration of the model was undertaken to improve the dynamic Murray Mouth representation and improve performance against salinity, water level and water temperature data. This additional calibration is outlined in Appendix A.

The model was used to simulate the period 1/1/1990 to 1/3/2019 (aligned to the availability of the BARRA meteorological data), and three simulations, adopting different boundary conditions were undertaken for each scenario:

1. Historic: observed historical conditions and representing barrage flows as they occurred. These conditions are useful for understanding what would have happened had the option been implemented in the past.

2. Current: observed historical conditions but with barrage flows representing current conditions, derived from the Source Murray Model Current Conditions model (MDBA, 2015). Current conditions barrage flow assumes current environmental water recovery and delivery patterns are implemented across the full period (i.e. current level Basin Plan implementation hind-cast to earlier years).

3. Climate change: observed historical conditions albeit with adjustments to atmospheric drivers to represent projected conditions at 2050 under an RCP8.5 (high emissions) climate change scenario. The adopted projections are as per DEW's 'guide to climate projections for risk assessment and planning in South Australia' (Green and Pannell, 2020). Relevant changes are:

    - Increased tide level of 0.24 m
    - Wind reduced by 0.8%
    - Temperature increase of 1.5 degrees
    - Reduction in rainfall of 6.6%.

    Historic barrage flows were adopted, based on Whetton and Chiew (2020), which states:
    Recent hydrological modelling studies, informed by future projections from global climate models, show a median projected decrease in mean annual runoff of 14% in the southern MDB (10–90 percentile range of _38% to +8%) by 2046–75 under the medium warming scenario. In the northern MDB the median projection is a decline in mean annual runoff of 10% (10–90 percentile range of -38% to +21%). The median projected decline in runoff is similar to the volume of water returned to the environment under the Basin Plan.

3 Options refinement

3.1 Scenarios

Investigations from Phase 1 modelling highlighted benefits and trade-offs for all options investigated, and sensitivity of the system in the scale of infrastructure options (e.g. pumping rates). Generally, the Phase 1 scenarios were intended to evaluate the relative performance of the different options in 'best case' scenarios, for example very large dredging profiles were assumed.

The intent of this component of work is to refine and improve on options that were identified as favourable from the Phase 1 ecological investigations process, to determine the appropriate scale of infrastructure options required for the Coorong to achieve a desired state, and management actions required to reduce any trade-offs. Acknowledging the complex interdependencies between ecological responses and environmental variables, for the purpose of hydrodynamic modelling, a preliminary definition of 'desired state' is presented in Table 3-1, to guide refinement of options.

Table 3-1 Hydrological parameters indicative of the 'desired state' for the Coorong. Coorong South Lagoon water levels and Coorong North Lagoon salinity optimal conditions are derived from the draft resource condition target from the draft Ramsar Management Plan (DEW, in prep). The Coorong South Lagoon salinity reflects the optimal condition, as described in the Desired State of the Coorong (DEW, 2021).

Parameter	Optimal conditions
Coorong South Lagoon water levels	Water levels in the Coorong South Lagoon to be maintained >+0.3 m AHD in June and July, between +0.4 m AHD and +0.2 m AHD from August to December (part of the Resource Condition Targets (RCT))
Coorong South Lagoon salinity	Average daily salinity in the South Lagoon < 60 ppt year-round
Coorong North Lagoon salinity	Average monthly salinity < 45 ppt (RCT)

Options identified from Phase 1 for further refinement include:

1. Pumping water out (only) from the Coorong South Lagoon (CSL) with water level triggers to minimize impacts on CSL water levels;
2. Pumping water in (sea water) and out from one location (i.e. pumping only one direction at a time);
3. Circulation pumping, i.e. pumping water out from one location, while pumping in sea water at a second location;
4. A passive connection between the CSL and southern ocean.

Table 3-2 specifies the scenarios that have been modelled as a means of refining the above options, alongside comparable options from Phase 1. Various pumping locations have been considered, the locations of which are provided in Figure 3-1.

Note that some scenarios were not modelled because they were favourable options, but rather, to provide upper or lower bounds on the extent of impact on salinity and water level. Further, not all scenarios were identified up front, but in response to findings throughout the refinement process.

While dredging alone was not considered a favourable option, it has been included in some scenarios as a complementary management action (e.g. to increase the connection between the north and south lagoons, to prevent undesirable water level drawdown). In addition to the original dredge profiles adopted in Phase 1 modelling, four more detailed profiles were provided by KBR (2021). These profile alignments are provided in Figure 3-2.

Table 3-2 Scenarios modelled using short-term (3 year) simulations for refinement

Group	ID	Description	Model used
Pump out trigger	*Out500_0.2m (Phase 1)*	*Pump out 500 ML/d from Policeman Point when water levels in CSL > 0.2m*	*Original BMT*
	Out500_0.3m (Phase 1)	*Pump out 500 ML/d from Policeman Point when water levels in CSL > 0.3m*	*Original BMT*
	Out1000_0.3m	Pump out 1,000 ML/d from Policeman Point when water levels in CSL > 0.3m	Original BMT
	Out500_0m	Pump out 500 ML/d from Policeman Point when water levels in CSL > 0.0m	Original BMT
	Out500_-0.2m	Pump out 500 ML/d from Policeman Point when water levels in CSL > -0.2m	Original BMT
	Out1500_0.3m	Pump out 1,500 ML/d from Policeman Point when water levels in CSL > 0.3m	Original BMT
Pump out + dredge	Out250_Dredge	As per Phase 1 Original BMT model run. Pump out 250 ML/d from Policeman Point, combined with dredging. Dredge alignment is approximately 200m wide, at -1.2mAHD. This scenario is not considered as a feasible option, but included to determine the impact of changing scale of dredge.	High-res
	Out250_DredgeLarge	Pump out 250 ML/d from Policeman Point, combined with dredging. Dredge profile is along the entire length of the Coorong to a width of 300m, and depth of -2.0mAHd. This scenario is not considered as a feasible option, but included to determine the impact of changing scale of dredge.	High-res
	Out250_NoDredge	Pump out 250 ML/d from Policeman Point. This scenario is not considered as a feasible option, but included to determine the impact of changing scale of dredge.	High-res
	Out250_Dredge_KBR01	Pump out at 250 ML/d from Policeman point, combined with dredging at Parnka. The dredge profile is alignment option 1 provided by KBR, weighted towards the natural channels of the lagoon, with dredge widths of 25-50 m, and elevations from -1.4 to -1.6 mAHD.	High-res
	Out250_Dredge_KBR01a	Pump out at 250 ML/d from Policeman point, combined with dredging at Parnka. The dredge profile is alignment option 1 provided by KBR, weighted towards the natural channels of the lagoon, with dredge widths of 50-100 m, and elevations from -1.2 to -1.4 mAHD.	High-res
	Out250_Dredge_KBR02	Pump out at 250 ML/d from Policeman point, combined with dredging at Parnka. The dredge profile is alignment option 2 provided by KBR, with the alignment along the natural channels, except where a more direct route is present. Dredge widths are of 25-50 m, and elevations from -1.4 to -1.6 mAHD.	High-res
	Out250_Dredge_KBR02a	Pump out at 250 ML/d from Policeman point, combined with dredging at Parnka. The dredge profile is alignment option 2 provided by KBR, with the alignment along the natural channels, except where a	High-res

		more direct route is present. Dredge widths are of 50-100 m, and elevations from -1.2 to -1.4 mAHD.	
	Out250_Dredge_KBR02a_ meshaligned	Pump out at 250 ML/d from Policeman point, combined with dredging (KBR option 2A). The alignment is as per the simulation above, but adjusted to tie in with the model mesh.	High-res
Pump in/out (one location)	*Out500_0.2m_In0.1m (Phase 1)*	*Pump out 500 ML/d from Policeman Pt when water levels in CSL > 0.2m, and in when water levels in CSL <0.1m*	*Original BMT*
	Out500_0.3m_In0.15m (Phase 1)	*Pump out 500 ML/d from Policeman Pt when water levels in CSL > 0.3m, and in when water levels in CSL <0.15m*	*Original BMT*
	Out250_0.3m_In0.15m (Phase 1)	*Pump out 250 ML/d from Policeman Pt when water levels in CSL > 0.3m, and in when water levels in CSL <0.15m*	*Original BMT*
	Out350_0.3m_In0.15m	Pump out 350 ML/d from Policeman Pt when water levels in CSL > 0.3m, and in when water levels in CSL <0.15m	Original BMT
	Out350_0.3m_InDeltaN-S	Pump out 350 ML/d from Policeman Pt when water levels in CSL > 0.3m, and in when water levels in CSL < CNL. Note that the modelling had limited functionality to embed this criteria, and as such, a time series of when water levels in CSL< CNL was produced from Basecase results. These conditions occur throughout the entire period of December to April (inclusive).	Original BMT
	Out350_0.3m_In0m	Pump out 350 ML/d from Policeman Pt when water levels in CSL > 0.3m, and in when water levels in CSL <0.0m	Original BMT
	Out350_In25dOut_23d_Seasonal	Pump out 350 ML/d from Policeman Pt from 1 May to 1 Oct; pump 350 ML/d in or out from 1 Dec – 1 May to fluctuate water levels. Note that the model had limited functionality to embed the water level fluctuation criteria, and as such, a time series of pump in/out over this period was developed by determining the volume of water between these levels, and accounting for evaporation. The result is to pump in at 350 ML/d for 25 days, and out 350 ML/d for 23 days.	Original BMT
	Out350_In25d_Out_5d_Seasonal	As above, however with different pumping fluctuation pattern of pumping. Pump out 350 ML/d from Policeman Point from 1 May to 1 Oct; pump in at 350 ML/d for 25 days and out 350 ML/d for 5 days, with 1 day between alternating pumping direction during 1 Dec – 1 May.	Original BMT
Circular location	*In250Rnd_Out250PolPt (Phase 1)*	*Pump in 250 ML/d at Round Is, and out 250 ML/d at Policeman Pt*	*Original BMT*
	In250PolPt_Out250Rnd	Pump in 250 ML/d at Policeman Pt, and out 250 ML/d at Round Is	Original BMT
	In250Parnka+2.5km_Out250Rnd	Pump in 250 ML/d at location 2.5km north of Parnka Point and out 250 ML/d at Round Is	Original BMT
	In250Parnka+0.95km_Out250Rnd	Pump in 250 ML/d at location 950 m north of Parnka Point and out 250 ML/d at Round Is	Original BMT
	In250_42MileX_Out250Rnd	Pump in 250 ML/d at Forty Two Mile Crossing and out 250 ML/d at Round Is	Original BMT
	Out250_42MileX_In250Rnd	Pump in 250 ML/d at Round Is and out 250 ML/d at 42 Mile Crossing	Original BMT

	Out250Parnka+0.95km_In250Rnd	Pump in 250 ML/d at Round Is and out 250 ML/d at 950 m north of Panka Point	Original BMT
	Out350Parnka_In350Wds Well	Pump in 350 ML/d at Woods Well and out 350 ML/d at Parnka Point	High-Res
	Out350Parnka+1.5km_In350WdsWell	Pump in 350 ML/d at Woods Well and out 350 ML/d at 1.5km north Parnka Point	High-res
Passive connection	*Pipe2000x10 (Phase 1)*	*10 pipes of nominal 2m diameter from CSL (Policeman Pt) to Southern ocean*	*Original BMT*
	Pipe2000x15	15 pipes of nominal 2m diameter from CSL (Policeman Pt) to Southern ocean	Original BMT
	Pipe2000x10_IN	10 pipes of nominal 2m diameter from CSL (Policeman Pt) to Southern ocean, with valves to allow only sea water flow into CSL	Original BMT
	Pipe2000x10_OUT	10 pipes of nominal 2m diameter from CSL (Policeman Pt) to Southern ocean, with valves to allow only CSL water to southern ocean	Original BMT

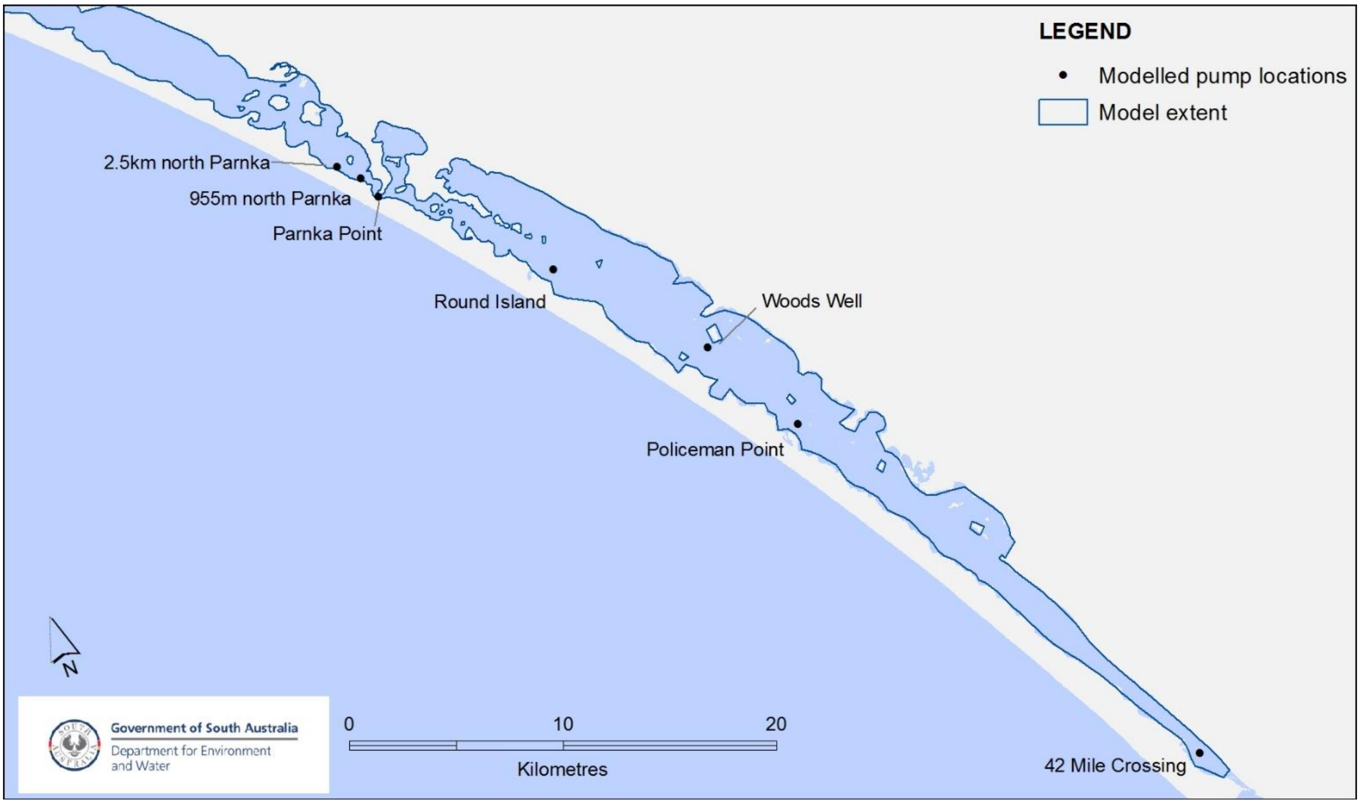

Figure 3-1 Modelled pump station locations

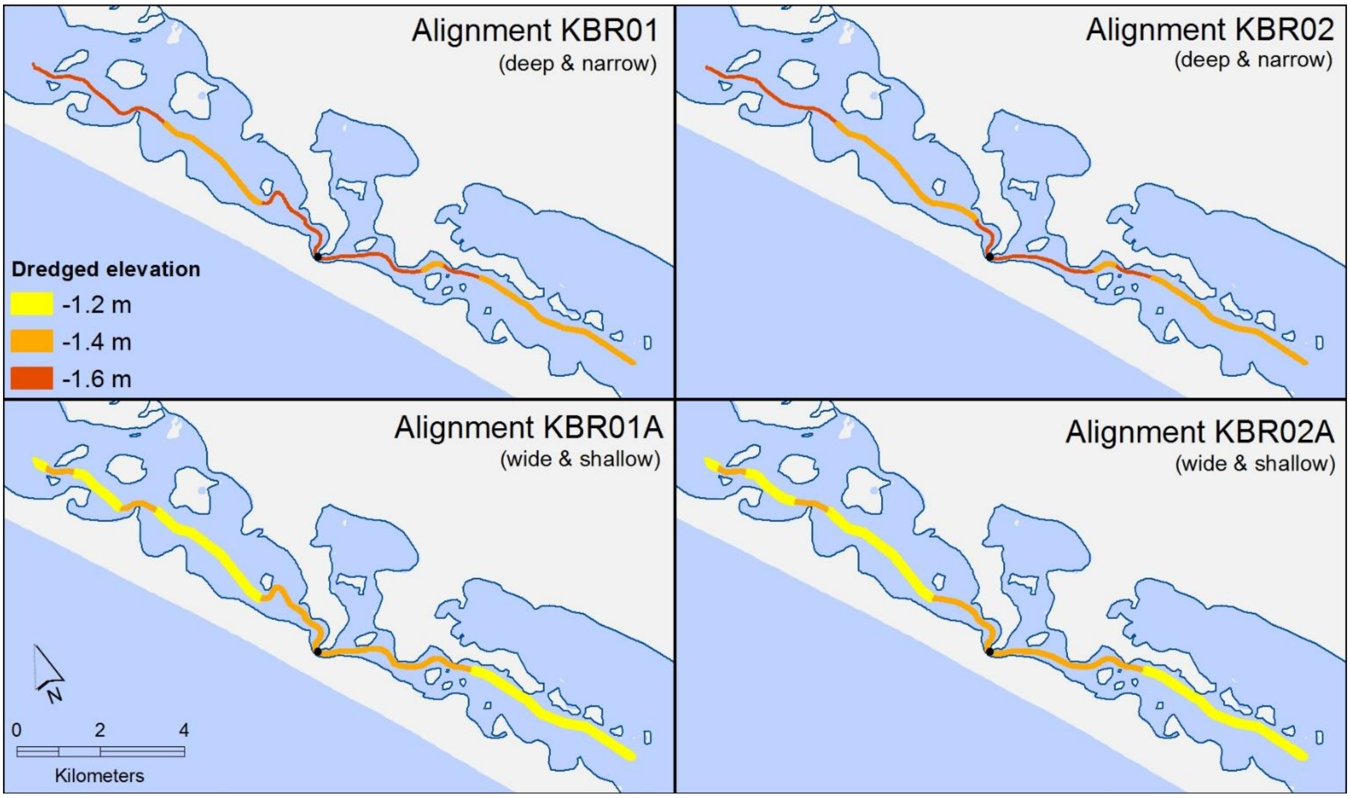

Figure 3-2 Dredge alignments modelled

3.2 Modelled outputs

For comparison of scenario performance, model results have been assessed as:

- Time series of water level and salinity at 7 point locations corresponding to existing monitoring stations (as indicated in Figure 2-1).
- Long sections, representing the water level and salinity at a distance from the mouth, along a centerline (as indicated in Figure 3-2). In order to represent the changes in time, we present average water levels and salinities experienced across seasons.
- Time series of the proportion of mass remaining in the Coorong South Lagoon. This represents how much of the total volume of water initially present remains in the CSL at a point in time, and is analogous to 'turn-over'. The smaller the amount of mass remaining in a given time period, the larger the flushing of the system that has occurred.

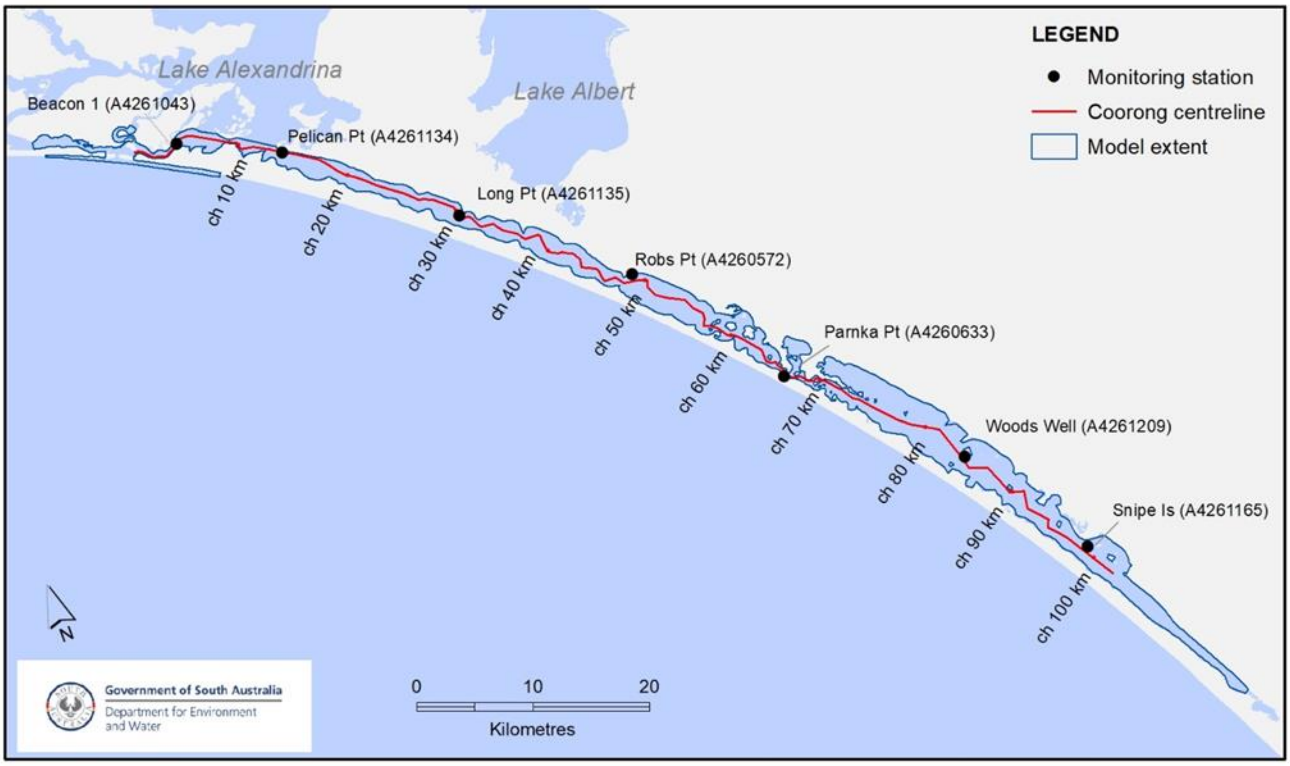

Figure 3-3 Location of reporting points for model outputs

3.3 Results

3.3.1 Pump out

The concern with the pump out scenario, as identified through Phase 1 modelling (DEW, 2021/10), is that it undesirably reduces water levels by relatively small amounts over spring, but larger amounts over late summer and autumn. Pumping out at 500 ML/d only when water levels in the CSL were above 0.2 or 0.3 m (when the north and south lagoons have a better connection) were trialled in the Phase 1 modelling but were insufficient in reducing salinity in CSL.

A pump rate of 1,000 ML/d at the higher trigger level of 0.3 m is found to have a significant improvement on salinity in the CSL (Figure 3-4) without a marked decrease in water levels (Figure 3-5), however it is insufficient to reduce salinities to below 60 ppt throughout the simulation (Figure 3-4). Peak salinities are in the region of 75 ppt.

A pump rate of 1,500 ML/d is sufficient to reduce salinities to within the desired rate (Figure 3-4) but has a marked impact on spring water levels in the south lagoon (Figure 3-6).

Lower trigger levels of 0 and -0.2m were also trialled, with the intention of increasing the period of pumping. Of all the options considered to date, pumping out 500 ML/d when water levels are greater than -0.2 m has the biggest reduction in salinity in the CSL (Figure 3-4 and Figure 3-6), however the impact on water levels (Figure 3-5 and Figure 3-6) are significant. Water level triggers below 0.2 m are not recommended for further consideration if there is a requirement to not reduce water levels below a do nothing case.

3.3.2 Pump out with dredge

Phase 1 model results indicated that pumping out from the Coorong South Lagoon alone had a negative impact on water levels. When combined with dredging, the improved connectivity between the north and south lagoons was able to reduce the water level draw down. Work undertaken by KBR (2021) in parallel to this Phase 2 of modelling sought to refine the potential dredge alignments, which was supported by high-resolution modelling. The original dredge profile, extreme (large) dredge profile and no dredging have also been modelled to provide an envelope of the potential impact.

There is minimal difference in salinity levels across either the north or south lagoon for the different dredge profiles (Figure 3-8). In general, the profile options that were narrower and deeper performed marginally better at reducing salinity. The dredge profile KBR02A was modestly better performing than the other profiles.

The drawdown of water in the south lagoon from pumping is offset by the dredging (Figure 3-9), with water levels in the CSL remaining at or above basecase conditions, except for a short window at the end of 2013 as water from the CSL can flow out to the CNL faster as water recede from the winter high levels.

The sensitivity of the model to the dredge profile was tested by re-configuring the KBR02A profile to align with the existing 'high resolution' model mesh. Despite the model used having a better resolution through Parnka Narrows, the mesh is coarser than the proposed alignments. There was negligible difference between the original and mesh aligned dredge profile, indicating that the difference in results across the different dredging scenarios is mostly representative of the system response rather than any difference between the mesh and profile alignments.

3.3.3 Pump in/out (one location)

Modelling from Phase 1 suggested that pumping in/out 500 ML/d with water level triggers of >0.3 m for pumping out and <0.15 m for pumping in was able to achieve desired salinity levels in the CSL, while a rate of 250 ML/d at the same triggers was not. The intermediate pump rate of 350 ML/d has been trialled and results indicate it is on the cusp of achieving desirable salinities in the CSL (Figure 3-10). Salinities are below 60 g/L over most of the simulation, with the exception of summer and the 1st autumn (Figure 3-11).

The trigger to stop pumping in at 0.15 m AHD resulted in salinities in the CNL higher than the base case, as south lagoon water pushed into the north lagoon over summer when pumping seawater into the CSL up to 0. 15 m AHD (Figure 3-11). Alternative triggers for this 350 ML/d pump rate do not perform as well with respect to reducing salinity (Figure 3-11), however do reduce the increase in salinity in the CNL. However, the increased salinities are still generally below 45 g/L, especially when considered as a lagoon average, and as such the salinity increases may not be of concern.

