Coorong Dynamics Model
sensitivity tests and gap identification

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Executive summary

Previous studies on the Coorong have laid the foundations for the development of a “Lagoon Response Model”, built on model software tools able to simulate hydrodynamics, water quality and ecological habitat conditions. Whilst these previous modelling efforts have assisted decision-making, the patchy data and restricted scope of previous modelling has left uncertainty as to their suitability in capturing nutrient and sediment budgets, and the responses of algae and *Ruppia tuberosa*.

With this in mind, the aim of this study has been to compare a range of model simulations that explore different model configurations and setup options, in order to inform future projects about the critical needs of the model for more accurate future assessments. The previously developed coupled hydrodynamics-biogeochemistry model was used for the investigation, built on the TUFLOW-FV hydrodynamic platform linked with the Aquatic EcoDynamics biogeochemistry and ecology model.

Specifically, the model simulations presented have aimed to assist with focusing efforts for future model improvements and associated data collection activities to support the next generation of model development. It is envisaged that further exploration of the model sensitivity and undertaking higher validation steps will transition the model from a more heuristic tool to a trusted decision support platform, suitable for management and guiding future restoration efforts.

Areas explored include assessing the role of tributary nutrient inputs, wind-wave resuspension, sea level rise, and sediment-water interaction. The results identified that there remain numerous areas where refining model setup and parameterisation, which are currently predominantly based on assumptions and literature review, could lead to significant improvements in accuracy. In particular, the model showed sensitivity to littoral zone processes and sediment-water fluxes in the Coorong South Lagoon. Nutrient budgeting demonstrated the extent to which internal vs external loading was driving water quality conditions, and how this balance shifts along the gradient from the north to the south of the Coorong. It demonstrated the degree to which uncertainty in these processes can manifest in predictions of water quality and estimation of habitat extent of *Ruppia tuberosa*. This is used as the basis for recommendations for data collection and model development that will help refine the model accuracy for decision support.

The simulations have highlighted the need for future simulations to consider the inclusion of 3D resolution, littoral zone benthic productivity, sediment early diagenesis (including aerobic/anaerobic biogeochemistry) and the connection with wind-wave induced resuspension. The potential for improved parameterisation of macroalgal mat formation and redistribution has also been identified.

Based on the model simulations undertaken and consideration of unknowns, priority areas for future data collection have been suggested, covering the following areas:

<u>Priority measures for refining model inputs:</u>

- *Salt creek inputs of flow and nutrient concentrations*
- *Barrage nutrient inputs and flow and salinity exchange*
- *Estimation of Coorong South Lagoon groundwater seepage*
- *Mouth channel morphology/bathymetry and oceanic exchange*

<u>Priority measures to assist model setup:</u>

- *Maps depicting spatial variability of sediment type and geochemical properties*
- *Maps depicting benthic coverage and density of seagrasses and infauna*

<u>Priority measures to assist model validation:</u>

- *Collection of high-frequency* in situ *multiparameter water quality data*
- *Routine nutrient and chlorophyll-a sampling, including periodic algal species identification*
- *Remotely sensed estimation of Ulva surface accumulations*

Priority experimental data to support setup and process justification:

- *Evaporation rates*
- *Sediment flux rates*
- *Sediment total and pore-water nutrients*
- *Resuspension rates*
- *Denitrification rates*
- *Organic matter breakdown and quality*
- *Particulate matter (total suspended solids) composition*
- *Ulva buoyancy and photosynthesis rates*
- *Bivalve filtration rates*
- *Benthic productivity as a function of depth/light*

Model uncertainty assessment and reporting:

- *Development of cloud computing options to support uncertainty assessment*
- *Development of predictive uncertainty workflows*

Aside from the above recommendations, the present study has contributed to improvements in model output analytics to support more robust use of the model to tackle questions about restoration and future policies.

Acknowledgments

This program is part of the Department for Environment and Water's Healthy Coorong Healthy Basin Program, which is jointly funded by the Australian and South Australian governments.

The work undertaken in this assessment follows development of the *Ruppia* habitat model during the *Optimising Ruppia Habitat* project with significant inputs in model design and assessment from Paul Erftemeijer, Michelle Waycott, Catherine Collier, and Kor jent Van Dijk. Prior work on model development in the Lower Lakes and Coorong has also been supported by the Australian Research Council (ARC) and carried out in collaboration with SARDI and The University of Adelaide, with assistance from Luke Mosley, Justin Brookes and Kane Aldridge. We would like to acknowledge Luke Mosley, Jody O'Connor, and Mark de Jong for their insightful reviews that have improved this work.

1 Introduction

1.1 Overview and scope

Previous studies on the Coorong have laid the foundations for the development of a “Lagoon Response Model”, built on model software tools able to simulate hydrodynamics, water quality and ecological habitat conditions (see Collier et al., 2018). Predicting the response of the system to potential future changes in hydro-meteorological conditions, barrage and dredge operations is essential to inform management for effective system conservation and adaptation. Previous models have predicted maps of high- and low-quality seagrass (*Ruppia tuberosa*) habitat, allowing for an assessment of where conditions would be “suitable” under any given hydro-biogeochemical conditions by adopting a “Habitat Suitability Index” (HSI) approach. The prior assessment included environmental sensitivities for different stages of the *Ruppia* life-cycle. Collier et al. (2017) ran the model for historical conditions based on data from 2014, 2015 and 2016. They demonstrated that the hydrodynamic complexity of the system, and different requirements of each life phase, make it difficult to generalise about flow conditions that would lead to optimum overall habitat availability. Nonetheless, the results have shown that the interaction of water level, salinity and filamentous algae are important drivers shaping the overall extent of good-quality *Ruppia* habitat.

Despite the previous modelling efforts, the patchy data and narrow scope of the previous modelling means that there remains uncertainty as to the suitability of the models to capture nutrient and sediment budgets, and the responses of algae and *Ruppia tuberosa*. Future research programs can fill many knowledge gaps, and thereby help constrain uncertainty in model predictions. The model can also help prioritise data collection activities and other experiments by highlighting the sensitivity of important variables to modelled processes or boundary inputs.

With this in mind, the aim of this study has been to compare model simulations that explore different model configurations and setup options, in order to inform future projects about the critical needs of the model for more accurate future assessments. Such areas of interest include assessing the role of nutrient inputs, wind-wave resuspension, sea-level rise, sediment water interaction, and others. The report discusses a range of areas where improved data can aid in driving the next generation of model development activities.

1.2 Model description

In this study, we use the previously developed coupled hydrodynamics-biogeochemistry model, termed the Coorong Dynamics Model (CDM), hereafter. The CDM is built on the TUFLOW-FV hydrodynamic platform, linked with the Aquatic EcoDynamics (AED2) biogeochemistry and ecology model. Initial setup using the model platform adopted here was reported in Ye et al. (2016) for environmental flow assessment and Mosley et al. (2017) for Coorong flow options assessment. The model was validated in detail (using data from 2014-2016) as part of the *Optimising Ruppia Habitat* project (Collier et al. 2017) and used for scenario assessment of weir options being considered between the lagoons of the Coorong (BMT WBM 2017; Hipsey et al. 2017).

In brief, the model adopts an unstructured mesh, tailored to resolved littoral zone conditions and exchange between the South and North lagoons (Figure 1). The model can be run in 2D (depth-averaged) or 3D (vertically-resolved) mode – both are used in this report. The model dynamically links with AED2 to simulate the mass balance and redistribution of carbon, nutrients and sediment, including partitioning between organic and inorganic forms and resolution of the relevant biotic components. This includes turbidity (including particle resuspension and sediment redistribution), chlorophyll *a* (chl-a), and filamentous algae (*Ulva*), plus habitat quality of *Ruppia*.

Of relevance to a shallow lagoon like the Coorong, the model can capture wave and current induced resuspension and spatial variation in sediment properties; wave stress requires linking the model with the SWAN model. Benthic and pelagic properties can also be resolved. A summary of simulated model variables is shown in Table 1. For this specific application, the extent of the modelled domain is as shown in Figure 1, and this was used to assess various scenarios, by using the base validated simulation reported previously.

Table 1: Summary of the variables resolved by the TUFLOW-FV – Aquatic EcoDynamics (AED2) platform in the present Coorong model setup. Note some of the variables are optional and enabled in selected simulations.

VARIABLE ABBREVIATION	UNITS *	COMMON NAME	PROCESS DESCRIPTION
Physical variables			
T	°C	Temperature	Temperature modelled by hydrodynamic model, subject to surface heating and cooling processes
S	psu	Salinity	Salinity simulated by TUFLOW-FV, impacting density. Subject to inputs and evapo-concentration
EC	uS cm^{-1}	Electrical conductivity	Derived from salinity variable
I_{PAR}	mE m^{-2} s^{-1}	Shortwave light intensity	Incident light, I_0, is attenuated as a function of depth
I_{UV}	mE m^{-2} s^{-1}	Shortwave light intensity	Incident light, I_0, is attenuated as a function of depth
η_{PAR}	m^{-1}	PAR extinction coefficient	Extinction coefficient is computed based on organic matter and suspended solids
η_{UV}	m^{-1}	UV extinction coefficient	Extinction coefficient is computed based on organic matter and suspended solids
Biogeochemical variables			
DO	mmol O_2 m^{-3}	Dissolved oxygen	Impacted by photosynthesis, organic decomposition, nitrification, surface exchange, and sediment oxygen demand
RSi	mmol Si m^{-3}	Reactive Silica	Algal uptake, sediment flux
FRP	mmol P m^{-3}	Filterable reactive phosphorus	Algal uptake, organic mineralization, sediment flux
PIP	mmol P m^{-3}	Particulate inorganic phosphorus	Adsorption/desorption of/to free FRP
NH_4^+	mmol N m^{-3}	Ammonium	Algal uptake, nitrification, organic mineralization, sediment flux
NO_3^-	mmol N m^{-3}	Nitrate	Algal uptake, nitrification, denitrification, sediment flux
CPOM	mmol C m^{-3}	Coarse particulate organic matter	Enzymatic hydrolysis to particulate organic matter
DOC-R	mmol C m^{-3}	Refractory DOC	Sediment release, photolysis
DON-R	mmol C m^{-3}	Refractory DON	Sediment release, photolysis
DOP-R	mmol C m^{-3}	Refractory DOP	Sediment release, photolysis
DOC	mmol C m^{-3}	Dissolved organic carbon	Mineralisation, algal mortality/excretion, photolysis
DON	mmol N m^{-3}	Dissolved organic nitrogen	Mineralisation, algal mortality/excretion, photolysis
DOP	mmol P m^{-3}	Dissolved organic phosphorus	Mineralisation, algal mortality/excretion, photolysis
POC	mmol C m^{-3}	Particulate organic carbon	Breakdown, settling, algal mortality/excretion
PON	mmol N m^{-3}	Particulate organic nitrogen	Breakdown, settling, algal mortality/excretion
POP	mmol P m^{-3}	Particulate organic phosphorus	Breakdown, settling, algal mortality/excretion
TP	mmol P m^{-3}	Total Phosphorus	Sum of all phosphorus state variables
TN	mmol N m^{-3}	Total Nitrogen	Sum of all nitrogen state variables
TKN	mmol N m^{-3}	Total Kjedahl Nitrogen	Sum of relevant nitrogen state variables
CDOM	mmol C m^{-3}	Chromophoric Dissolved Organic Matter	Related from DOC-R and DOC concentrations

Planktonic variables			
BGA	mmol C m^{-3}	Cyanobacteria	Photosynthesis, nutrient uptake, respiration, sedimentation
GRN	mmol C m^{-3}	Green	Photosynthesis, nutrient uptake, respiration, sedimentation
DIA	mmol C m^{-3}	Diatom	Photosynthesis, nutrient uptake, respiration, sedimentation
ULVA	mmol C m^{-3}	Ulva (floating)	Sloughing, sedimentation and transport, photosynthesis & respiration
TCHLA	mmol C m^{-3}	Total Chlorophyll-a	Sum of planktonic algal groups, converted to chlorophyll-a
Sediment & Turbidity			
SS	g SS m^{-3}	Suspended sediment	Sedimentation, resuspension
Turbidity	NTU	Turbidity	Derived from particulate components in suspension
Benthic variables			
MPB	mmol C m^{-2}	Benthic algae	Benthic photosynthesis & respiration.
$ULVA_{BEN}$	mmol C m^{-3}	Ulva (benthic)	Benthic photosynthesis, nutrient uptake, respiration & sloughing
Ruppia HSI	-	Ruppia Habitat Suitability	Computed from light, depth, salinity, temperature and algae

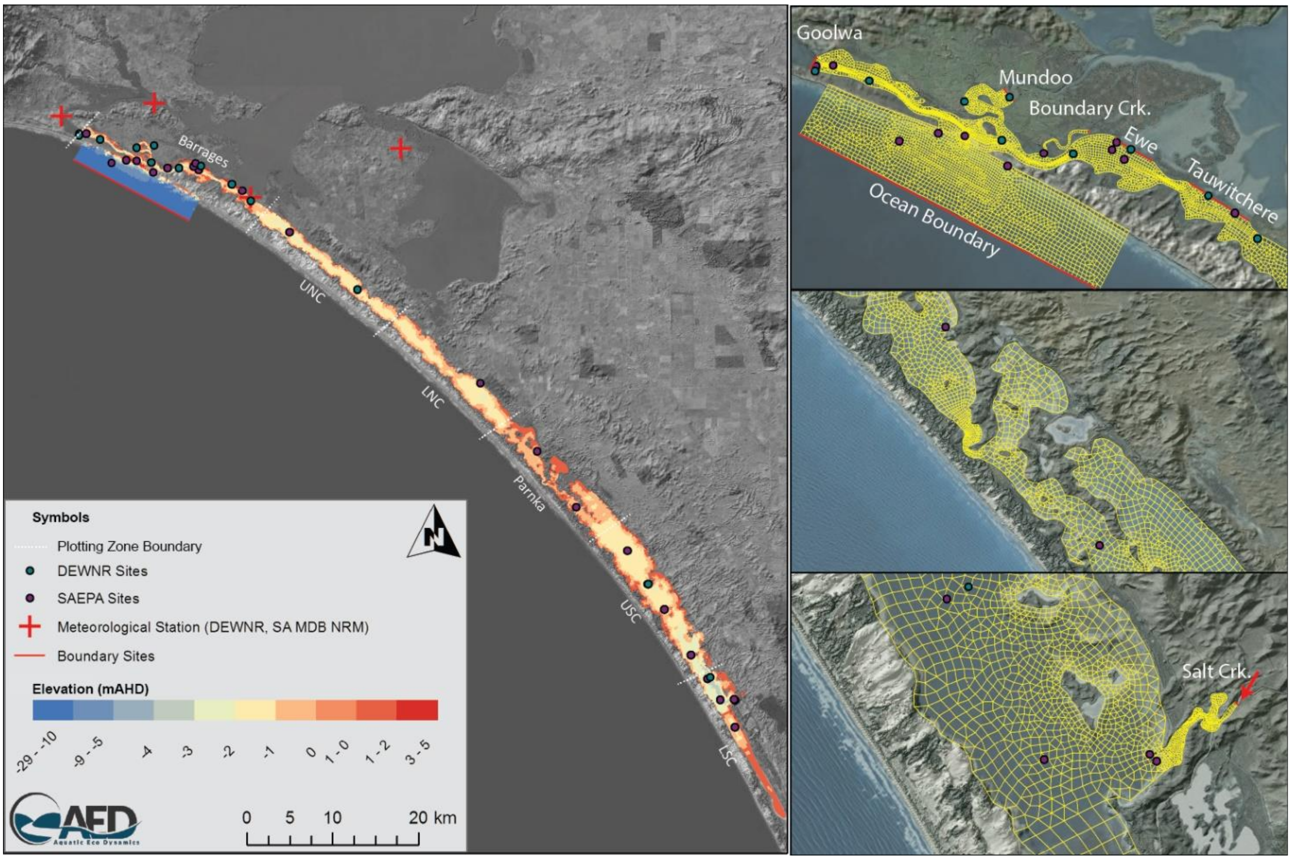

Figure 1. Outline of the simulated model domain, indicating the model mesh, analysis regions, and monitoring sites.

2 Simulation approach

A range of uncertainty exists in model simulations. This arises from uncertainty in external inputs (boundary condition uncertainty), uncertainty in parameter value specification (parameter uncertainty), and uncertainty in assumptions around model approach and variable interactions (structural uncertainty). To fully quantify uncertainty in multi-parameter models, it is possible to use an application like the Parameter Estimation Tool (PEST), however, this is computationally restrictive for long-term high-resolution simulations such as the CDM. Therefore, to gauge the level of uncertainty brought about by key areas identified in the Healthy Coorong, Healthy Basin program we instead designed a range of simulations to strategically explore model sensitivity to specific settings.

For this assessment, the base-case 3-year simulation was run using actual environmental conditions for the period from 2014-2016; this simulation was consistent with the validation simulations of the "Optimising Ruppia Habitat" project (Collier et al., 2017). The annual barrage volumes were 919.3 GL, 754.9 GL and 5694.8 GL for 2014, 2015 and 2016, respectively. The initial conditions were interpolated based on observed data from 1/1/2014. A set of 18-month "what-if" scenarios were then run over the period April 2014 - December 2015, with each scenario therefore capturing two growing seasons, and capturing the potential for "carry-over" effects from one winter/spring to the next summer/autumn. Any difference in initial conditions presented in the figures is due to the model simulation starting on 1 January 2014, with results presented from the start of the Ruppia life cycle, assumed in the CDM to start on 1 April 2014.

A summary of the simulations undertaken is shown in Table 2. It is important to note that there may be additional longer-term "carry-over" effects that were not considered in these scenarios. Furthermore, the assessment also does not consider the current (starting) condition of *Ruppia* populations within Coorong, nor additional factors that may limit its recovery (e.g. sulfidic sediments). In addition, it was not possible to investigate all factors that may influence habitat availability for *Ruppia* and that may change in response to management interventions (e.g. geomorphology, sediment characteristics). Nonetheless, the scenarios have been designed to investigate the sensitivity of the results from the CDM to different uncertainties, to inform the most valuable components for future model development and data collection.

3 Scenario comparison and sensitivity assessment

Results from the models include hydrodynamic, biogeochemical and habitat related measures, across the domain, over the multi-year simulation period. To enable interpretation of the scenarios, the simulation matrix reported above is reported on below from a strategic point of view of using model sensitivity to help prioritise addressing important knowledge gaps.

- ***Salt Creek and minor tributary nutrient loads***
  - Scenarios ORH, Dep. False, SC40, SC40 x 1.5, SC40 x 2.
  - Figures 2-6
- ***Mouth morphometry and sea level rise (SLR) effects on lagoon water quality***
  - Scenarios ORH and SLR 0.2 m
  - Figures 7-16
- ***Atmospheric deposition***
  - Scenarios ORH and Dep. False
  - Figures 17
- **Sediment biogeochemistry and sediment-water interactions**
  - Scenarios ORH, FSED 0, FSED 2
  - Figures 18-25
- **Benthic productivity and littoral oxygen metabolism**
  - Scenarios ORH and MBP 2000
  - Figures 26-30
- ***Ruppia* life-stage sensitivity**
  - Scenarios ORH, MBP 2000, FSED 2, SLR 0.2 m
  - Figures 31-32

Table 2: Overview of simulations undertaken to explore Coorong Dynamics Model sensitivity.

SIMULATION	DESCRIPTION	ANNUAL SALT CREEK FLOW (GL) 2014/2015(/2016)
ORH	Base Case 2014-2016, as Collier et al. (2017)	18.8 / 6.6 / 19.7
MBP 2000	2014-2015 of ORH, with 6 vertical layers included and benthic productivity (MPB)	
FSED 0	ORH with no internal nutrient loading	
FSED 2	ORH with x2 internal nutrient loading	
SLR 0.2m	ORH with +20cm sea level	
Dep. False	ORH with atmospheric wet deposition of nitrogen and phosphorus disabled	
SC40	ORH with 40 GL/year salt creek inflow	40 / 40
SC40 NUTx1.5	ORH with 40 GL/year salt creek inflow and nutrient load x 1.5	
SC40 NUTx2	ORH with 40 GL/year salt creek inflow and nutrient load x 2	
SC70	ORH with 70 GL/year salt creek inflow	70 / 70

For each grouping indicated above, custom plots are produced to compare salinity and nutrients, along with assessment of habitat suitability (HSI) and the total suitable habitat area (A^{HSI}). Note that, in order to facilitate comparisons, some scenarios are repeated between groups.

Other areas considered in the assessment, but not resolved in the simulation matrix, include:

- Organic matter quality and cycling
- Wind-wave induced resuspension
- *Ruppia* seed-dispersal
- Bivalve filtering and bioturbation
- *Ulva* surface mat formation and redistribution
- Zooplankton density and grazing rates
- Groundwater nutrient inputs
- Benthic coverage mapping

To assist in building an overall summary of the effect of the different scenarios on conditions within the Coorong, a simple summary section is provided at the end of the results (Figure 34 & 35). For further reference of specific seasons and regions, quantitative summaries of assessed variables are also listed as a table in the Appendix (Tables A.1 – A.8).

3.1 Boundary conditions and input uncertainty

3.1.1 SALT CREEK AND MINOR TRIBUTARY NUTRIENT LOADS

The relative sensitivity of the Coorong South Lagoon (CSL) to Salt Creek inflows was explored by comparing flow and nutrient levels, and assessing the influence of this on the overall South Lagoon nutrient budget. Previous exploration of Salt Creek flows is described in Collier et al., (2017), where the Salt Creek flow hydrograph is shown. In these simulations we compare the SC40 (C1 and C2) and SC70 (C4) simulation hydrographs, but look at sensitivity to nutrients in this inflowing water. Figures 2-4 show the time-series of salinity, TN and TP changes in response to changing Salt Creek flows and nutrient inputs. They highlight that the fresher water entering from Salt Creek can reduce salinity in the South Lagoon, by dilution and also by pushing the more saline water further into the North Lagoon (see also Mosley et al., 2017).

The simulated effects of these changes on the total nutrient concentrations (TP and TN), however, was relatively minor in the water, consistent with the expectation that dilution of this relatively small volume of water into the larger lagoon volume is only fractional. This doesn't consider that the inflow nutrient loads will likely deposit rapidly and accumulate in the sediment, fuelling later nutrient release, so should be viewed with caution. More aggressive nutrient reduction efforts over the long-term will be required to have a notable reduction.

Figure 5 summarises the Coorong South Lagoon nutrient budget, and input/output fluxes for the different SC scenarios tested. Whilst the concentrations are different in the South Lagoon under these scenarios (i.e. SC40 x 1.0, SC40 x 1.5, SC40 x 2.0), the overall effect on the mass balance is surprisingly minor. However, when zoomed into the Salt Creek outlet region (Figure 6) the nutrient pulse is more obvious.

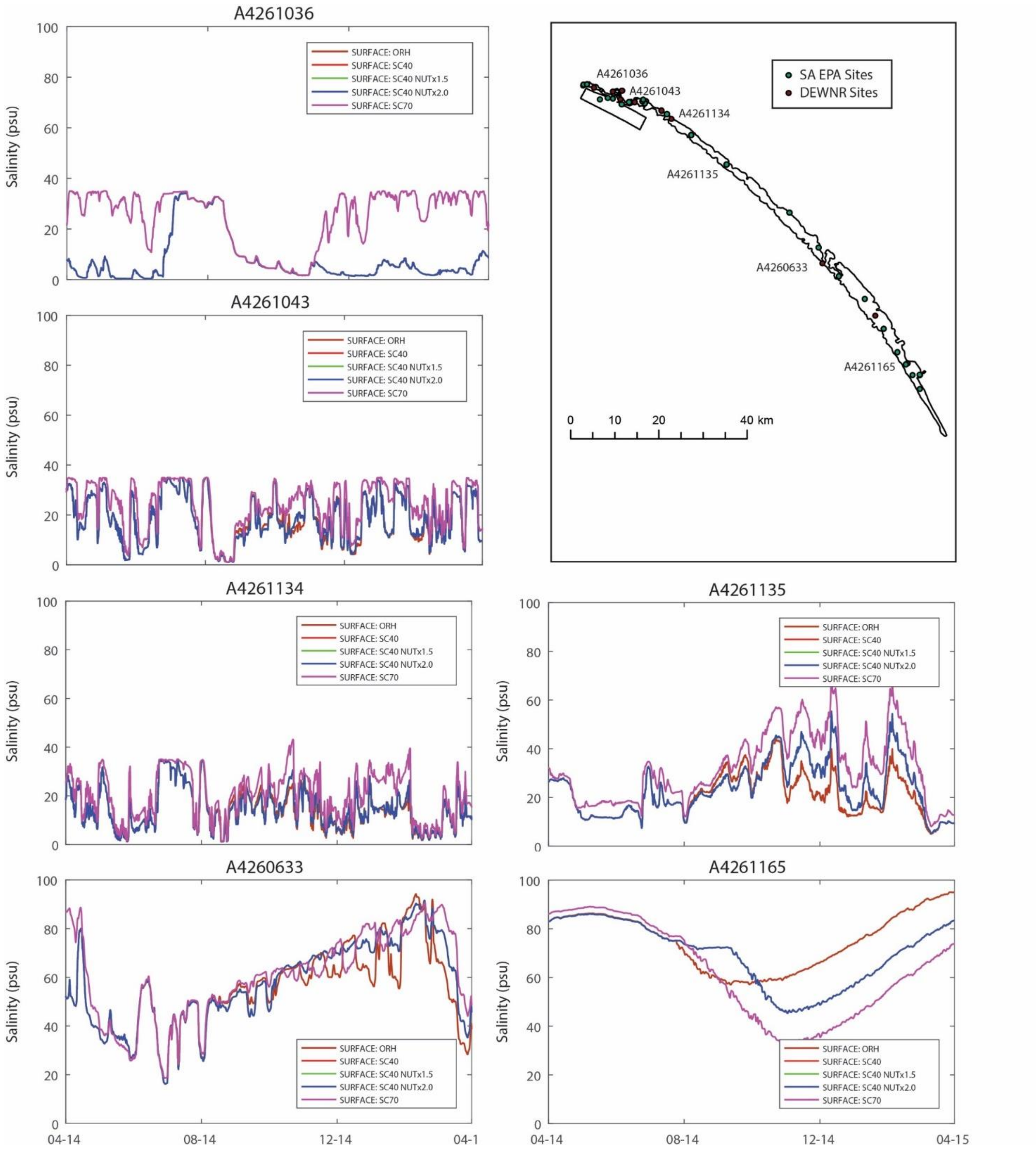

Figure 2. Coorong salinity time-series showing sensitivity to salt creek inputs, comparing different Salt Creek inflow volumes and nutrient loads. Note the green and red series are indistinguishable as they have the same flow and salinity as the blue series.