The seasonal pumping scenarios (pumping in for 25 days and out for either 23 or 5 days, scenario dependent) had the fastest impact on the volume of water turned over in the CSL (Figure 3-12), as the scenario is not constrained by a water level trigger at the beginning of the simulation. These option perform equally in the long term for water turnover as pumping out at a higher rate (500 ML/d) with water level triggers of 0.3m (for pumping out) and 0.15m (pumping in), with the 23 day pumping out resulting in marginally lower mass remaining by the end of the three year simulation. These options have the benefit of pumping out of the CSL when the highest concentrations occur. They are not, however, as efficient at reducing peak salinities, most likely due to the lower water levels, and hence reduced dilution effect, over late summer-autumn. Scenarios with a higher pumping rate have a greater ability to reduce salinity in the south lagoon, and the water level triggers prevent undesirable draw down of water levels. The results are similar for the 350 ML/d pumping scenarios, the water level triggers of 0.3 and 0.15 m has the greatest reduction in salinity.

3.3.4 Circular pumping (in/out at separate locations)

The 'circular location' results provide insights on both the direction of circulation, and the impact of the pump locations.

Results for the 'In250Rnd_Out250PolPt' and 'In250PolPt_Out250Rnd' scenarios, which are identical except in the direction of circulation (in at Round Island and out at Policeman Point for the former, and vice versa for the latter), indicate that direction has only marginal impact on resulting salinities (Figure 3-13 to Figure 3-14) and mass turnover in the CSL (Figure 3-15). Pumping in at Round Island results in slightly lower salinities in the CSL at the end of the simulation (Figure 3-14), however salinities at Snipe Island (Figure 3-13) are slightly elevated during autumn compared to the pumping in at Policeman Point scenario, given the pipe outlet is closer to the Snipe Island reporting point. There is negligible difference in the resultant water levels in either the north or south lagoon for these two scenarios. The results further indicate that pumping location has limited impact on overall south lagoon salinity.

For comparable scenarios which all have the same pump out location at Round Island, but different pump in locations, as proposed through consultation processes. Figure 3-13 and Figure 3-14 indicate that the three scenarios which pump in north of Parnka Point have a substantial effect on reducing salinity within the Parnka Narrows section. This, however, can be explained by the fact that the channel through Parnka Point is particularly narrow compared to the rest of the CSL. Hence the impact appears greatest because the volume of water over which the pump can influence is spread more longitudinally and therefore presents as a difference on the long section plot. The impact seen in Figure 3-13, which is marked at Parnka Point is because this station is closer to the pump in location than any other stations for any other scenario. This scenario can also be seen to increase water levels within this constriction by a small amount (Figure 3-16, note y axis scale). The options that pump in north of Parnka Point are slightly less effective at reducing south lagoon salinities compared to the other locations.

To understand the impact of pump location, it is best to consider Figure 3-15, which shows the overall impact on the CSL through export of the initial body of water in the CSL. The results indicate the pump located at Forty-two Mile Crossing is most effective, though the difference in the end result is minimal. The Forty Two Mile Crossing scenario generally also has the smallest impact on water levels compared to basecase.

An option to pump out from Parnka Narrows was considered, as from an engineering design and cultural site perspective this site is well suited to the pump out location, even though it would not be expected to have as large a salinity benefit as the out pump located further south. This option was modelled in the high-resolution model, as the resolution of the Parnka Narrows was not sufficient in the original model. For this reason, the results are presented separately.

Initial modelling with the pump continuously operating at 350 ML/d indicated that the constriction in this narrow section prevented sufficient inflow of water (from the north or south lagoon) to replace the volume that was being pumped out. As a result, the area was becoming dry. Two strategies were tested to mitigate this impact, stopping the out pump at approximately the minimum water level experienced at the Parnka Point monitoring station, of -0.3 m AHD, and dredging from the pump location through to the CSL to improve the connection and ability for the volume removed to be replaced from the main body of the south lagoon. The results indicate that the two scenarios produce a similar reduction in south lagoon salinity (Figure 3-17), suggesting that the water level trigger is not reducing the pump operation period for a material amount of time. Water levels in the CSL (Figure 3-18 and Figure 3-19) were also slightly higher with the water pumped into the main body of the CSL slightly increasing water levels compared to the base case. The increased water level is less pronounced in the scenario that incorporates dredging.

3.3.5 Passive connection

Phase 1 testing of pipes to act as a passive connection between the CSL and southern ocean did not trial a sufficient number or size of pipes to meet the desired CSL criteria. A scenario of 15 pipes at 2.0 m diameter, trailed here, reduces salinities in the CSL to below 60 g/L year round (Figure 3-20 and Figure 3-21). The impact of this option is decreased water levels in the CSL during winter and spring (to potentially undesirable levels), and increased water levels during summer and autumn (Figure 3-22).

A further option that was considered in Phase 2 was for a unidirectional passive pipe system, not dissimilar to that employed at West Lakes. The residence times in the Coorong are much longer than the West Lakes system, and there is not the second water body of the Port River to exploit a water level difference to drive flows out of the system separate to the tidal influence. Options for only allowing flow into or out of the Coorong (when there is sufficient head difference to naturally drive this flux) showed the unidirectional flow out to have similar magnitude impact on salinity reduction (Figure 3-20) and mass turnover (Figure 3-23) as the bi-directional option. This option, however, had the most negative impact on water levels in winter and spring (Figure 3-22). Further discussion on the expected operational approach to managing a unidirectional pipes configuration is required to explore further.

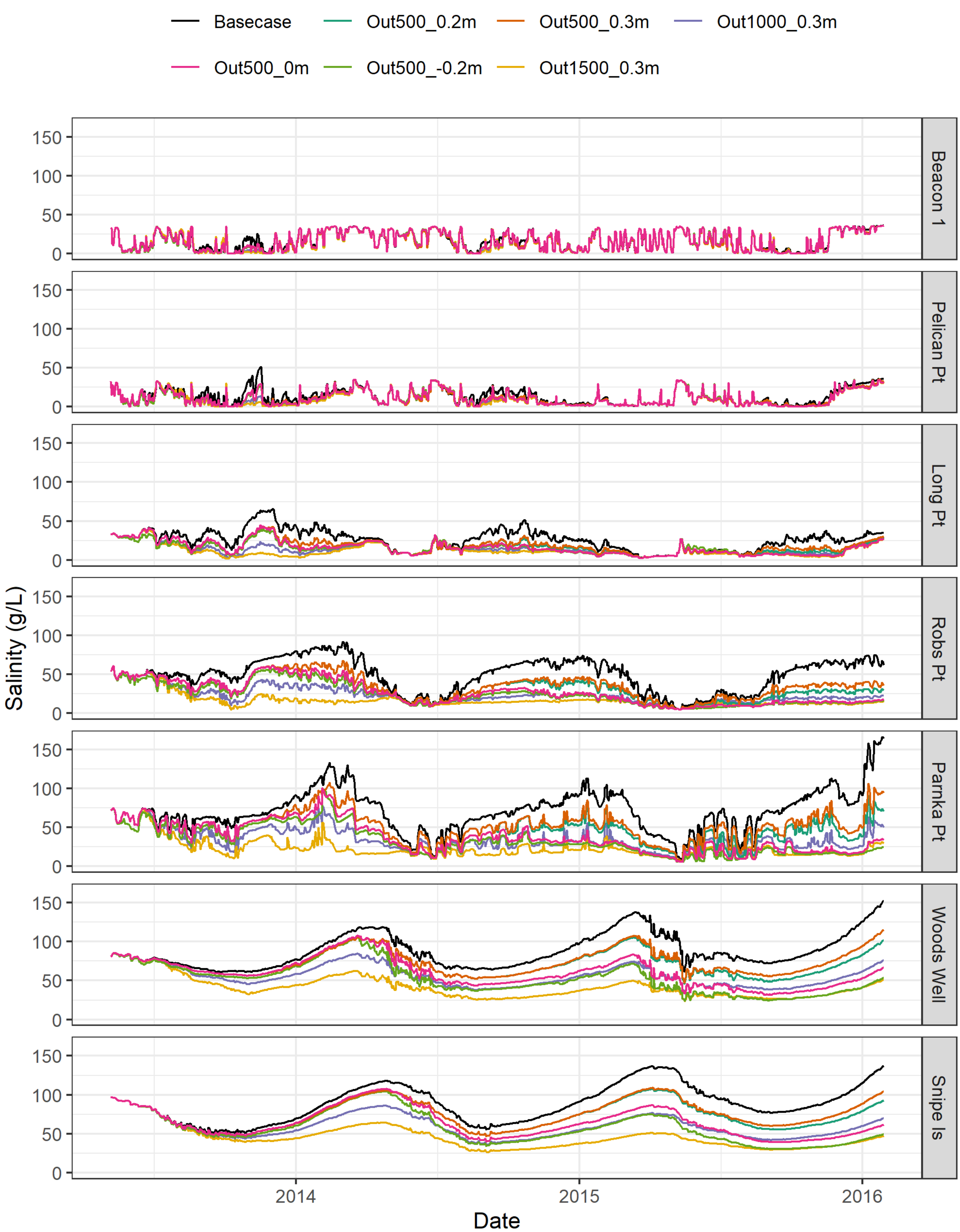

Figure 3-4 Modelled salinity under base case and pump out scenarios

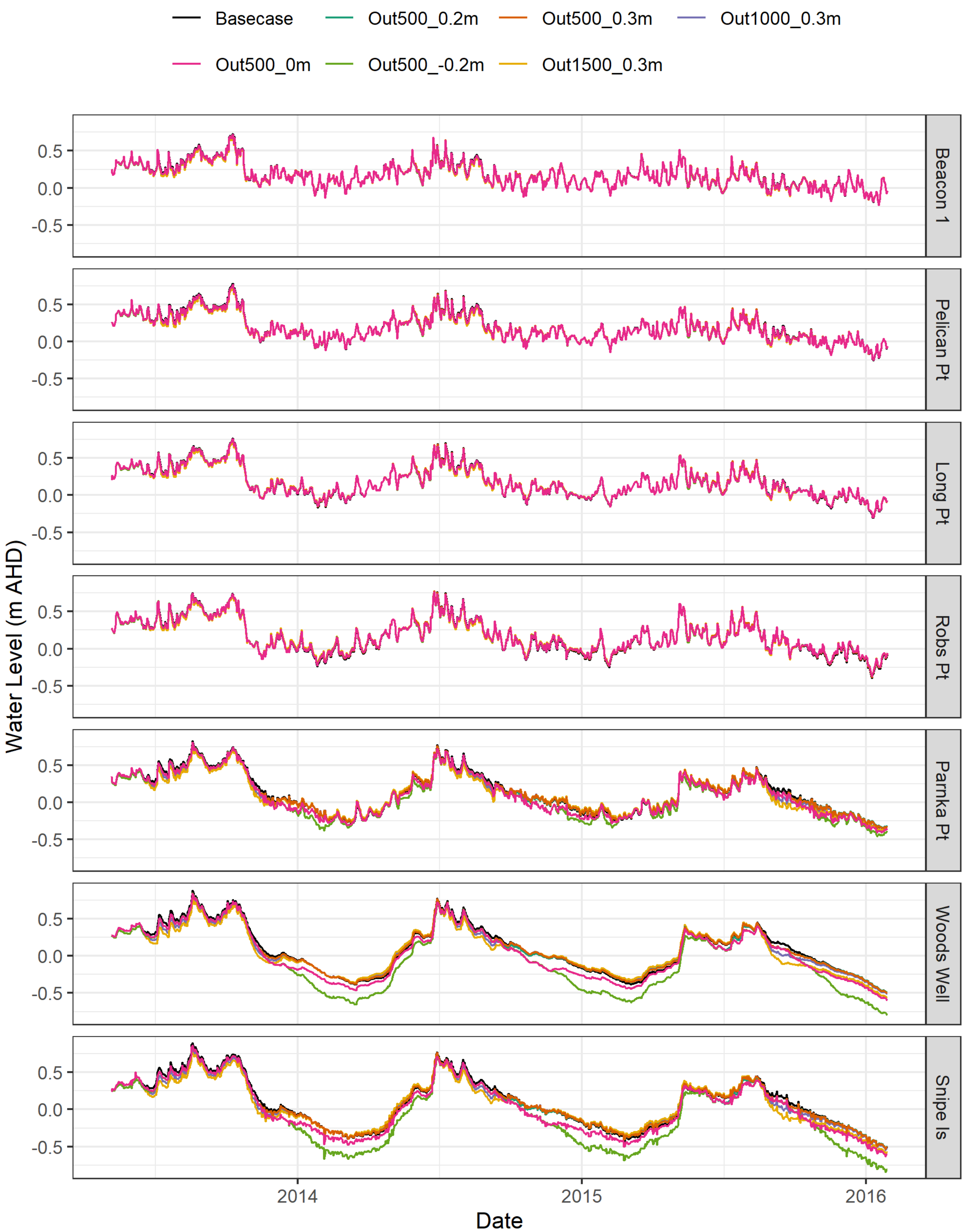

Figure 3-5 Modelled water level under base case and pump out scenarios

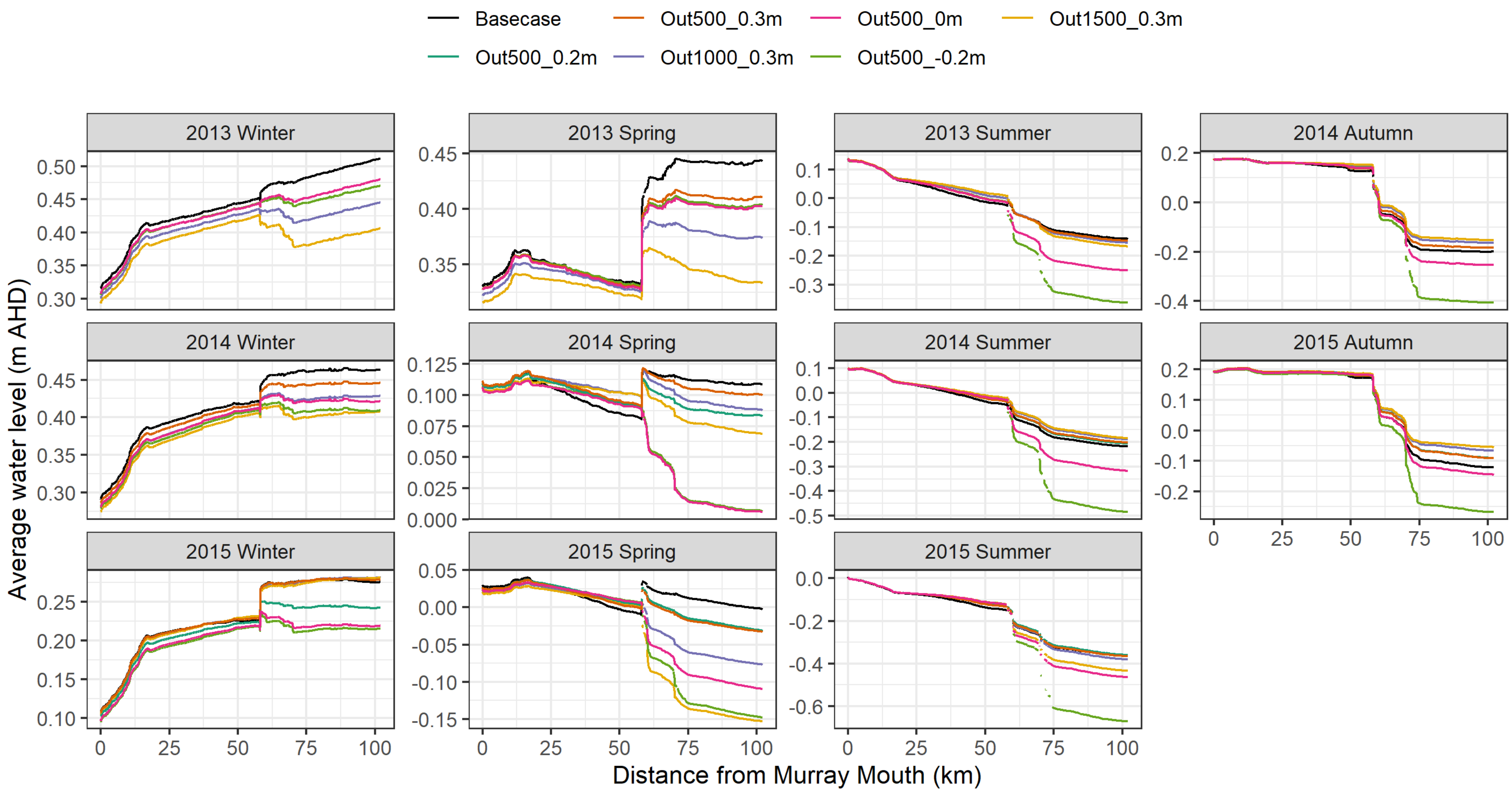

Figure 3-6 Modelled water level along the length of the Coorong (north to south) for base case and pump out scenarios

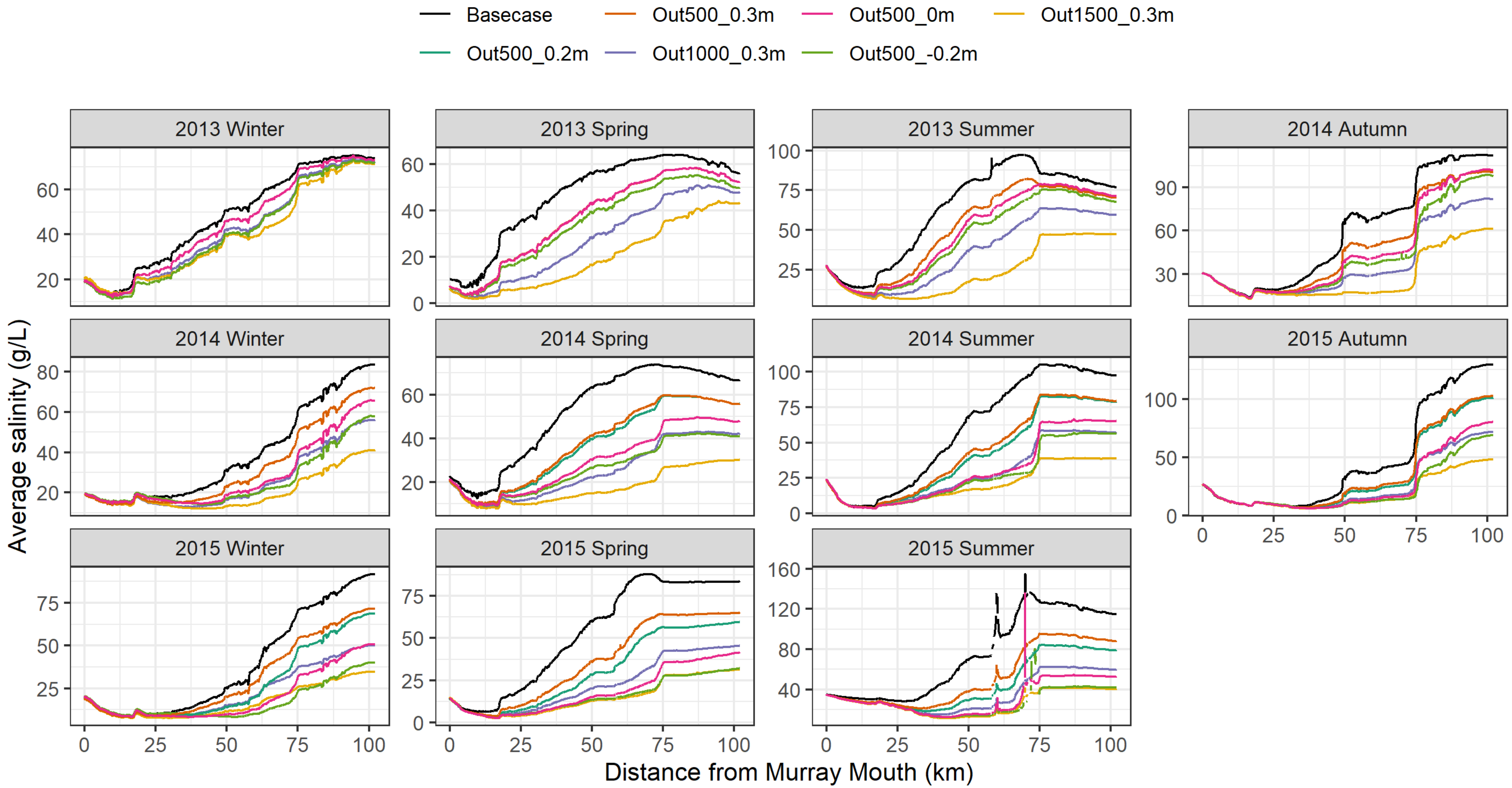

Figure 3-7 Modelled salinity along the length of the Coorong (north to south) for base case and pump out scenarios

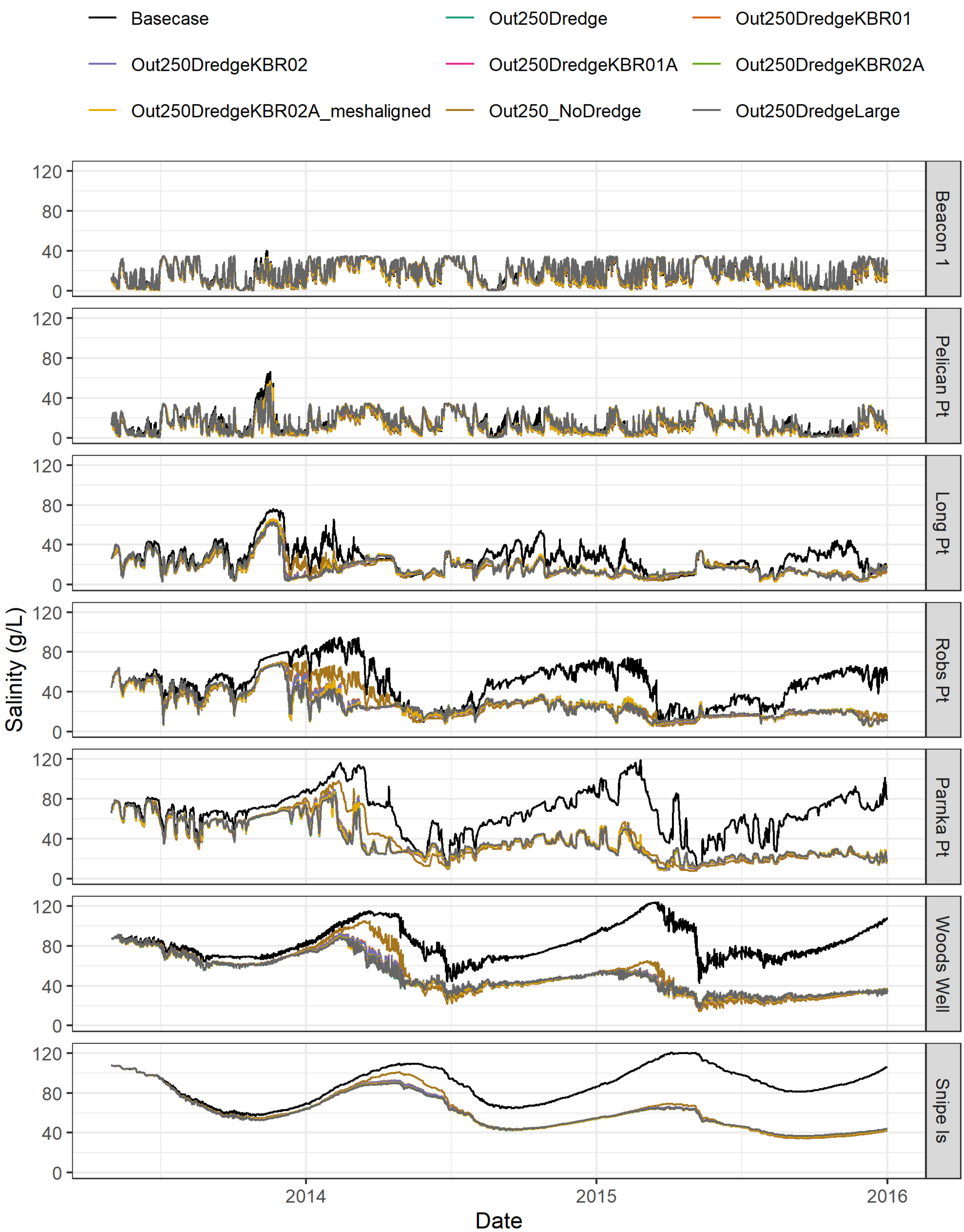

Figure 3-8 Modelled salinity under base case and pump out (250 ML/d) combined with dredging scenarios

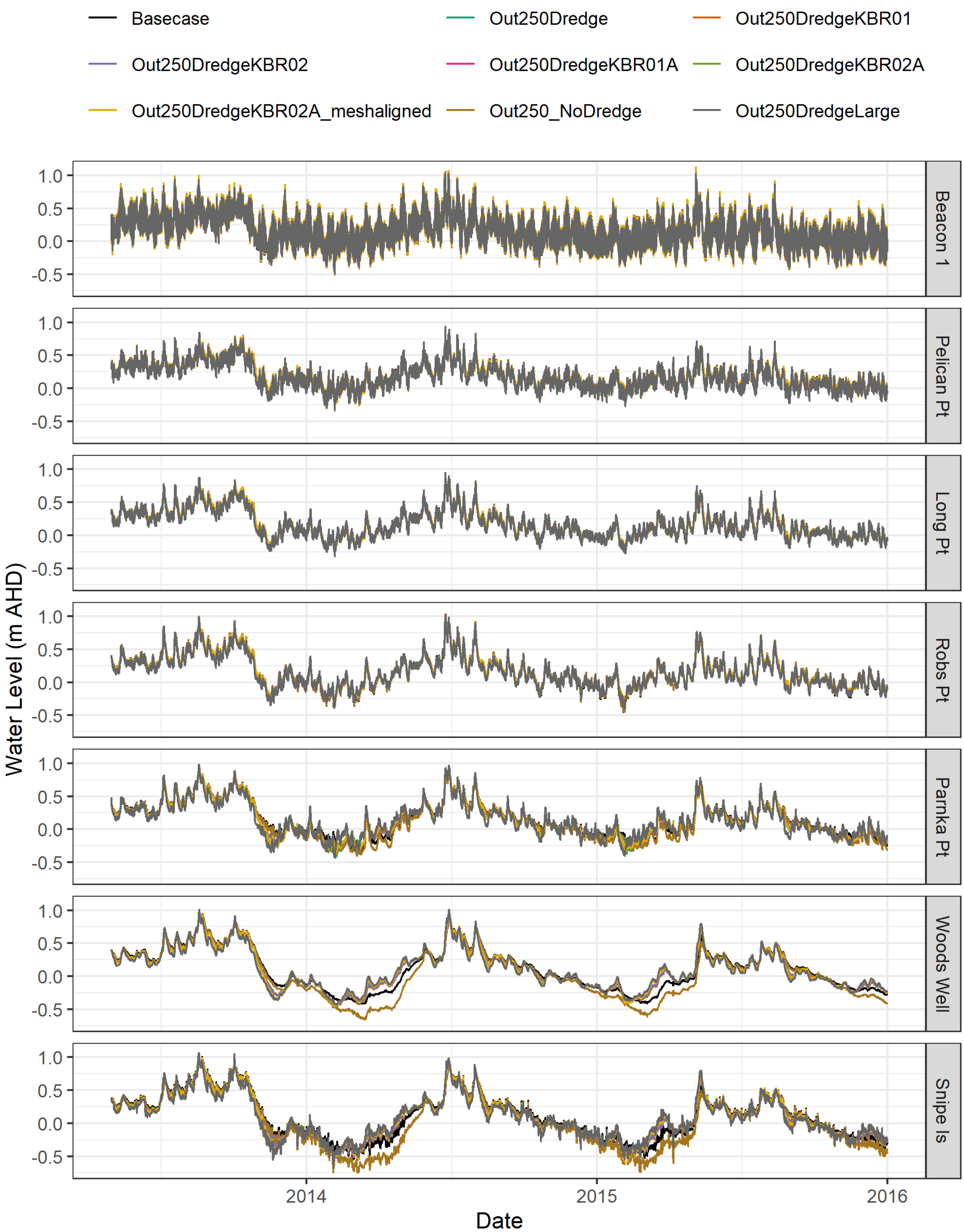

Figure 3-9 Modelled water level under base case and pump out (250 ML/d) combined with dredging scenarios

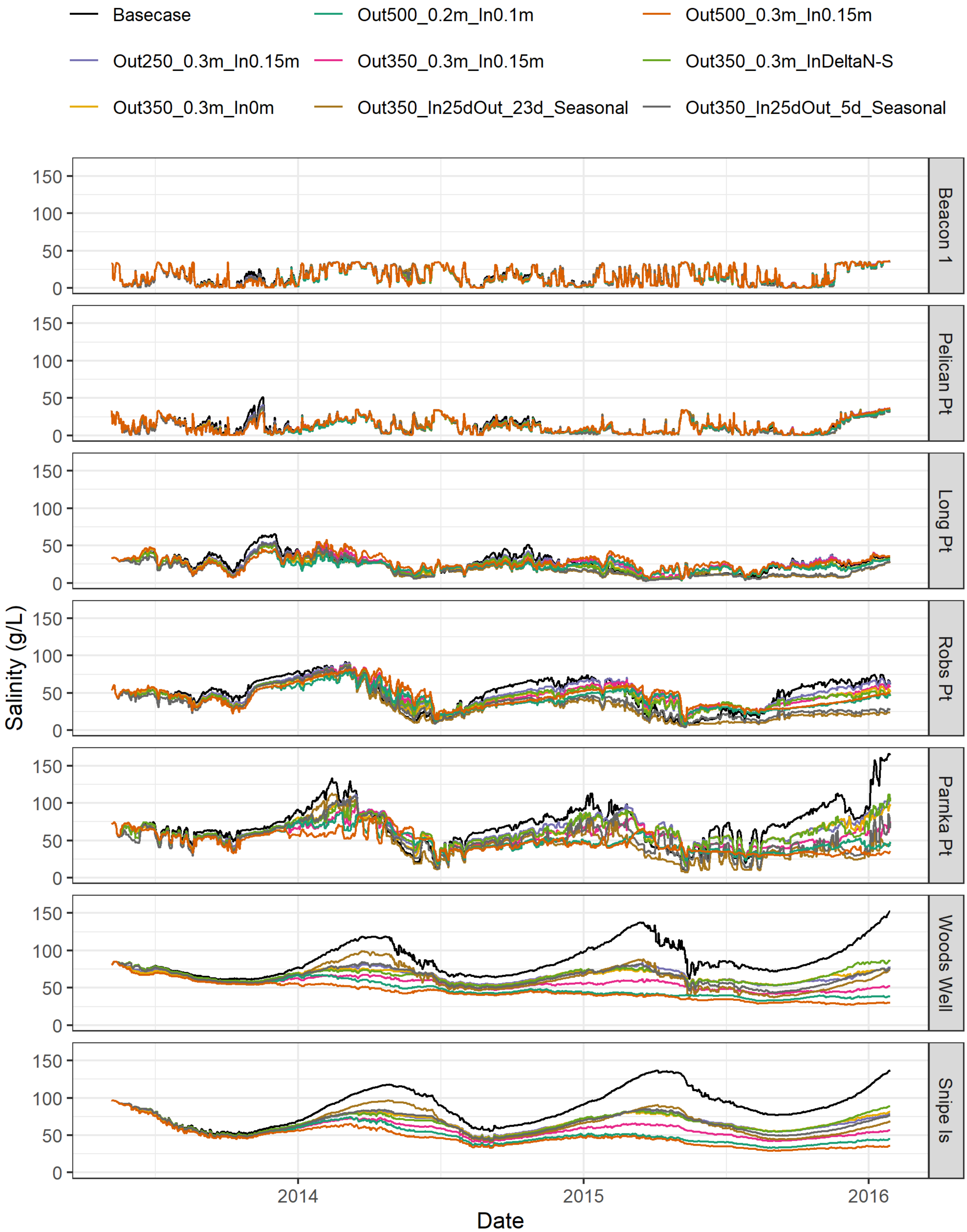

Figure 3-10 Modelled salinity under base case and pump in/out (one location) scenario

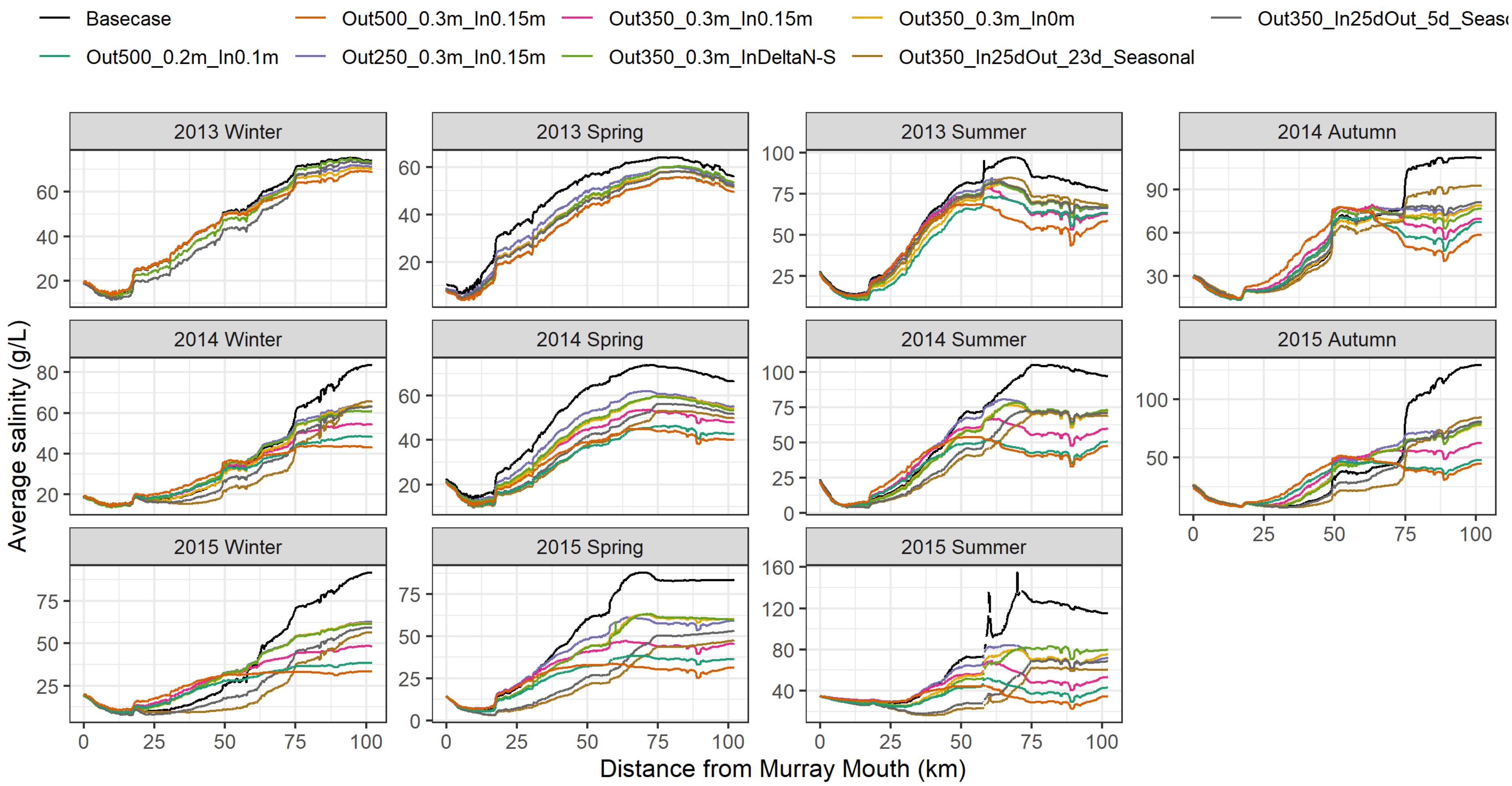

Figure 3-11 Modelled salinity along the length of the Coorong (north to south) for base case and pump in/out (one location) scenarios

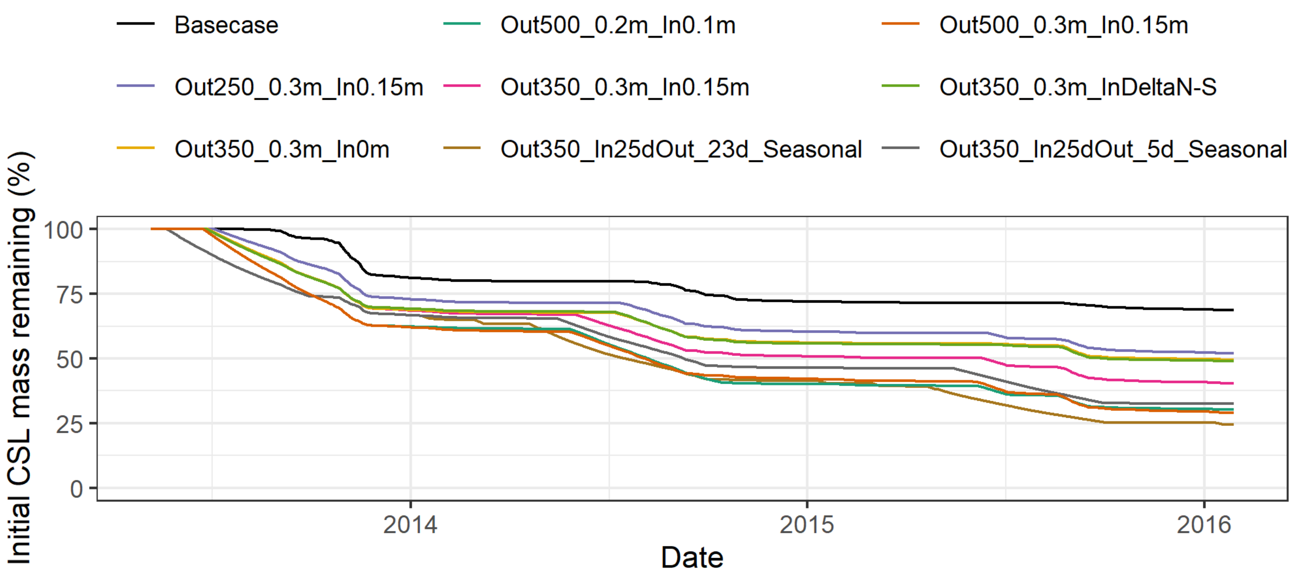

Figure 3-12 Modelled proportion of CSL mass remaining for basecase and pump in/out (one location) scenarios

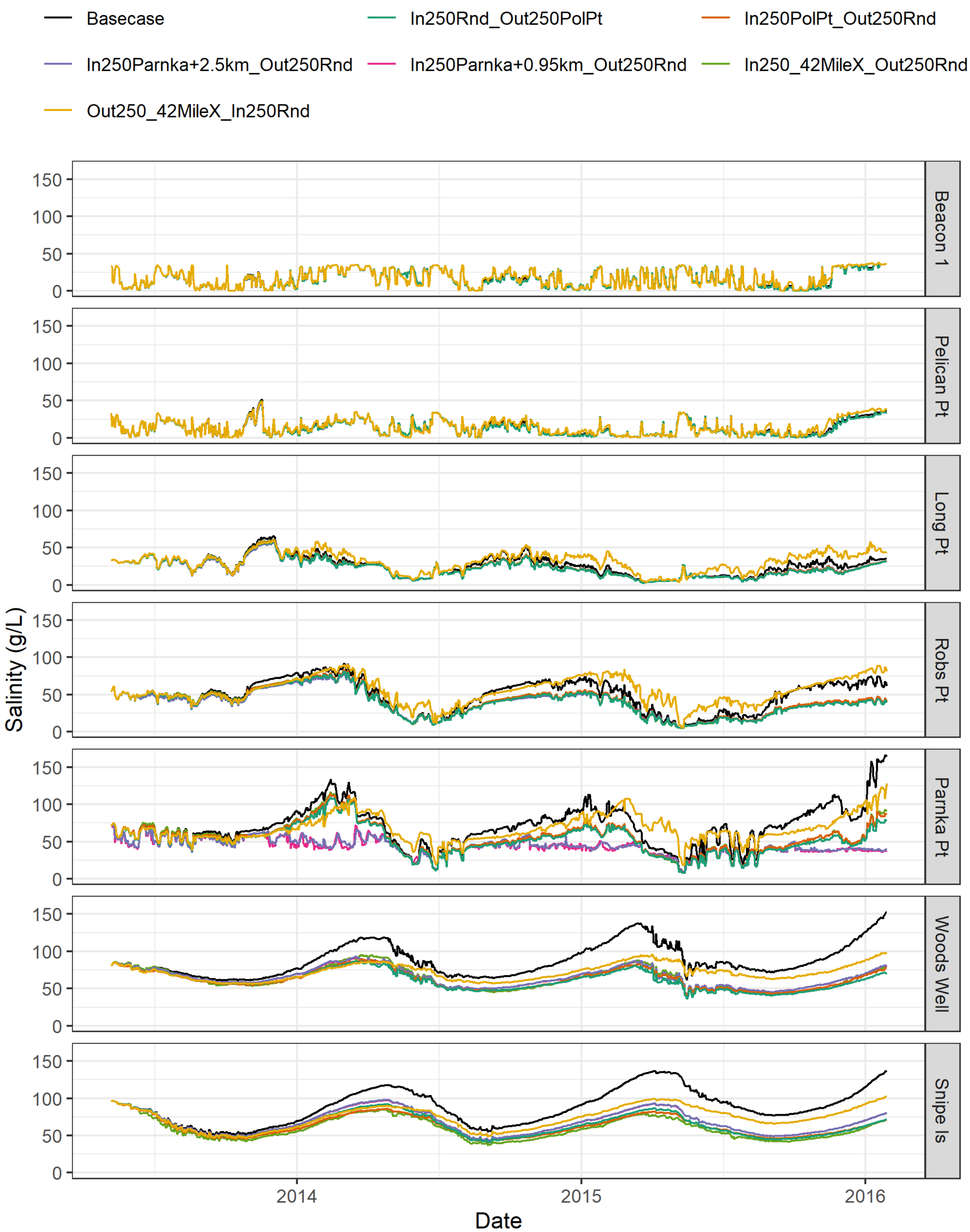

Figure 3-13 Modelled salinity under base case and circulation pumping scenarios at different locations

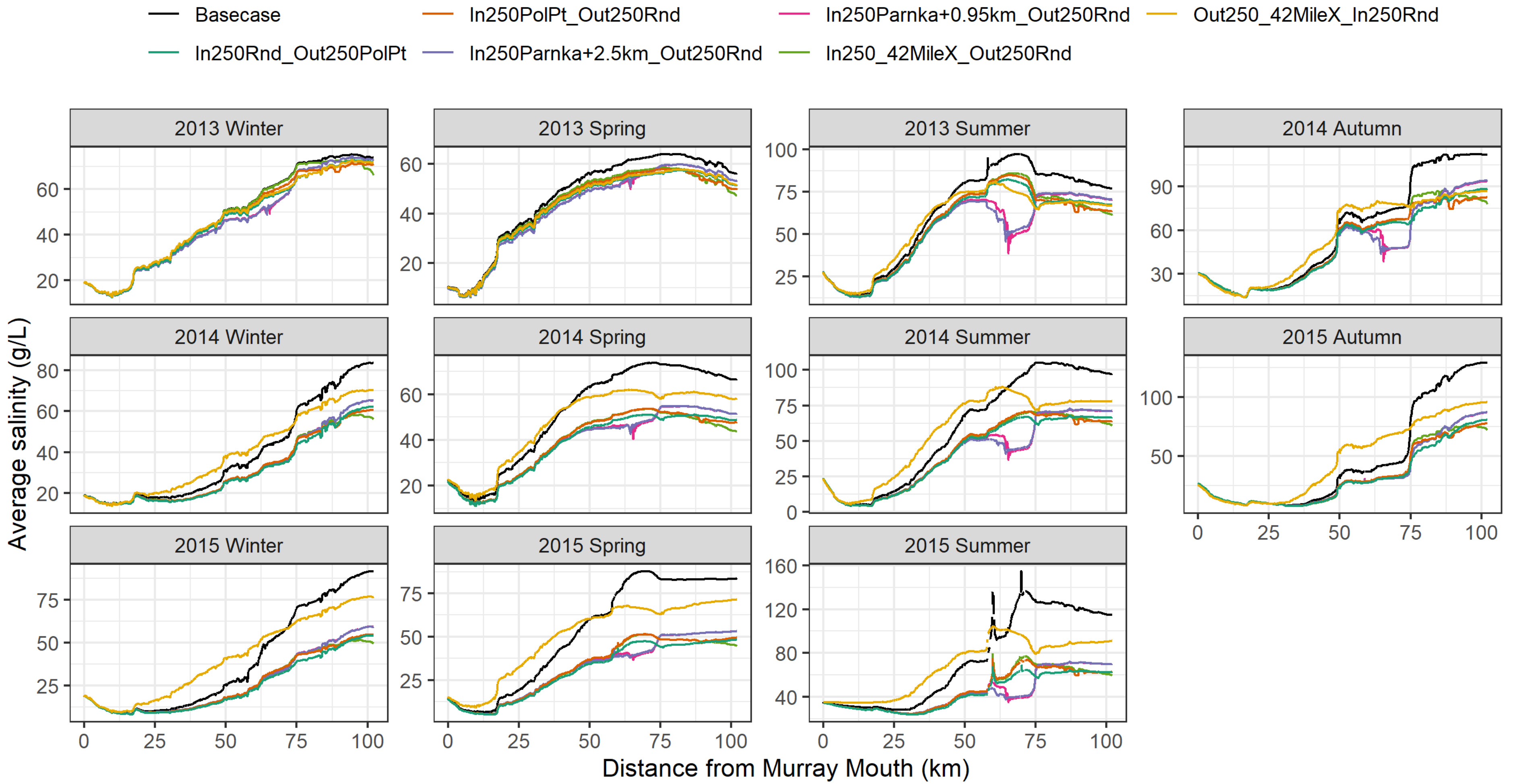

Figure 3-14 Modelled salinity along the length of the Coorong (north to south) for base case and circulation pumping scenarios at different location

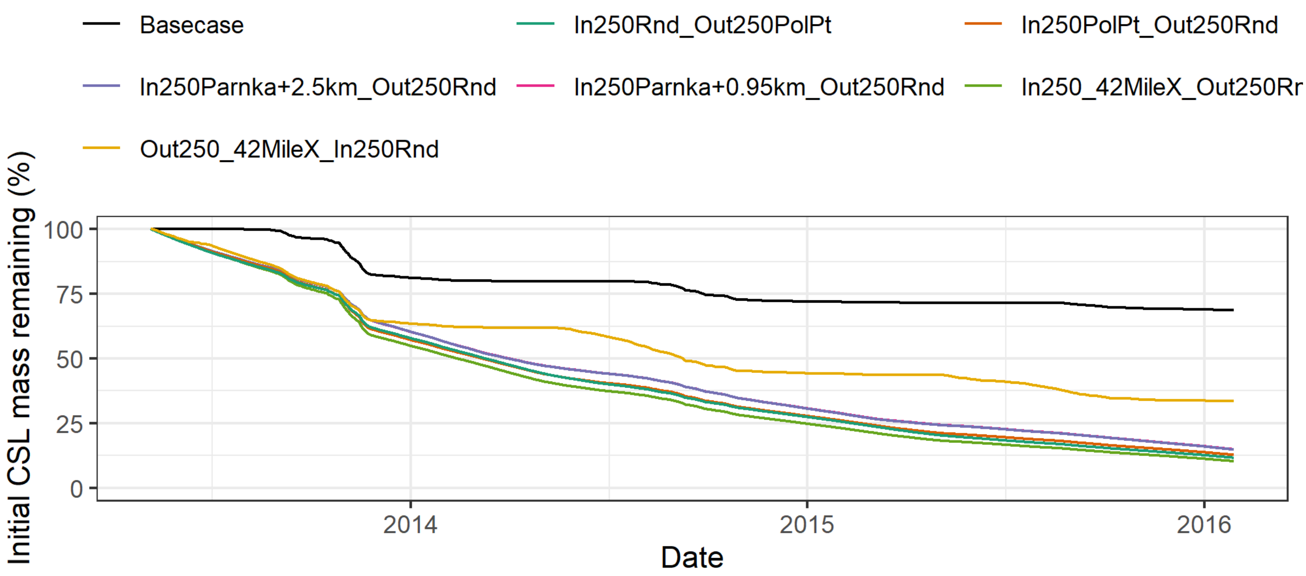

Figure 3-15 Modelled proportion of CSL mass remaining for base case and circulation pumping scenarios at different location

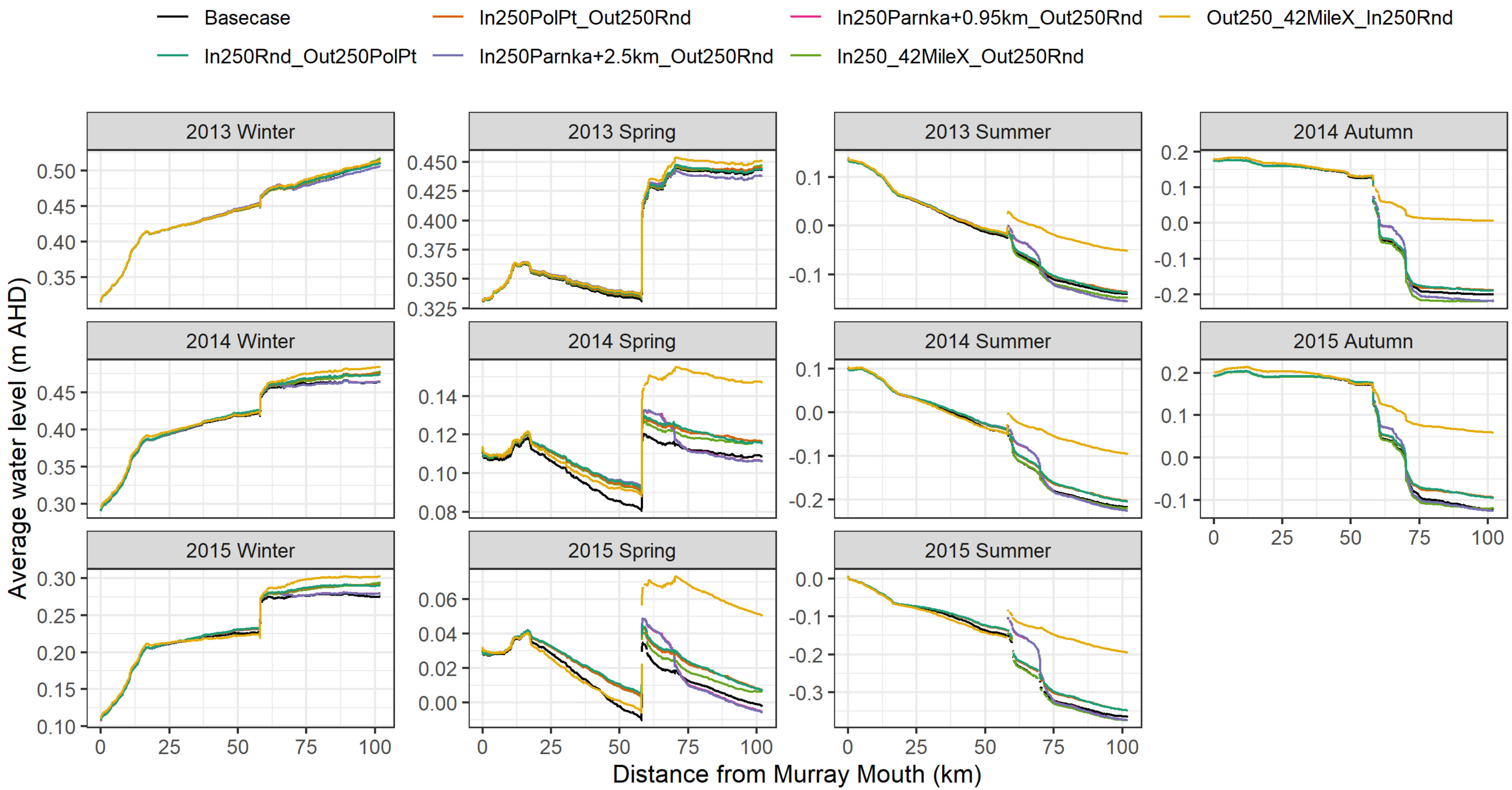

Figure 3-16 Modelled water level along the length of the Coorong (north to south) for base case and circulation pumping scenarios at different location