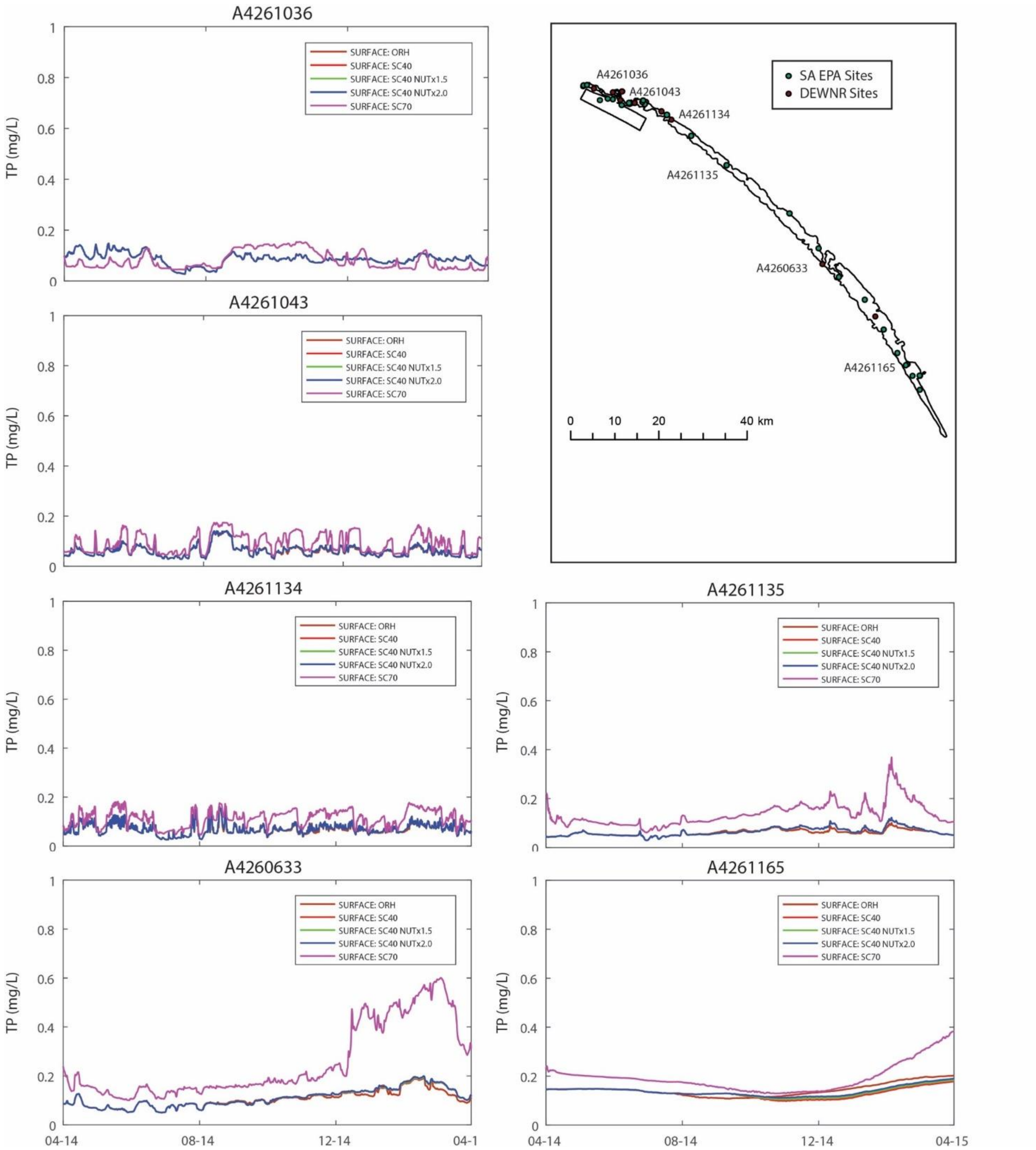

Figure 3. Coorong total phosphorus concentration (TP) time-series showing sensitivity to salt creek inputs.

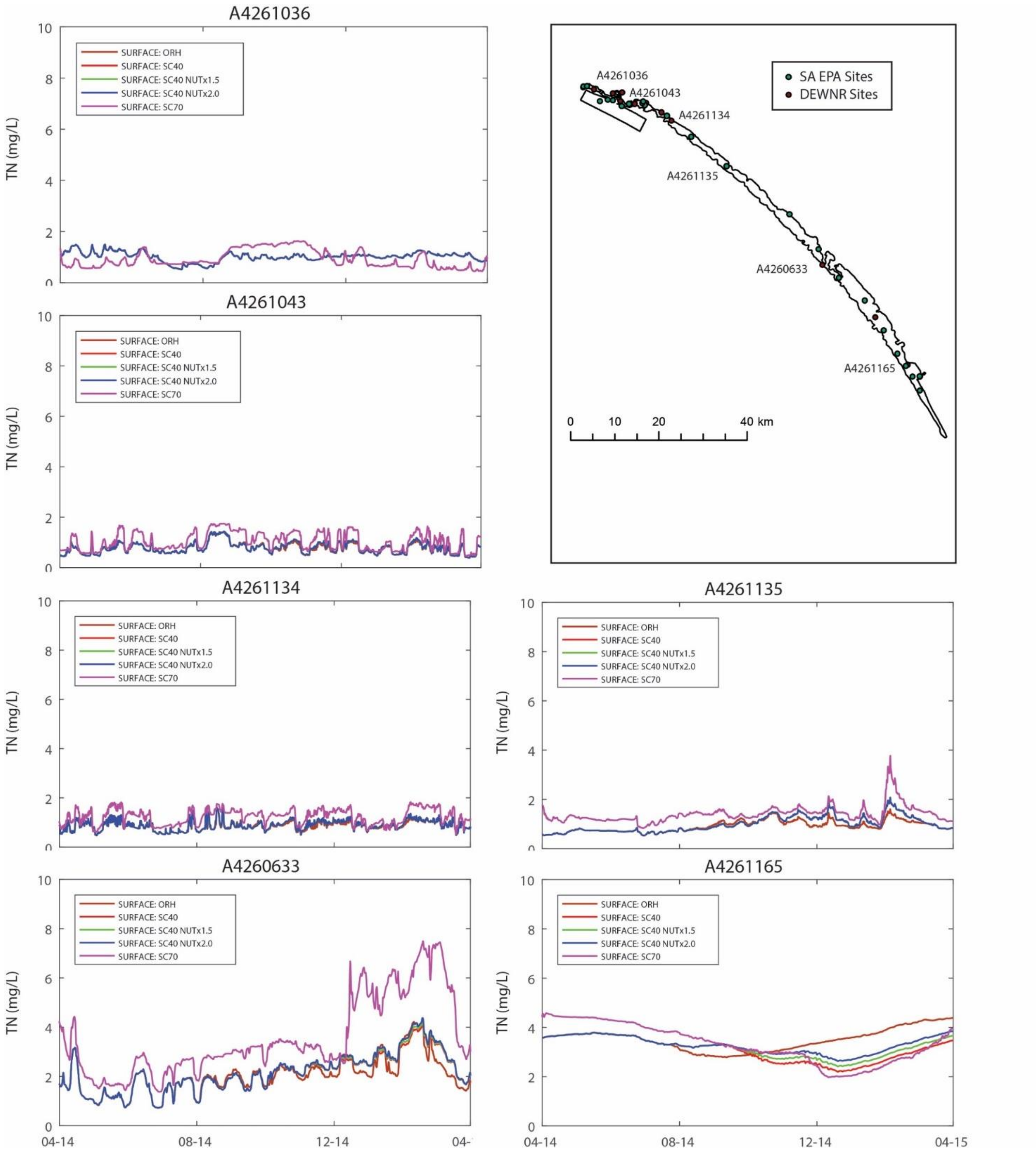

Figure 4. Coorong total nitrogen concentration (TN) time-series showing sensitivity to salt creek inputs.

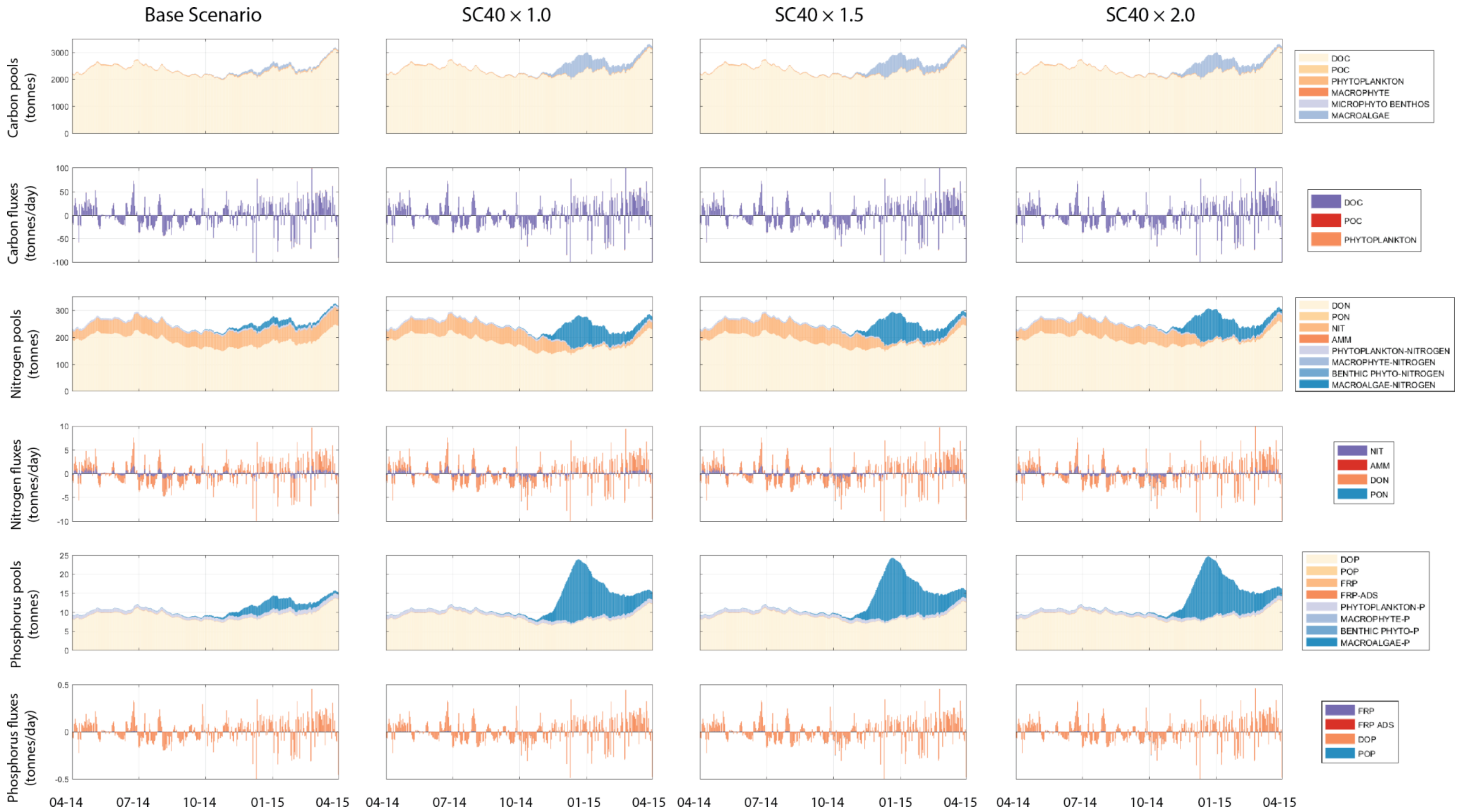

Figure 5. South Lagoon nutrient pools and input/output loads for carbon nitrogen and phosphorus species, comparing scenarios with different Salt Creek inputs, (Base scenario = *ORH, and SC40 x 1.0 = SC40).* Refer to Table 1 for nutrient pool descriptions.

Given the nutrient budget is similar across the scenarios with varying nutrient concentrations, it is expected that the increase in macroalgae N and P biomass is driven by the lower salinity from the increased Salt Creek flow increasing habitat availability (i.e. minimum salinities of approximately 45 psu and 60 psu, respectively). The increase in N and P macroalgal biomass extends later into summer around Salt Creek in Figure 6, as the macroalgal growth peak is seen in Figure 5, but it decreases earlier when the budget is looked at within this smaller region.

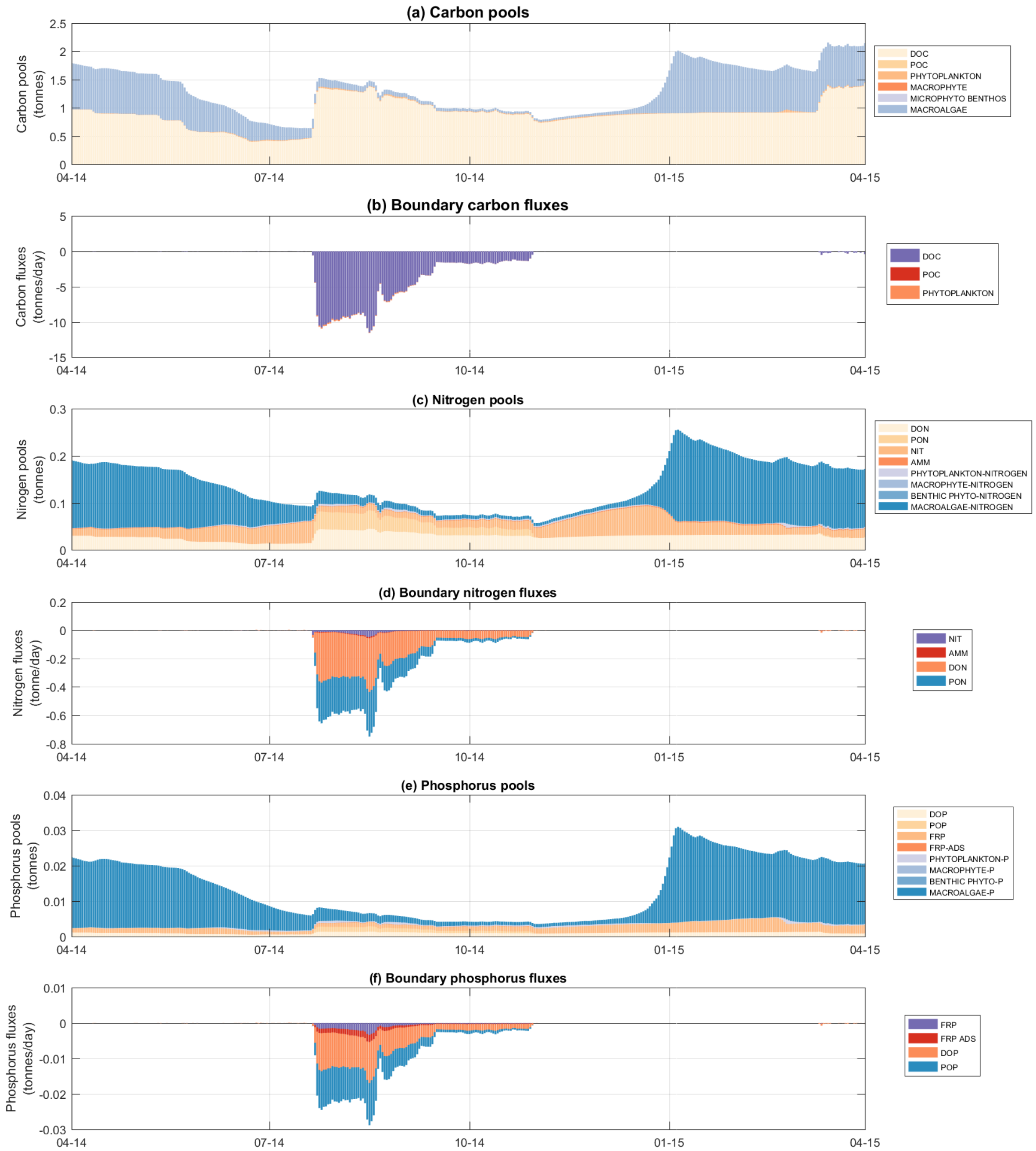

Figure 6. Salt Creek region nutrient pools and input/output loads for carbon, nitrogen and phosphorus species for SC40. The negative fluxes are material leaving the Salt Creek entrance region and entering the main lagoon. There is a high build-up of macroalgae predicted after the winter water and nutrient pulse.

3.1.2 MOUTH MORPHOMETRY AND SEA-LEVEL RISE EFFECTS ON LAGOON WATER QUALITY

The shallow nature of the Coorong makes it sensitive to mean sea-level properties since a modest change in sea-level can make a considerable difference to the overall lagoon volume and exchange at the flow constriction points (e.g., Parnka Point). Since it has not been previously assessed we sought to undertake a simulation to investigate the sensitivity of simulated water quality and *Ruppia* habitat to an increase in mean sea-level of +0.2m. The results are shown for salinity (Figure 7), water age (Figure 8), TN (Figure 9), TP (Figure 10) and *Ruppia* HSI (Figure 11).

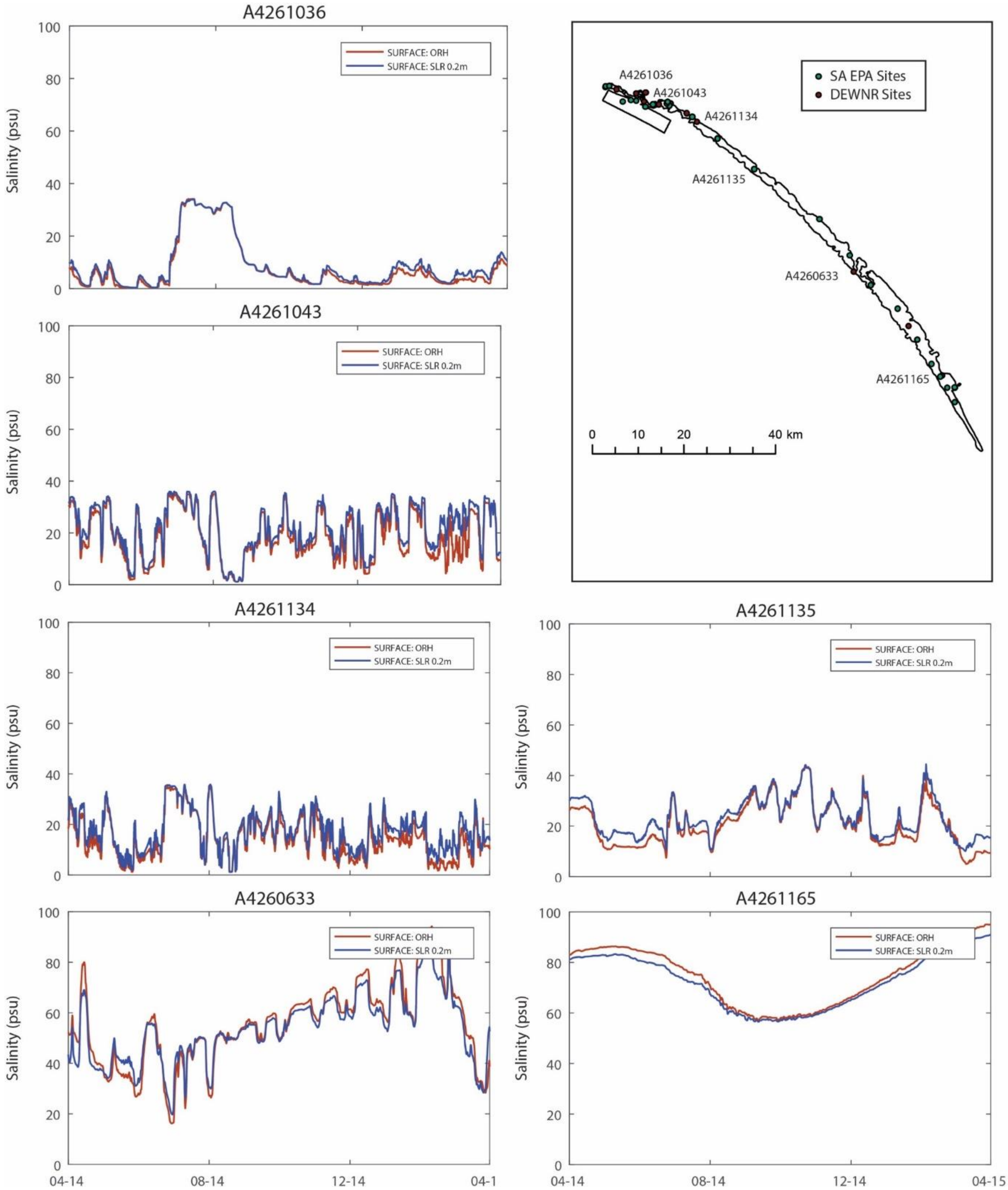

Figure 7. Comparison of predicted salinity concentrations at various monitoring locations within the Coorong comparing the effect of the base simulation (ORH) and an increase in mean sea level (+0.2m).

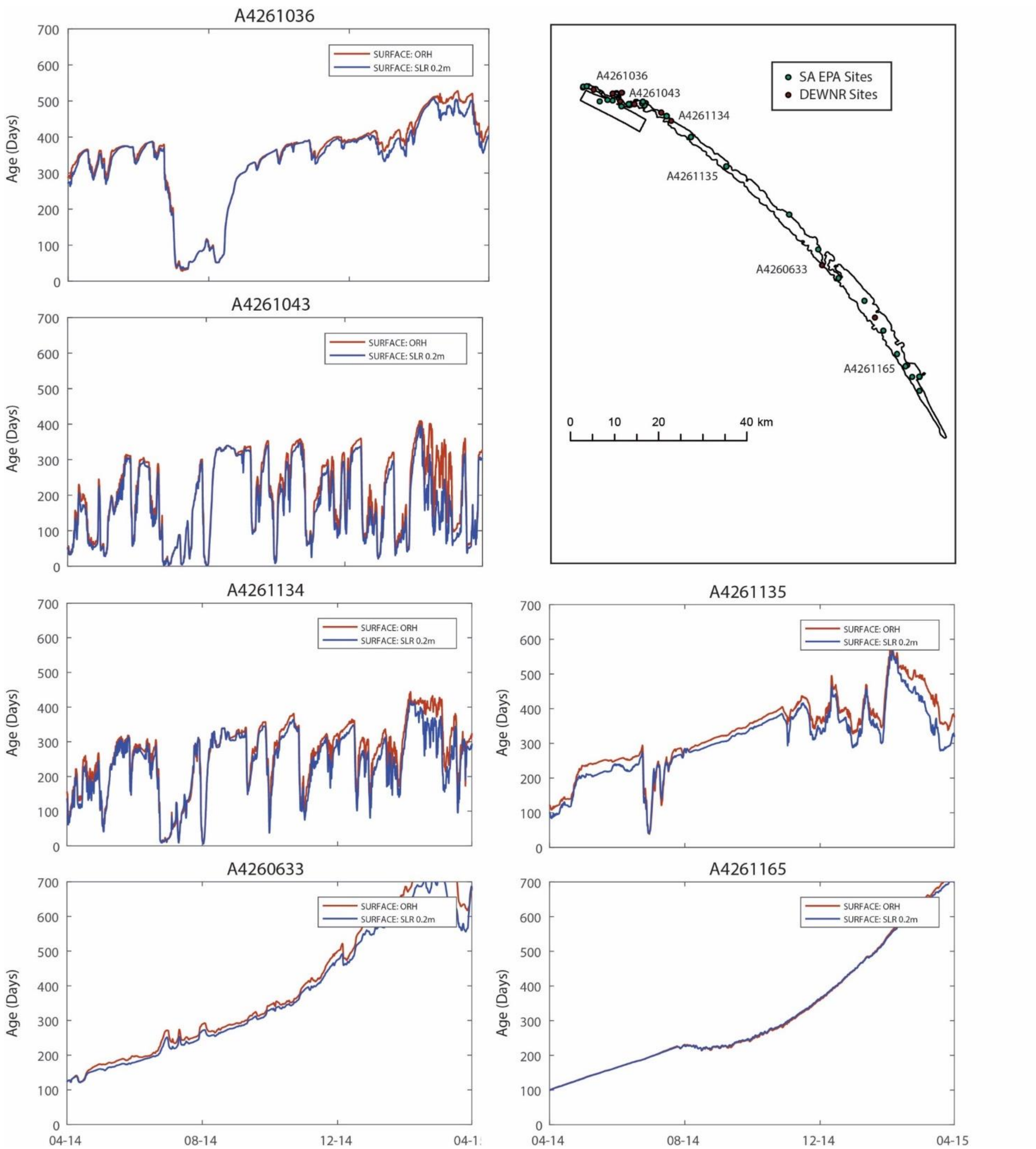

Figure 8. Comparison of predicted water age at various monitoring locations within the Coorong comparing the conditions within the base simulation (ORH) and the simulation with an increase in mean sea level (+0.2m).