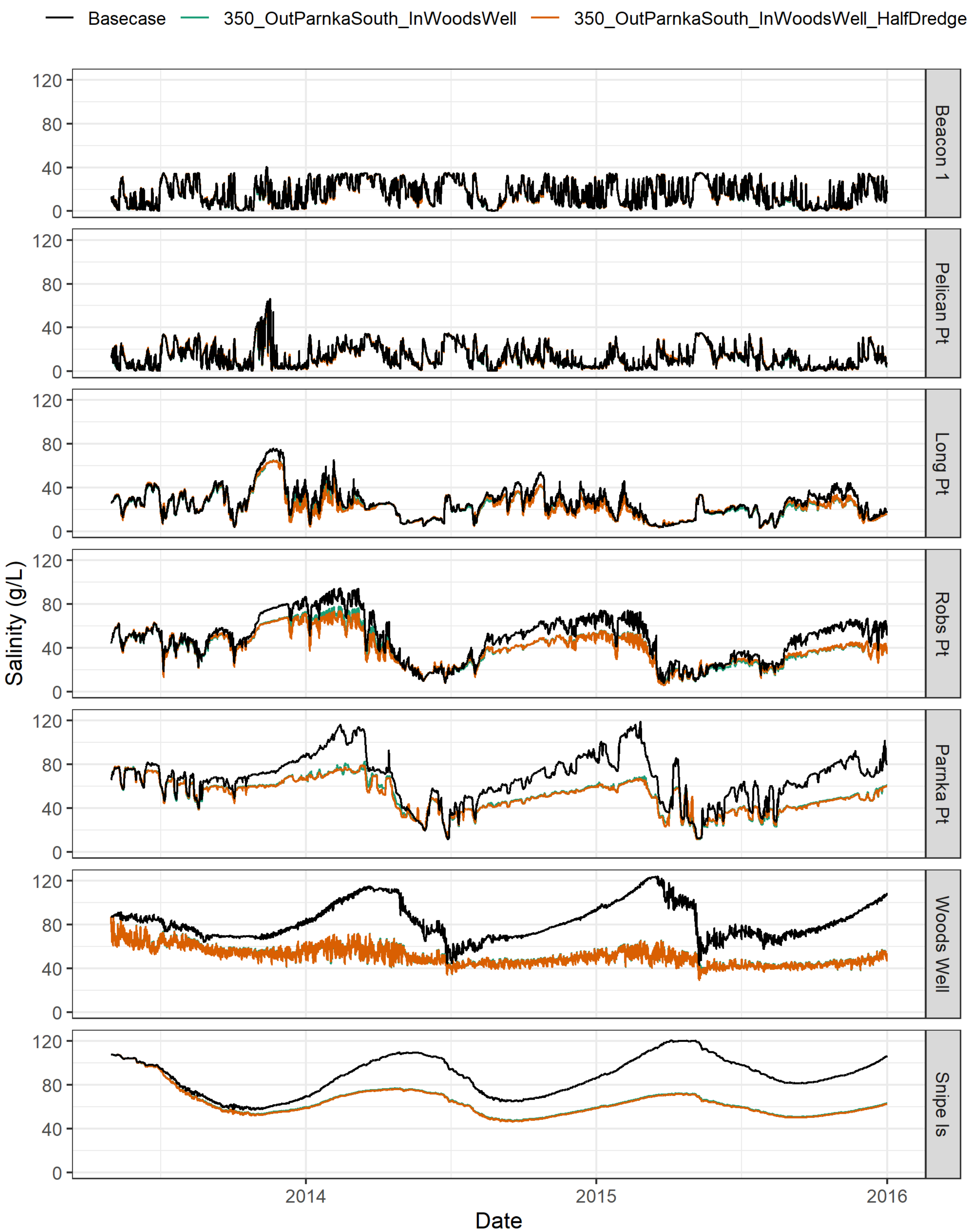

Figure 3-17 Modelled salinity under base case and circulation pumping scenarios with pump out from Parnka Point

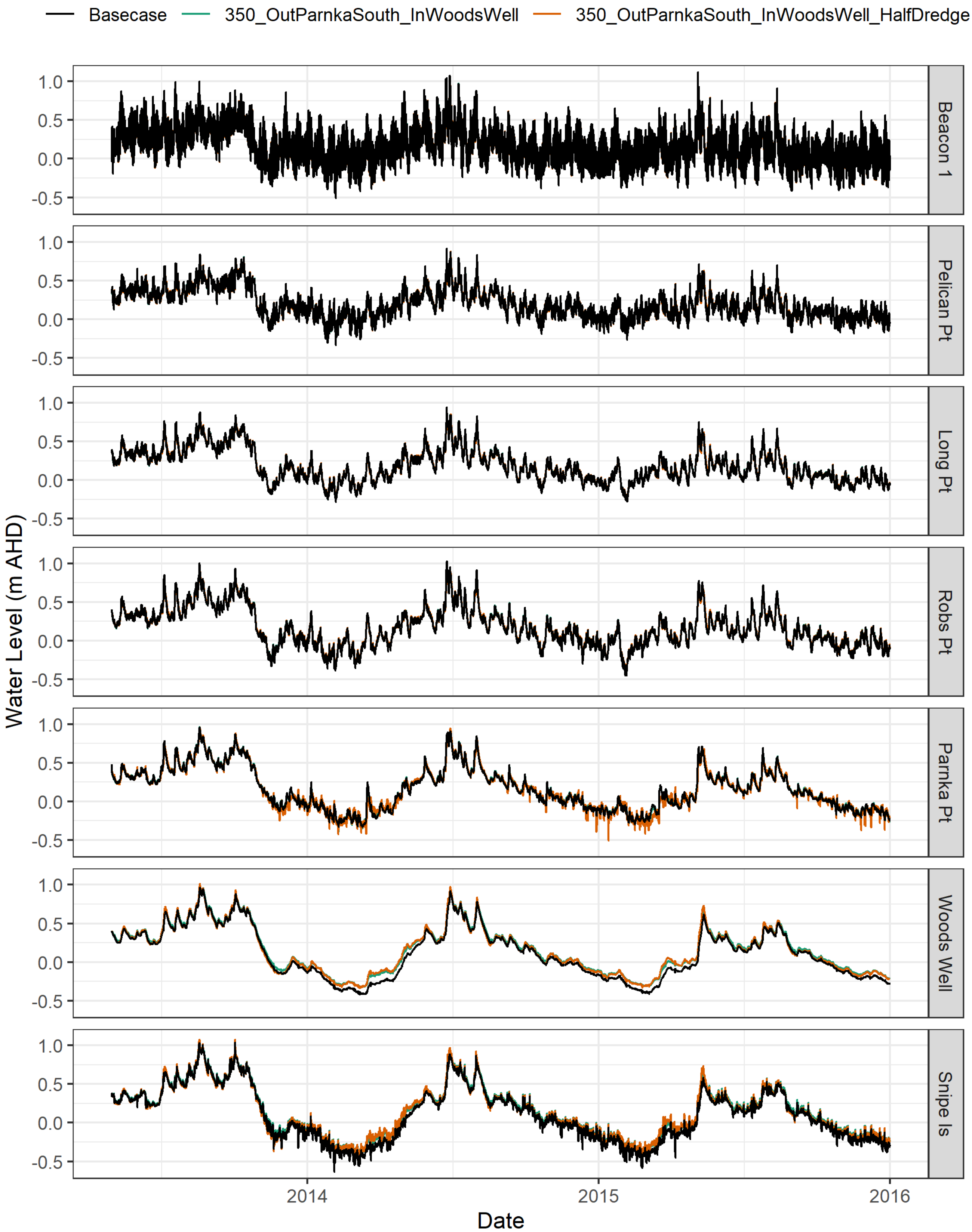

Figure 3-18 Modelled water level under base case and circulation pumping scenarios with pump out from Parnka Point

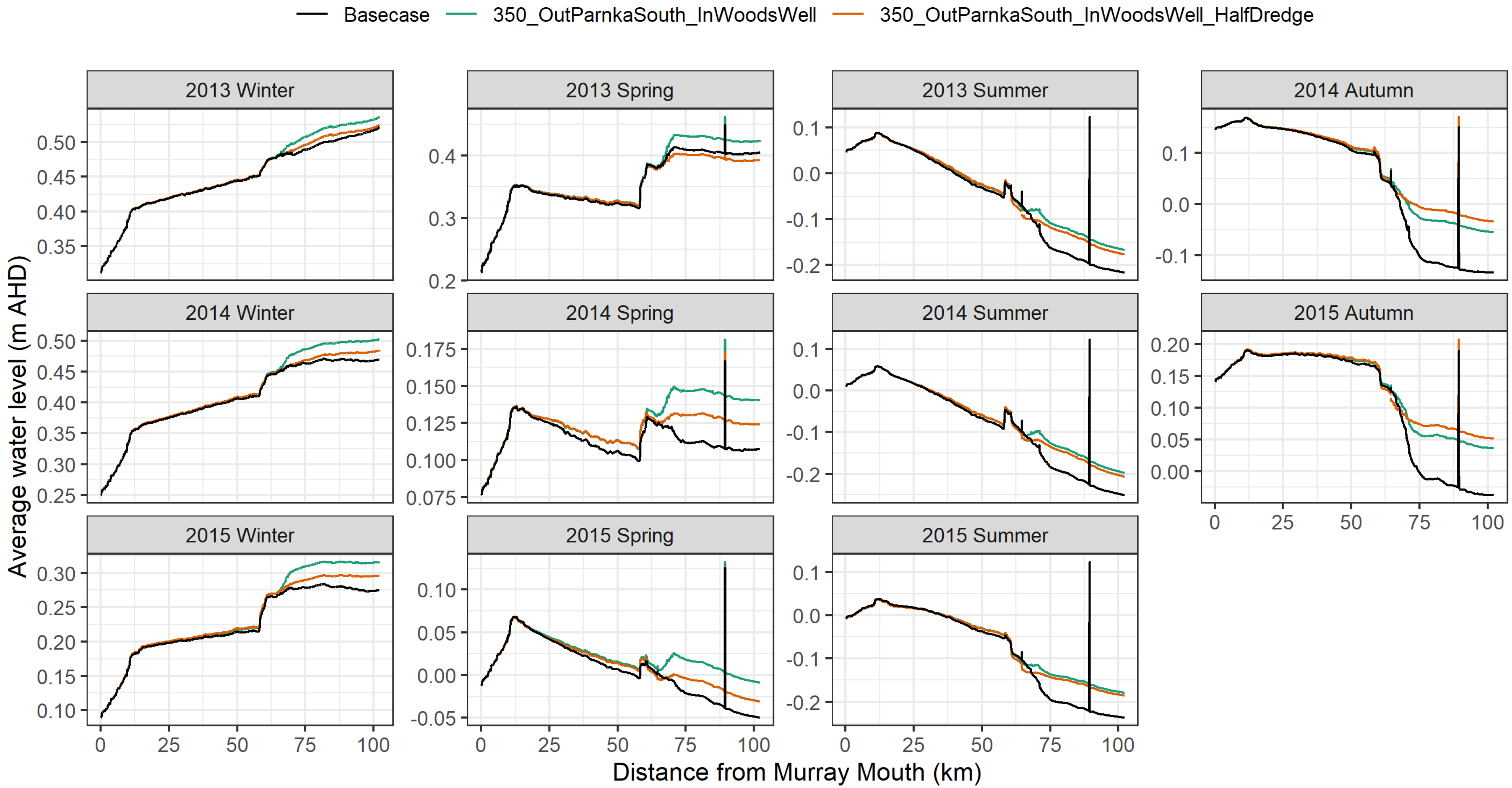

Figure 3-19 Modelled water level along the length of the Coorong (north to south) for circulation pumping scenarios with pump out from Parnka Point (note that the water level spike at approximately ch 90km is an artefact caused by the specific alignment used to extract the long section, and not demonstrative of an actual peak in water level)

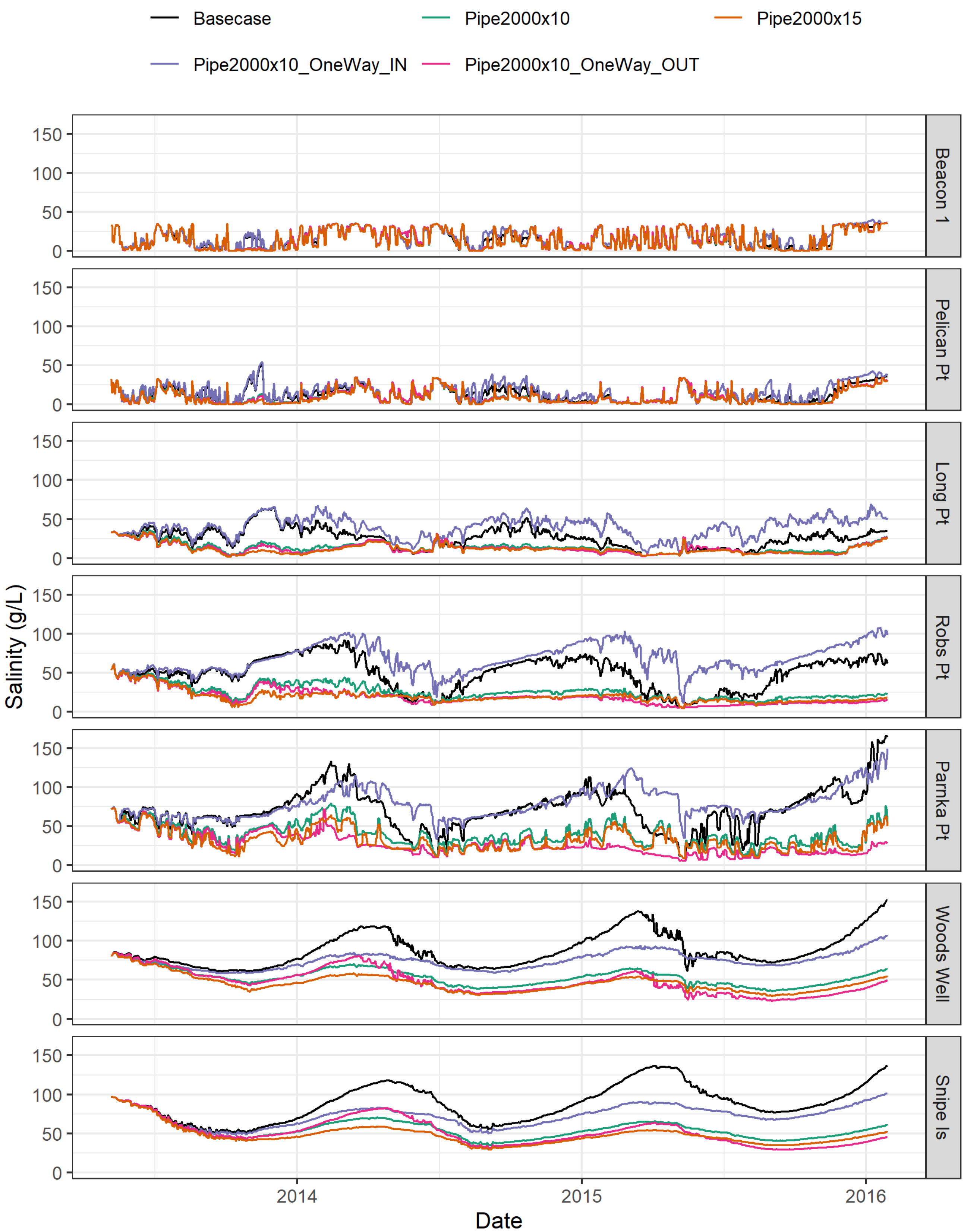

Figure 3-20 Modelled salinity under base case and passive pipe scenarios

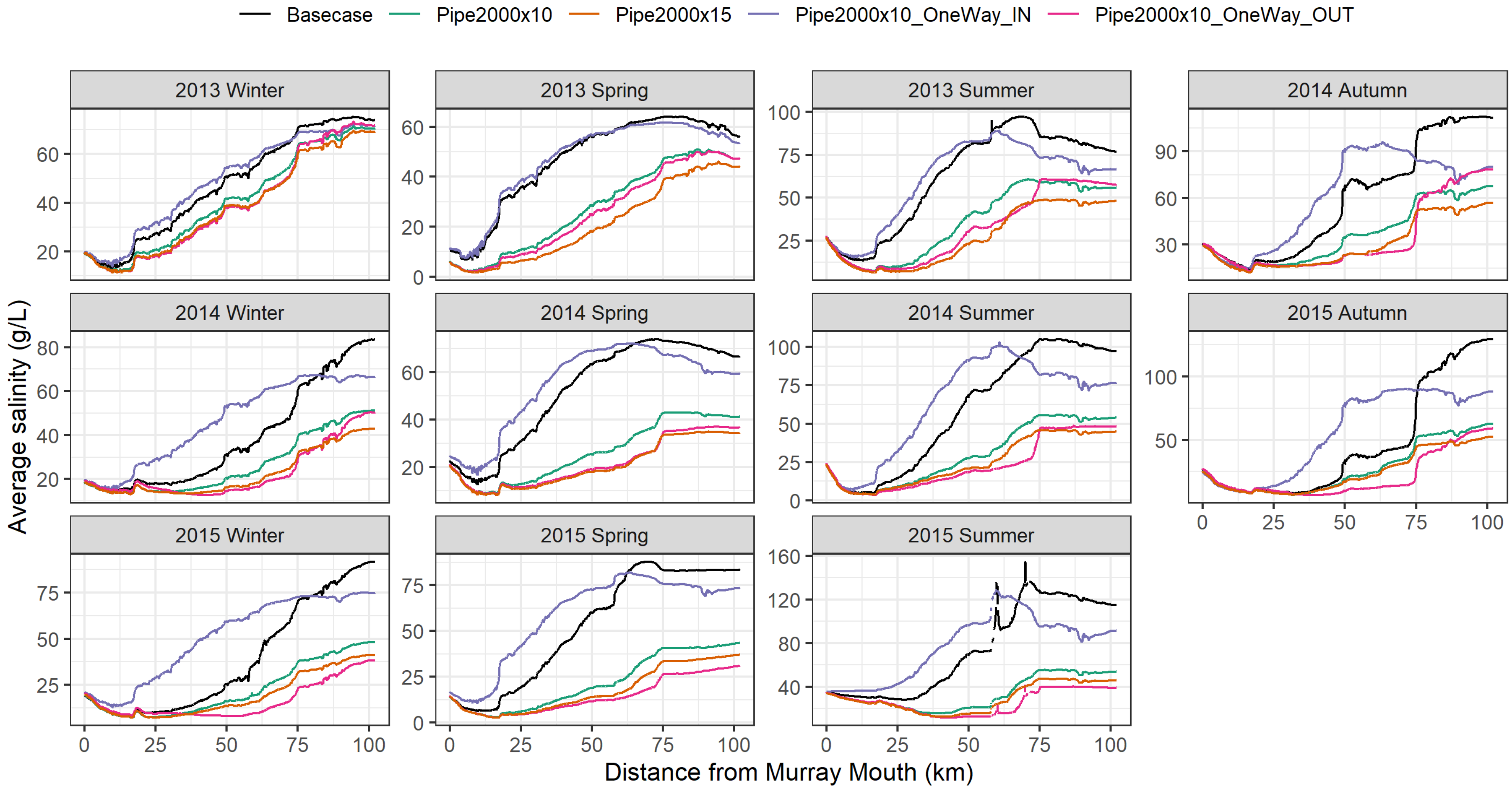

Figure 3-21 Modelled salinity along the length of the Coorong (north to south) for base case and passive pipe scenarios

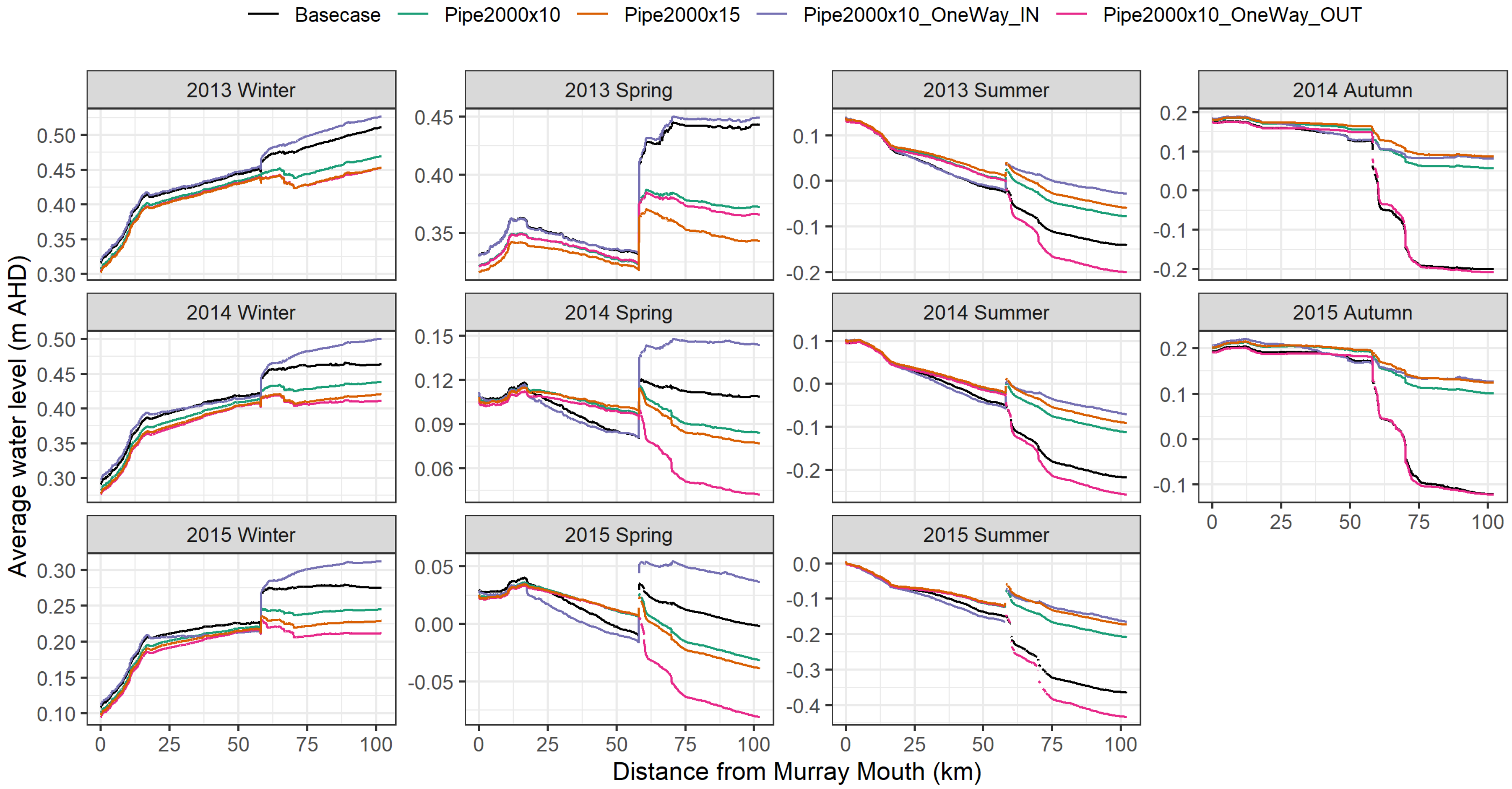

Figure 3-22 Modelled water level along the length of the Coorong (north to south) for base case and passive pipe scenarios

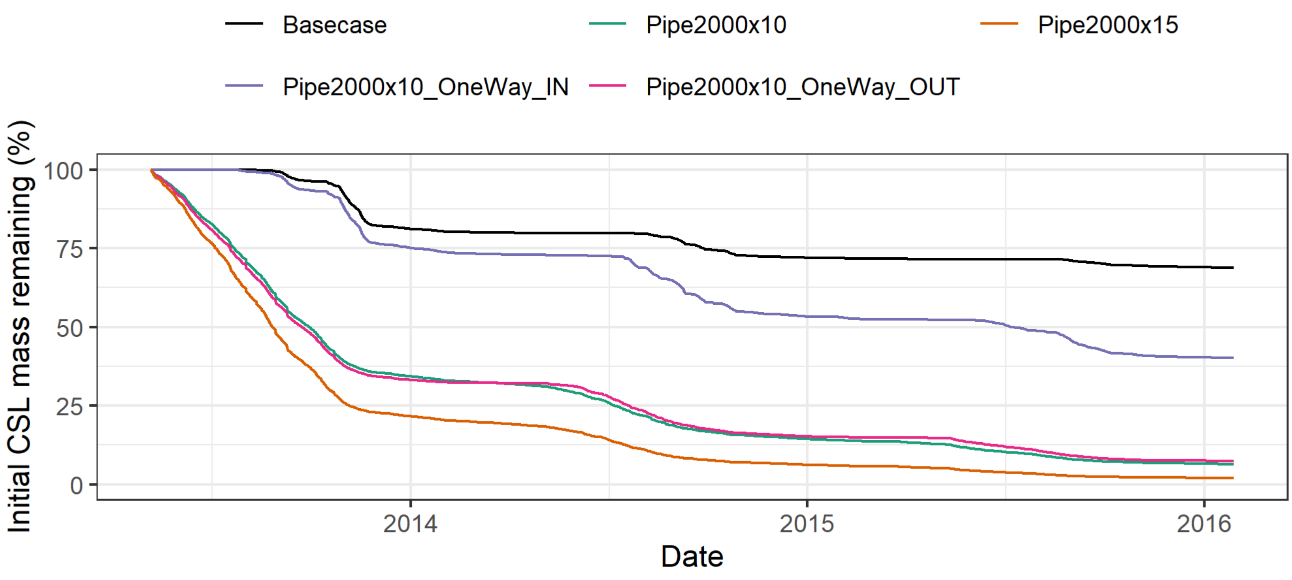

Figure 3-23 Modelled proportion of CSL mass remaining for base case and passive pipe scenarios

4 Long term simulations

4.1 Scenarios

Results of the short-term simulations (Section 3.1) were presented to the ecological investigations and engineering project teams for discussion, and development of a list of scenarios for progression to long term modelling. The following options were adopted for progression to long term simulations:

1. Pumping out of the CSL at 250 ML/d. While this is not an option being considered by CIIP more broadly (e.g. engineering design) it has been included out of completeness following the Phase 1 ecological risk assessment report;
2. Pumping out of the CSL at 1,000 ML/d when water levels are >0.3mAHD to provide the desired salinity reductions without reducing water levels;
3. Pumping out of the CSL at 250 ML/d, combined with dredging. Noting that the coarse model used for long term runs has limited representation for the Parnka Narrows section, and the impacts of constrictions on flow between lagoons is not represented in detail.
4. Barrage flow diverted through a Lake Albert Connector (see details below);
5. Dredging in combination with a Lake Albert Connector;
6. Pumping in and out of the CSL on one pipeline but with bi-directional flow at a rate of 350 ML/d, with fluctuation timing refined during the modelling process;
7. Circulation pumping (pumping in and out at two locations so that pumping can occur in both directions simultaneously) at a rate of 350 ML/d, with outflow from Policeman Point and inflow at Round Island when water levels < 0.3 mAHD, on the assumption that at higher water levels, the water removed by pumping can be readily replaced from the north lagoon.
8. Passive pipes (10 x 2m diameter pipes) connecting the CSL and southern ocean.

Table 4-1 summarises the scenarios modelled, and provides further details of assumptions.

As noted in Section 2.4, the long term model was run for three different boundary conditions:

1. Historic: observed historical conditions and representing barrage flows as they occurred. These conditions are useful for understanding what would have happened had the option been implemented in the past.
2. Current: observed historical conditions but with barrage flow representing current conditions, derived from the Source Murray Model Current Conditions model (MDBA, 2015). Current conditions barrage flow assumes current environmental water recovery and delivery patterns are implemented across the full period (i.e. current level Basin Plan implementation hind-cast to earlier years).
3. Climate change: observed historical conditions albeit with adjustments to atmospheric drivers to represent projected conditions at 2050 under an RCP8.5 (high emissions) climate change scenario. The adopted projections are as per DEW's 'guide to climate projections for risk assessment and planning in South Australia' (Green and Pannell, 2020). Historical barrage flows are used in these scenarios.

Barrage flows under historic and current conditions are shown in Figure 4-1. Flow through the barrages is relatively high in the 1990's, with a significant reduction seen in 2000-2010 as a result of the Millennium drought. Note that the barrage flows under climate change are the same as historic conditions.

Table 4-1 Scenarios modelled for a 30 year period

ID	Infrastructure option	Description
Basecase	-	Do nothing scenario
Pump out – 250 ML/d constant	Pump out	Pump out 250 ML/d continuously from Policeman Point
Pump out – 1000 ML/d (>0.3m trigger)	Pump out	Pump out 1,000 ML/d at Policeman point when water levels in the CSL are above 0.3 mAHD
Pump out 250 ML/d constant + dredge	Pump out Dredge	Pump out 250 ML/d continuously from Policeman Point, combined with dredging profile 2A provided by KBR and re-aligned to coarser model mesh)
LAC	LAC	Assume a Lake Albert Connector can divert barrage flow into the north lagoon opposite Bascombe Bay. Up to 1 GL/d is diverted through the connector if available, only after the first 2 GL/d is passed over the barrages. Note that this logic is only applied when there is sufficient head across Lake Albert and the Coorong for the connector to feasibly deliver water
LAC + dredge	LAC Dredge	Dredging profile 2A provided by KBR and re-aligned to coarser model mesh, combined with Lake Albert Connector, using the same logic outlined above.
Pump in/out 350 ML/d (one site)	Bi-directional pumping (one location)	Pump out at 350 ML/d from Policeman Point continuously from May to September (inclusive), with fluctuating pumping in/out at 350 ML/d during December to May (pump in over 25 days and out over 23 days)
Circulation pump 350 ML/d (Policeman Pt / Round Is)	Circulation pumping (two locations)	Pump out 350 ML/d constantly from Policeman Point, and pump in 350 ML/d when water levels in the CSL <0.3 mAHD. The intent is that the when water levels are greater than 0.3 mAHD, the north and south lagoons are sufficiently connected for inflow to the CSL to come from CNL.
Circulation pump 350 ML/d (Parnka Pt / Policeman Pt)	Circulation pumping (two locations)	Pump out 350 ML/d from Parnka point when water levels are greater than -0.3 mAHD; pump in 350 ML/d when water levels are less than 0.3 mAHD from Policeman Point (the intention is that at water levels > 0.3m AHD, the north and south lagoons are sufficiently connected, that freshening of the south lagoon should occur from inflow from the north.
Circulation pump 350 ML/d (Parnka Pt / Policeman Pt)+ Dredge	Circulation pumping (two locations) Dredge	Pump out 350 ML/d from Parnka point when water levels are greater than -0.3 mAHD; pump in 350 ML/d when water levels are less than 0.3 mAHD from Policeman Point, combined with a portion of the dredge profile (KBR02A) that begins at Parnka Narrows and extends south.
Passive pipelines (10x2000)	Passive pipe	10 x 2m diameter, connecting CSL (near Policeman Point) to southern ocean with a length of 2500 m.

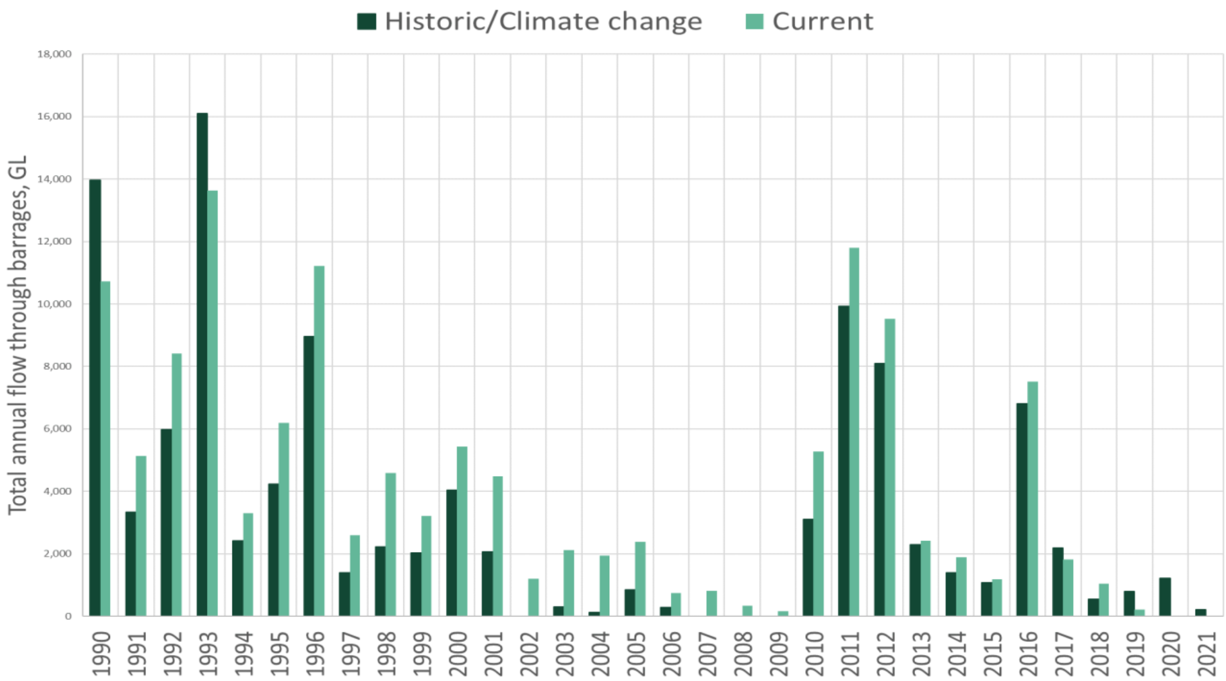

Figure 4-1 Total annual barrage flow under historic and current conditions

The LAC channel was conceptually designed to pass 1 GL/d when water levels in the Lake and CSL are 0.5 mAHD, and 0.3 mAHD respectively. To ensure accurate representation of flows that could be achieved through a Lake Albert Connector, consideration was given to the head difference across Lake Albert and the CNL where the connector would enter the Coroong. Based on advice from the CIIP engineering team, two relationships between head difference between Lake Albert and the Coorong and the capacity of the channel were developed, one relationship based on a Lake Albert water level of 0.9 m AHD, and another for the Lake Albert level of 0.5 m AHD. These two relationships were interpolated each day, based on the Lake Albert water level (observed levels for Historic and Climate Change scenarios, from the Source Murray Model output for Current Conditions scenario) and the head difference between Lake Albert and the Coorong. At large head differences the capacity of the channel is expected to exceed 1 GL/d, however this additional capacity has not been included in the modelling. A summary of the flows that are achieved through the LAC using this logic, under the three boundary conditions, is provided in

Table 4-2, with flow duration curves provided in Figure 4-2.

The salinity assumed for Lake Albert connector flows was the long term average in the lake of 1500 EC, however it is likely that after some time of operating the connector it is likely the Lake Albert salinity would reduce with the additional flushing.

Table 4-2 Average annual LAC flow statistics for modelled period 1990-2019

Parameter	Historic	Current	Climate change
Days of operation per year	175 (43%)	241 (66%)	138 (38%)
Days of operation at 1 GL/d per year	122 (33%)	177 (49%)	96 (26%)
Total annual flow through LAC, GL	141	204	120
Average daily flow through LAC, ML	386	558	330

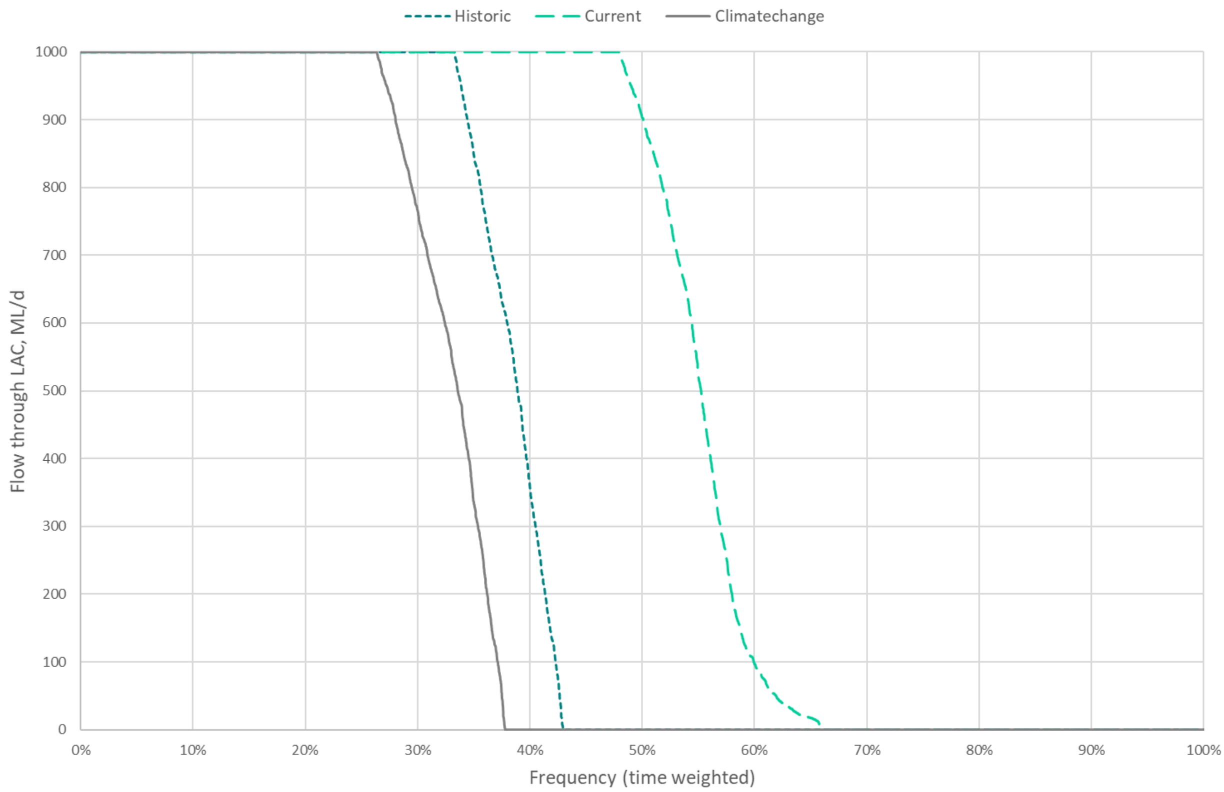

Figure 4-2 Flow duration curve for flow through LAC under different climate conditions

4.2 Modelled outputs & interpretation

As with the short term simulations, water level and salinity outputs were provided as time series for the 7 point locations corresponding to existing gauging stations, and as seasonal averages along the length of the Coorong. The proportion of initial mass remaining in the CSL is also provided.

In addition, spatial results have been post-processed to provide time series daily averages for each of the north and south lagoons, with the demarcation of the two lagoons shown in Figure 4-3. Note that the demarcation aligns only with the area in the model that experiences permanent inundation to ensure more representative lagoon average results (cells that disconnect and evapoconcentrate to very high salinities are not included, for example). The average water level is weighted by the cell areas, where concentration outputs (salinity, tracers, water age) are weighted by cell volume.

The daily averages have been further processed to provide statistics for each of the metrics, which are based on the Resource Condition Targets and Management Triggers (defined in the Ramsar Management Plan (DEW, in prep)). Metrics have been calculated over the full model period as well as each water year. Definitions of each of these are provided in Table 4-3.

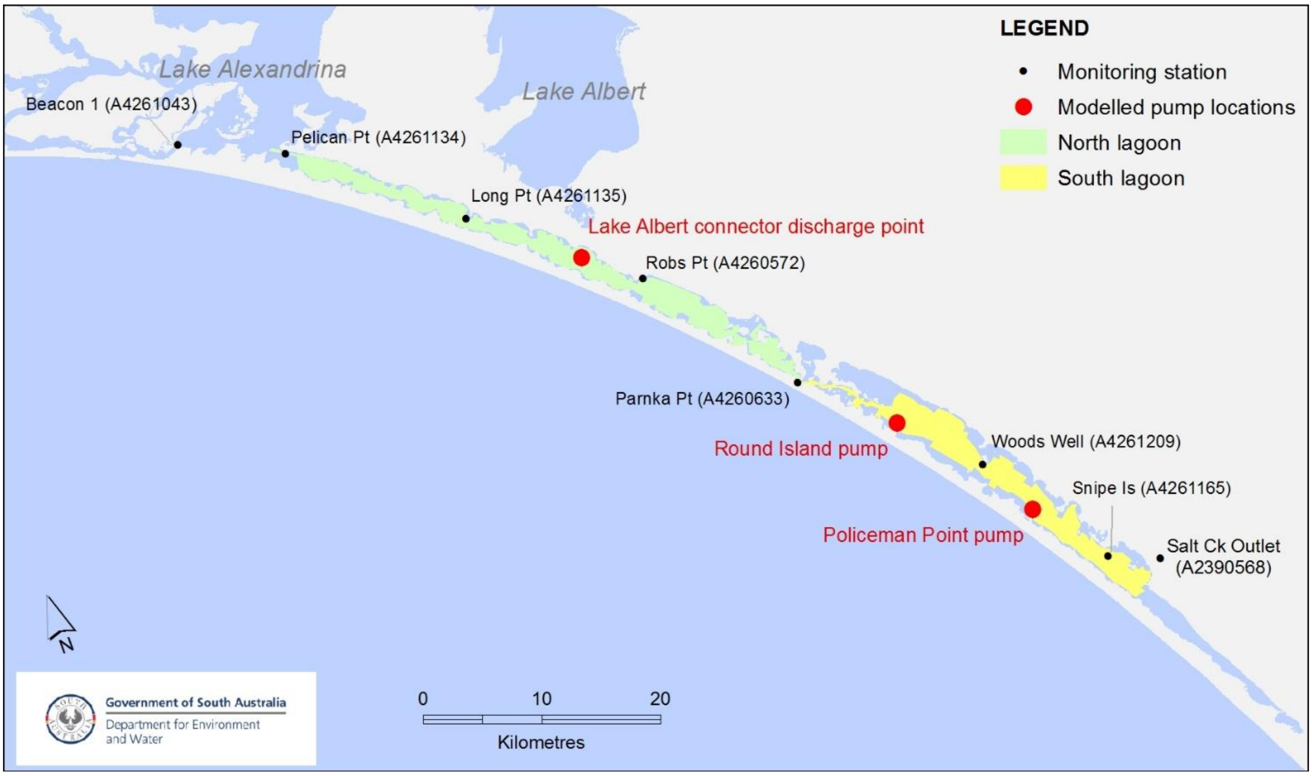

Figure 4-3 Model output points (monitoring stations) and zones

Table 4-3 Long term modelling summary metrics

ID	Description
CSLpc60winter	Percentage of days in June to August (inclusive) with salinity < 60 g/L in CSL
CSLpc60	Percentage of days with salinity < 60 g/L in CSL
CSLpc100	Percentage of days with salinity < 100 g/L in CSL
CSLconsec100	Maximum number of consecutive months with the monthly average salinity > 100 g/L in CSL
CSLWLJJ	Percentage of days in June and July with water level > 0.3 m AHD in CSL
CSLWLSD2	Percentage of days in September to Dec (inclusive) with water level > 0.2 m AHD in CSL
CSLWLSD4	Percentage of days in September to Dec (inclusive) with water level > 0.4 m AHD in CSL
CSL_WL_SD_ Between0.2_0.4	Percentage of days in September to Dec (inclusive) with water level between 0.2 and 0.4 m AHD in CSL
CSLWL_JM_0.2	Percentage of days in January to March (inclusive) with water level <0.2 mAHD in CSL
CSLWL_JM_m0.5	Percentage of days in January to March (inclusive) with water level < - 0.5 mAHD in CSL
CSLWLJM	Average water level over January to March (inclusive) in CSL
CSLWL0	Maximum number of consecutive days with water level below 0 m AHD (converted to months) in CSL
CNL45	Percentage of months with monthly average salinity < 45 g/L in CNL
CNLconsec45	Maximum number of consecutive months with the monthly average salinity > 45 g/L
CNLconsec70	Maximum number of consecutive months with the monthly average salinity > 70 g/L in CNL
CSLWaterAge	Average age of water in CSL
CSLOcean	Average percentage of water in CSL that originated in the ocean
CSLBarrage	Average percentage of water in CSL that originated from the barrages
CSLSE	Average percentage of water in CSL that originated from South East drains
CNLWaterAge	Average age of water in CNL
CNLOcean	Average percentage of water in CNL that originated in the ocean
CNLBarrage	Average percentage of water in CNL that originated from the barrages
CNLSE	Average percentage of water in CNL that originated from South East drains

4.3 Results

As the scenarios which progressed to the long term modelling are all generally able to meet the broad objectives described in Table 3-1, the detailed assessment through the Ecological Risk Assessment Framework (ERAF) in the Phase 2 ecological investigations will determine the relative performance of each option. However, some general interpretations are able to be made from the time series plots.

Figure 4-4 shows the relative impact of the three different boundary conditions, on salinity and water level under the base case (i.e. do nothing) scenario. Of interest is that the historic and climate change conditions result in similar salinities across the north and south lagoon, although salinities are higher due to the increases in temperature resulting in increased evaporation under climate change conditions, despite increased dilution from higher sea levels

The fresher conditions in the CSL for the current conditions scenario are a result of greater inflow from the barrages, which is evident from Figure 4-5, which demonstrates the origin of water in the south lagoon, and the average age (lower age implies greater turnover).This highlights the importance of the Basin Plan implementation in providing some resilience in system adaptation.

The influence of barrage flow (Figure 4-1) on the salinity and water levels in the system is evident. For all scenarios, under all boundary conditions, it generally takes around 3 years for the response of the Coorong to the infrastructure to stabilise. Flow through the barrages is maintained above 2,000 GL/year across this period, up until around 2001 (with the exception of 1997 under historic conditions). Flow is consistently low from around 2002 to 2009 as a result of the millennium drought. The system response to this is evident, with salinity in both lagoons increasing over this period, and water levels in the south lagoon not reaching the same level of seasonal peaks until high flows occur again in 2010-12.

Time series of water level and salinity for each of the scenarios is provided in Figure 4-6 to Figure 4-12. The scenarios have been subset to prevent overcrowding of the graphs, with the exception of Figure 4-6, which shows all scenarios under current boundary conditions, to demonstrate the relative difference across all scenarios.

Regarding the relative performance of each of the scenarios, the passive pipe option results in the fastest reduction in salinity of the south lagoon, in part due to the very wet years at the start of the simulation period, resulting in higher water levels in the CSL compared to the ocean, and hence increased discharge through the passive pipes. However, this relative performance is not maintained across the simulation in drier conditions when the reverse occurs, and the difference between CSL and ocean water levels are smaller. Pumping out 1,000 ML/d (for water levels greater than 0.3 mAHD) has a similar dependence on the period of time where water levels in the CSL are high and has similar performance at the start of the simulation period, but is still able to maintain a lower salinity in the CSL during the drier years.

The Lake Albert Connection options show the most variable changes in salinity. There is a particular flow range where this option can make more efficient use of barrage flow available. This is in the range of 1000-2000 GL/year (e.g. 2002-2005) where there is enough barrage flow to operate the LAC for a large proportion of the year, but not so much barrage flow that the Coorong is able to be freshened from the existing barrages. At very low barrage flows (2006-2009) the LAC cannot be operated, and hence provides no benefit to the Coorong.

Pumping out constantly at 250 ML/d is able to reduce salinities in the CSL well, however the resulting water levels in the lagoon are reduced below desirable levels (though the impact is less with the dredge combination). This result is the main driver for many of the infrastructure option variations, to mitigate this water level reduction through water level triggers, dredging, or pumping in sea water to compensate, either on the same pipeline or a second pipeline.

There is negligible difference in the results between scenarios with and without dredging. Despite efforts to improve the bathymetry through the Parnka narrows to represent both historical data and the pump out at 250 ML/d scenario, this dredging result is likely an artefact of the model resolution, which is relatively coarse to allow the long simulations to be undertaken in a practical time frame. A finer scale model (particularly through the Parnka Narrows section) is required to determine any influence of the dredging options, as used in Section 3.

None of the options were able to maintain salinity below 60 g/L in the CSL throughout the Millennium drought, even in the current conditions simulation.

It is noted that some options, under modelled conditions, appear to 'over-freshen' the system, i.e. there are extended periods where salinities in the CSL are less than 35 g/L (for example, from 1993 in the case of the Passive Pipelines, and 2011/12-2015 for pumping out 1,000 ML/d). The modelled scenarios do not incorporate any logic to scale back the infrastructure operation during years when barrage flows are high, and sufficient to maintain the salinity in the Coorong at lower levels. The over freshening that occurs in the modelled outputs is not considered a risk, because in reality, operations can be scaled to achieve the desired state (e.g. pumping stopped, or pipe valves shut).

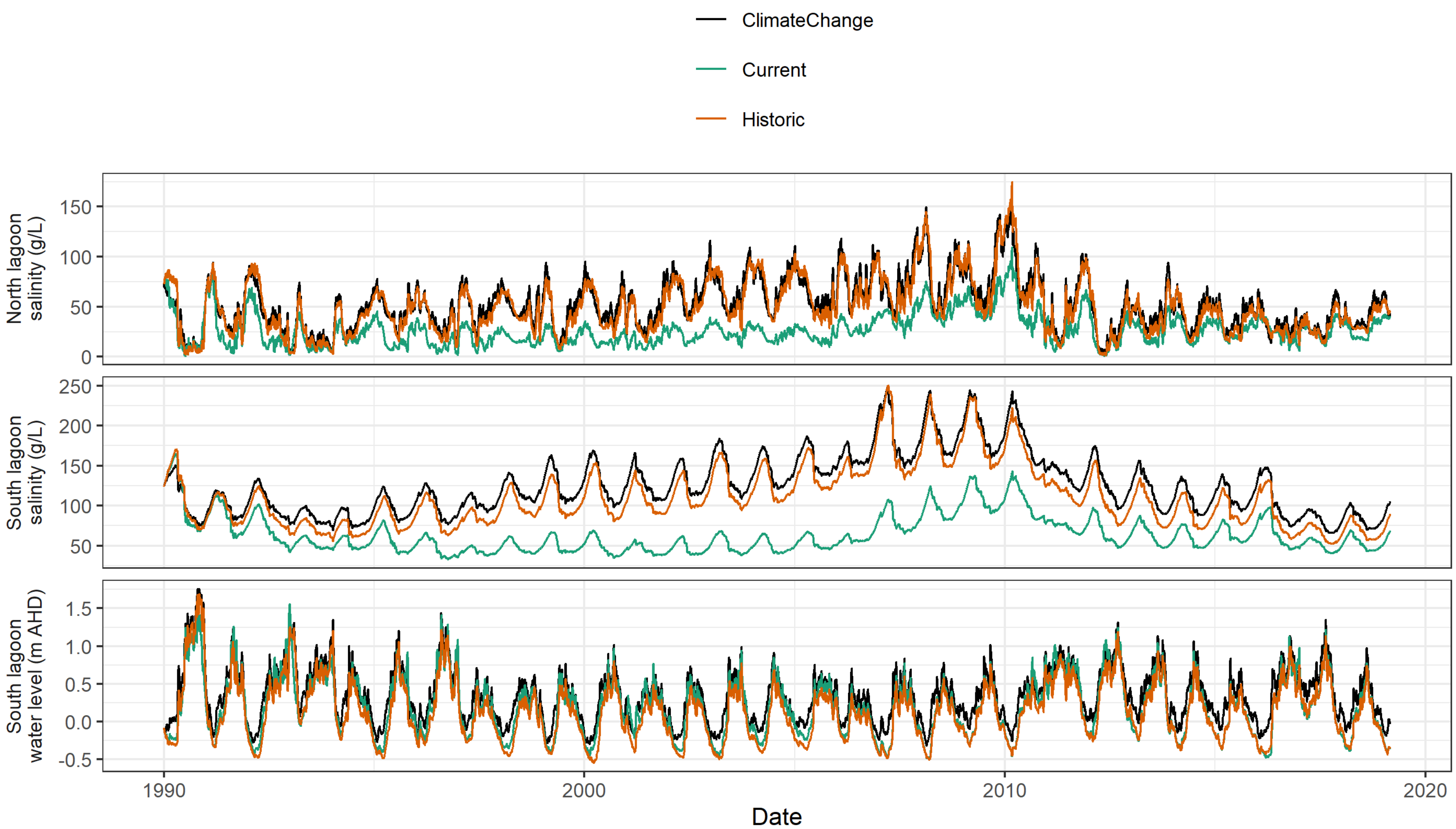

Figure 4-4 Modelled average water level across the CSL and average salinity across the CSL and CNL for the base case scenario under historic, current and climate change boundary conditions

Figure 4-5 Proportion of water in the CSL derived from the barrages and ocean respectively, and water age for the base case scenario under historic, current and climate change boundary conditions. These metrics provide an indication of the relative mix of barrage and ocean water in the CSL over time.