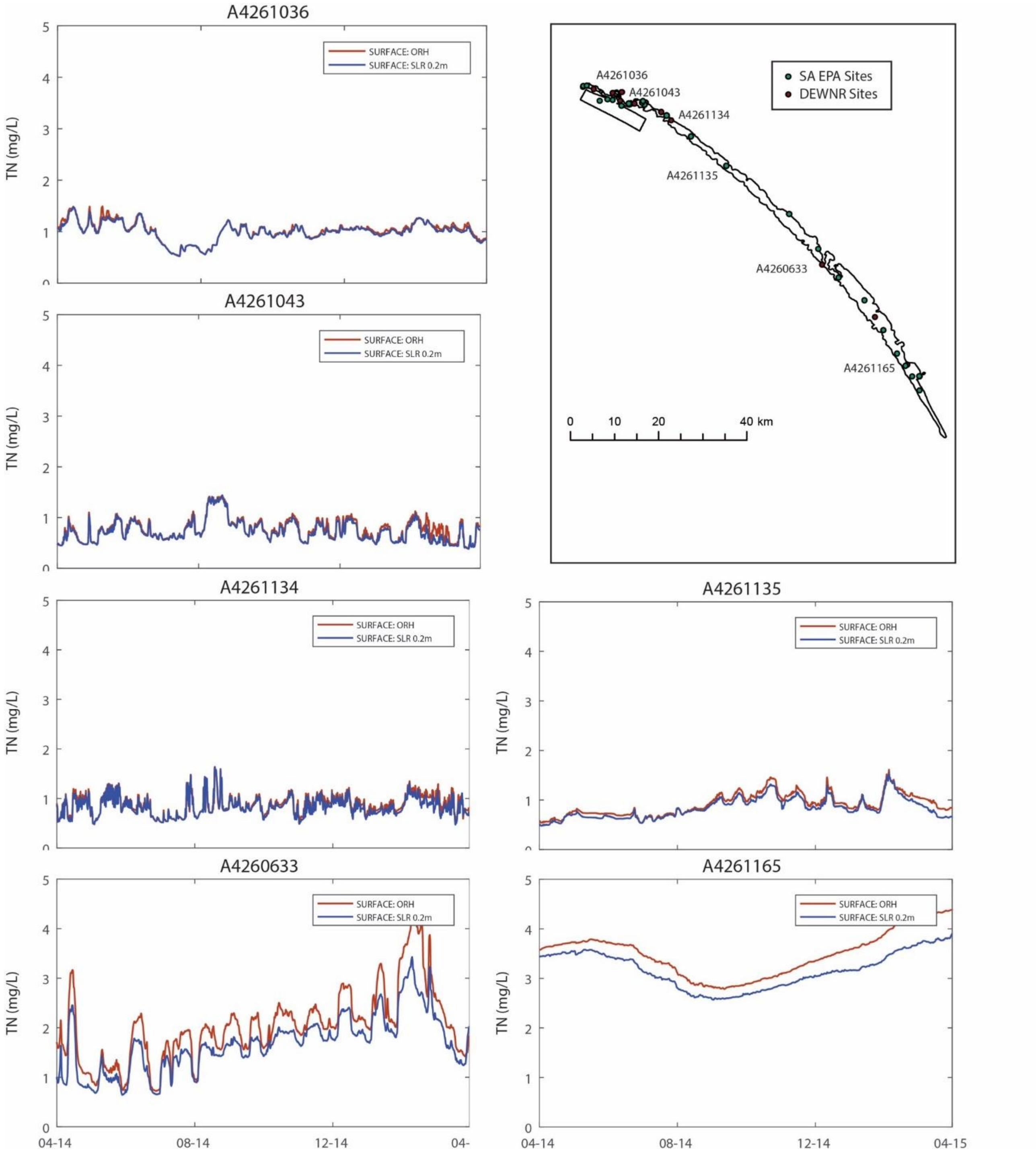

Figure 9. Comparison of predicted total nitrogen (TN) concentrations at various monitoring locations within the Coorong comparing the conditions within the base simulation (ORH) and the simulation with an increase in mean sea level (+0.2m).

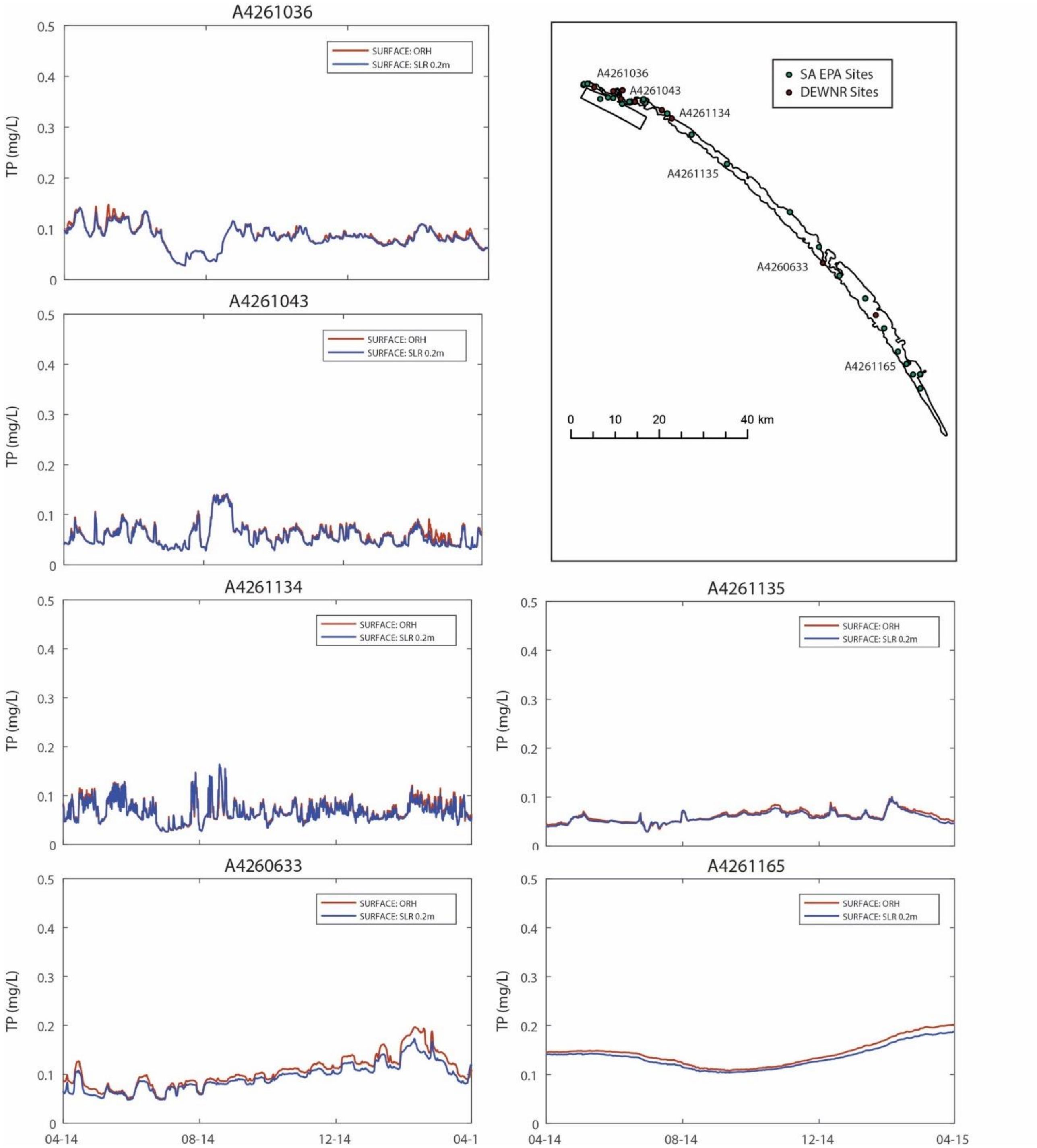

Figure 10. Comparison of predicted total phosphors (TP) at various monitoring locations within the Coorong comparing the conditions within the base simulation (ORH) and the simulation with an increase in mean sea level (+0.2m).

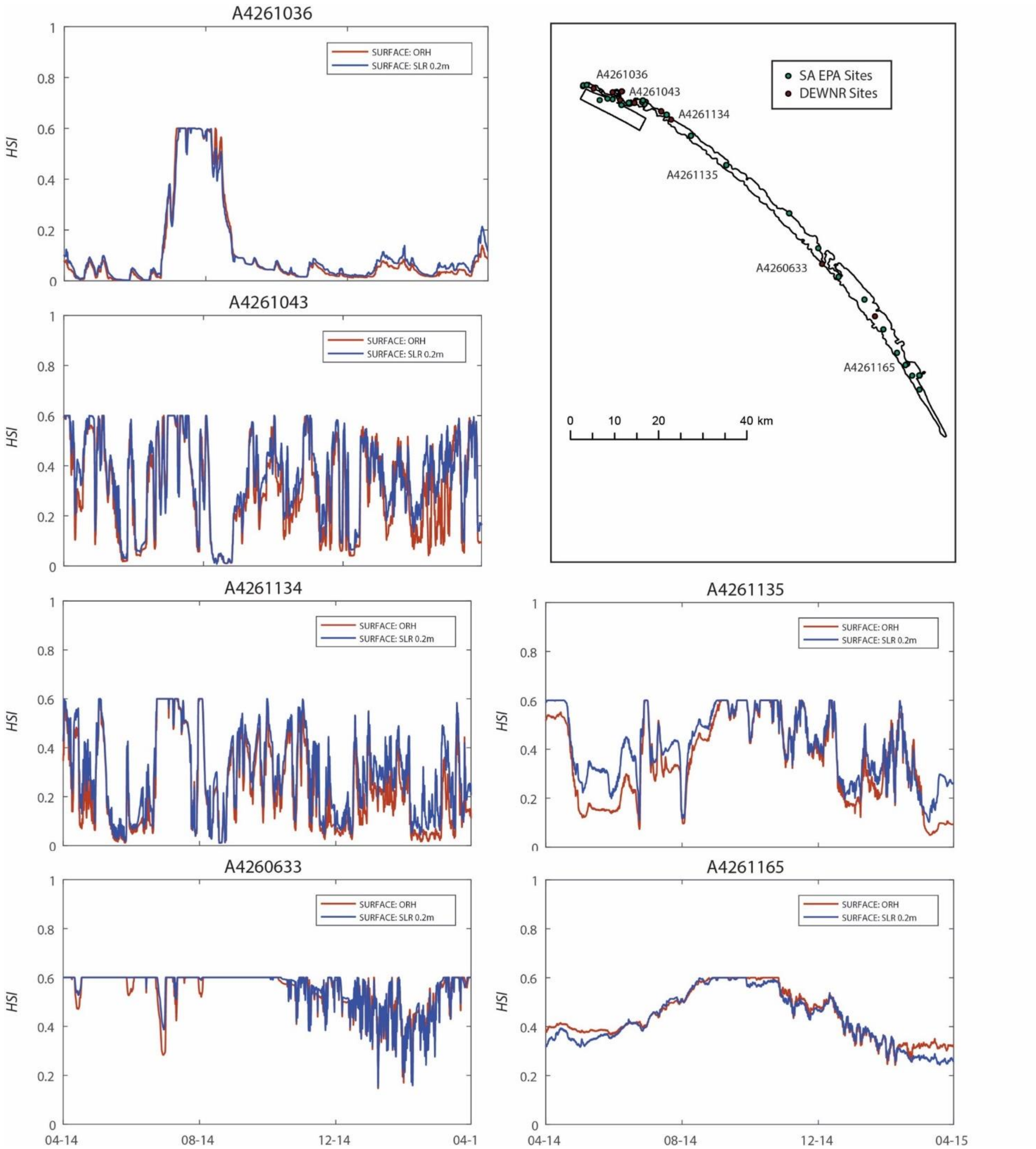

Figure 11. Comparison of predicted *Ruppia* Habitat Suitability Index (HSI) at various monitoring locations within the Coorong comparing the conditions within the base simulation (ORH) and the simulation with an increase in mean sea level (+0.2m).

The spatial variability in the differences brought about by sea-level rise is shown more clearly in "delta-maps" of the lagoon; these are computed by taking the difference of the average seasonal value at a point in the base-case relative to the scenario simulation. They are presented below for salinity (Figure 12), water age (Figure 13), TN (Figure 14), TP (Figure 15) and *Ruppia* HSI (Figure 16).

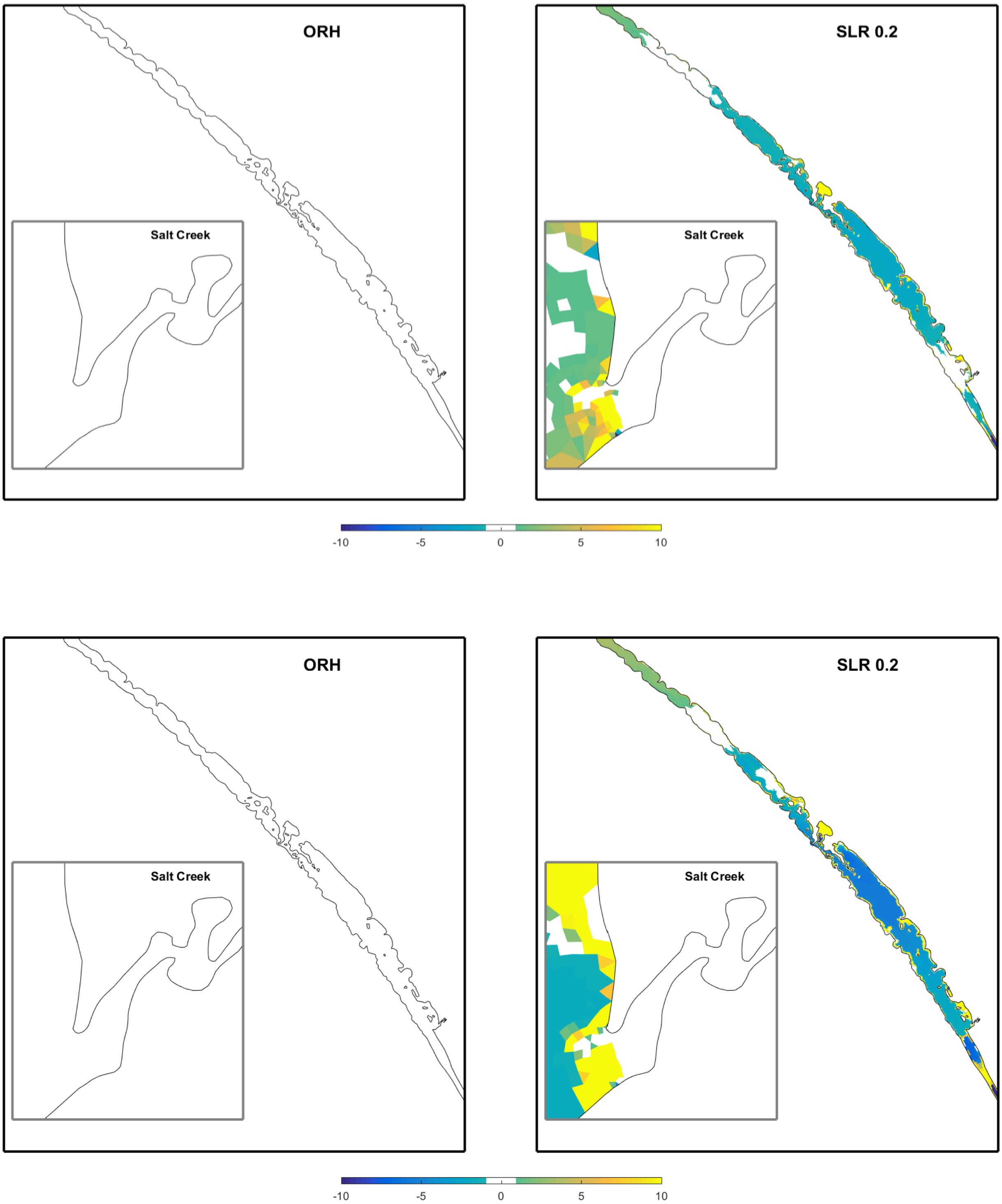

Figure 12. Difference map of mean spring (top) and summer (bottom) salinity concentration between the base-case (ORH) simulation and the sea-level rise (SLR 0.2) simulations. A positive delta salinity indicates an increase in average salinity relative to the base-case.

The results show sensitivity to SLR with an extra 0.2 m decreasing salinity, particularly in the South Lagoon in summer. There is a positive effect on Ruppia HSI predicted also in summer, indicating a sensitivity in this response and further consideration in future planning. These results suggest that possible removal of some channel sedimentation via dredging to get better ocean exchange may assist in improving water quality, and can help motivate further work in this area.

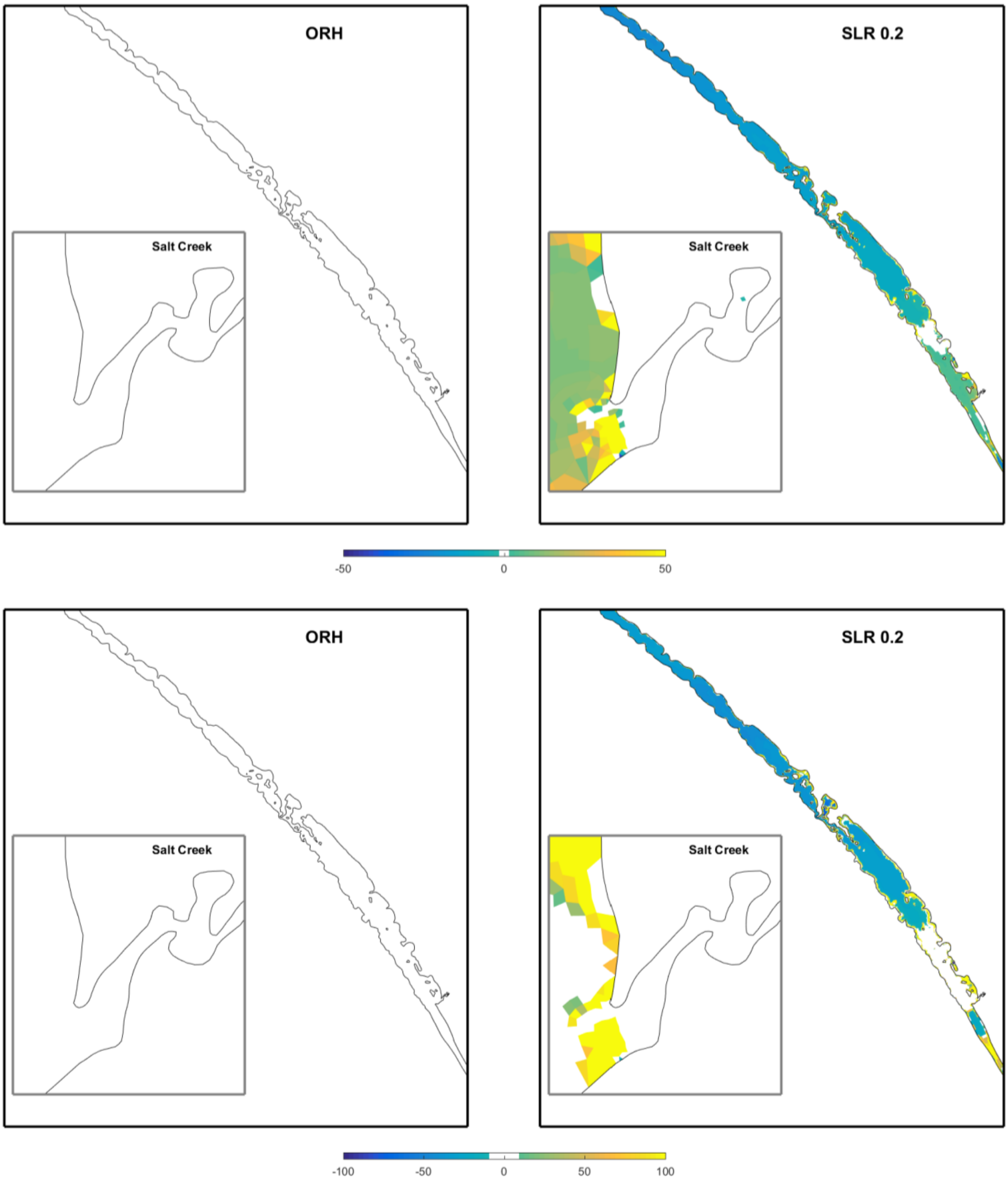

Figure 13. Difference map of mean spring (top) and summer (bottom) water age (days) between the base-case (ORH) simulation and the sea-level rise (SLR 0.2) simulations. A positive delta age indicates an increase in average water age relative to the base-case.

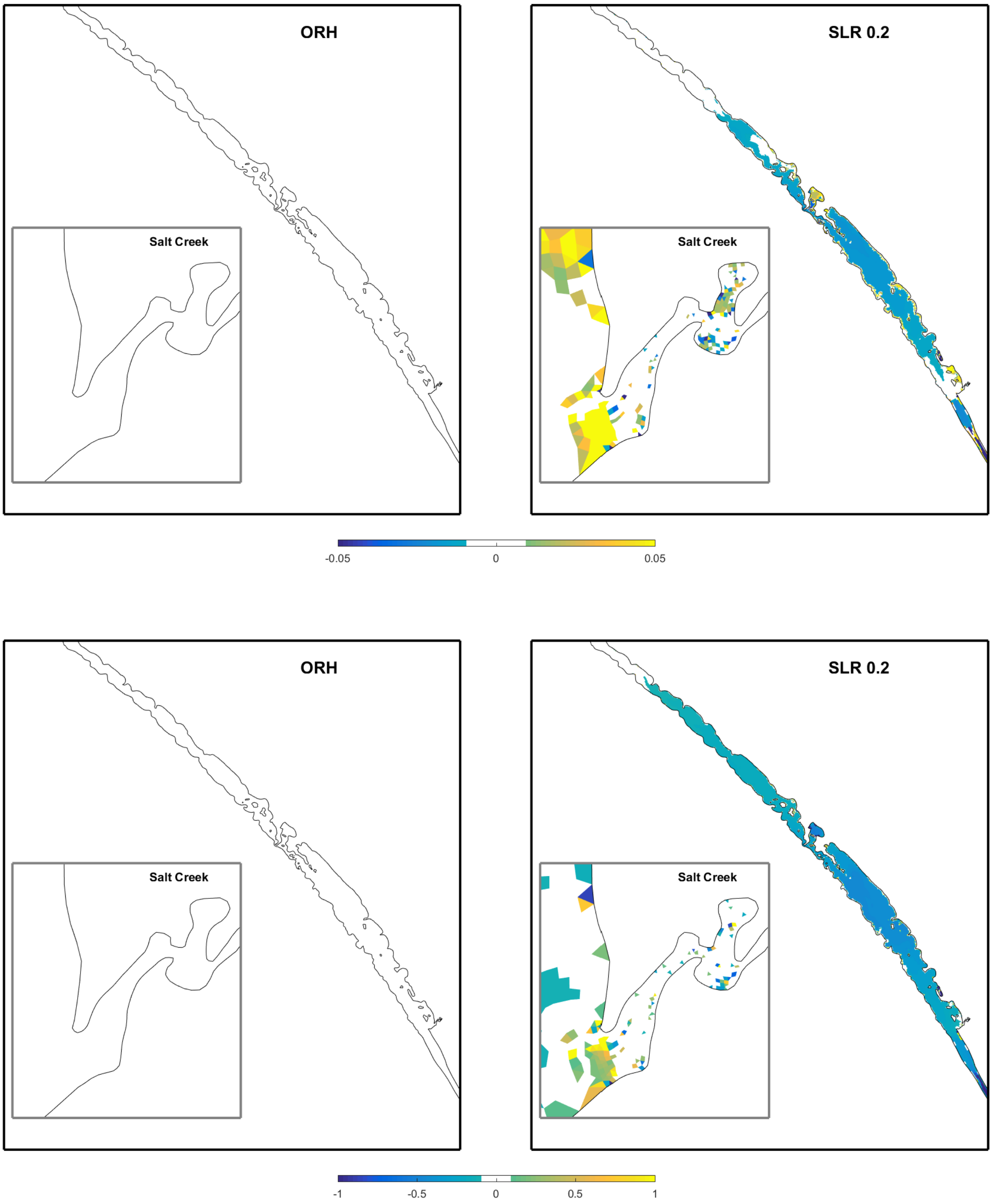

Figure 14. Difference map of mean spring (top) and summer (bottom) total nitrogen (TN) concentration (mg/L) between the base-case (ORH) and the sea-level rise (SLR 0.2) simulations. A positive delta-TN indicates an increase in average TN relative to the base-case.