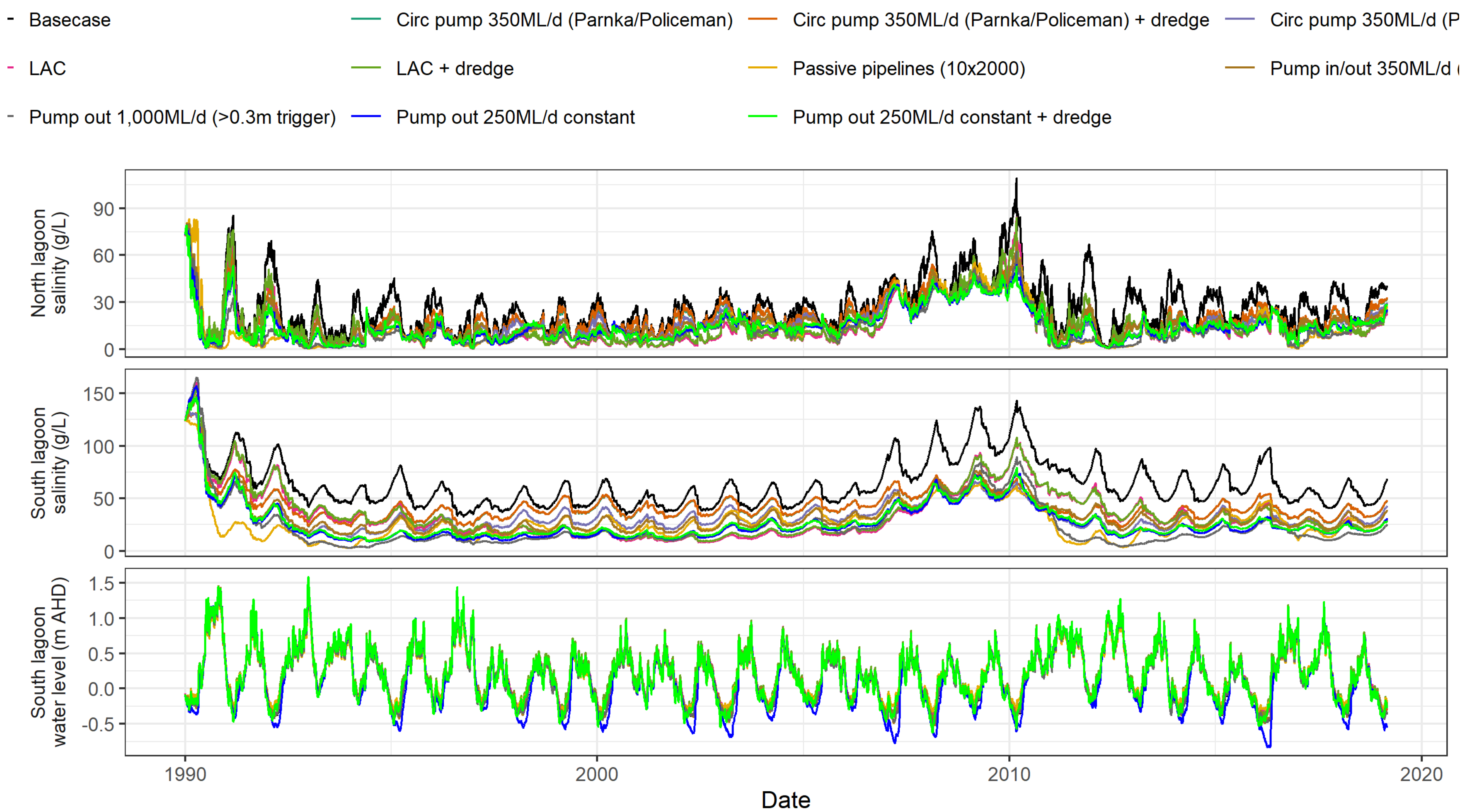

Figure 4-6 Modelled average water level across the CSL and average salinity across the CSL and CNL for the base case and all scenarios current boundary conditions

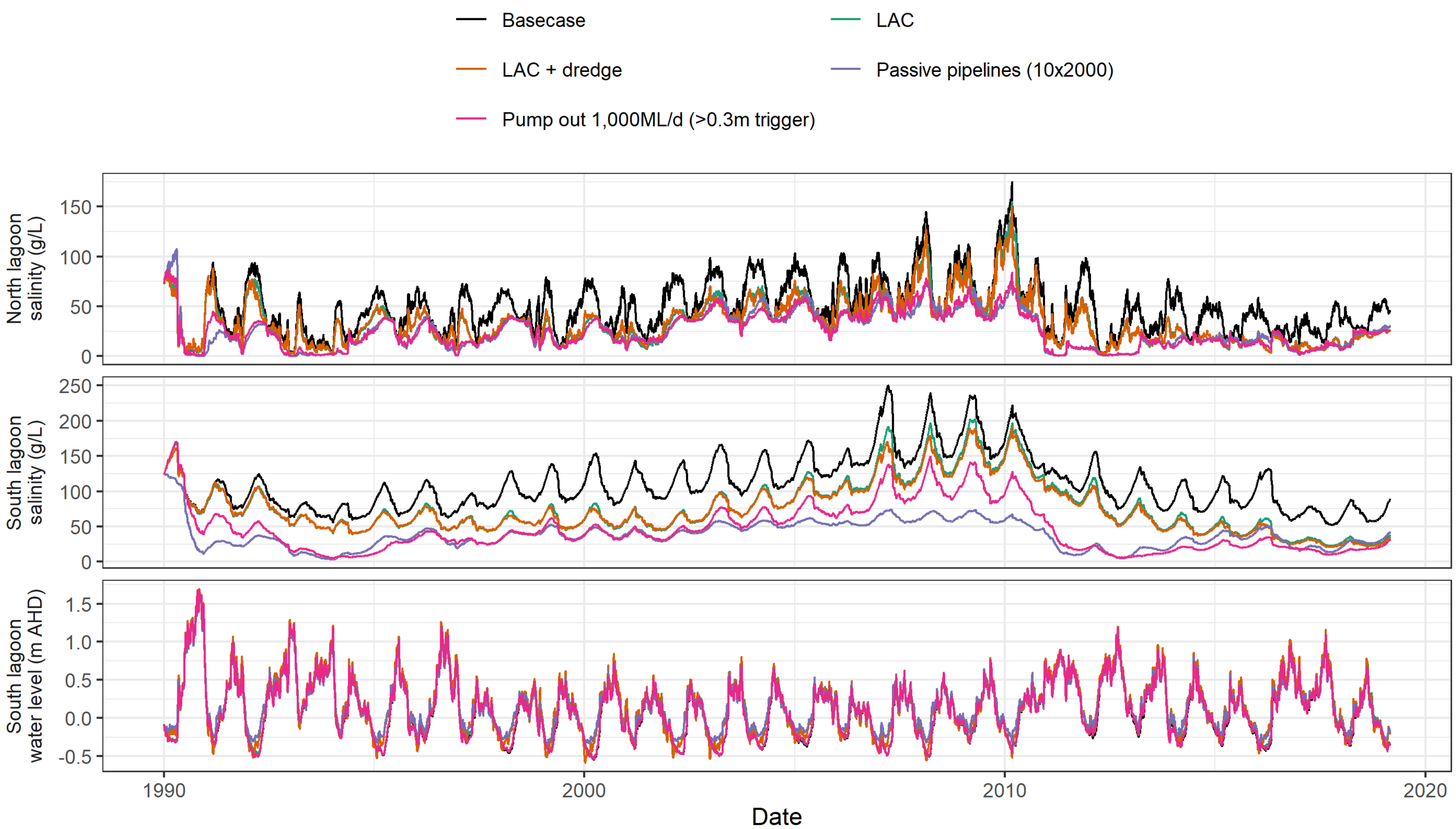

Figure 4-7 Modelled average water level across the CSL and average salinity across the CSL and CNL for the base case and subset 1 scenarios for historic conditions

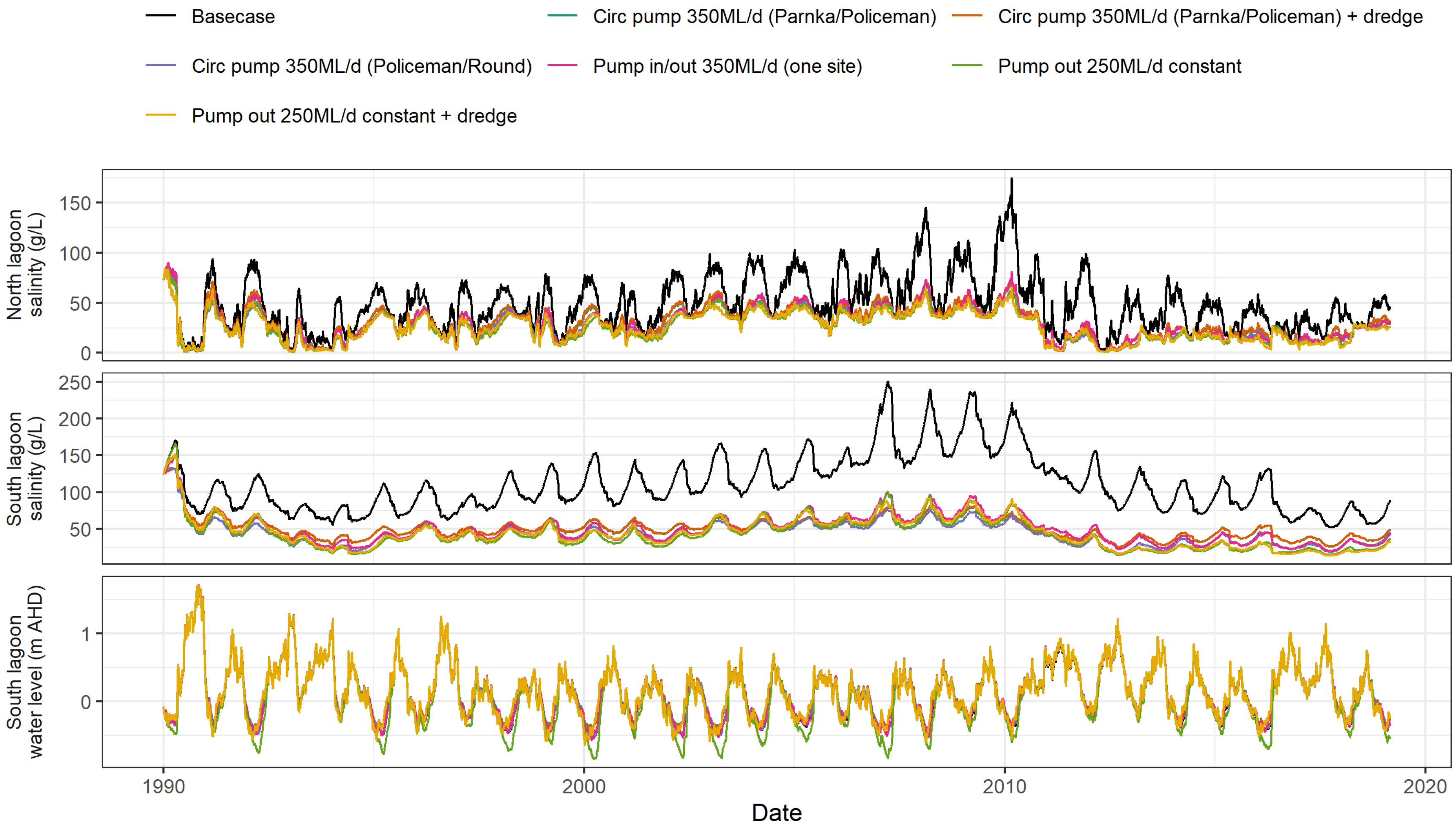

Figure 4-8 Modelled average water level across the CSL and average salinity across the CSL and CNL for the base case and subset 2 scenarios for historic conditions

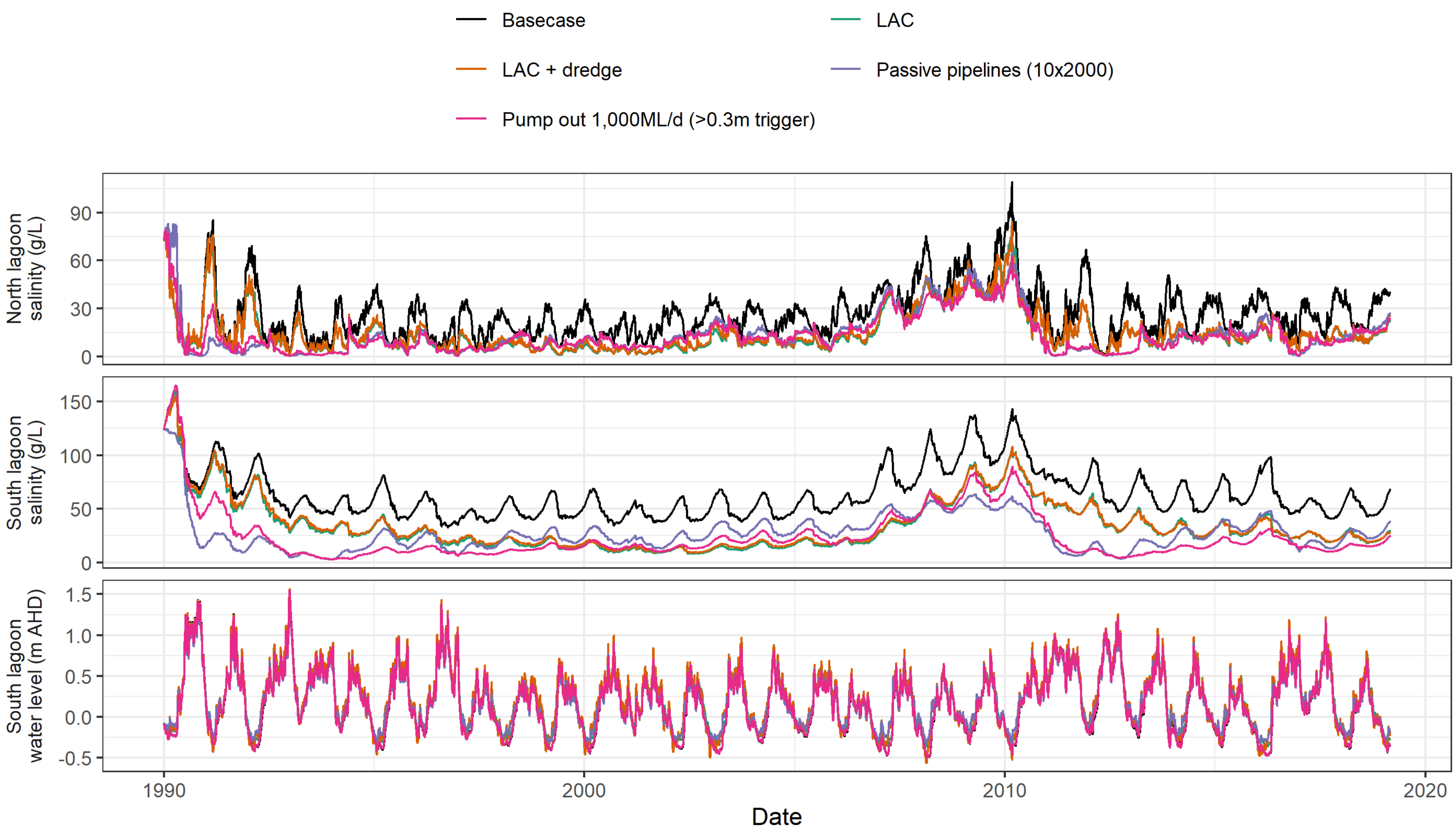

Figure 4-9 Modelled average water level across the CSL and average salinity across the CSL and CNL for the base case and subset 1 scenarios for current conditions

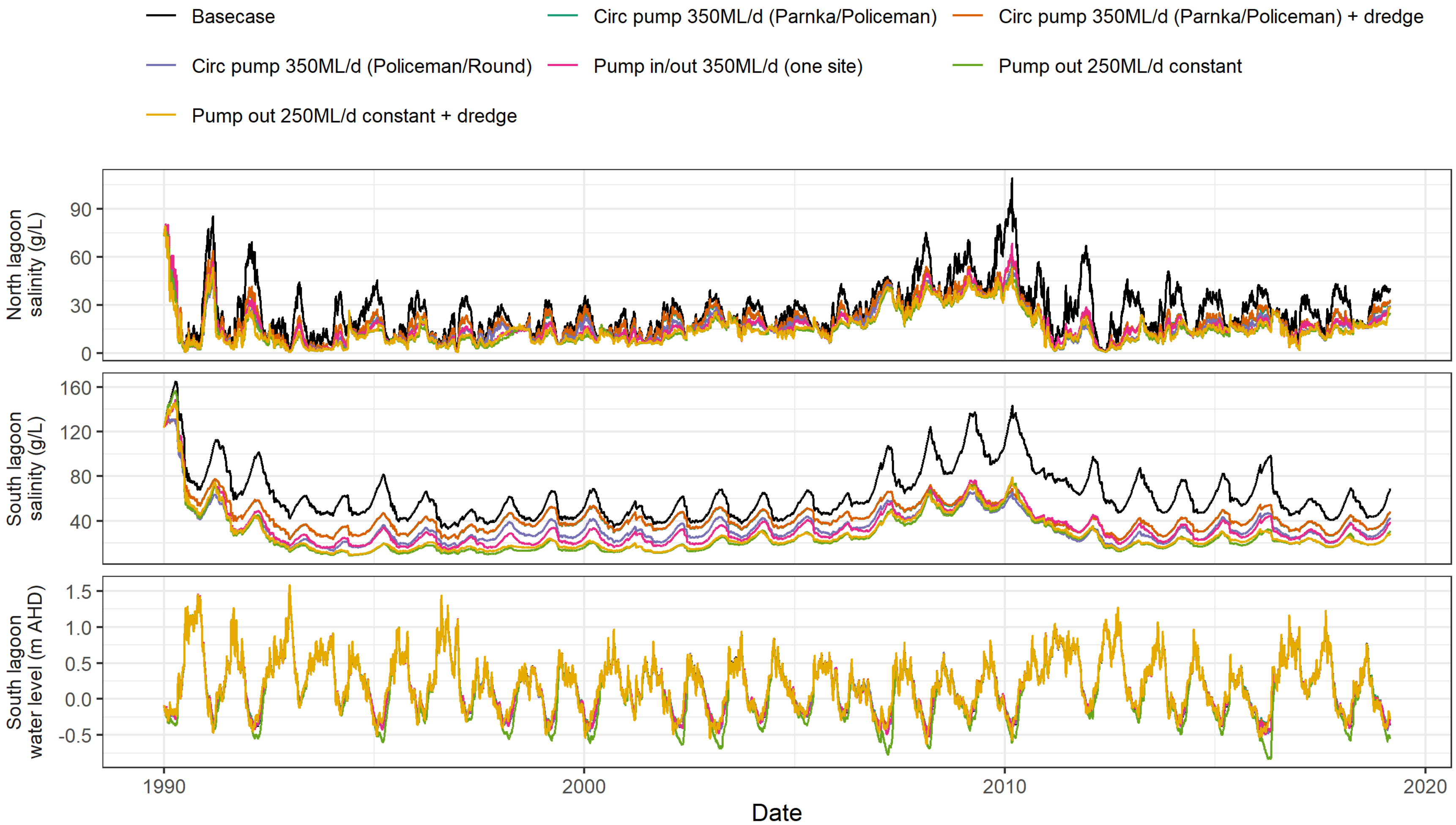

Figure 4-10 Modelled average water level across the CSL and average salinity across the CSL and CNL for the base case and subset 2 scenarios for current conditions

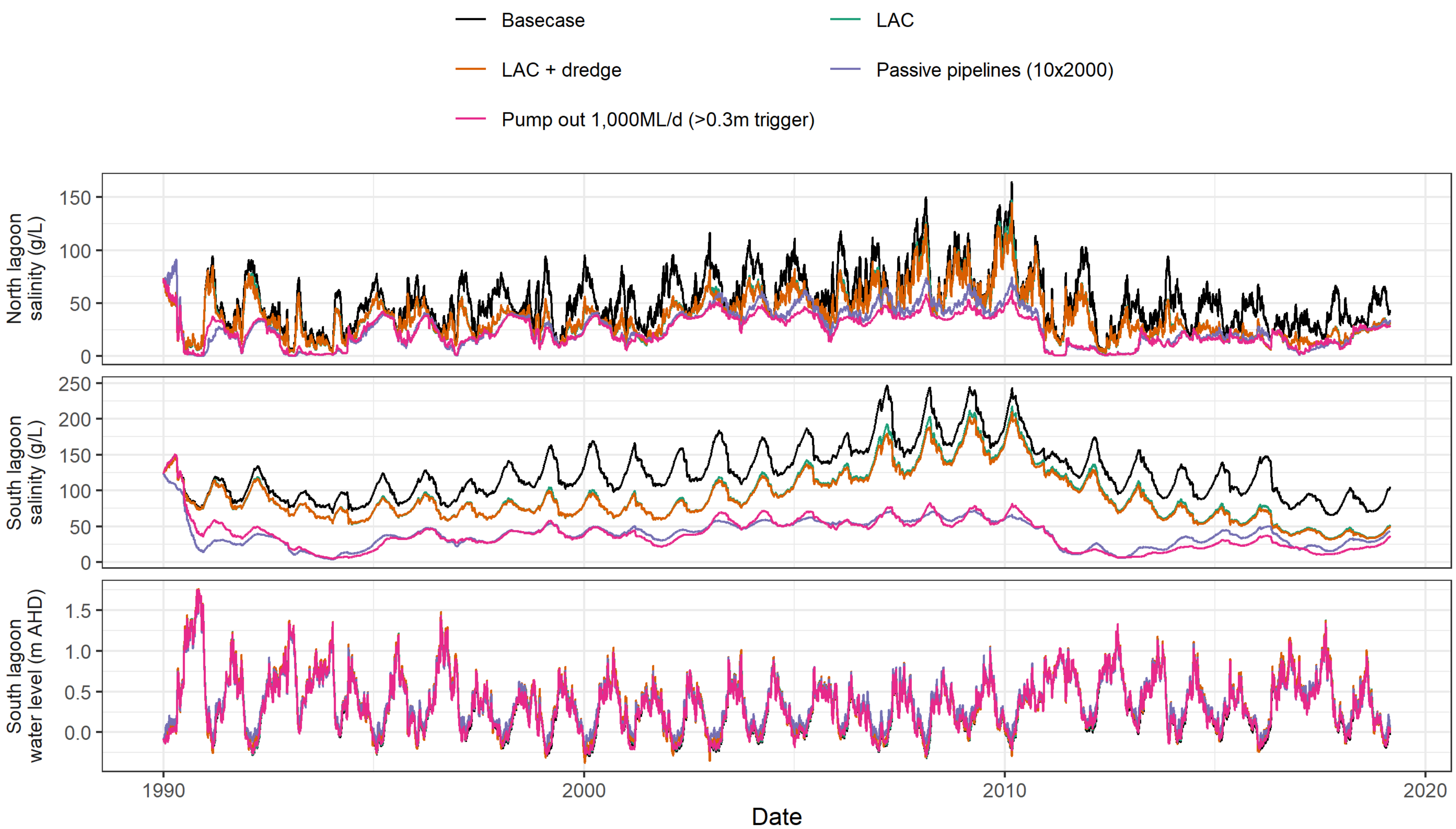

Figure 4-11 Modelled average water level across the CSL and average salinity across the CSL and CNL for the base case and subset 1 scenarios for climate change conditions

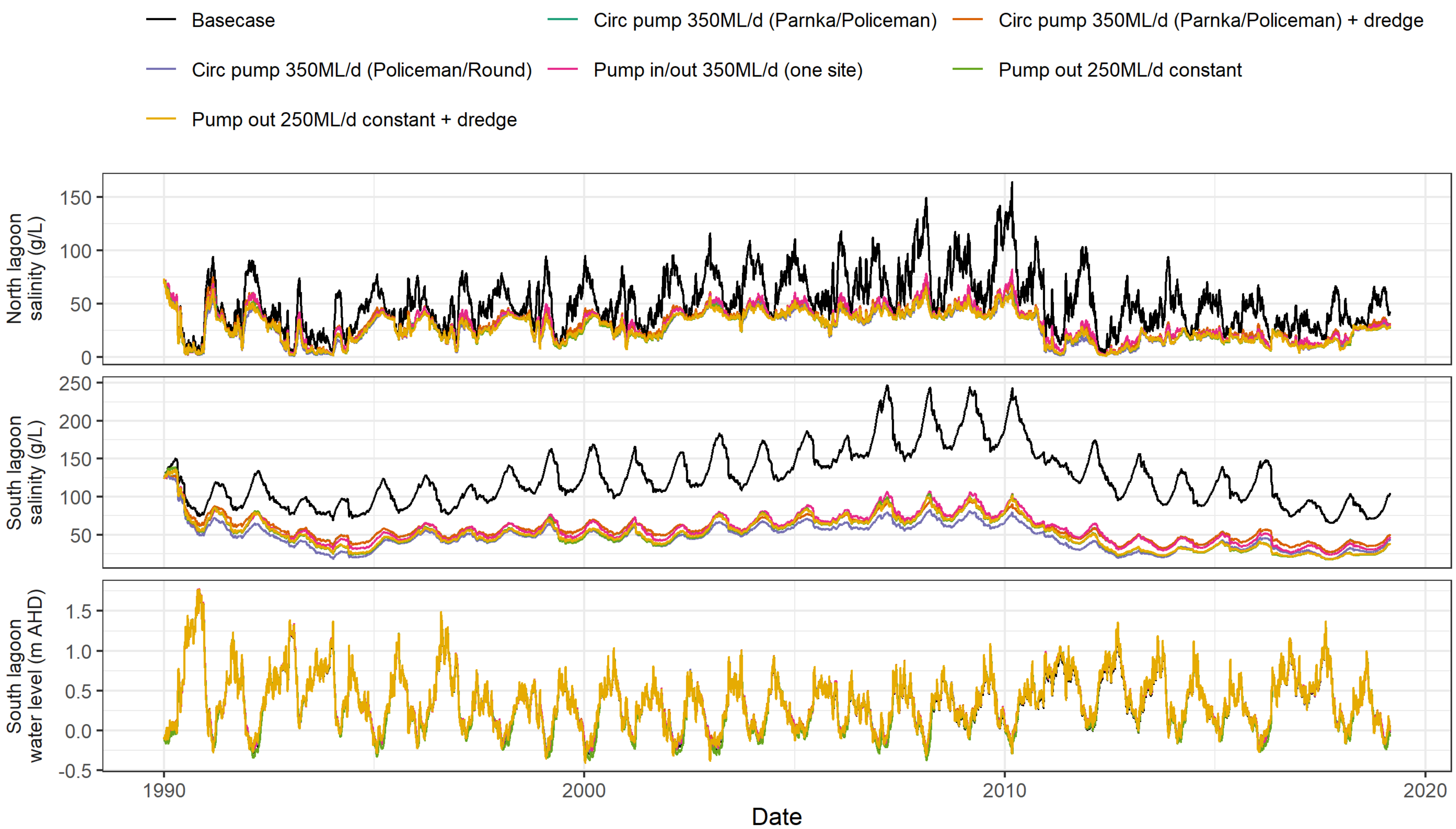

Figure 4-12 Modelled average water level across the CSL and average salinity across the CSL and CNL for the base case and subset 2 scenarios for climate change conditions

5 Discussion

A total of 106 three-year simulations have been undertaken to assess and refine potential infrastructure options, evaluating the impact on water level, salinity and flushing in the Coorong. From these, a refined version was identified for each of the 9 infrastructure options to be progressed to long term modelling under three different boundary/climate conditions.

Based on the broad ecological objectives specified in Table 3-1, all options perform better than the base case/do nothing scenario, indicating the potential to improve the system. However, none of the scenarios were able to meet all optimal conditions indicative of a ‘desired state’ over the entire simulation period.

It should be noted that none of the scenarios modelled consider antecedent salinity conditions or incorporate any scaling back of infrastructure operations during periods where the CSL is being naturally maintained at ‘optimal’ salinities by high barrage flow., For example, the ‘stress’ periods (for example, the Millennium drought) in the model do not necessarily consider the antecedent salinity and for some infrastructure options, the CSL salinity is reduced to less than 35 g/L in the years preceding the drought, whereas in reality, the infrastructure operation would be scaled back, and salinity would be higher. The performance of the options throughout the drought may therefore be overstated,

The scenarios respond differently to different stressors, i.e. some show a faster response at the beginning of the simulation, or respond better during periods of stress (e.g. low barrage flow), such that there is no one option that performs best across the entire simulation period.

All scenarios reduce salinity in the CSL and achieve an equilibrium after approximately 3 years, with the fastest/largest response seen in the passive pipe option and pump out 250 ML/d from a single location.

After reaching equilibrium, all scenarios are able to maintain salinity in the CSL to less than 60 g/L up to mid-2000s, after which the impact of reduced barrage flows from 2000-2010 is evident in increasing CSL salinity from around 2005 onwards. Throughout the period of equilibrium, the best performing options (in terms of salinity reduction) are the passive pipe, and pump out scenarios. Circulation pumping is as effective under drought conditions but is less effective at reducing salinity during comparatively fresh conditions (i.e. periods of reasonable barrage flows).

Over the Millennium drought ‘stress’ period of low barrage flows, salinity in the CSL increases. This is most evident under LAC scenarios, highlighting the limitation of this option to providing benefits only when flow is available. Scenarios including some form of pumping (either in/out at one location, or at two separate locations) were able to best maintain salinity under this ‘stress’ period.

As the scenarios perform differently across the simulation period, there is no obvious ‘best’ option, and ultimately the Environmental Risk Assessment Framework (ERAF) and Multi Criteria Analysis (MCA) process will determine the merits of each scenario.

6 Appendices

A. Rapid (long term) model calibration

Modifications

The mouth morphology and Parnka Narrows bathymetry were reviewed and subsequently updated prior to adopting the model for infrastructure scenario modelling.

Mouth morphology

The Diurnal tide ratio (DTR) calculations for observed conditions were provided by SA Water from 2002-2021. The DTR values were reproduced from two hourly averaged observed water levels at Victor Harbor and Tauwitchere to ensure the correct methodology was used, using Fourier Transforms implemented in R 4.0.2.

The modelled water level at the location of the Tauwitchere station (A4261048) were extracted and used to calculate the DTR. The results indicate that the model typically overestimates the observed DTR (Figure 6-1), "Original" line), and very rarely produces values less than 0.1, double the minimum value targeted by the dredging program.

A number of modifications were trialled to improve the representation of the observed DTR:

- The original model used the Tauwitchere barrage flow to interpolate between the bathymetric surfaces. Goolwa barrage is closer to the mouth than Tauwitchere, and releases are typically made from this barrage to improve mouth openness. Hence, using the Goolwa barrage flow was tested.
- A flow rate is assigned to each bathymetric surface, for the model to interpolate between dynamically. Higher index flow rates were trialled, to maintain more constricted bathymetric surfaces for higher flows.
- More constricted bathymetric surfaces were included in the database, by extrapolating difference between the original "medium-low" and "low" surfaces to be at a higher elevation than the "low" surface. Two new surfaces were created, "very low" and "no" flow. These two surfaces, along with the original surfaces, can be seen in Figure 6-2 and Figure 6-3.
- A bathymetric response timescale parameter is used by the model to control the rate of evolution to a new surface. Two parameters are available, as the erosion response typically occurs over much shorter timescales than the deposition response. The erosion time was increased from 168 hours (7 days) to 336 hours (2 weeks).
- The original model increased the bulk latent heat coefficient by 15% to increase the modelled evaporation rates and increase salinities. While not influencing the DTR, the default value of 1.3e-3 was also tested following the changes to the mouth morphology.

The error metrics from the different model configurations trialled are presented in Table 6-1, with the original model in the first column.

- Using Goolwa barrage flow as the controlling parameter generally produced worse results for comparable configurations. It is noted for higher flows that would be expected to scour the mouth Goolwa and Tauwitchere barrages flow are typically highly correlated.
- The inclusion of the more constricted bathymetry surfaces, "very low" and again to "no flow" improve the representation of the DTR.
- The slower erosion rate from 168 to 336 days also slightly improved the error metrics.

The final selected dynamic mouth configuration is shown in the last column of Table 6-1. The error measures in units of DTR (MAE and RMSE) are 50% lower than the original model, the IOA also increased by 50%. NSE value is low compared to other applications, but in the final model has a positive value indicating better performance than average for this metric. The KGE has also increase substantially.

The time series of the observed DTR, compared to the original and updated models, can be seen in Figure 6-1. There are some events where the model has scoured open the mouth that didn't happen in reality (e.g. late 2014), but in general the model can be seen to replicate the observed DTR relatively well, particularly for the current dredging operations, since dredges were reinstated in 2015 after a period of higher flows form 2010-2013. It should be noted that the bathymetric database developed assumes dredging is in place, even for the "no flow" bathymetric surface.

Table 6-1 Model accuracy statistics compared to the DTR calculated from observed data for the different model configurations trialled. For each metric darker green indicates better performance. The metrics are calculated on weekly average values of DTR.

Flow source	Tau	Goolwa	Goolwa*	Goolwa	Tau	Tau*	Tau	Tau	Tau	Tau
Min. Mouth	Low	Low	Low	very low	very low	very low	No flow	No flow	No flow	**No flow**
erosion rate (days)	168	168	168	168	168	168	168	336	168	**336**
heat coefficient factor	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.0	**1.0**
MAE	0.09	0.09	0.08	0.06	0.06	0.05	0.04	0.04	0.04	**0.04**
RMSE	0.1	0.11	0.09	0.07	0.07	0.06	0.05	0.05	0.05	**0.05**
R^2	0.32	0.17	0.13	0.15	0.36	0.34	0.32	0.33	0.32	**0.33**
IOA	0.51	0.47	0.49	0.56	0.62	0.65	0.73	0.74	0.73	**0.74**
NSE	-3.33	-3.82	-2.71	-1.09	-1.24	-0.62	-0.08	0.02	-0.07	**0.03**
KGE	-0.31	-0.39	-0.2	0.09	0.11	0.25	0.49	0.52	0.5	**0.53**

* Indicates higher flow thresholds used to transition between bathymetry grids.

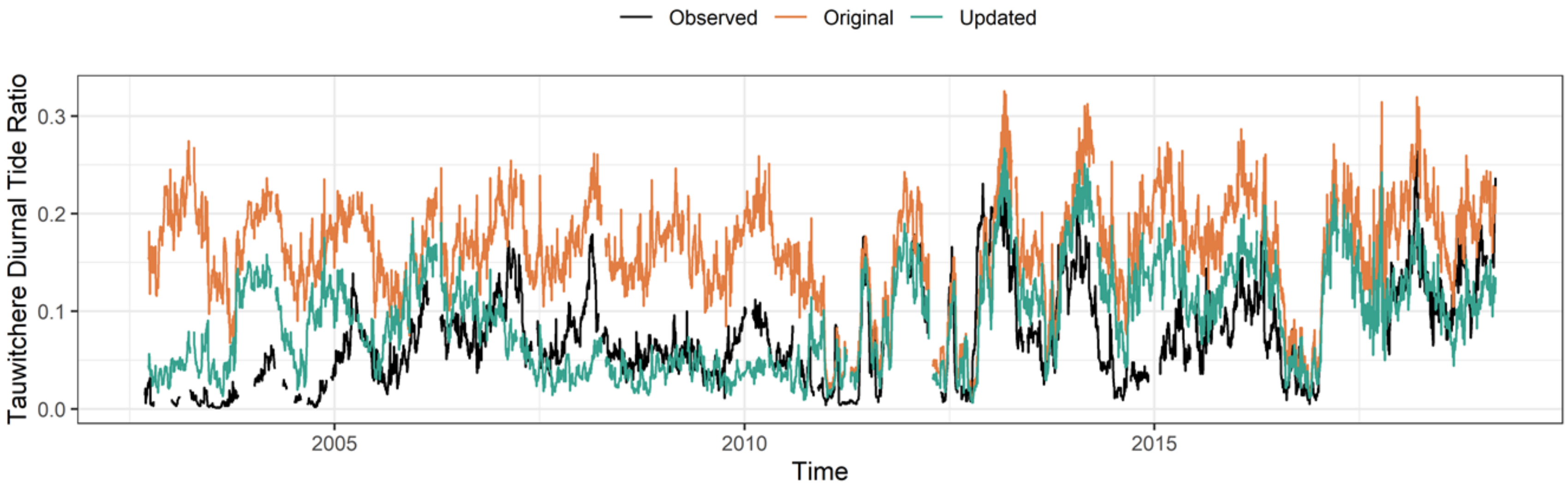

Figure 6-1 Time series of modelled and observed Tauwitchere diurnal tide ratio.

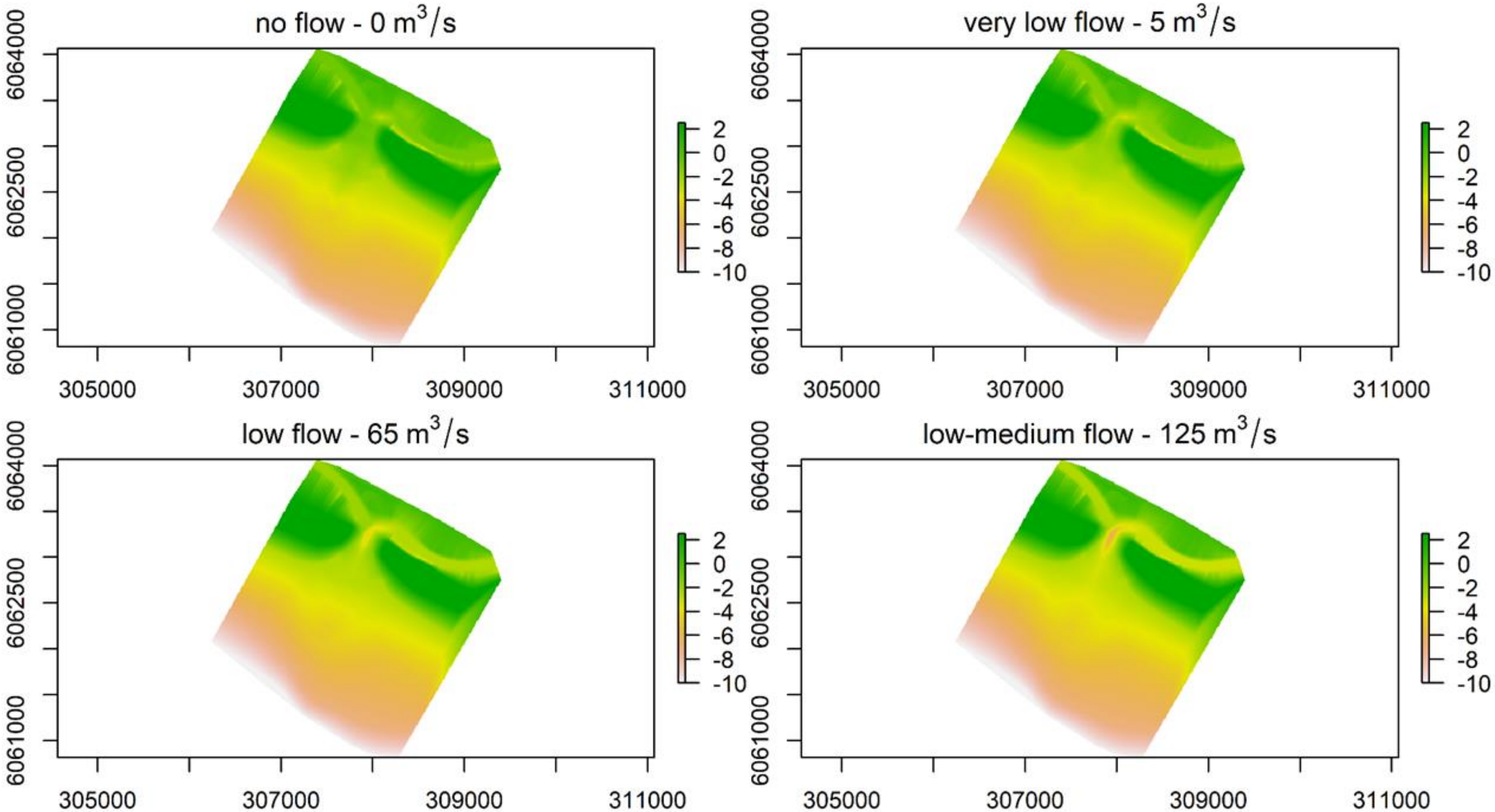

Figure 6-2 Bathymetric surfaces, and flow thresholds used to evolve toward each surface, used in the model for flows up to 125 m^3/s.

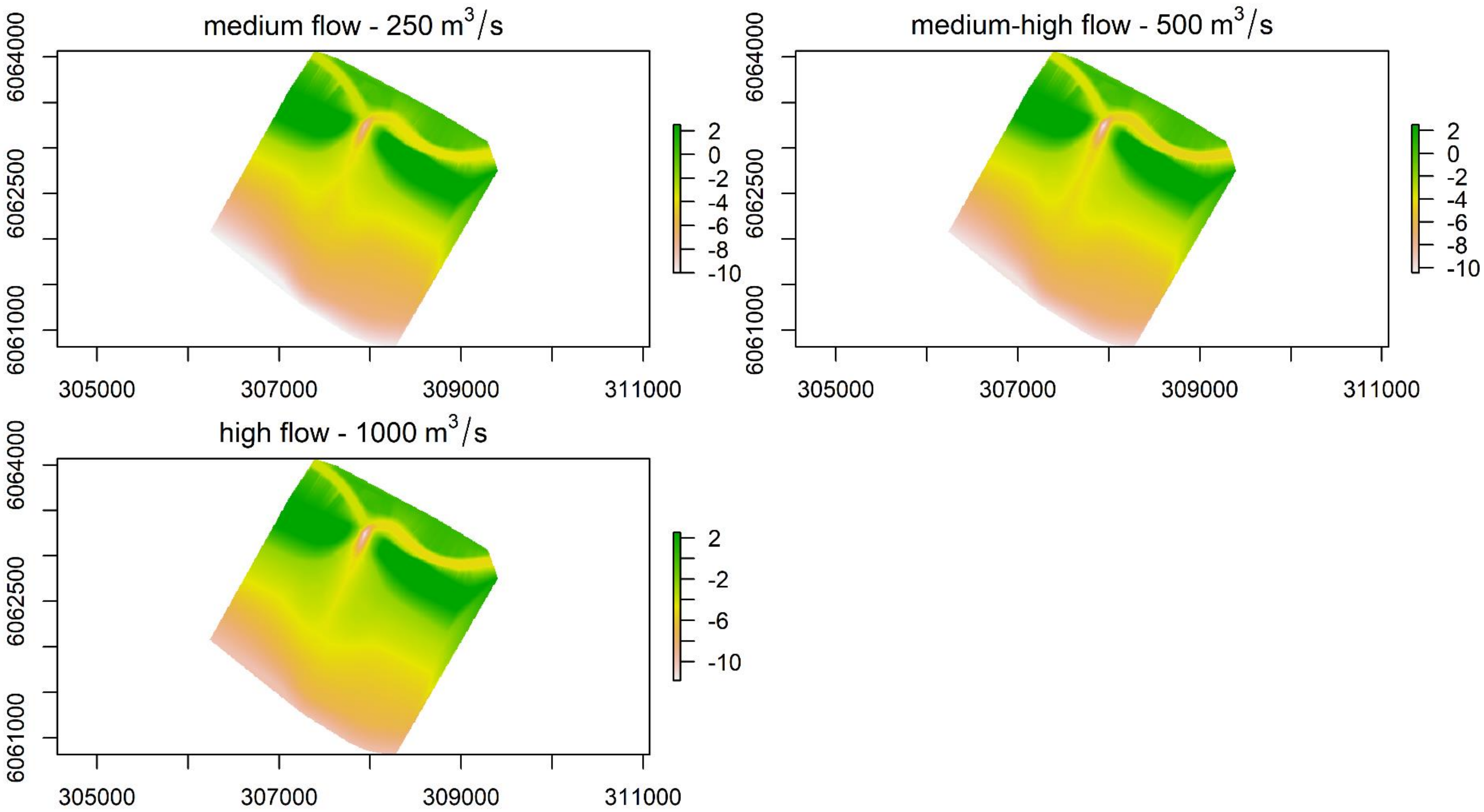

Figure 6-3 Bathymetric surfaces, and flow thresholds used to evolve toward each surface, used in the model for flows greater than 250 m^3/s.

Parnka Narrows bathymetry

A sensitivity assessment was undertaken to determine the effect of the sampling method for assigning an elevation to the model mesh from the digital elevation model (DEM).

For the section of the model between the two lagoons at the Parnka Narrows the DEM was used to sample a suitable elevation for each model element The 50th (median) and 33rd percentile of the DEM raster values within each element were adopted, and resulting modelled salinity compared to the high resolution model for the base case and constant 250 ML/d pump out scenarios from DEW (2021).

The initial conditions between the rapid and high resolution models are slightly different due to the difference in mesh resolution, which is one cause for the difference in salinity results seen in Figure 6-4. However, both the median and 33rd percentile coarse model configurations produce similar salinities to the high resolution model, which provides some confidence that the changes due to infrastructure options are not overly sensitive to the bathymetry representation in the model.

The resulting water level from the two rapid model configurations and the high resolution model can be seen in Figure 6-5. The two rapid model bathymetries produce water levels either side of the high resolution model, with the 50th percentile model having a higher 'sill' between lagoons and hence lower water levels over late summer – autumn, with the 33rd percentile model higher water levels with the improved connection between the north and south lagoon. The high resolution model did fill late compared to observed data for this period (see DEW 2021), hence the high water levels with the 33rd percentile bathymetry may provide an improved representation of this response (see next section). With the improved connection through Parnka narrows the 33rd percentile has a smaller impact on water levels compared to the other models, however there is a reduction in water levels with this configuration, which was not the case in the original rapid model, based on the minimum node elevation in the high resolution model. Both bathymetric configurations have been used in the following section to compare to the observed data.

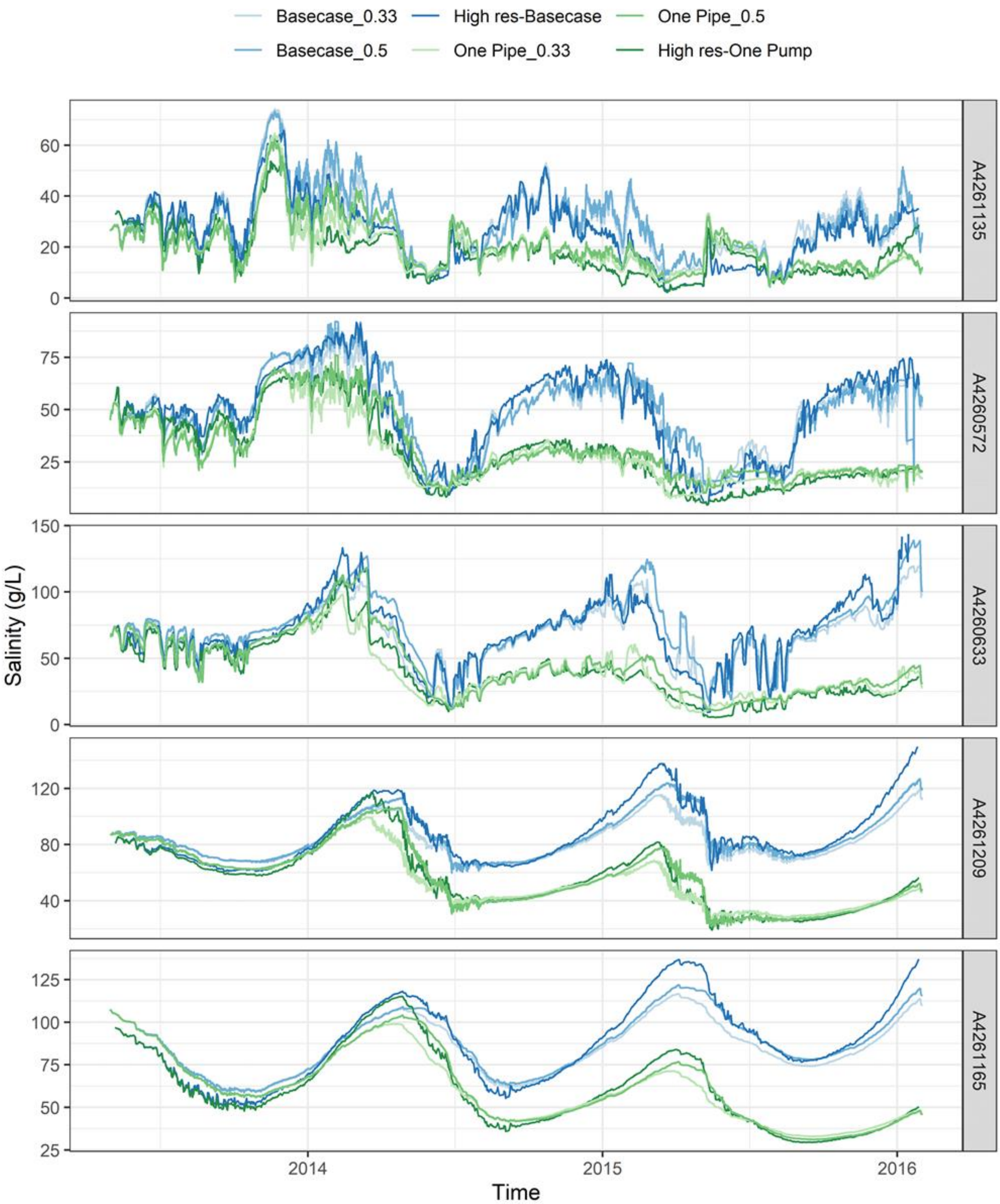

Figure 6-4 Time series of modelled salinity along the Coorong, from north to south. Scenarios are a base case (modelled actual) and 250 ML/d constant pumping rate (One Pipe) for the high resolution model, and rapid model with Parnka Narrows bathymetry based on 50th and 33rd percentile values within each element from the DEM.

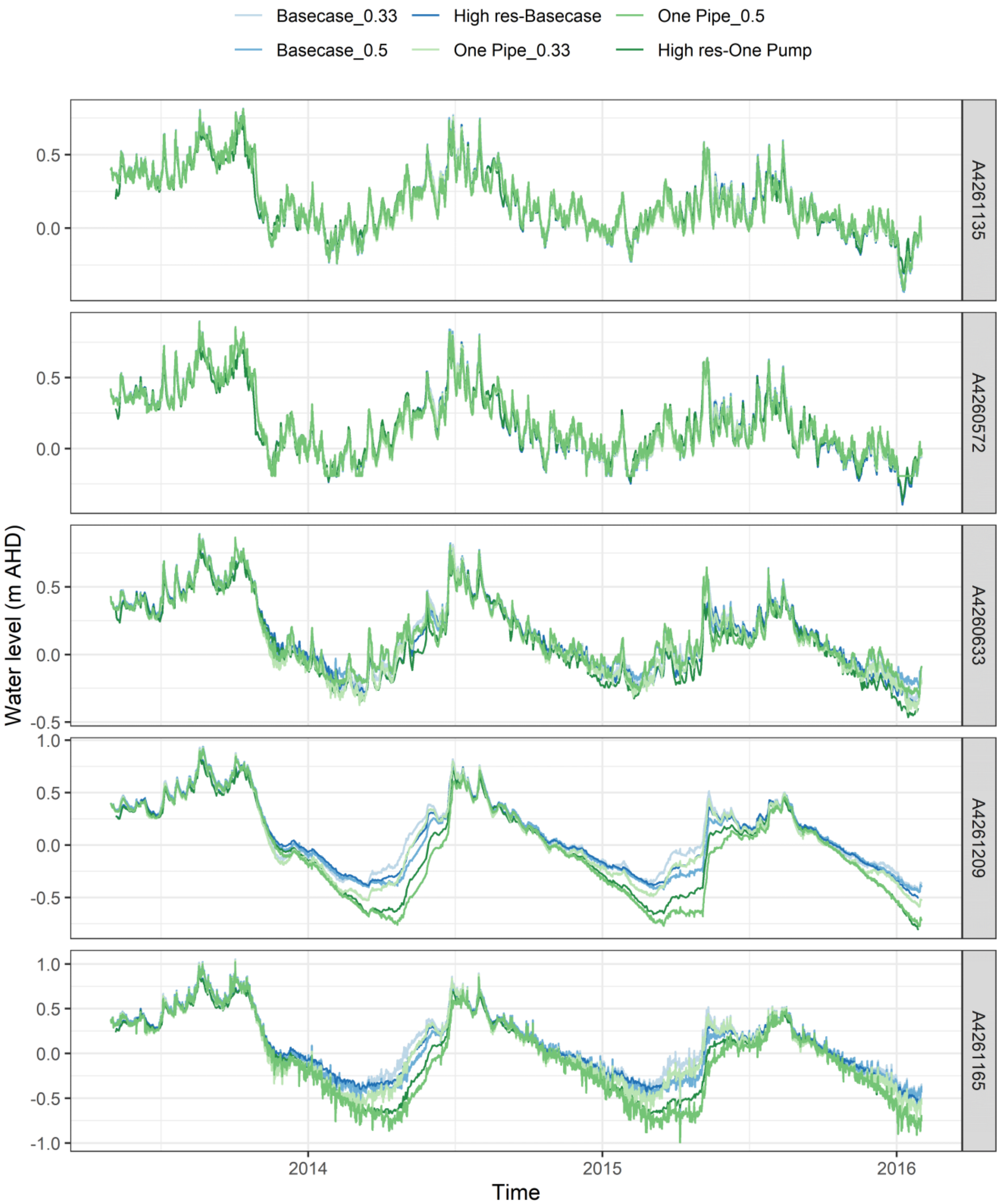

Figure 6-5 Time series of modelled water level along the Coorong, from north to south. Scenarios are a base case (modelled actual) and 250 ML/d constant pumping rate (One Pipe) for the high resolution model, and rapid model with Parnka Narrows bathymetry based on 50th and 33rd percentile values within each element from the DEM.