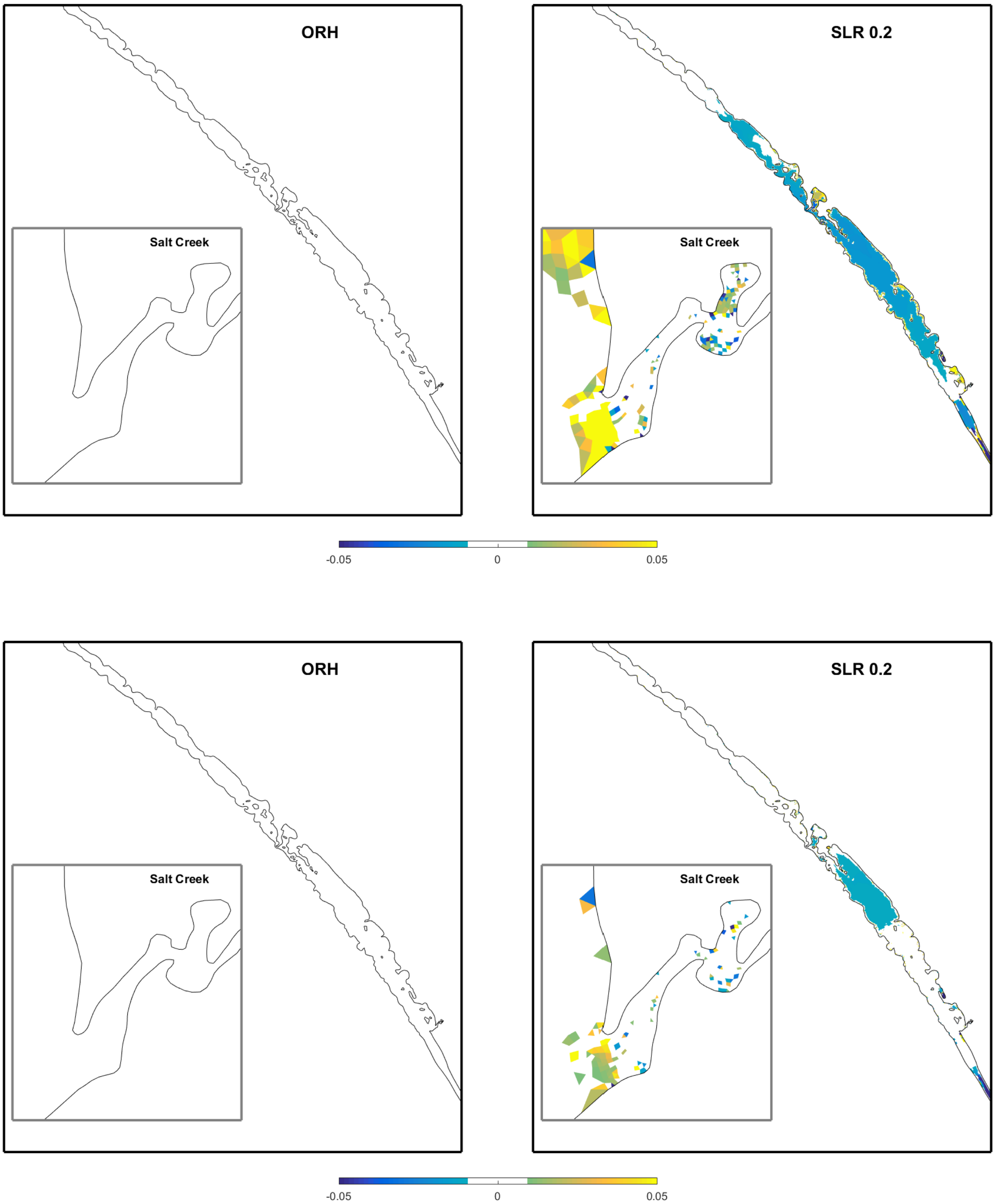

Figure 15. Difference map of mean spring (top) and summer (bottom) total nitrogen (TP) concentration (mg/L) between the base-case (ORH) and sea-level rise (SLR 0.2) simulations. A positive delta-TP indicates an increase in average TP relative to the base-case.

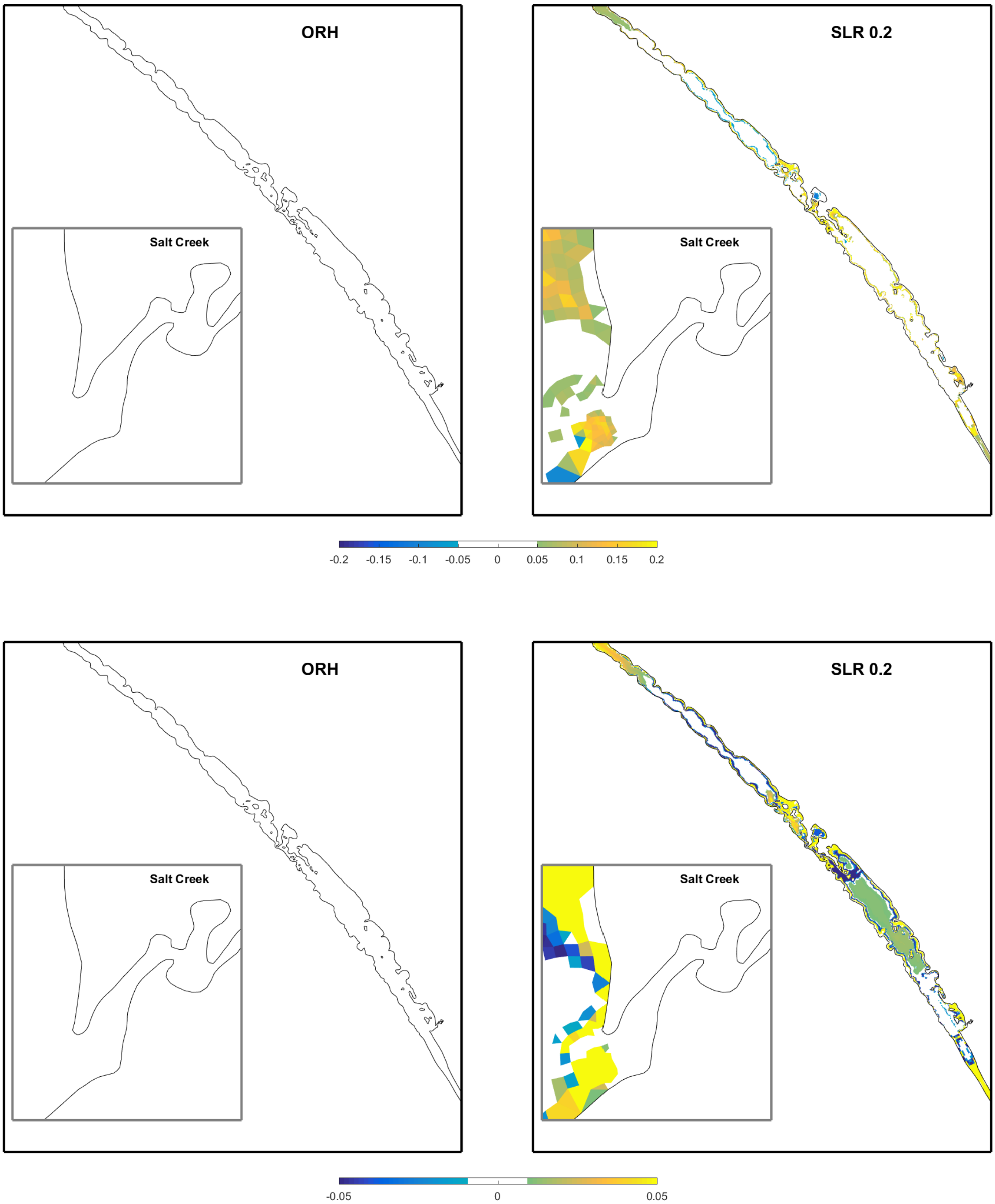

Figure 16. Difference map of mean spring (top) and summer (bottom) *Ruppia* Habitat Suitability Index (HIS) value between the base-case (ORH)and sea-level rise (SLR 0.2) simulations. A positive delta-HSI indicates an increase in average HSI relative to the base-case.

3.1.3 ATMOSPHERIC DEPOSITION

The shallow nature of the Coorong also makes it potentially sensitive to loading from atmospheric nitrogen deposition, which to date has been largely unexplored. However, using an assumed wet deposition rain concentration of 4 μM (based on data from Peel-Harvey; Naomi Wells pers. comm.), the effect on the lagoon concentration was relatively small, as shown below for NO_3 (Figure 17). Nonetheless, further work on resolving atmospheric fluxes for phosphorus and nitrogen, including wet and dry deposition and NH_4 volatilisation, for example, could will help constrain this largely understudied process.

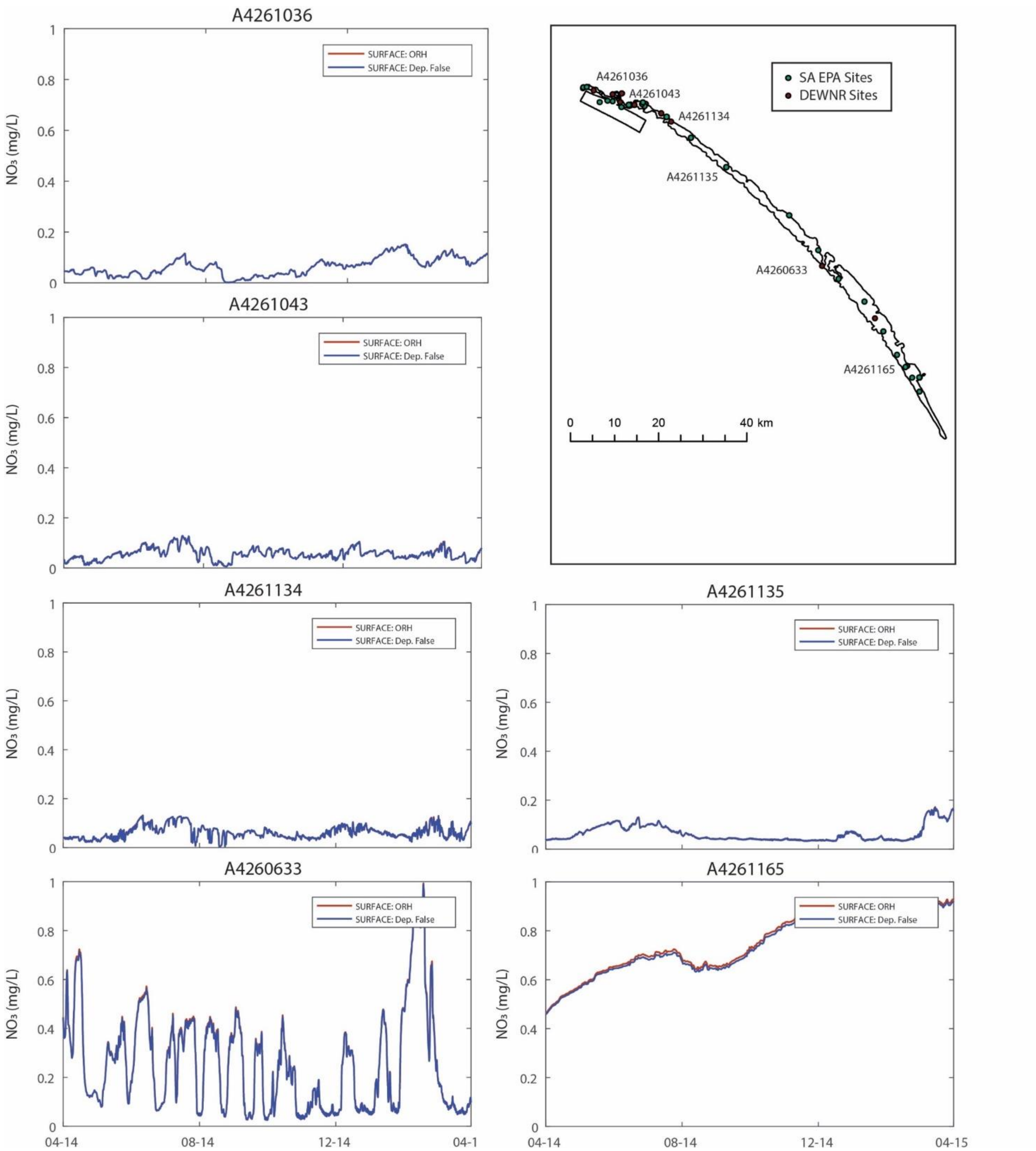

Figure 17. Comparison of predicted NO_3 concentrations at various monitoring locations within the Coorong comparing the conditions within the base simulation (ORH) and the simulation with no deposition assumed (Dep. False).

3.2 Model parameter and process uncertainty

3.2.1 SEDIMENT BIOGEOCHEMISTRY AND SEDIMENT-WATER INTERACTIONS

The model demonstrates the increasing sensitivity of the water column nutrient concentrations to internal loading from the sediments. The impact manifests along a gradient from the North to the South Lagoon (Figure 18 – 21), in response to the changing hydrology (reduced flushing and increased evapo-concentration) towards the south, and the increasing sediment area to volume ratio.

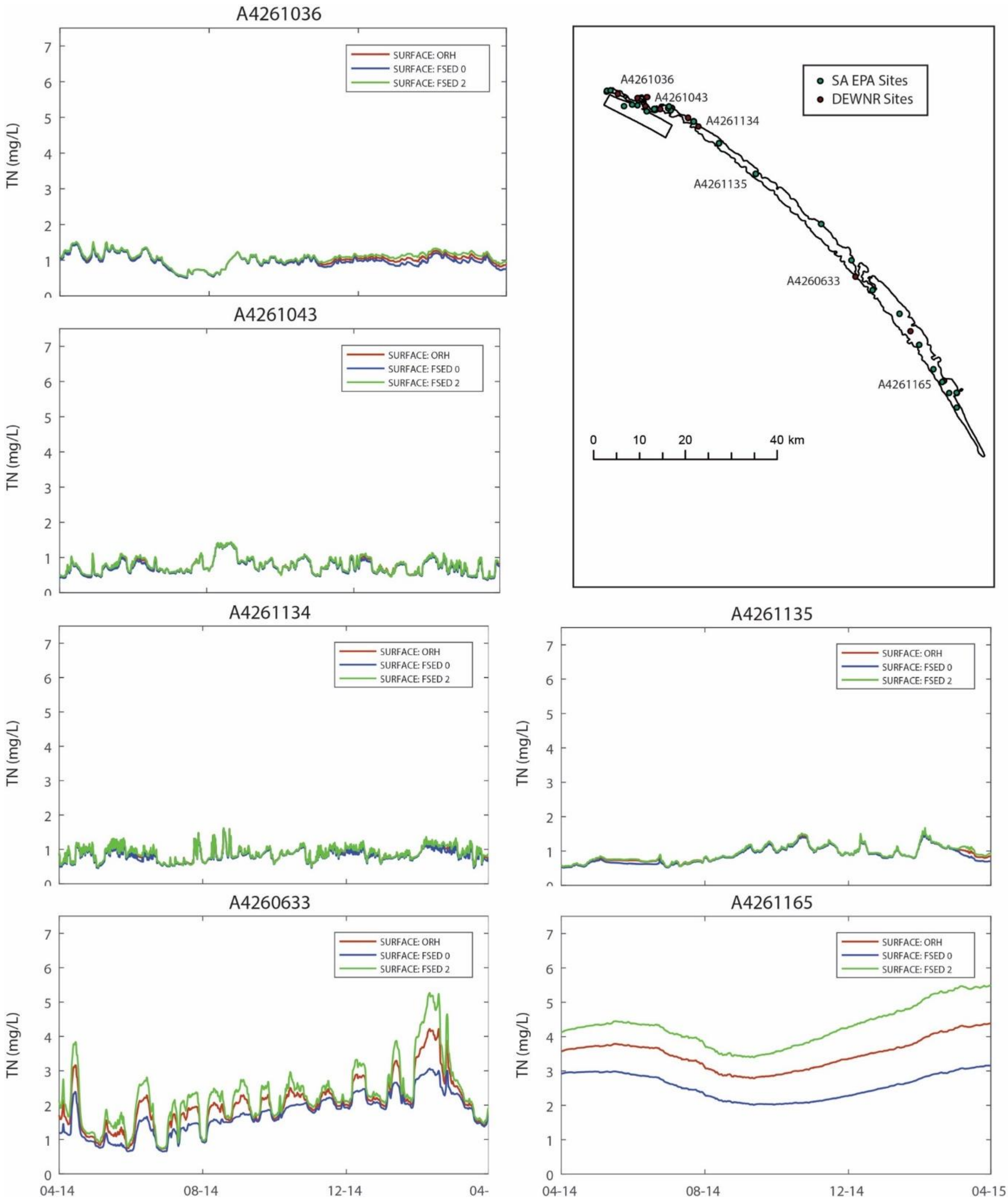

Figure 18. Comparison of predicted total nitrogen (TN) concentrations at various monitoring locations within the Coorong comparing the conditions within the base simulation (ORH; default sediment fluxes) and the simulations with no sediment fluxes (FSED 0) and twice the assumed base-case values (FSED 2).

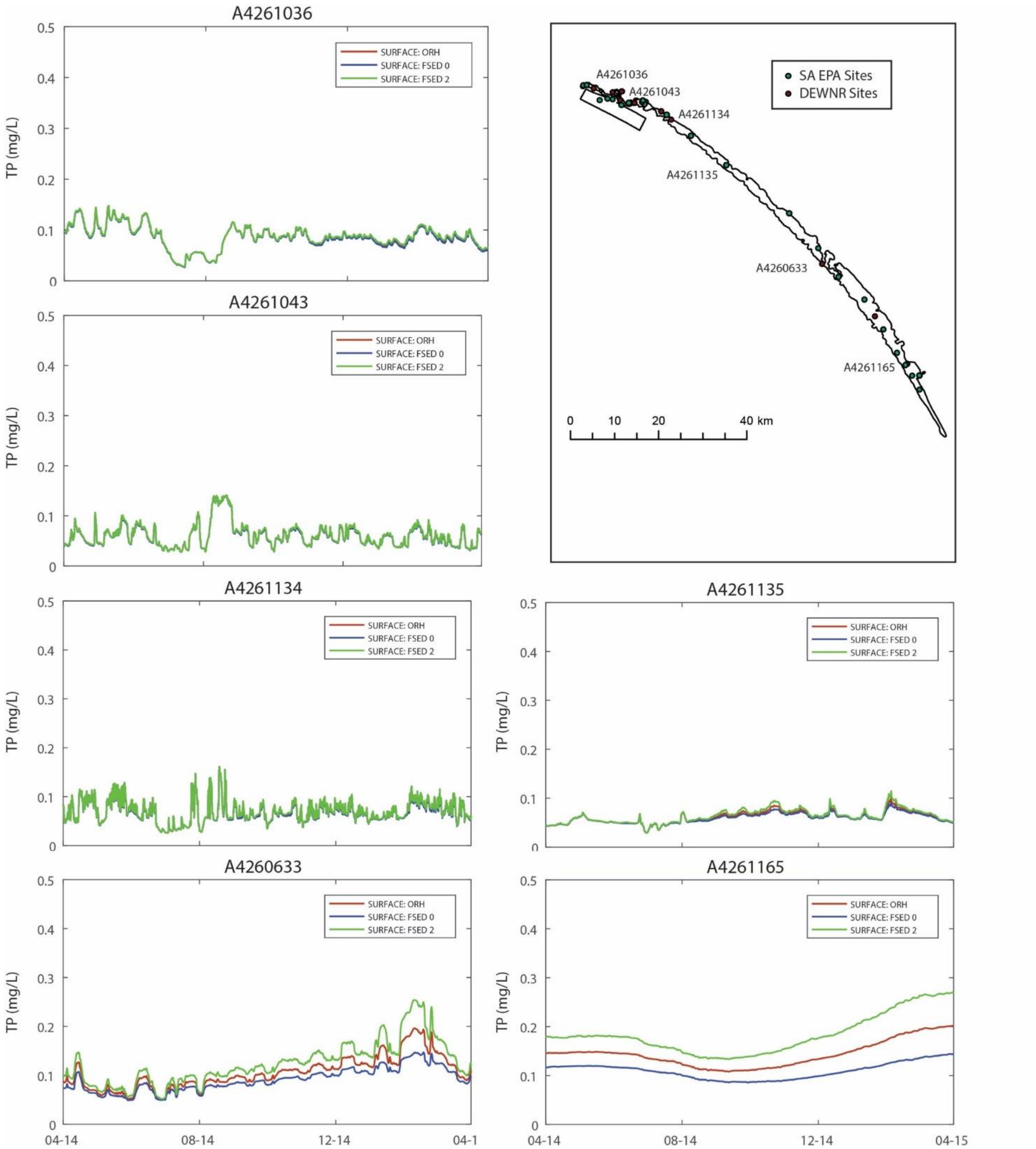

Figure 19. Comparison of predicted total phosphorus (TP) concentrations at various monitoring locations within the Coorong comparing the conditions within the base simulation (ORH; default sediment fluxes) and the simulations with no sediment fluxes (FSED 0) and twice the assumed base-case values (FSED 2).

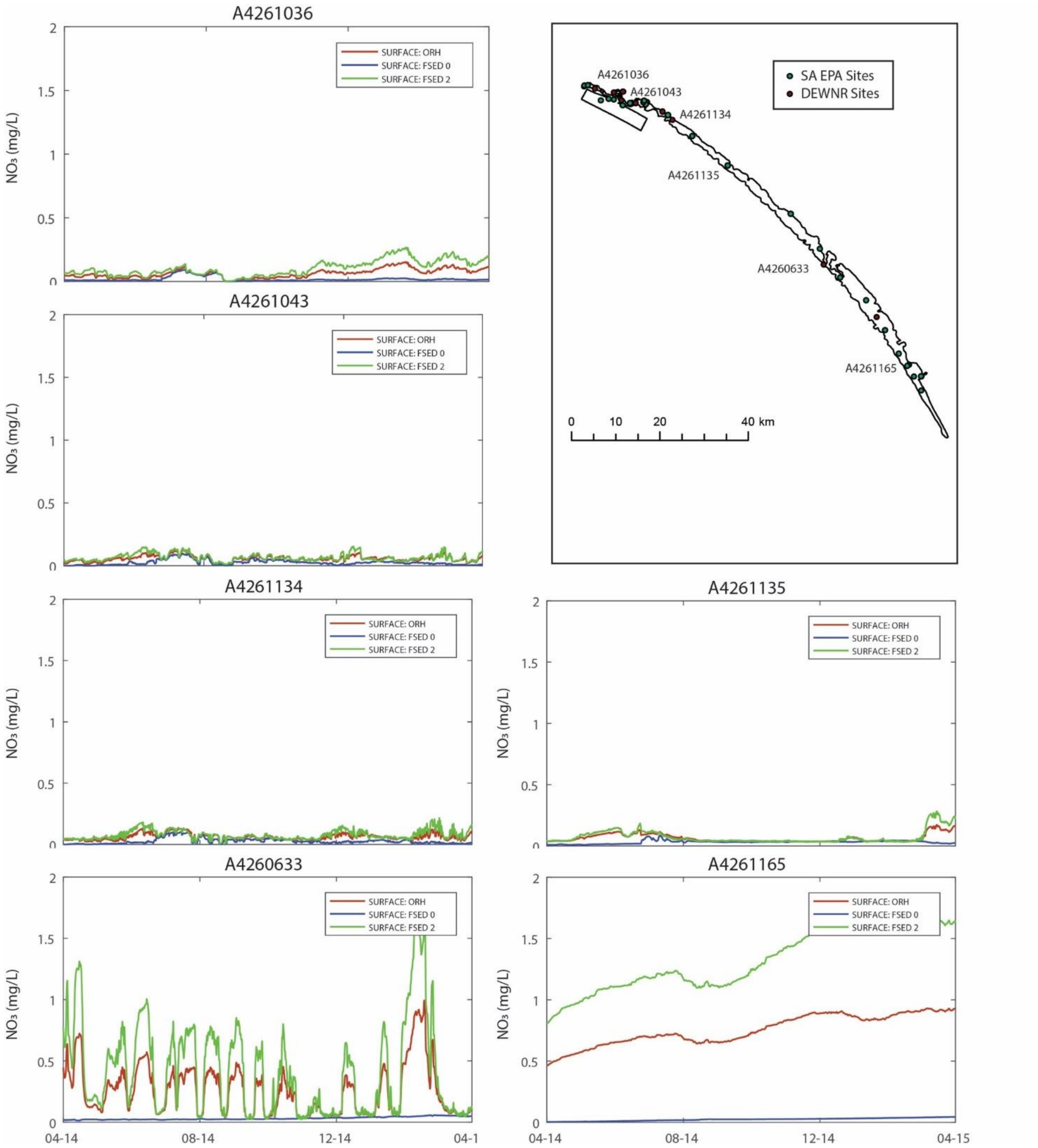

Figure 20. Comparison of predicted nitrate (NO_3) concentrations at various monitoring locations within the Coorong comparing the conditions within the base simulation (ORH; default sediment fluxes) and the simulations with no sediment fluxes (FSED 0) and twice the assumed base-case values (FSED 2).

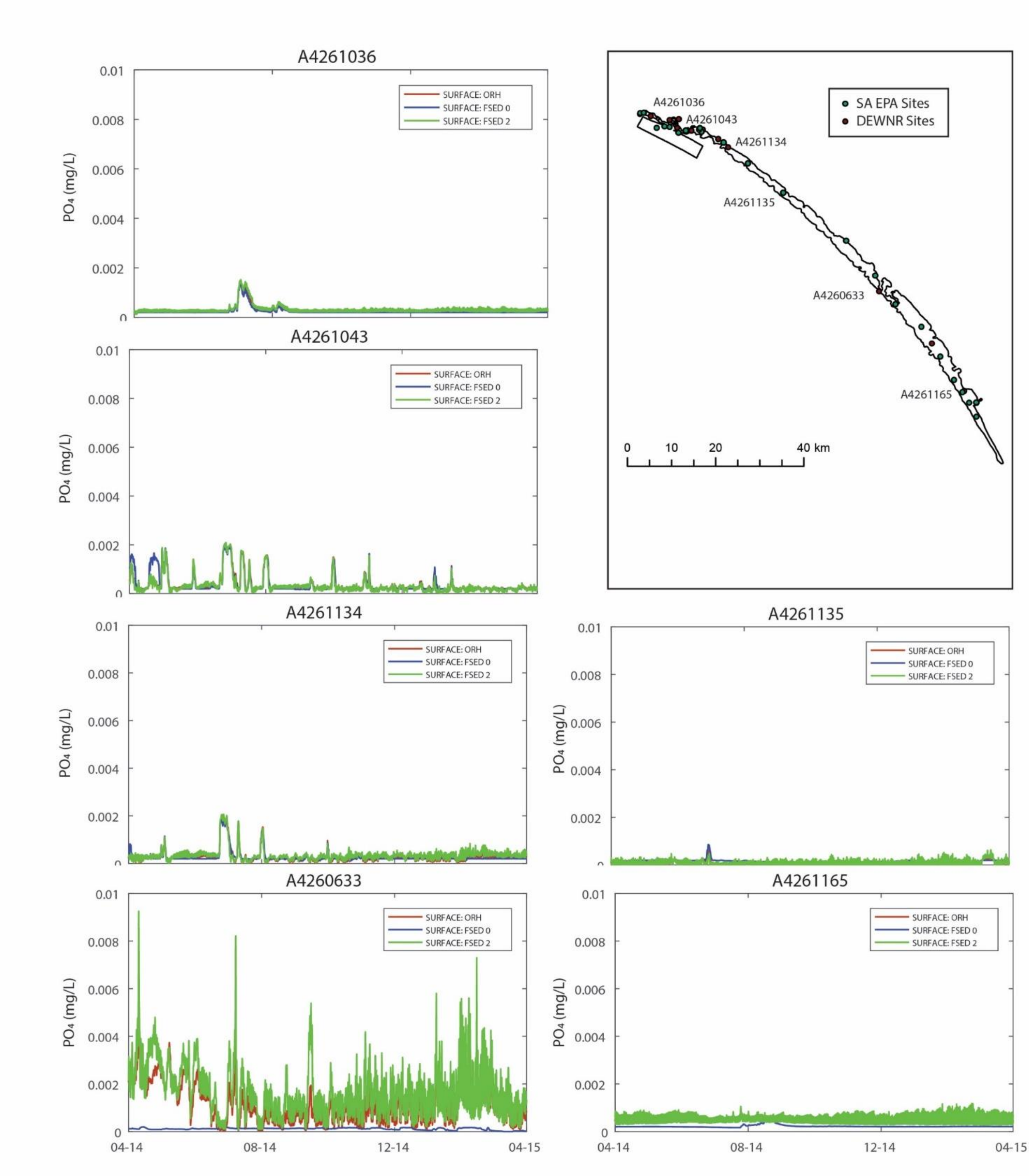

Figure 21. Comparison of predicted phosphate (PO_4) concentrations at various monitoring locations within the Coorong comparing the conditions within the base simulation (ORH; default sediment fluxes) and the simulations with no sediment fluxes (FSED 0) and twice the assumed base-case values (FSED 2).

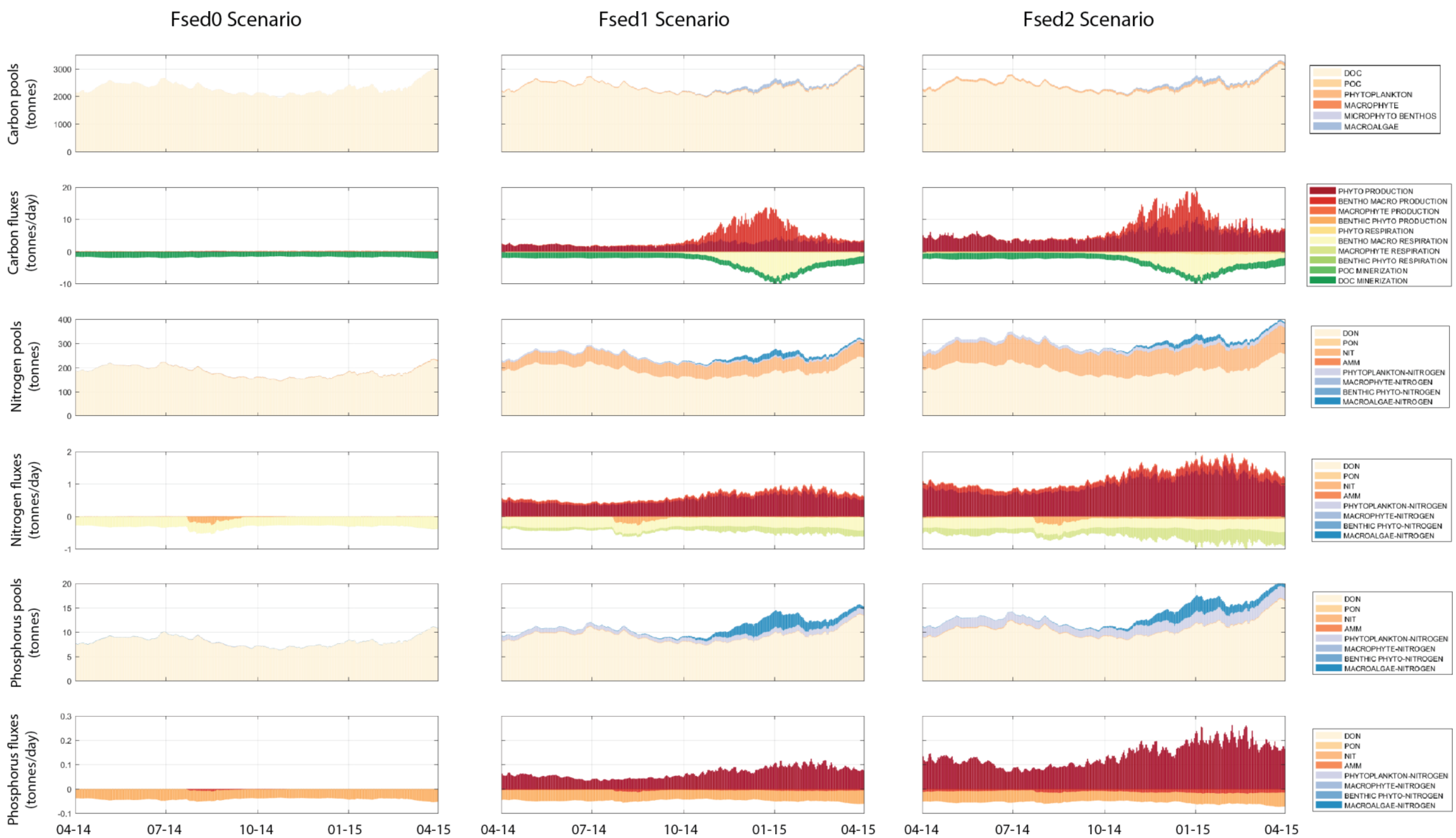

Figure 22. Reconstruction of variation in Coorong South Lagoon carbon, nitrogen and phosphorus pools, and positive and negative fluxes of each, comparing the conditions within the base simulation (ORH; default sediment fluxes) and the simulations with no sediment fluxes (FSED 0) and twice the assumed base-case values (FSED 2).

The nutrient budgets were notably different with and without sediment flux contributions to the dissolved pools, and the scale of the overall contribution to the South Lagoon is depicted in Figure 22 for the carbon, nitrogen and phosphorus pools. The difference also manifests spatially which is shown with increasing sediment flux sensitivity as you head further south (Figure 23 – 24) for the delta-concentration of dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP). The effect of these changes in sediment (internal) nutrient loading on Ulva habitat is depicted also as a delta-map, showing the notable reduction in Ulva HSI if internal loading was disabled (FSED 0), and a relative insensitivity to the values of internal loading was doubled (FSED 2) (Figure 25). This is due to the already high nutrients leading to nutrient saturation, leaving only limited change between x1 and x2 sediment nutrient fluxes.

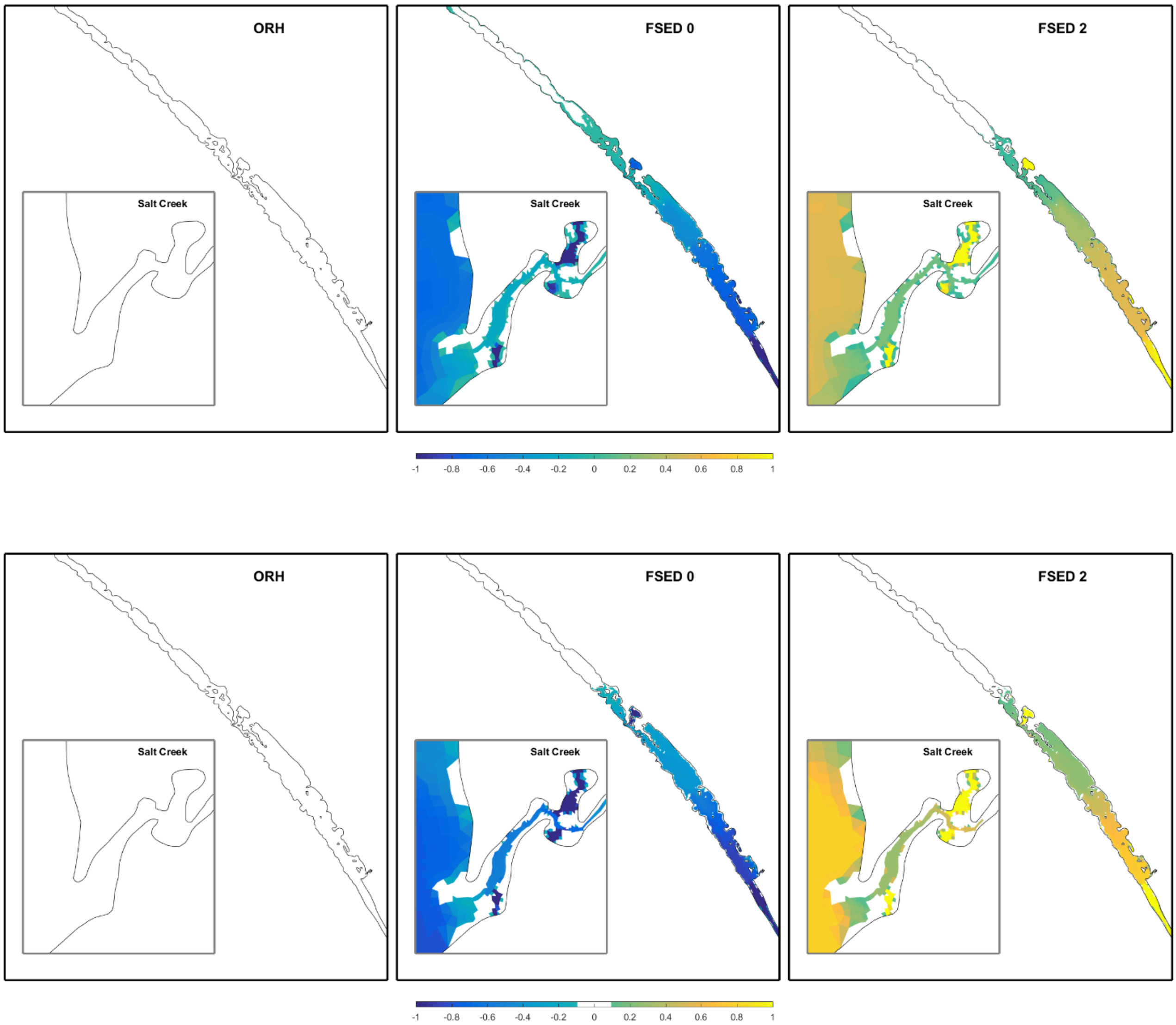

Figure 23. Difference map of mean spring (top) and summer (bottom) dissolved inorganic nitrogen (DIN) concentration (mg/L) between the ORH simulation and the FSED scenarios. A positive delta-DIN indicates an increase in average DIN relative to the base-case.

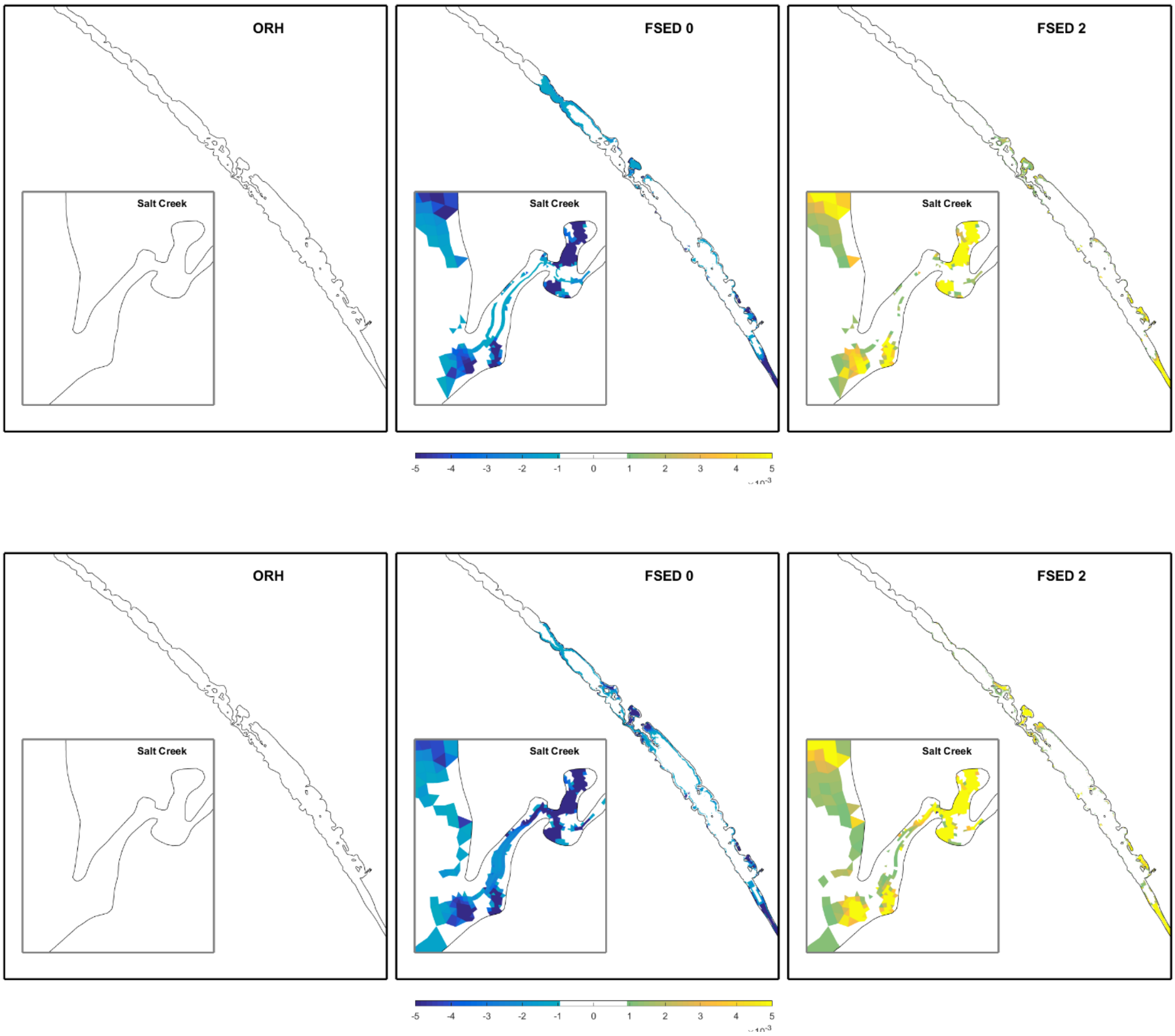

Figure 24. Difference map of mean spring (top) and summer (bottom) dissolved inorganic phosphorus (DIP) concentration (mg/L) between the ORH simulation and the FSED scenarios. A positive delta-DIP indicates an increase in average DIP relative to the base-case.

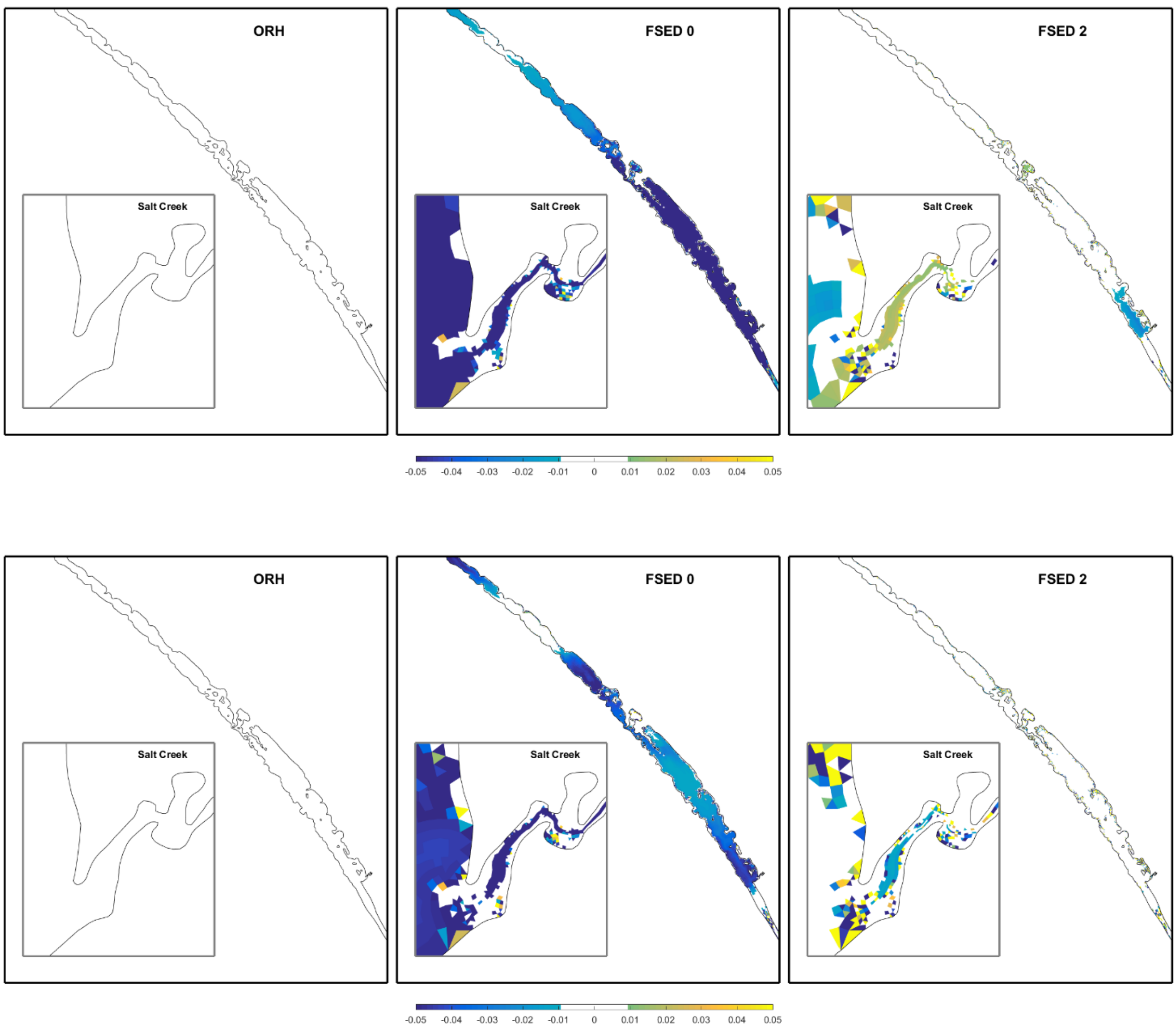

Figure 25. Difference map of mean spring (top) and summer (bottom) Macroalgal (Ulva) HSI value between the ORH simulation and the FSED scenarios. A positive delta-HSI indicates an increase in average HSI relative to the base-case.

3.2.2 BENTHIC PRODUCTIVITY AND LITTORAL OXYGEN METABOLISM

In the base-case model the role of benthic primary production in shallow littoral areas was not explicitly captured. We explored the sensitivity of modelled oxygen to this process by running a three-dimensional simulation with benthic productivity accounted for using a simple light-dependent algorithm. In this model, shallow waters will receive more light at the sediment-water interface which will drive photosynthesis and accumulate benthic chlorophyll-a until a maximum density is reached, whereas deeper waters will receive inadequate light for benthic plant growth. The effect on mean oxygen is shown in Figure 26, which does highlight interesting effects in the South Lagoon such as higher highs and lower lows, which is in response to vertical mixing events.

Bearing in mind that the above plots shows the centre rather than edge of the lagoons, it is interesting to note the littoral zone metabolism is predicted to be much more significant than in the centre, when the benthic productivity module is enabled (Figure 27). This has important implications for shallow water nutrient cycling and fuelling of near shore macroalgal growth. Figures 28-30 highlight this spatial heterogeneity in the diurnal (and seasonal) effects in the sensitivity testing, including low DO around Salt Creek entrance and also around Parnka Point. In both cases this is consistent with the high content of Mono-sulfidic Black Oozes (MBO) that has been previously reported in these regions. These results demonstrate the relative importance of resolving carefully the littoral zone processes and including three-dimensional effects.

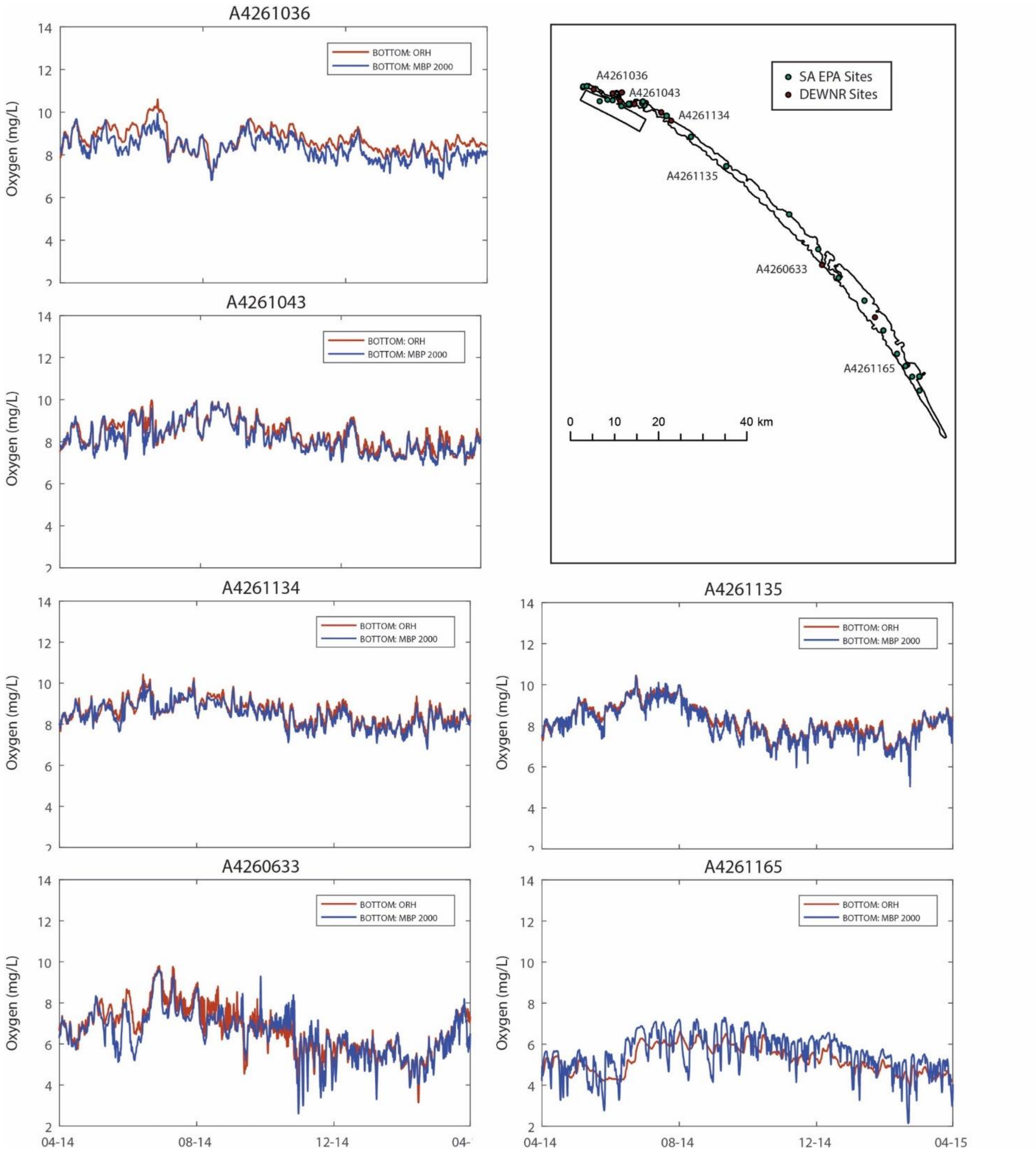

Figure 26. Comparison of predicted dissolved oxygen concentrations at various monitoring locations within the Coorong comparing the conditions within the base simulation (ORH) and the simulation with and benthic productivity included at an assumed (light-dependent) rate (MPB 2000).

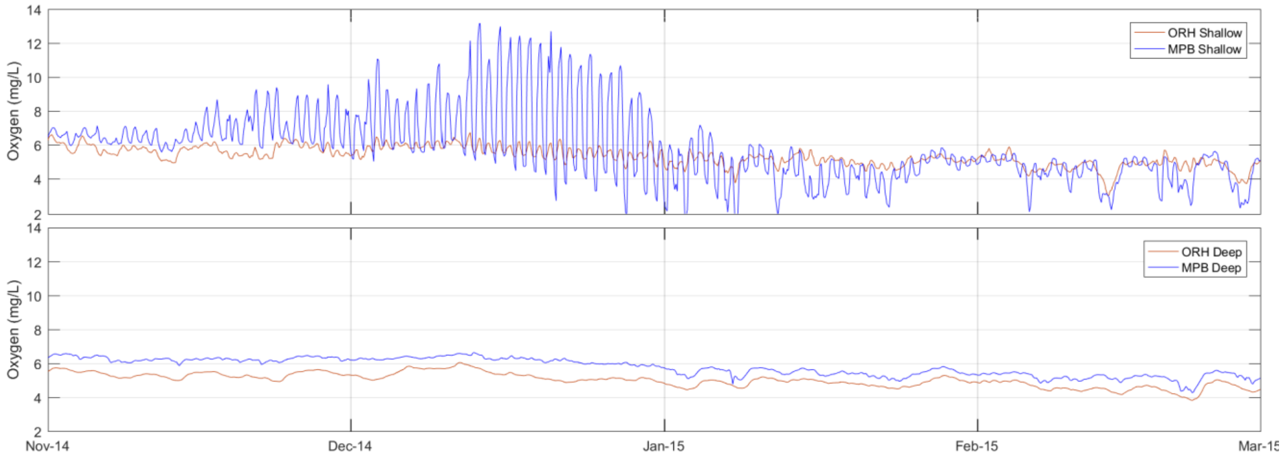

Figure 27. South Lagoon shallow (top) and deep (bottom) dissolved oxygen time-series, comparing the base (2D) model simulation (ORH) and the 3D simulation configured with benthic productivity terms (BP 2000).