Validation

Following calibration of the mouth bathymetry and Parnka Narrows bathymetry the best performing model configurations were compared to observed data, for salinity, water level and water temperature. For the salinity error metrics, the Snipe Island station was extended back in time using the nearby, but closed, Sand Spit Point station data (A4260634). Also, observed salinities above 160 g/L were not included in the calculation of the error statistics. This was because the 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 (Webster, 2012).

Mouth Morphology

Given DTR is derived from water level, it could be expected water level error metrics improved slightly when going from the original to updated model. However, for the salinity and temperature metrics, which can be more related to the energy balance, almost all error metrics at each monitoring site considered indicates reduced performance (Table 6-2). This is not unexpected, as the original model was calibrated using the original bathymetric structure.

The results for the "Update 1.15x" configuration had a higher salinity than the original model, particularly in the south lagoon where evaporation is a dominant process. Reducing the bulk latent heat coefficient back to a default value of 1.3e-3 ("1x") improve most error metrics for all three parameters compared to other configurations considered. The reduced coefficient reduced the error in the water temperature for almost all metrics and sites, excluding a small number of metrics for the two south lagoon sites of Snipe Island and Woods Well.

Parnka Narrows bathymetry

The "Update 1x" model was used as the basis to revise the Parnka Narrows bathymetry elevation. The 50th percentile elevation was found to provide a closer water level result to the high resolution model above, however this model reduced performance for most salinity metrics compared to the "Update 1x" model (Table 6-3). The 33rd percentile model improves almost all metrics compared to the 50th percentile model, with the exception of water level at Parnka Point, and very small difference in salinity at Tauwitchere.

The 33rd percentile model produces slightly reduced error metrics for salinity for most monitoring stations compared to the "Update 1x model" with the exception of Robs Point. This location is at the southern end of the North Lagoon, and potentially reduced connectivity with the south lagoon in the 33rd percentile model has improved the salinity in the model for this location. Given the 33rd percentile model already provides greater connection between lagoons for the pumping scenario compared to the high resolution model (Figure 6-4) it is considered a reasonable balance between the impact on south lagoon water levels from the high resolution model for pumping scenarios and the slightly improved historical data accuracy of the "Update 1x" model.

During periods of low flow, residences times in the southern Coorong are a number of years (approximately 300 – 550 days, as indicated in Figure 4-5), and as such the modelled salinity and associated error metrics are strongly influenced by the previous periods of the simulation, with no obvious reset season (in comparison to water level). The salinity in the south lagoon during the Millennium drought period is overestimated by the model, and it takes a number of years for the salinity to reduce from these higher levels to the observed values again (Figure 6-6). However, the seasonal dynamics, in terms of the relative increase and decrease in salinity for these years (e.g. 2011 – 2014) are in line with the observed data. The higher salinities during the drought period may indicate slight overestimation of the evaporation rates and the impact of this accumulating over time, or possibly fresher groundwater inflows not represented in the model that are a larger proportion of the water and salt balance during this period of no barrage flow.

Summary

The rapid Coorong model developed by BMT (2021a) has been reviewed before being used for scenario modelling for CIIP. It was found that the original proof-of-concept dynamic Murray mouth structure represented a mouth that was more open than in reality, based on the Tauwitchere diurnal tide ratio. The mouth structure was revised by including more constricted bathymetric surfaces, and reducing the rate of erosion during high flows.

The changes to the Murray mouth structure enabled the default value for the bulk latent heat coefficient to be adopted, as opposed to this value being scaled up by 15%. This gives increased confidence in the configuration of the model, if default values for coefficients can provide accurate model results.

On initial testing of infrastructure scenarios, the bathymetry assumed through the Parnka Narrows was also found to provide too much connection between the lagoons compared to the high resolution model. By resampling the DEM of the area a higher cell elevation was selected, based on the 33rd percentile DEM value within the cell. This percentile was found to provide a good balance between accuracy against historical data, and the high resolution model for the 250 ML/d constantly pumping out scenario.

The updated model calibration results in increased accuracy in salinity (Figure 6-6), water level (Figure 6-7), water temperature (Figure 6-8) and Tauwitchere DTR compared the original model, and demonstrate a fit-for-purpose level of accuracy over the period with high resolution reanalysis input climate data and frequent monitoring data across the site, from 1998-2019.

Table 6-2 Model accuracy statistics for Mouth morphology calibration models and variables of salinity, water level and water temperature, for the original model configuration, as well as the updated mouth bathymetry, with and without the bulk latent heat parameter increased by a factor of 1.15. For each metric darker green indicates better performance.

		Salinity			Water Level			Water Temperature		
Site	Metric	Orig.	Update (1.15x)	Update (1x)	Orig.	Update (1.15x)	Update (1x)	Orig.	Update (1.15x)	Update (1x)
Snipe Island, A426165	MAE	24.37	30.4	16.77	0.11	0.11	0.11	1.04	1.05	1.14
	RMSE	31.13	38.26	22.28	0.14	0.14	0.14	1.31	1.31	1.38
	R^2	0.81	0.75	0.78	0.87	0.87	0.86	0.91	0.91	0.91
	IOA	0.8	0.74	0.88	0.96	0.96	0.96	0.97	0.97	0.97
	NSE	-0.41	-1.13	0.28	0.81	0.82	0.82	0.9	0.9	0.89
	KGE	0.39	0.28	0.56	0.75	0.79	0.83	0.87	0.87	0.9
Woods Well, A4261209	MAE	19.6	27.63	15.89	0.12	0.11	0.11	1.3	1.29	1.34
	RMSE	24.36	33.86	19.2	0.14	0.14	0.14	1.7	1.69	1.69
	R^2	0.86	0.83	0.81	0.86	0.86	0.86	0.84	0.84	0.85
	IOA	0.84	0.75	0.88	0.95	0.96	0.96	0.95	0.95	0.95
	NSE	-0.14	-1.2	0.29	0.8	0.81	0.82	0.84	0.84	0.84
	KGE	0.42	0.23	0.5	0.73	0.77	0.81	0.83	0.84	0.86
Parnka Point, A4260633	MAE	17.4	20.08	15.24	0.18	0.17	0.16	1.34	1.33	1.3
	RMSE	23.31	27.58	19.85	0.21	0.2	0.19	1.83	1.81	1.73
	R^2	0.75	0.73	0.73	0.81	0.82	0.82	0.81	0.81	0.82
	IOA	0.88	0.84	0.9	0.87	0.88	0.89	0.94	0.94	0.95
	NSE	0.23	-0.07	0.44	0.4	0.44	0.48	0.8	0.8	0.82
	KGE	0.45	0.34	0.59	0.41	0.44	0.47	0.84	0.84	0.86
Robs Point, A4260572	MAE	11.7	11.76	12.6	0.15	0.15	0.15	2.07	2.07	1.9
	RMSE	14.66	14.6	15.41	0.18	0.18	0.17	2.76	2.77	2.55
	R^2	0.53	0.55	0.55	0.72	0.73	0.72	0.64	0.64	0.65
	IOA	0.78	0.8	0.76	0.85	0.86	0.86	0.85	0.85	0.87
	NSE	-0.23	-0.22	-0.36	0.39	0.43	0.45	0.49	0.49	0.57
	KGE	0.52	0.42	0.59	0.45	0.48	0.5	0.74	0.74	0.77
Long Point, A4261135	MAE	9.61	11.18	9.79	0.12	0.11	0.11	1.3	1.29	1.18
	RMSE	13.62	16.65	13.52	0.15	0.15	0.15	1.75	1.73	1.55
	R^2	0.78	0.76	0.78	0.72	0.72	0.72	0.85	0.85	0.87
	IOA	0.91	0.89	0.92	0.9	0.91	0.91	0.95	0.95	0.96
	NSE	0.54	0.31	0.55	0.56	0.58	0.59	0.82	0.83	0.86
	KGE	0.61	0.45	0.61	0.71	0.73	0.74	0.85	0.85	0.88
Tauwitchere, A4261048	MAE	7.01	7.36	7.22	0.18	0.17	0.17	1.4	1.4	1.28
	RMSE	9.57	10.22	9.85	0.23	0.21	0.21	1.88	1.88	1.71
	R^2	0.71	0.71	0.71	0.45	0.51	0.51	0.83	0.83	0.84
	IOA	0.9	0.89	0.9	0.75	0.78	0.78	0.94	0.94	0.95
	NSE	0.52	0.45	0.49	-0.29	-0.09	-0.08	0.79	0.79	0.83
	KGE	0.68	0.63	0.66	0.4	0.47	0.47	0.84	0.85	0.87

Table 6-3 Model accuracy statistics for bathymetric calibration salinity, water level and water temperature, for the original model configuration, as well as the updated mouth bathymetry, with and without the bulk latent heat parameter increased by a factor of 1.15. For each metric darker green indicates better performance.

Site	Metric	Salinity			Water Level			Water Temperature		
		Update (1x)	33%ile	50%ile	Update (1x)	33%ile	50%ile	Update (1x)	33%ile	50%ile
Snipe Island, A426165	MAE	16.77	21.11	27.42	0.11	0.11	0.13	1.14	1.15	1.16
	RMSE	22.28	27.76	35.09	0.14	0.14	0.17	1.38	1.39	1.4
	R^2	0.78	0.77	0.74	0.86	0.88	0.82	0.91	0.91	0.91
	IOA	0.88	0.83	0.76	0.96	0.96	0.94	0.97	0.97	0.97
	NSE	0.28	-0.12	-0.79	0.82	0.82	0.72	0.89	0.89	0.88
	KGE	0.56	0.46	0.34	0.83	0.79	0.7	0.9	0.9	0.9
Woods Well, A4261209	MAE	15.89	19.22	25.07	0.11	0.11	0.13	1.34	1.35	1.36
	RMSE	19.2	23.9	30.67	0.14	0.13	0.17	1.69	1.69	1.7
	R^2	0.81	0.83	0.83	0.86	0.88	0.84	0.85	0.85	0.85
	IOA	0.88	0.84	0.78	0.96	0.96	0.94	0.95	0.95	0.95
	NSE	0.29	-0.1	-0.81	0.82	0.83	0.73	0.84	0.84	0.84
	KGE	0.5	0.42	0.3	0.81	0.76	0.67	0.86	0.86	0.86
Parnka Point, A4260633	MAE	15.24	18.47	24.74	0.16	0.16	0.14	1.3	1.71	1.81
	RMSE	19.85	24.65	33.02	0.19	0.18	0.17	1.73	2.33	2.44
	R^2	0.73	0.71	0.63	0.82	0.83	0.79	0.82	0.7	0.68
	IOA	0.9	0.86	0.79	0.89	0.9	0.9	0.95	0.9	0.89
	NSE	0.44	0.14	-0.54	0.48	0.53	0.6	0.82	0.67	0.64
	KGE	0.59	0.43	0.23	0.47	0.5	0.59	0.86	0.79	0.79
Robs Point, A4260572	MAE	12.6	10.47	11.14	0.15	0.14	0.15	1.9	1.87	1.85
	RMSE	15.41	13.18	14.43	0.17	0.17	0.17	2.55	2.5	2.48
	R^2	0.55	0.63	0.54	0.72	0.72	0.72	0.65	0.66	0.67
	IOA	0.76	0.83	0.8	0.86	0.87	0.86	0.87	0.88	0.88
	NSE	-0.36	0.01	-0.19	0.45	0.45	0.44	0.57	0.58	0.59
	KGE	0.59	0.51	0.37	0.5	0.5	0.5	0.77	0.78	0.78
Long Point, A4261135	MAE	9.79	10.77	11.75	0.11	0.11	0.11	1.18	1.17	1.17
	RMSE	13.52	15.35	16.37	0.15	0.14	0.14	1.55	1.54	1.53
	R^2	0.78	0.76	0.72	0.72	0.73	0.73	0.87	0.87	0.87
	IOA	0.92	0.9	0.88	0.91	0.91	0.91	0.96	0.96	0.96
	NSE	0.55	0.41	0.33	0.59	0.59	0.59	0.86	0.87	0.87
	KGE	0.61	0.53	0.52	0.74	0.73	0.73	0.88	0.89	0.89
Tauwitchere, A4261048	MAE	7.22	7.44	7.5	0.17	0.17	0.17	1.28	1.28	1.28
	RMSE	9.85	9.99	9.88	0.21	0.21	0.21	1.71	1.71	1.71
	R^2	0.71	0.71	0.72	0.51	0.51	0.51	0.84	0.84	0.84
	IOA	0.9	0.9	0.9	0.78	0.78	0.78	0.95	0.95	0.95
	NSE	0.49	0.48	0.49	-0.08	-0.08	-0.09	0.83	0.83	0.83
	KGE	0.66	0.64	0.65	0.47	0.47	0.47	0.87	0.87	0.87

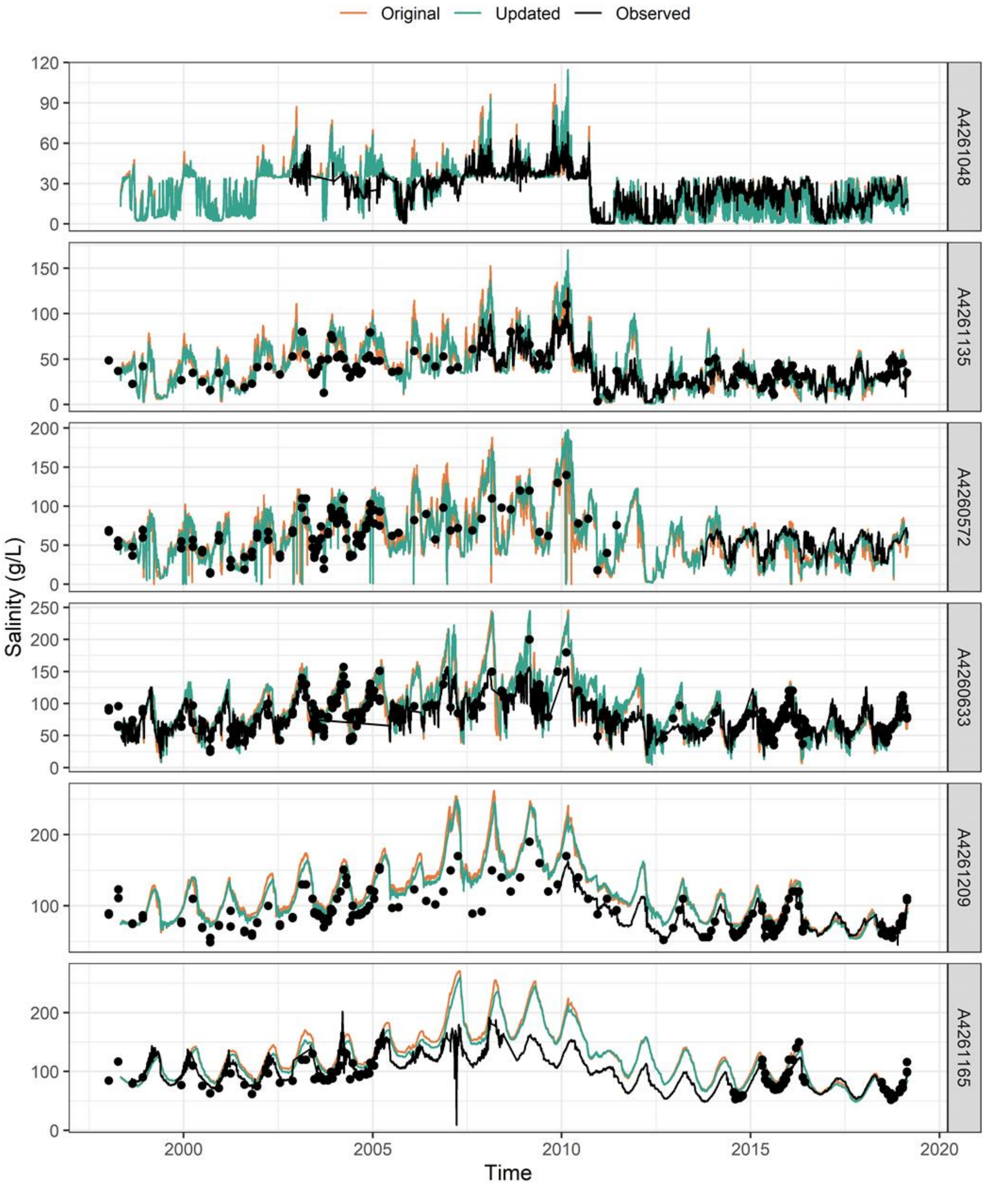

Figure 6-6 Time series of modelled and observed salinity along the Coorong, from north to south. Black dots represent salinity values from grab sample locations near each of the permanent monitoring stations. Gaps in the observed data, plotted as straight lines, have not been included in the error metric calculations.

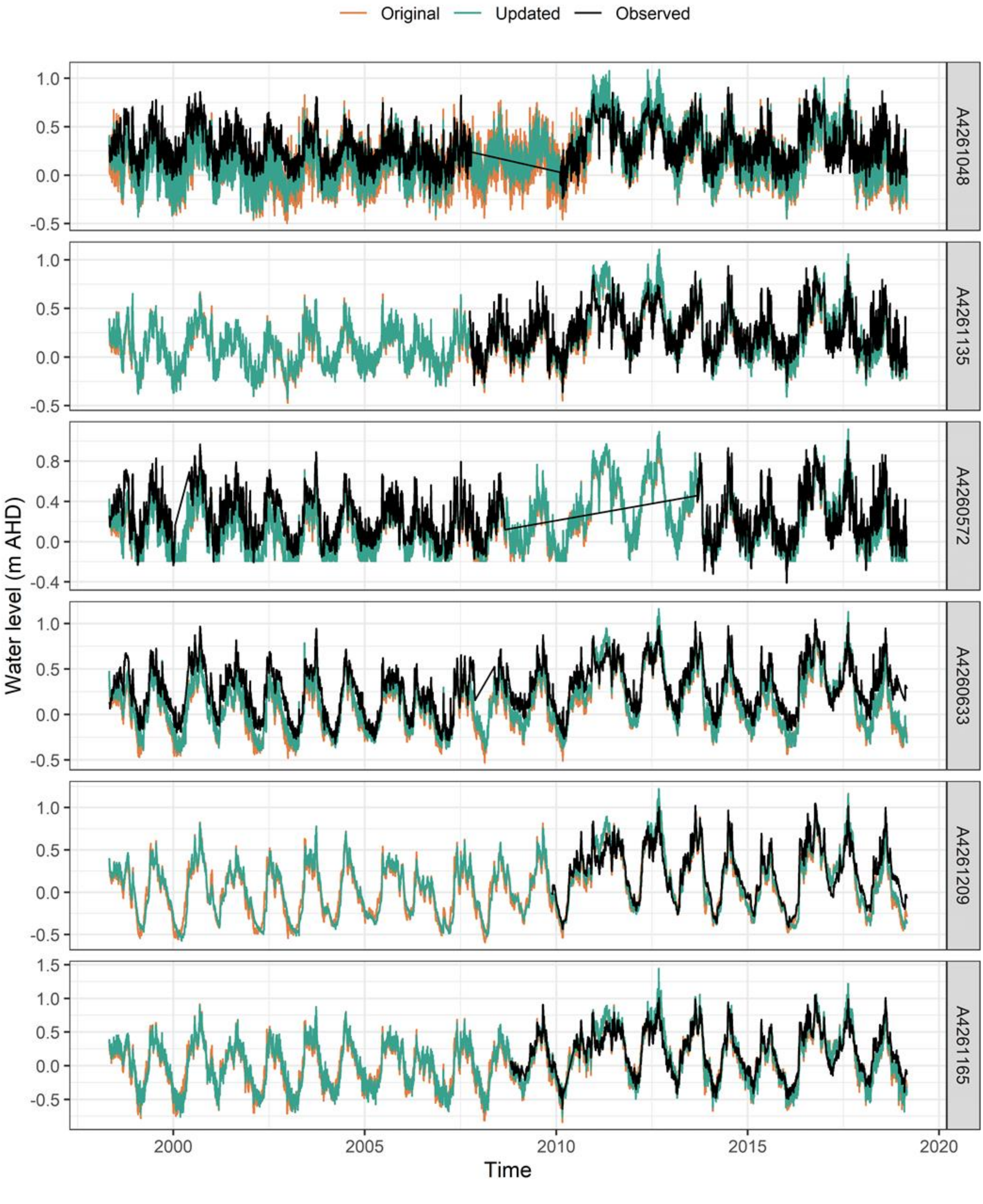

Figure 6-7 Time series of modelled and observed water level along the Coorong, from north to south. Gaps in the observed data, plotted as straight lines, have not been included in the error metric calculations.

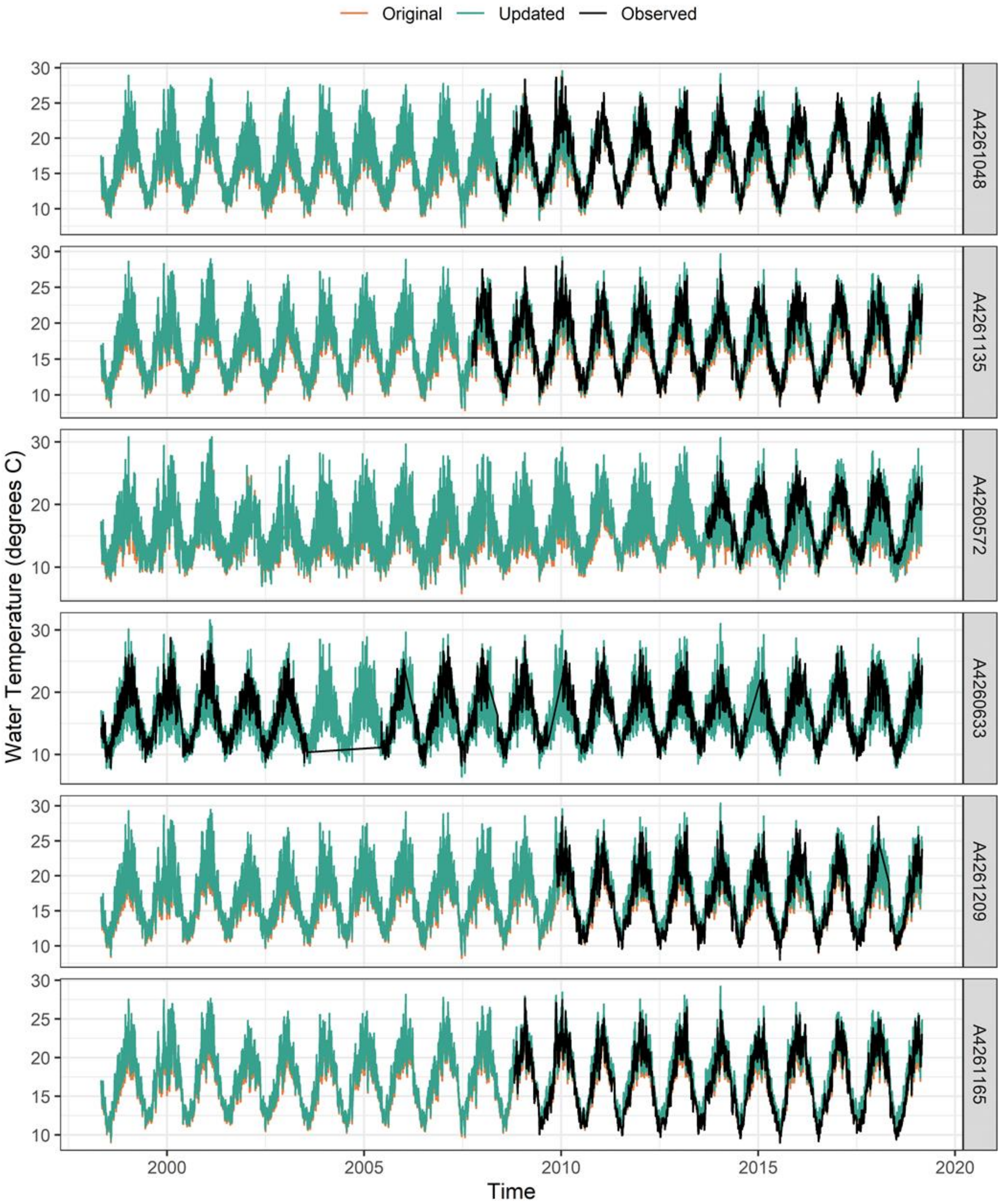

Figure 6-8 Time series of modelled and observed water temperatures along the Coorong, from north to south.

7 Units of measurement

7.1 Units of measurement commonly used (SI and non-SI Australian legal)

Name of unit	Symbol	Definition in terms of other metric units	Quantity
cubic metre	m^3	10^3 L	volume
day	d	24 h	time interval
gigalitre	GL	10^6 m^3	volume
gram	g	10^{-3} kg	mass
hour	h	60 min	time interval
kilometre	km	10^3 m	length
litre	L	10^{-3} m^3	volume
megalitre	ML	10^3 m^3	volume
metre	m	base unit	length
parts per thousand	ppt		concentration
second	s	base unit	time interval
year	y	365 or 366 days	time interval

7.2 Shortened forms

BARRA Bureau of Meteorology's Atmospheric high resolution regional reanalysis for Australia

BMT BMT Limited – maritime-orientated design and technical consulting firm

CIIP Coorong Infrastructure Investigations Project

CLLMM Coorong, Lower Lakes and Murray Mouth

CNL Coorong North Lagoon

CSL Coorong South Lagoon

DEM Digital Elevation Model

DEW Department for Environment and Water

ERAF Ecological Risk Assessment Framework

LAC Lake Albert Connector

MCA Multi criteria analysis

MDB Murray Darling Basin

RCP Representative Concentration Pathway

RCT Resource Condition Targets (from the Ramsar Management Plan)

SILO Database of Australian climate date from 1889 to the present

UWA University of Western Australia

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