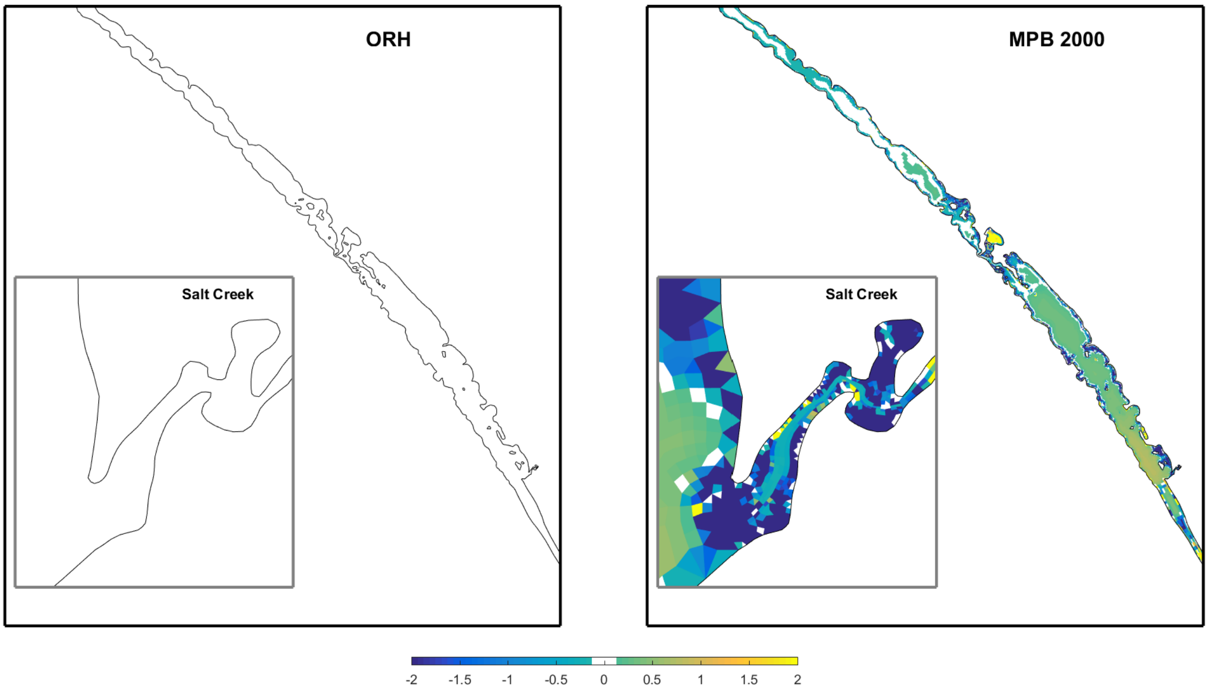

Figure 28. Difference map of mean spring bottom dissolved oxygen (DO) concentration between the ORH simulation and with benthic productivity (MBP 2000) scenario. A positive delta-DO indicates an increase in average DO relative to the base-case.

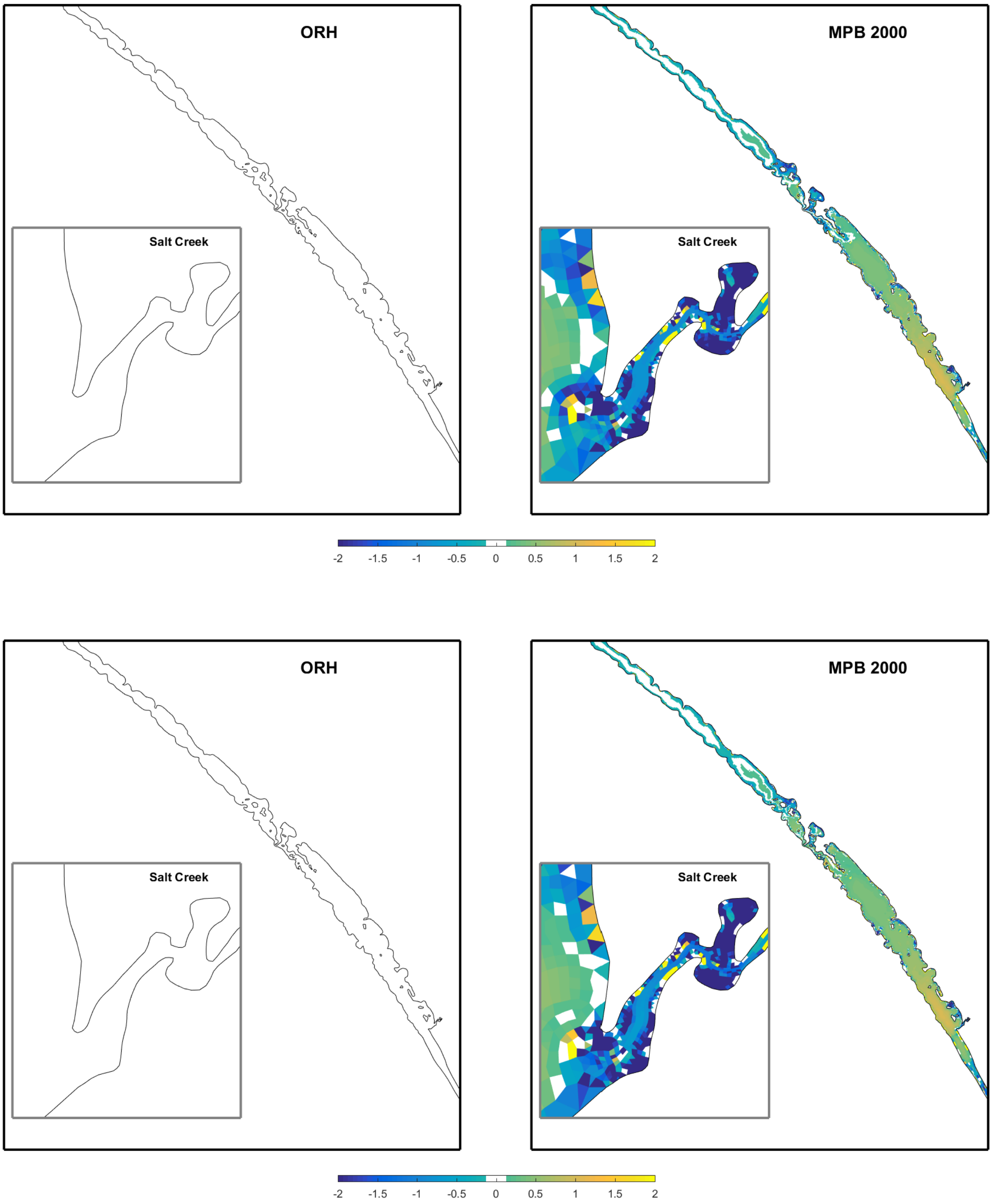

Figure 29. Difference map of mean midday (top) and midnight (bottom) dissolved oxygen (DO) concentration between the ORH simulation and the benthic productivity (MBP 2000) scenario. A positive delta-DO indicates an increase in average DO relative to the base-case.

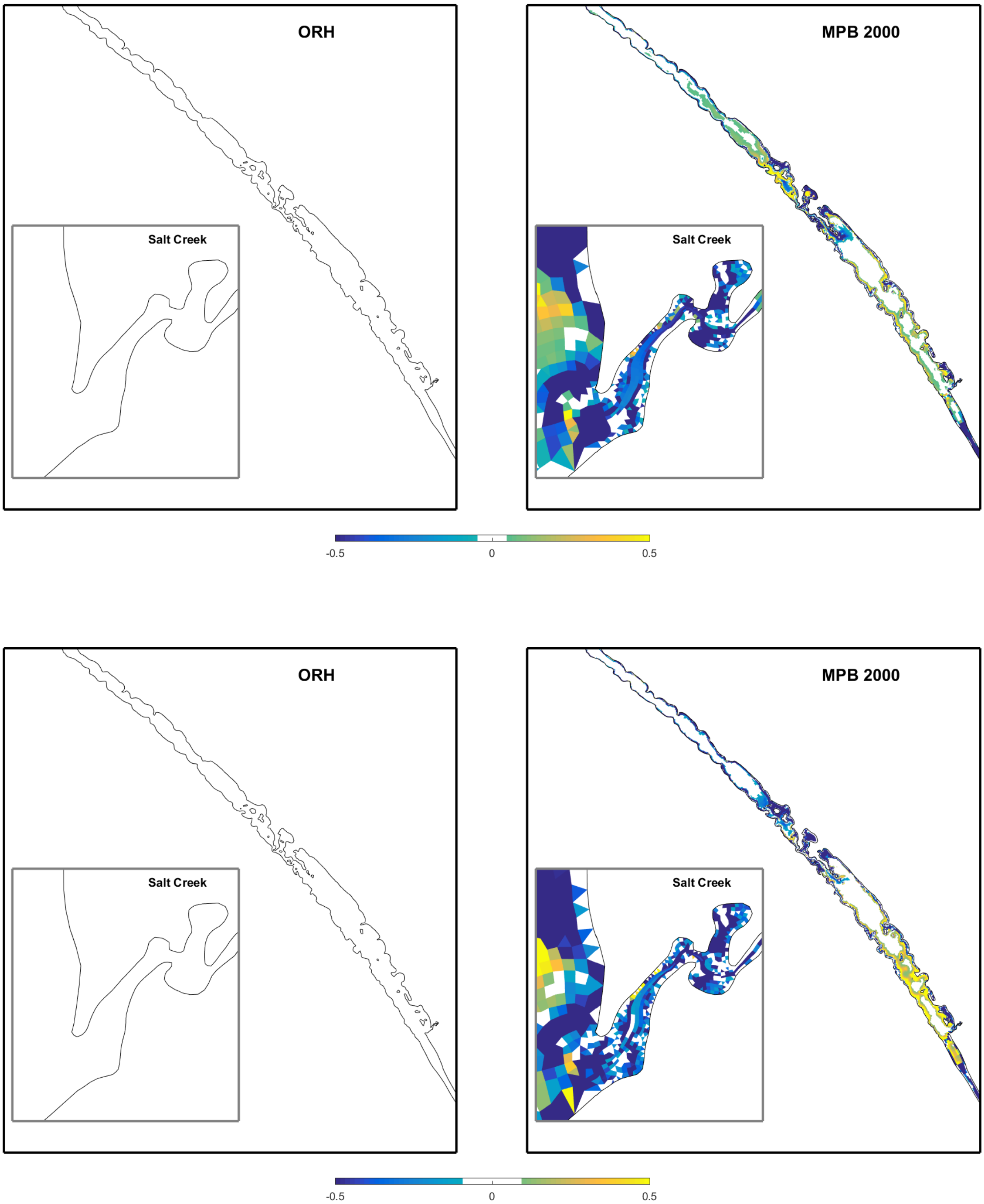

Figure 30. Difference map of the daily variation in dissolved oxygen (ΔDO; max daily – min daily), comparing the difference between the base-case and simulation with benthic metabolism.

3.3 Habitat and biota uncertainty

3.3.1 RUPPIA LIFE-STAGE SENSITIVITY

The *Ruppia* habitat (HSI) model was based on literature and expert judgement of the requirements of the plant life-cycle as outlined in detail in Collier et al. (2017). This approach did make simplifying assumptions, and in particular the length of the windows of life-stage "relevance", which in practice remain uncertain.

To assess the sensitivity of these life-stage windows, we re-ran the *Ruppia* HSI calculation with different integration windows ranging from 80-160 days (90 was assumed in the original analysis), and plotted it along the length of the Coorong, for a range of different condition averaging windows. This is shown in Figure 31 – whilst the trend is similar between the simulations, increasing the averaging time available for each life-stage, decreases the strength of the niche that emerges centred around the Parnka Point region. This is consistent with a longer averaging window smoothing out the dynamic variability across the lagoon. This has implications for modelling of *Ruppia* habitat suitability and identifying restoration target areas and potential areas of concern. These results suggest future work to refine the opportunity window for successful completion of specific *Ruppia* life-stages will support more accurate predictions and have a substantial influence on the modelled results for a given scenario.

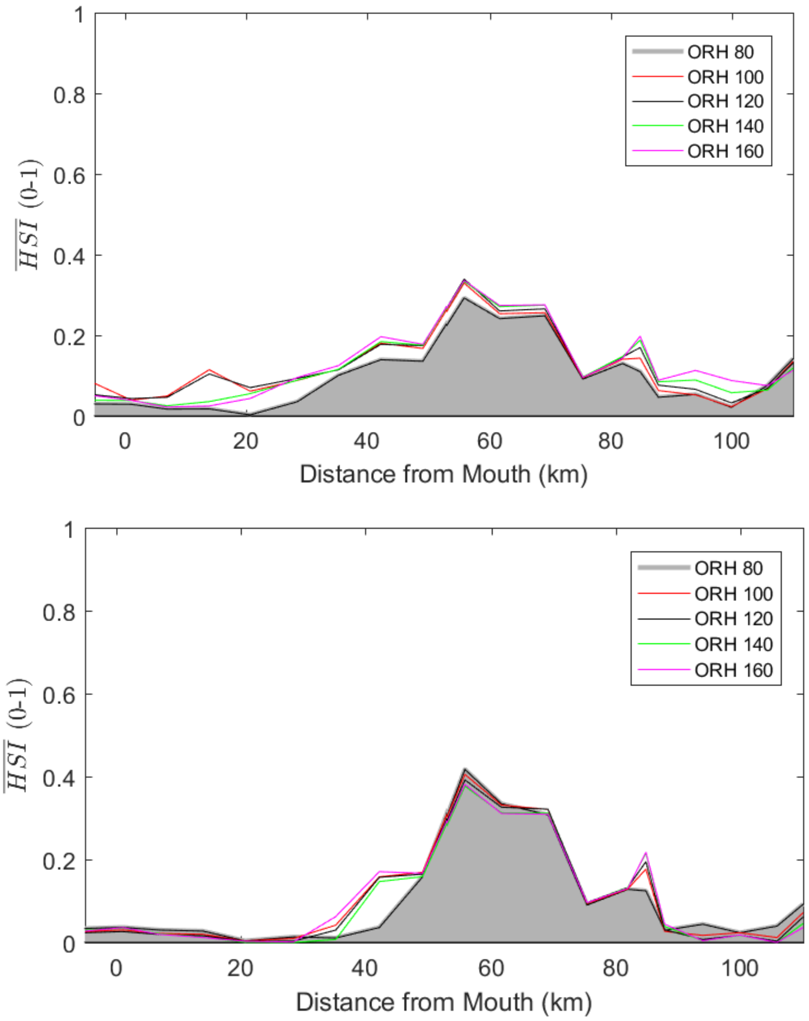

Figure 31. Graph of *Ruppia* area along the Coorong for different life stage lengths. Calculated as normal (ORH, i.e. based on Collier et al., 2017) and then recalculated again but changing the averaging time periods of the life-stages (life-stage period lengths varying from 80-160 days as indicated in figure legend as ORH 80, 100, 120, 160 and 180). Results from the 2014 year of the simulation (top) and the 2015 year (bottom) shown separately.

The suitable extent of *Ruppia* based on the HSI approach is considerably sensitive to changes in mean water level as depicted in Figure 32. This shows how water level changes can shift the most suitable locations for each life-stage. Notably, the predictions suggest sea-level increase can expand the suitable area in the North Lagoon, whilst decreasing it around Parnka Point, the current hot-spot of suitable conditions.

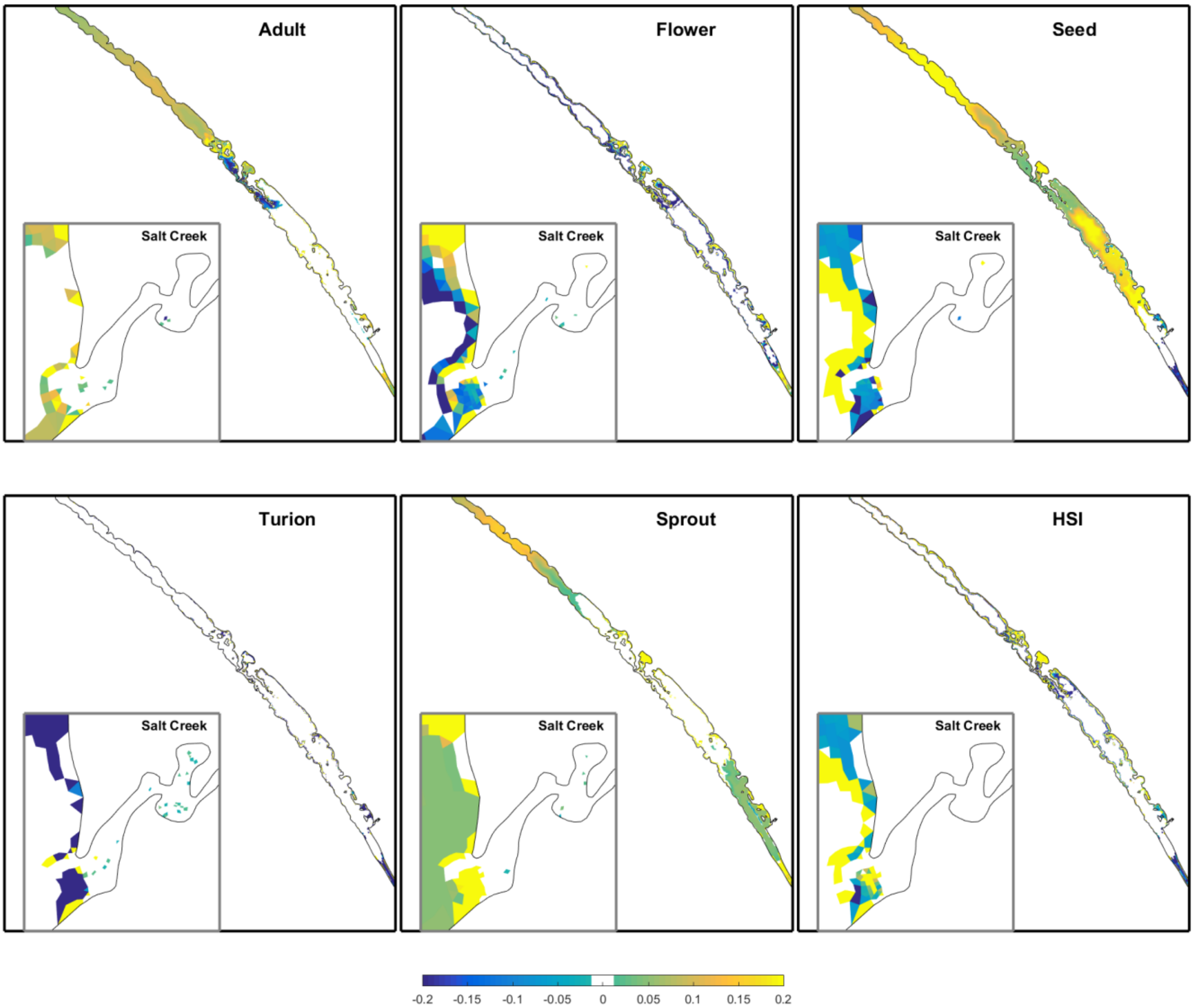

Figure 32. Sensitivity of life-stage habitat suitability showing relative difference between base-case (ORH) and sea level rise (SLR 0.2m) simulation.

3.3.2 ULVA SURFACE MAT FORMATION & REDISTRIBUTION

The challenge of understanding and predicting macroalgal bloom dynamics remains difficult in spatially resolved models. In the previous modelling, the biomass of *Ulva* was estimated based on light and nutrient availability in certain locations, but it was essentially assumed to be stationary. To demonstrate the potential impact of floating macroalgae on lagoon biogeochemistry, we simulated “bio-active” particles within AED2, in order to capture the mobility and redistribution of the floating biomass subject to wind-driven currents. The results highlight the potential for the model to capture accumulation hotspots, and the oxygen “sag” within the South Lagoon, changing between time-steps (Figure 33).

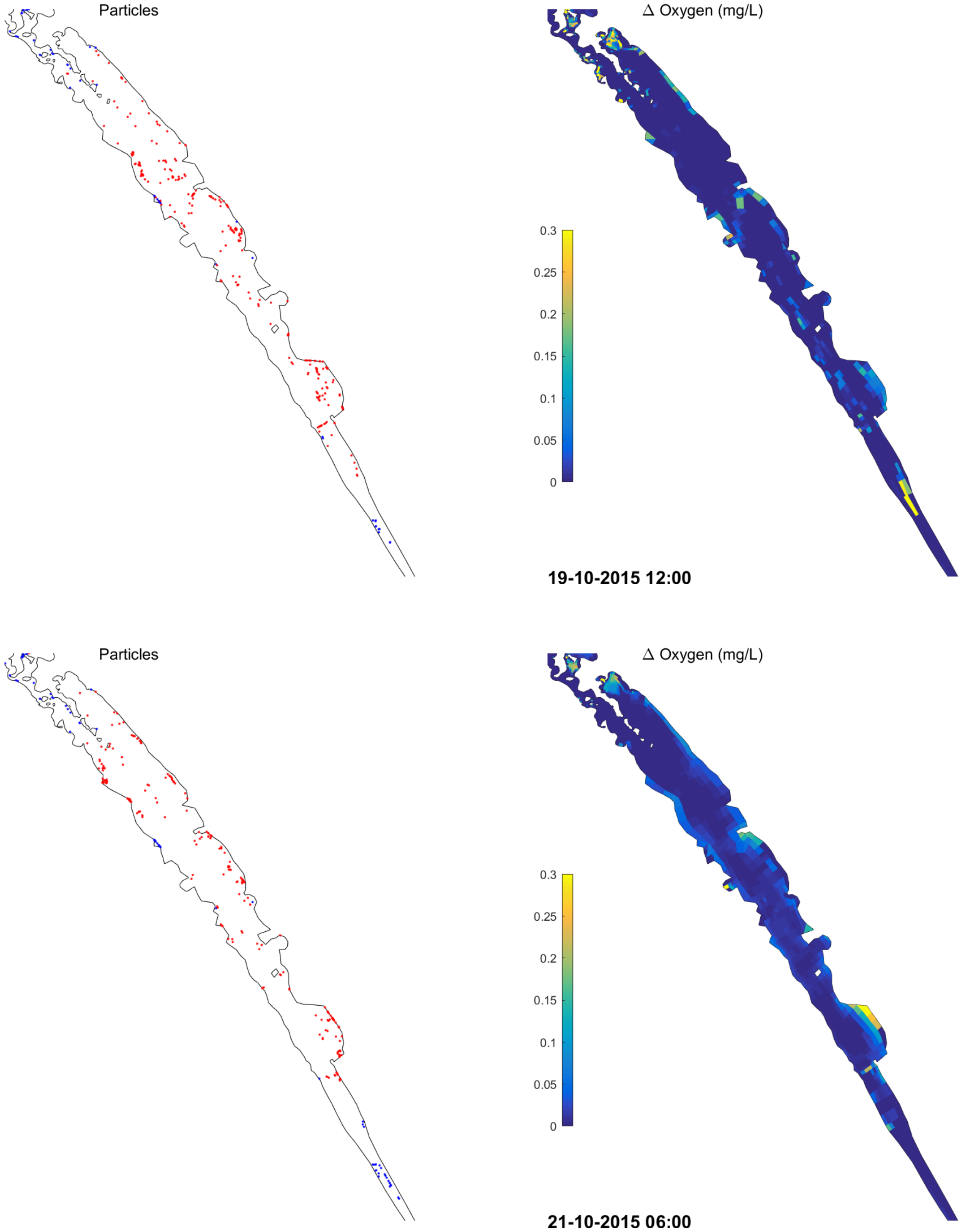

Figure 33. Demonstration of bio-active particles within the Coorong model, showing particles able to move with wind-driven currents (left, compare top and bottom times), and impact the surface water quality though oxygen consumption (right) and nutrient uptake and/or release.

3.3.3 ZOOPLANKTON DENSITY AND GRAZING RATES

The current model has no zooplankton dynamics explicitly configured. Zooplankton form an important intermediate step between primary production and higher trophic organisms, and whilst there has been some *ad hoc* studies on abundance and distribution, the rates of grazing and cycling contributed to by secondary producers remains uncertain in the Coorong. Future work to improve the understanding of the role of zooplankton in the Coorong trophic dynamics will help refine the planktonic dynamics of the model setup in future iterations.

4 Summary and recommendations

The model simulations presented have been undertaken to assist in focusing future model improvements and associated data collection activities to support the next generation of model development. It is envisaged that resolving the knowledge gaps and model validation presented herein will transition the model from a more heuristic model based on literature to support understanding of the site to a trusted decision support tool suitable for supporting management decisions.

The results have identified that there remain numerous areas where refining the model setup and parameterisation, which are currently based on assumptions and literature review, could lead to significant improvements and reduced uncertainty in outcomes. In particular, the model showed sensitivity to littoral zone processes and sediment-water fluxes. These uncertainties manifest in water quality, and the habitat extent of *Ruppia*, which are summarised in the sections below. This is used as the basis for recommendations for data collection and model development that will help refine the model accuracy for decision support.

4.1 Water quality

The simulation average values for selected water quality variables in the South Coorong are summarised in four regions of the Coorong (Figures 34-37). Interestingly, at this scale there is variability, of the order of approximately 10% in these properties, with some higher values seen in Scenario F2 for nutrients (30-50% increases in the CSL). These figures must be interpreted with caution since they only compare averages, which as seen in Figure 27 for oxygen, may misrepresent important areas of habitat.

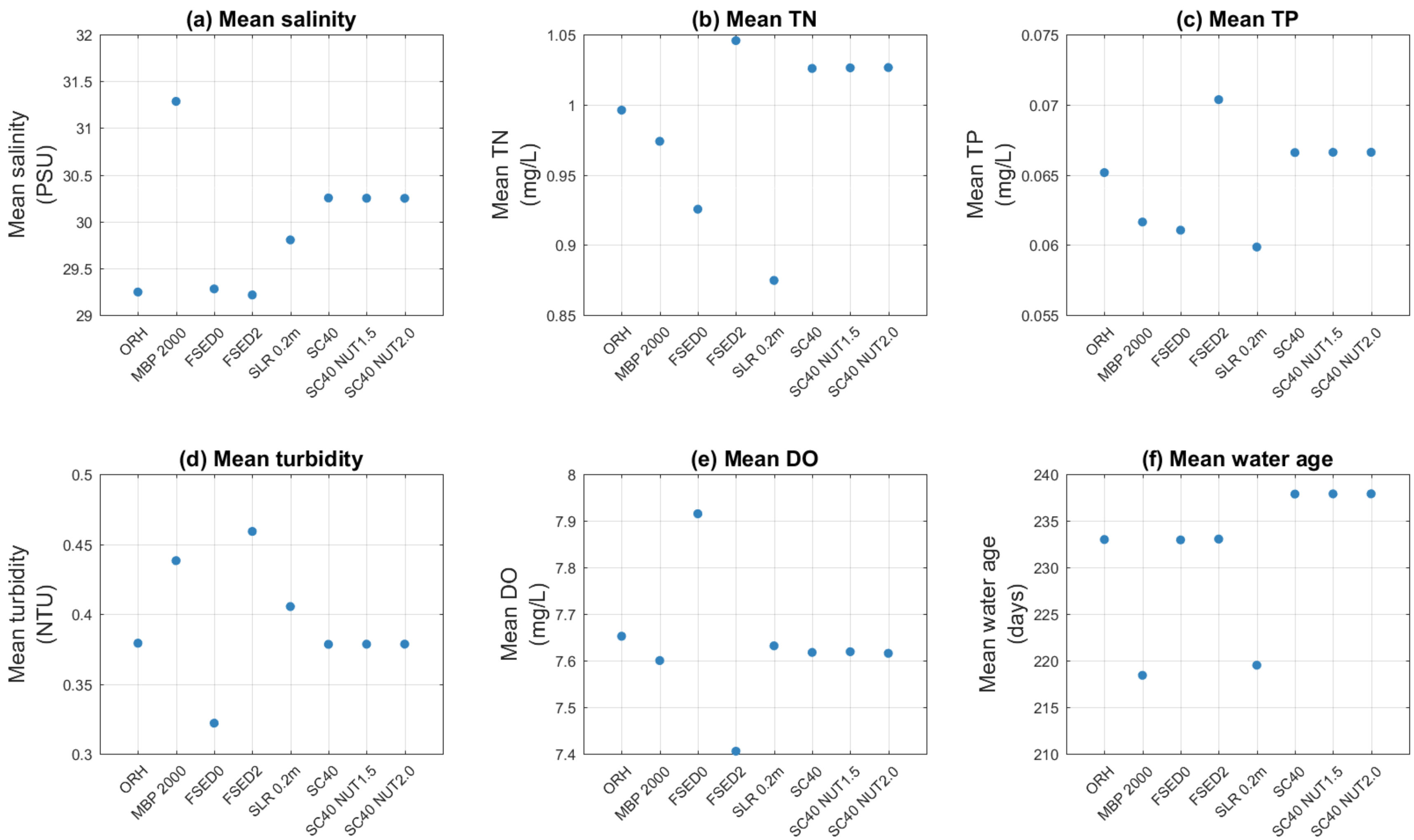

Figure 34. Summary of average water quality properties in the Coorong North Lagoon, comparing the various simulations undertaken.

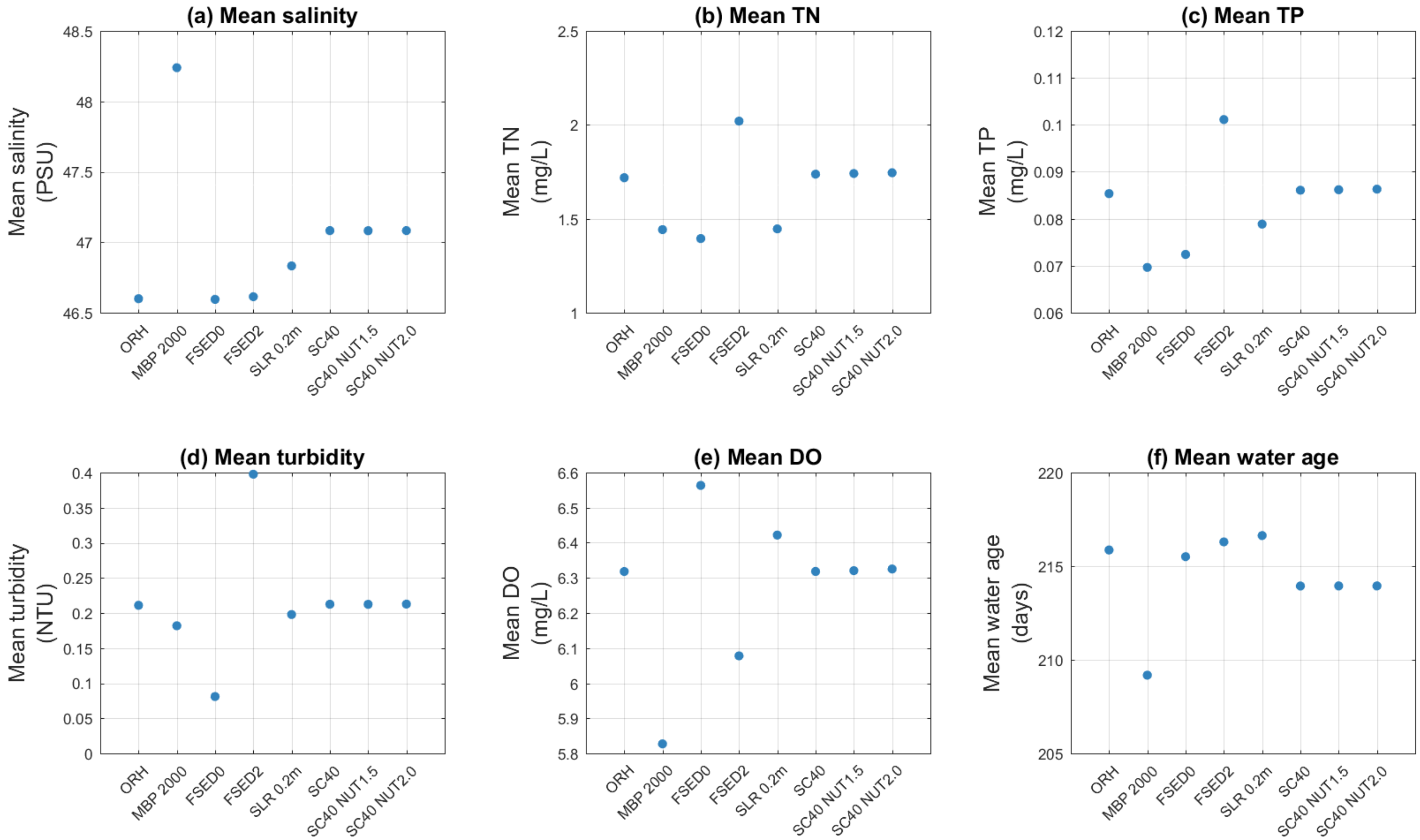

Figure 35. Summary of average water quality properties in the middle reach of the Coorong between the North and South Lagoons, comparing the various simulations undertaken.

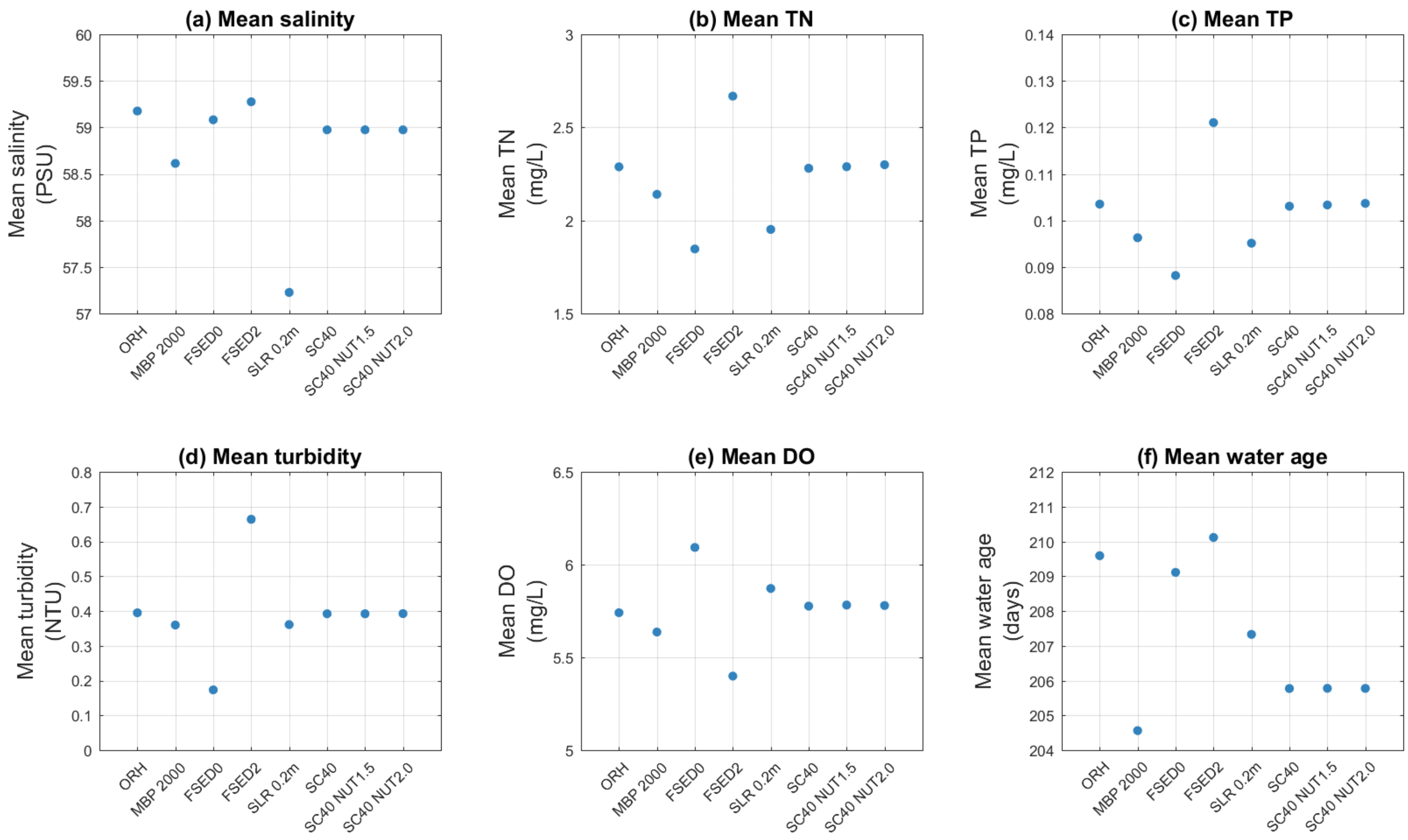

Figure 36. Summary of average water quality properties in the upper reach of the Coorong South Lagoon, comparing the various simulations undertaken.

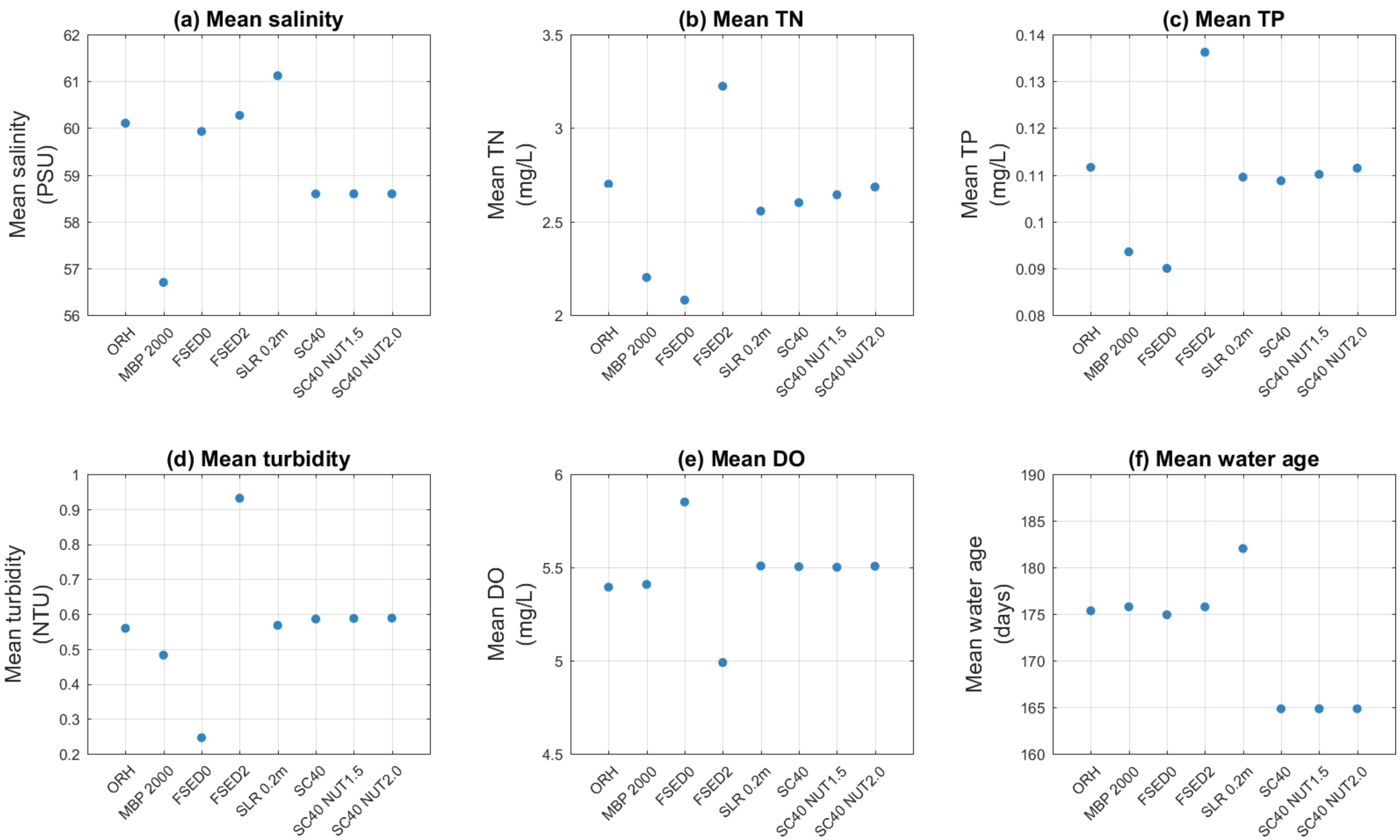

Figure 37. Summary of average water quality properties in the upper reach of the Coorong North Lagoon, comparing the various simulations undertaken.

4.2 *Ruppia* extent and life-cycle

Changes in the model settings between the simulations led to site-specific changes in *Ruppia* HSI values. For example, Figure 38 highlights the relative difference in habitat quality for the flowering life-stage for three sub-regions for selected simulations, with notable differences in quality occurring, particularly around the shallow Parnka region. This is further complicated since each life-stage has its own pattern of sensitivity; for example, Figure 39 shows adult habitat sensitivity as being quite different than for flowering.

These site-specific changes in the life-stage habitat quality maps, did however seem less significant when comparing the total area at the whole-of-system scale (Figure 40). Interestingly, the modelled areas were sensitive to whether or not the model was being run with three-dimensional resolution. Changing the mean sea-level had a notable impact, as expected due to the expansion of the inundated area at higher water levels.

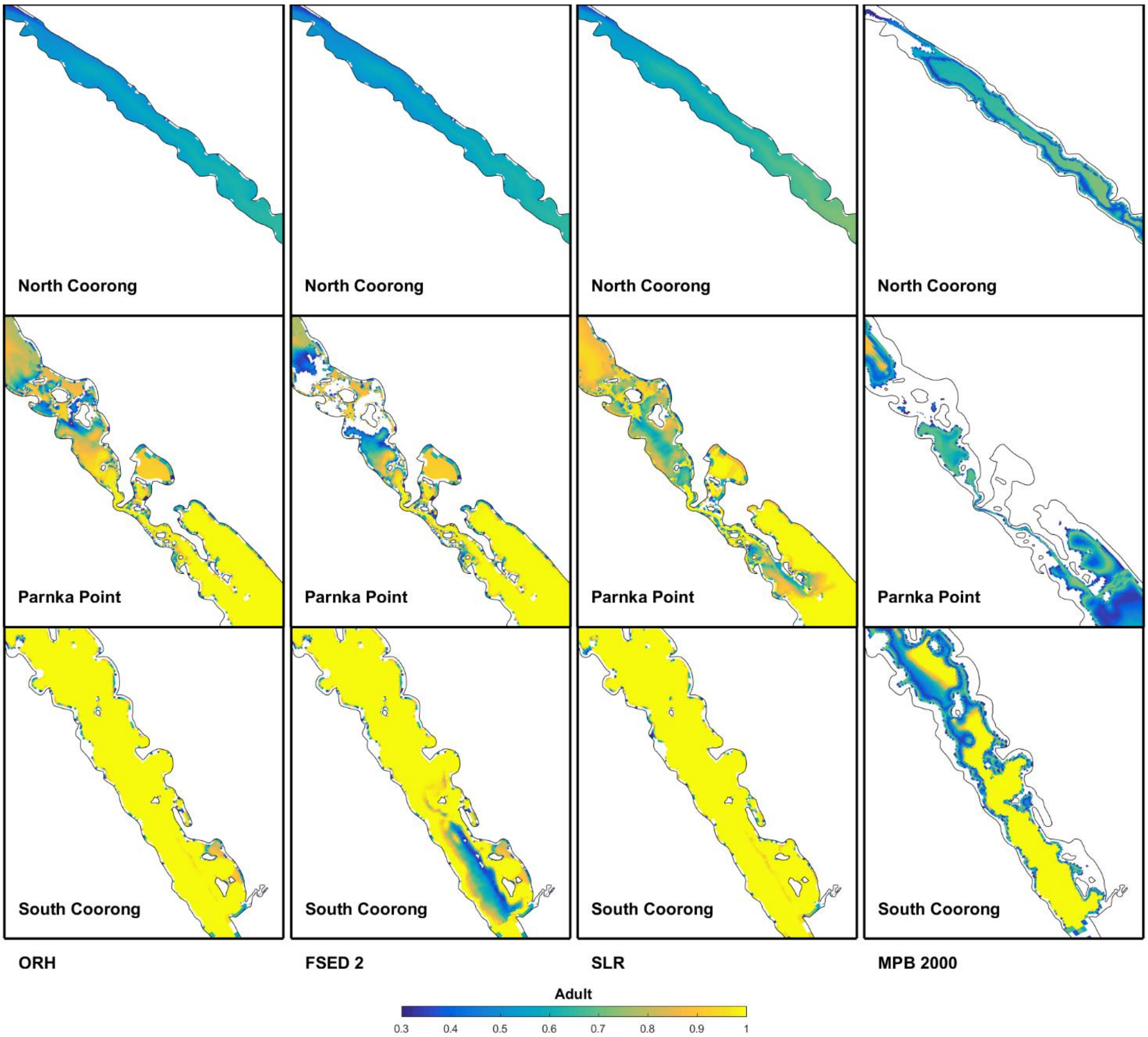

Figure 38. Sensitivity of *Ruppia* habitat index (HSI) for the adult life-stage to the base case (ORH) and three selected scenarios (FSED 2, SLR 0.2m and MBP 2000).

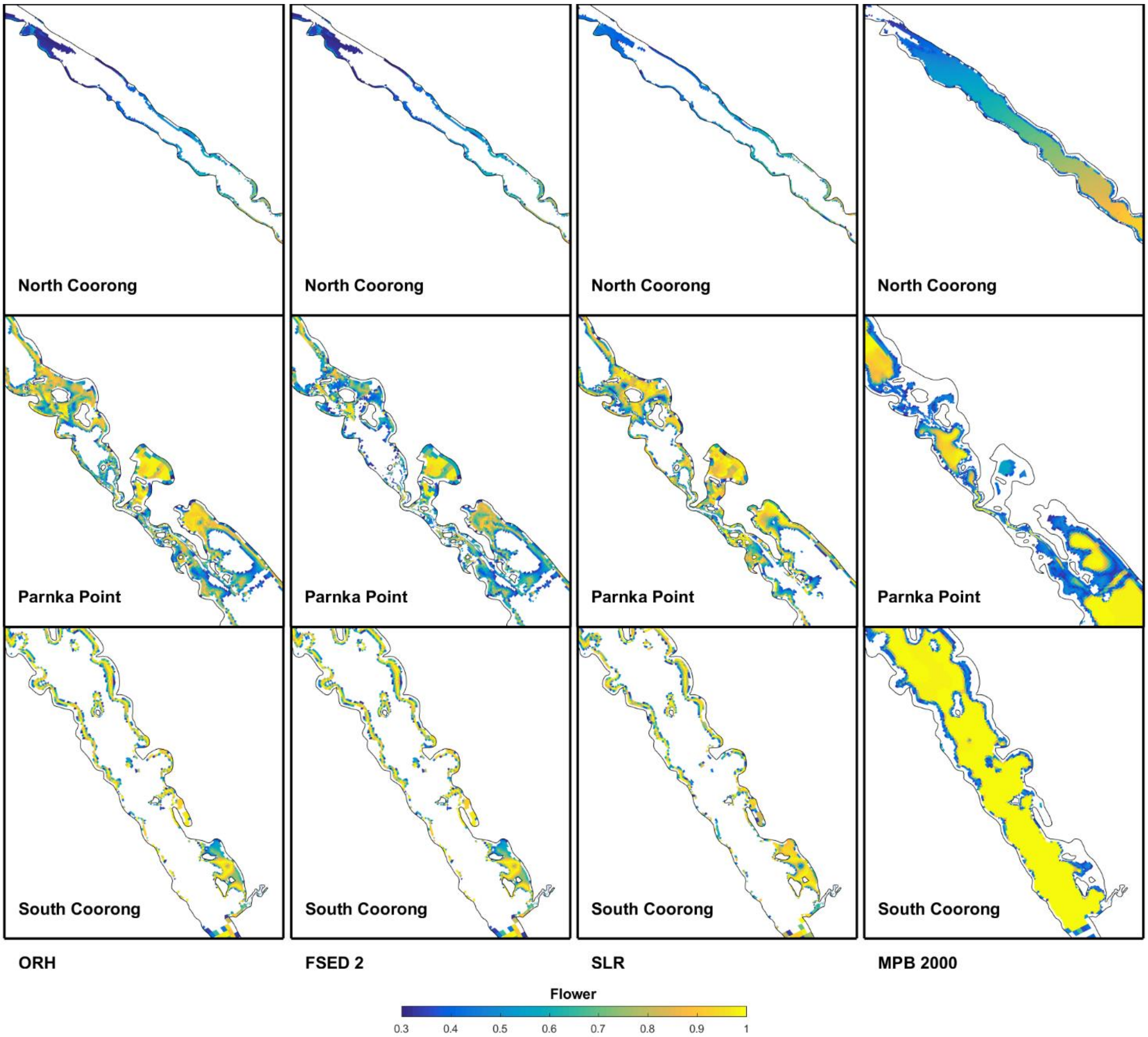

Figure 39. Sensitivity of *Ruppia* habitat index (HSI) for the flower life-stage to the base case (ORH) and three selected scenarios (FSED 2, SLR 0.2m and MBP 2000).

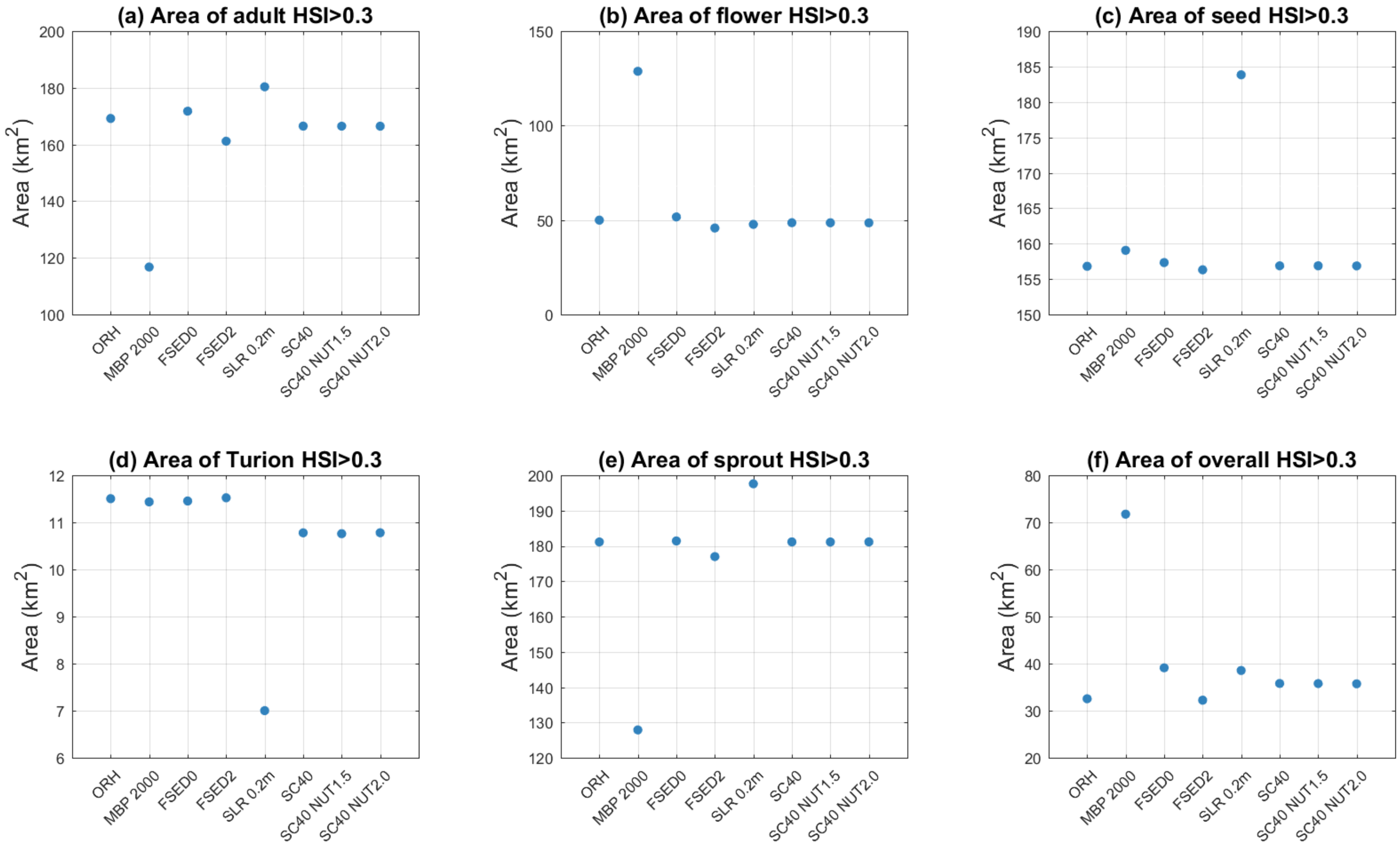

Figure 40. Summary of *Ruppia* habitat area with HSI>0.3 for individual life stages and overall, comparing the various simulations undertaken.

4.3 Recommendations

Based on the model simulations undertaken and consideration of the unknowns, a list of priority areas for future data collection and model improvement has been made below.

Priority measures for refining model inputs:

- *Salt creek inputs* of flow and nutrient concentrations – the nature of the restricted hydrology of the Coorong South Lagoon means that incoming nutrients are weakly flushed and demonstrate a tendency to accumulate. Improving the frequency of data on the nutrient amount and how its partitioned between ON, OP, PO4, NO3, and NH4, will refine the specification of the nutrient loads entering the CSL, and subsequently the load available for internal recycling. Improved data-driven methods (e.g. multi-variate regression or machine-learning tools) for providing higher temporal resolution nutrient estimates can be employed to improve load variability estimation.
- *Barrage inputs of nutrients and salinity* – there is evidence from the dissolved nutrient plots in Mosley and Hipsey (2019) data analysis that high nutrient concentrations are coming over the barrages, or possibly some dissolved nutrient releases are being accelerated by cation exchange processes as freshwater enters the small estuarine mixing zone. Further work on barrage overflow nutrient monitoring will help us to constrain these pathways, and the persistence of these nutrients once they are within the Coorong.
- *Estimation of Coorong South Lagoon groundwater seepage* – whilst not simulated here, the role of groundwater pushing in nutrient rich sediment pore-water may be significant given the heterogeneity of water levels around the lagoon, and the lagoon's shallow nature. Seepage estimates through seepage meters and/or seepage modelling calibrated on data from local piezometer transects can facilitate prediction of seepage rates.
- *Mouth channel morphometry* – As highlighted by our +0.2m sea-level rise simulation, the current model is sensitive to changes in the ocean mean water level. While not incorporated here, improvements to the sediment transport representation in the model has recently been undertaken to support the Murray Mouth dredging program. It also therefore follows that changes in the mouth morphometry, for example through long-term infrastructure investigations, may change the tidal propagation, which will lead to changes in the mean water level and salinity. A strategy for accurate depiction of the mouth morphometry can therefore help improve the model's prediction of exchange between the ocean and lagoon. Furthermore, improved understanding of the coastal seawater nutrient inputs via the Murray Mouth will also help to further refine the overall nutrient budget. It is therefore recommended that future data collection resolves the mouth bathymetry and that a water quality monitoring station outside the mouth channel is included.

Priority measures to assist model setup:

The current modelling studies have assumed relatively homogenous and steady state conditions in sediment properties. Given the shallow nature of the system, and therefore the relative sensitivity to benthic conditions, the data collection to support the following will be informative to constrain the model setup and improve model accuracy:

- S*ediment type and quality spatial variability* – collating and interpolating data on sediment condition can help to constrain sediment nutrient fluxes and erosion/deposition areas. Characterising spatial variability is challenging, but even simple measures outlined in Hallett et al. (2019) can be highly informative. Understanding organic matter, sulfide minerals and total nutrient concentrations, plus particle size and porosity over the depth profile is necessary to support oxygen and nutrient flux predictions. A detailed sediment quality assessment, could be used to define sediment zones, thereby allowing transition to a dynamic sediment biogeochemical model able to resolve spatial heterogeneity in sediment processes and temporal variability in oxygen and nutrients fluxes (see process measurement recommendation also below).
- *Benthic coverage and extent of bivalves and sea grasses* – as outlined above, bivalve filtration and the role of benthic macroinvertebrates is important for shaping ecosystem function. It is known that

the density of filtering organisms is now low in the South Lagoon, but that previously they have served an important role (Dittmann et al. 2017). What is not known is how their disappearance may have influenced nutrient cycling and flux and contributed to declining sediment condition. Capturing this processes and feedback in future studies is important to help map future restoration trajectories.

Priority measures to assist model validation:

Whilst the model presented has been validated against prior collected sampling data (e.g., see Mosley et al. (2017) for data availability and Collier et al. (2017) for model performance), the patchy and intermittent nature of this data is unable to fully resolve model uncertainty. Strategic deployment of instrumentation and use of remotely sensed data can help provide the necessary data density and variety to support a higher level of validation. Specific recommendations include:

- *Collection of high-frequency* in situ *water quality data* (e.g., temperature, dissolved oxygen, chlorophyll a, salinity, turbidity) using a multiparameter sonde in shallow and deep water environments, to resolve variability as shown in Figure 27, for example. It is understood that installation of a multi-parameter sonde is in process at present at an existing station in the South Lagoon with more planned.
- *Routine nutrient and chlorophyll-a analysis* – recent data collection has been reported in Mosley and Hipsey (2019), and this data is important to resolve baseline trends and deviations in response to drought and/or environmental watering. Algal community identification will also help resolve gradients in productivity, so we know what algae might be responding to nutrient and salinity conditions (e.g. green algae vs cyanobacteria).
- *Remotely sensed estimation of Ulva surface accumulations* – spatial changes in macroalgal biomass accumulations is difficult to model directly. Whilst it will be always difficult to model fully the processes leading to large accumulations, and their subsequent decay and dispersion, the regular use of imagery to detect the likelihood of presence or absence of floating macroalgae can be used to build a dataset to cross-check and validate hotspots of *Ulva* growth and accumulation predicted by the model. This is an important validation step to build confidence in these predictions.

Priority experimental data to support setup and process justification:

The model settings associated with biogeochemical fluxes and transformations are largely based on literature review and expert judgement, bringing in significant uncertainty, especially considering the unique nature of the Coorong eco-hydrology and large salinity gradient, extending to hypersaline ranges not commonly assessed in the literature. Whilst the selected model parameters are not thought to have significant errors, *in situ* evidence can help ensure that water and nutrient budgets are being resolved as accurately as possible, which are important given the implications for management policies related to environmental watering and nutrient load reduction. Based on the assessed model simulations and discussions, further data on the following biogeochemical processes are recommended:

- *Evaporation rates* – evapo-concentration of salt and nutrients shape peak summer concentrations, most notably in the CSL. The model is very sensitive to evaporation rates applied, and small errors can accumulate year to year to lead to quite different CSL salinity, TN and TP predictions. Given the high salinities, direct measurements will allow this to be constrained.
- *Sediment flux rates* – the analysis here with no, modest and high nutrient flux rates demonstrates that the assigned fluxes are important, and internal loading should be taken into account in order to inform future decisions. However, to date they remain largely unknown, and equally as important is how they vary spatially. Laboratory sediment incubations and *in situ* benthic chamber assessments over key sediment types can allow improved constraint on the nutrient mass balance.
- *Sediment total and pore-water nutrients* – the present analysis has adopted a simplified sediment nutrient approach, that needs to be extended in future simulations to account for the depth-resolved concentration gradients and temporal variability in sediment dynamics. This next level of sediment modelling will greatly improve our ability to explore the drivers of the internal loads, and long-term benefits of restoration initiatives, but does require investment in the necessary input data related to

sediment condition. This is therefore related to the above priority “Sediment type and quality spatial variability”.

- *Resuspension rates* – the present study has not been able to resolve the relative importance of resuspension on the lagoon nutrient budgets, but approximations suggest that particulate remobilisation during resuspension can play an important role in this shallow lagoon. The rates of resuspension however, do vary considerably with sediment type, and the status of the sediment. Experimental assessment of the resuspension rate under different wind conditions will allow resolution of this process in future model simulations.
- *Denitrification rates* – the accumulation of nitrogen in a lagoon system like the Coorong is tempered only by the loss process of denitrification (which converts inorganic nitrogen to inert nitrogen gas, N_2). The relative efficiency of denitrification (the amount of incoming nitrogen that is denitrified) is known to be highly variable and sensitive to trophic status and oxygen dynamics. Also, in low oxygen water denitrification may encourage release of the greenhouse gas N_2O, which is undesirable. *In situ* determination of denitrification rates in the sediment and water through isotope pairing or similar will allow cross-validation of the modelled rates.
- *Organic matter breakdown and quality* – the dissolved and particulate organic matter mass within the lagoons was demonstrated to be significant. The quality and rate of cycling of this nutrient pool is sensitive to the source of the organic matter and also temperature, salinity and light intensity. Little is known about organic matter reactivity in the Coorong and surrounding region. Understanding organic matter characteristics (including carbon, nitrogen and phosphorus stoichiometry) and reactivity through Excitation Emission Mass Spectroscopy (EEMS) and bioassays will improve the model parameterisation.
- *Particulate matter (total suspended solid) composition* – related to the above item, the makeup of floating material in the water (seston) is largely unknown in the Coorong. Understanding the mix of POC, SS and Chl-a will help validate the model resuspension and sedimentation algorithms.
- Ulva *buoyancy and photosynthesis rates* – the tendency of *Ulva* to form floating mats and high densities highlights its ability to accumulate biomass rapidly. The recent study by Waycott et al. (2020) has demonstrated the sensitivity of photosynthesis to salinity and temperatures, and this can be translated to model growth parameterisations. To capture accumulation hotspots, the model also needs to resolve the tendency to form surface accumulations. This requires that we also need to study how algal buoyancy changes (based on cell densities) in response to photosynthesis and environmental changes.
- *Bivalve filtration rates* – in the simulations of this study, the role of benthic macroinvertebrate in filtering water was not included. This can be a significant contributor to nutrient budgets, in terms of filtering particulates, and is sensitive to lagoon conditions (e.g. bottom oxygen).
- *Benthic productivity as a function of depth/light* – littoral (shallow) zone bottom photosynthesis was shown in the study to be significant in shaping biogeochemical conditions near to *Ruppia* hotspots and areas of macroalgal biomass accumulation. Use of benthic chambers to gather data on benthic primary producer biomass and their rates of photosynthesis under various light and salinity conditions is required to resolve this properly in future model simulations.

Model uncertainty assessment and reporting:

The present study has used a selective process of testing model sensitivity to boundary conditions, parameters and model structure to demonstrate the range of variability in predictions caused by uncertainty in these values. This has focussed on manipulating single parameters and assessing the water quality and algal responses, however, there could be interaction between parameters that was not able to be assessed for practical reasons in the current approach. More formal treatment of uncertainty is possible, for example using Bayesian methods for assigning appropriate prior ranges and undertaking Monte Carlo analysis (e.g Morris or Sobol sensitivity). Development of a computational framework for high-volume simulations would enable a more through treatment of uncertainty. Therefore, the following workflows to better assess predictive uncertainty are recommended:

- Development of cloud computing options to support high volume of model uncertainty simulations.

- Application of the model with a package able to quantify predictive uncertainty, such as PEST.

There are the “known unknowns” discussed above, and likely numerous “unknown unknowns”, in terms of parameter values that have not received sensitivity testing or dedicated research. This is particularly the case given the uniqueness of South Lagoon, which means default parameters generally applicable elsewhere may not apply as well. Future modelling therefore should adopt an adaptive approach, applied iteratively in conjunction with new data collection and experimental initiatives (Hipsey et al. 2015). This will ensure all future data is used to improve accuracy of the model and over time increase its suitability for supporting the increasingly complex decisions being made to restore this important ecosystem.

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Appendix A – Model results summary

Table A.1: Comparison of simulation average results for salinity (psu), separated by season and region. Simulations are described in Table 2, and colours represent values from low (blue) to high (red).

	ORH	MBP 2000	FSED 0	FSED 2	SLR 0.2m	SC40	SC40 x 1.5	SC40 x 2
Mouth/Barrages								
Autumn	12.7	13.7	12.7	12.7	14.6	12.7	12.7	12.7
Spring	11.1	13.5	11.1	11.1	13.5	11.3	11.3	11.3
Summer 2014	20.3	18.4	20.3	20.3	24.0	20.3	20.3	20.3
Summer 2015	12.4	13.9	12.4	12.5	16.1	12.6	12.6	12.6
Winter	17.1	17.3	17.1	17.1	18.1	16.8	16.8	16.8
North Coorong								
Autumn	20.3	20.6	20.3	20.3	23.8	20.3	20.3	20.3
Spring	33.3	35.4	33.4	33.3	33.7	39.2	39.2	39.2
Summer 2014	37.4	37.8	37.4	37.4	33.6	37.4	37.4	37.4
Summer 2015	25.3	27.9	25.4	25.1	27.8	32.1	32.1	32.1
Winter	26.1	29.9	26.1	26.0	28.1	24.1	24.1	24.1
Mid Coorong								
Autumn	35.2	38.1	35.3	35.1	37.7	35.2	35.2	35.2
Spring	55.2	53.8	55.1	55.3	56.1	58.7	58.7	58.7
Summer 2014	54.0	55.0	53.9	54.0	49.1	53.9	53.9	53.9
Summer 2015	54.1	52.8	54.2	54.1	56.5	60.0	60.0	60.0
Winter	42.1	45.5	42.1	42.2	44.4	40.5	40.5	40.5
Upper South Coorong								
Autumn	56.3	57.9	56.3	56.3	53.9	56.4	56.4	56.4
Spring	61.8	57.0	61.6	62.0	60.6	61.9	61.9	61.9
Summer 2014	68.3	68.4	68.1	68.4	63.9	68.3	68.3	68.3
Summer 2015	71.6	66.0	71.3	71.8	69.6	71.6	71.6	71.6
Winter	50.5	49.7	50.4	50.5	50.5	49.5	49.5	49.5
Lower South Coorong								
Autumn	68.0	65.3	67.8	68.2	67.8	67.9	67.9	67.9
Spring	57.6	50.8	57.4	57.8	58.9	48.0	48.0	48.0
Summer 2014	57.7	58.2	57.6	57.7	61.2	57.6	57.6	57.6
Summer 2015	70.8	62.9	70.3	71.3	73.8	61.1	61.1	61.1
Winter	57.2	51.5	57.0	57.3	56.6	60.9	60.9	60.9

Table A.2. Comparison of simulation average results for oxygen (mg/L), separated by season and region. Simulations are described in Table 2, and colours represent values from high (blue) to low (red).

	ORH	MBP 2000	FSED 0	FSED 2	SLR 0.2m	SC40	SC40 x 1.5	SC40 x 2
Mouth/Barrages								
Autumn	8.66	8.43	8.89	8.39	8.61	8.67	8.66	8.66
Spring	8.09	7.93	8.25	8.02	8.13	8.07	8.08	8.09
Summer 2014	7.36	7.24	7.44	7.25	7.32	7.37	7.36	7.38
Summer 2015	7.67	7.50	7.78	7.52	7.65	7.66	7.64	7.65
Winter	8.81	8.72	8.93	8.71	8.78	8.83	8.83	8.84
North Coorong								
Autumn	8.27	8.42	8.70	7.90	8.08	8.28	8.28	8.28
Spring	7.19	7.13	7.40	7.01	7.18	6.94	6.94	6.94
Summer 2014	6.66	6.63	6.78	6.54	6.90	6.68	6.68	6.67
Summer 2015	7.20	7.12	7.41	7.00	7.15	6.93	6.93	6.93
Winter	8.47	8.46	8.77	8.16	8.35	8.56	8.57	8.57
Mid Coorong								
Autumn	7.00	6.34	7.30	6.72	7.05	7.02	7.02	7.03
Spring	5.74	5.54	6.03	5.49	5.81	5.64	5.64	5.64
Summer 2014	5.09	4.28	5.25	4.96	5.54	5.12	5.12	5.14
Summer 2015	5.59	4.98	5.73	5.41	5.65	5.35	5.35	5.35
Winter	7.42	7.27	7.65	7.12	7.28	7.48	7.49	7.48
Upper South Coorong								
Autumn	5.99	5.87	6.48	5.54	6.17	6.02	6.03	6.02
Spring	5.48	5.69	5.76	5.22	5.54	5.47	5.48	5.46
Summer 2014	4.79	4.51	5.01	4.55	5.02	4.87	4.87	4.87
Summer 2015	4.93	4.77	5.22	4.69	5.02	4.91	4.87	4.87
Winter	6.69	6.93	7.10	6.28	6.75	6.73	6.73	6.75
Lower South Coorong								
Autumn	5.24	5.24	5.82	4.78	5.38	5.28	5.29	5.29
Spring	5.48	5.89	5.84	5.10	5.57	5.94	5.93	5.94
Summer 2014	4.61	4.24	4.94	4.33	4.76	4.68	4.68	4.69
Summer 2015	4.73	4.28	5.08	4.46	4.77	4.83	4.86	4.85
Winter	6.23	6.75	6.78	5.74	6.31	6.09	6.09	6.09

Table A.3. Comparison of simulation average results for total nitrogen (mg/L), separated by season and region. Simulations are described in Table 2, and colours represent values from low (blue) to high (red).

	ORH	MBP 2000	FSED 0	FSED 2	SLR 0.2m	SC40	SC40 x 1.5	SC40 x 2
Mouth/Barrages								
Autumn	0.842	0.834	0.803	0.870	0.830	0.843	0.842	0.843
Spring	0.850	0.820	0.803	0.879	0.823	0.873	0.872	0.871
Summer 2014	0.649	0.666	0.589	0.691	0.617	0.650	0.650	0.649
Summer 2015	0.800	0.795	0.748	0.833	0.760	0.809	0.809	0.809
Winter	0.839	0.850	0.817	0.852	0.831	0.835	0.835	0.835
North Coorong								
Autumn	0.725	0.703	0.669	0.748	0.659	0.725	0.725	0.725
Spring	1.287	1.248	1.242	1.335	1.159	1.456	1.457	1.458
Summer 2014	1.034	0.920	0.887	1.139	0.786	1.034	1.034	1.033
Summer 2015	1.271	1.178	1.202	1.334	1.149	1.497	1.504	1.512
Winter	0.937	1.011	0.900	0.959	0.890	0.886	0.886	0.886
Mid Coorong								
Autumn	1.264	1.032	0.912	1.570	1.032	1.266	1.266	1.266
Spring	1.993	1.805	1.828	2.157	1.794	2.134	2.148	2.162
Summer 2014	2.035	1.247	1.515	2.526	1.604	2.031	2.031	2.033
Summer 2015	2.391	1.913	2.011	2.744	2.172	2.635	2.676	2.719
Winter	1.585	1.654	1.321	1.832	1.353	1.520	1.520	1.520
Upper South Coorong								
Autumn	2.097	1.981	1.583	2.522	1.776	2.100	2.100	2.100
Spring	2.413	2.218	2.013	2.776	2.019	2.439	2.472	2.510
Summer 2014	2.632	2.341	2.250	2.978	2.290	2.628	2.628	2.631
Summer 2015	2.985	2.517	2.440	3.467	2.554	2.927	3.014	3.102
Winter	2.015	1.955	1.546	2.401	1.727	1.960	1.960	1.961
Lower South Coorong								
Autumn	2.870	2.257	2.228	3.400	2.727	2.870	2.872	2.872
Spring	2.896	2.260	2.048	3.641	2.631	2.413	2.568	2.720
Summer 2014	2.443	2.128	2.136	2.720	2.517	2.435	2.435	2.435
Summer 2015	3.415	2.487	2.491	4.296	3.143	2.665	2.822	2.974
Winter	2.584	2.117	1.911	3.122	2.348	2.686	2.696	2.707

Table A.4. Comparison of simulation average results for total phosphorus (mg/L), separated by season and region. Simulations are described in Table 2, and colours represent values from low (blue) to high (red).

	ORH	MBP 2000	FSED 0	FSED 2	SLR 0.2m	SC40	SC40 x 1.5	SC40 x 2
Mouth/Barrages								
Autumn	0.0735	0.0763	0.0728	0.0741	0.0723	0.0735	0.0735	0.0735
Spring	0.067	0.0673	0.0658	0.0678	0.0654	0.0684	0.0683	0.0683
Summer 2014	0.0508	0.0589	0.0497	0.0519	0.0491	0.0508	0.0508	0.0508
Summer 2015	0.0625	0.0662	0.0614	0.0635	0.06	0.0631	0.0631	0.0631
Winter	0.0668	0.0686	0.0663	0.0673	0.0661	0.0668	0.0667	0.0668
North Coorong								
Autumn	0.054	0.052	0.0528	0.0561	0.0514	0.0541	0.0541	0.0541
Spring	0.08	0.075	0.0732	0.0886	0.0741	0.0875	0.0876	0.0876
Summer 2014	0.0665	0.06	0.0608	0.0722	0.0551	0.0664	0.0664	0.0664
Summer 2015	0.0819	0.0752	0.0752	0.0902	0.0765	0.0923	0.0925	0.0928
Winter	0.0601	0.0602	0.0573	0.0645	0.0585	0.0582	0.0582	0.0582
Mid Coorong								
Autumn	0.0672	0.0537	0.0561	0.0803	0.0611	0.0674	0.0674	0.0674
Spring	0.1064	0.0911	0.0919	0.1257	0.0995	0.1111	0.1115	0.112
Summer 2014	0.0881	0.0556	0.0707	0.107	0.08	0.0881	0.0881	0.0882
Summer 2015	0.1278	0.1027	0.1053	0.1555	0.121	0.1374	0.1385	0.1398
Winter	0.0795	0.077	0.0707	0.0914	0.0746	0.0775	0.0775	0.0775
Upper South Coorong								
Autumn	0.093	0.0883	0.0795	0.1076	0.0856	0.0931	0.0931	0.0931
Spring	0.1157	0.104	0.0959	0.1403	0.1057	0.1154	0.1164	0.1176
Summer 2014	0.1154	0.1049	0.1002	0.1317	0.1055	0.1152	0.1152	0.1153
Summer 2015	0.1513	0.1344	0.1196	0.1887	0.1384	0.1501	0.1528	0.1556
Winter	0.09	0.086	0.0772	0.1044	0.0837	0.0886	0.0887	0.0887
Lower South Coorong								
Autumn	0.1173	0.0939	0.0943	0.1429	0.115	0.1173	0.1173	0.1173
Spring	0.1179	0.0969	0.0903	0.1507	0.1132	0.1019	0.1069	0.1118
Summer 2014	0.1068	0.093	0.0901	0.1253	0.1111	0.1066	0.1066	0.1066
Summer 2015	0.1587	0.1289	0.1134	0.2114	0.1556	0.1387	0.1437	0.1484
Winter	0.1043	0.0891	0.0852	0.1256	0.0988	0.1092	0.1095	0.1099

Table A.5. Comparison of simulation average results for nitrate (mg/L), separated by season and region. Simulations are described in Table 2, and colours represent values from low (blue) to high (red).

	ORH	MBP 2000	FSED 0	FSED 2	SLR 0.2m	SC40	SC40 x 1.5	SC40 x 2
Mouth/Barrages								
Autumn	0.047	0.028	0.012	0.072	0.048	0.047	0.047	0.047
Spring	0.059	0.033	0.017	0.085	0.056	0.057	0.057	0.057
Summer 2014	0.067	0.039	0.013	0.103	0.063	0.067	0.067	0.067
Summer 2015	0.060	0.032	0.014	0.088	0.054	0.059	0.059	0.059
Winter	0.057	0.043	0.036	0.071	0.058	0.058	0.058	0.058
North Coorong								
Autumn	0.067	0.066	0.017	0.080	0.053	0.067	0.067	0.067
Spring	0.045	0.040	0.033	0.049	0.041	0.048	0.048	0.048
Summer 2014	0.125	0.110	0.013	0.196	0.083	0.125	0.125	0.125
Summer 2015	0.073	0.052	0.036	0.095	0.054	0.087	0.087	0.087
Winter	0.061	0.076	0.036	0.061	0.054	0.060	0.060	0.060
Mid Coorong								
Autumn	0.344	0.238	0.021	0.610	0.166	0.345	0.344	0.345
Spring	0.109	0.121	0.030	0.163	0.076	0.125	0.125	0.125
Summer 2014	0.438	0.243	0.007	0.830	0.283	0.437	0.437	0.436
Summer 2015	0.295	0.100	0.043	0.489	0.229	0.315	0.317	0.316
Winter	0.244	0.312	0.024	0.431	0.095	0.231	0.230	0.231
Upper South Coorong								
Autumn	0.460	0.368	0.017	0.804	0.302	0.460	0.460	0.460
Spring	0.308	0.310	0.028	0.527	0.137	0.306	0.306	0.306
Summer 2014	0.289	0.205	0.004	0.531	0.266	0.289	0.289	0.289
Summer 2015	0.399	0.145	0.043	0.665	0.254	0.270	0.270	0.270
Winter	0.421	0.407	0.021	0.727	0.264	0.405	0.405	0.405
Lower South Coorong								
Autumn	0.535	0.400	0.012	0.931	0.482	0.536	0.536	0.536
Spring	0.692	0.457	0.026	1.232	0.560	0.443	0.443	0.443
Summer 2014	0.205	0.165	0.002	0.369	0.219	0.203	0.203	0.203
Summer 2015	0.676	0.131	0.035	1.234	0.524	0.176	0.176	0.175
Winter	0.585	0.450	0.021	1.004	0.486	0.619	0.619	0.619

Table A.6. Comparison of simulation average results for phosphate (mg/L), separated by season and region. Simulations are described in Table 2, and colours represent values from low (blue) to high (red).

	ORH	MBP 2000	FSED 0	FSED 2	SLR 0.2m	SC40	SC40 x 1.5	SC40 x 2
Mouth/Barrages								
Autumn	0.0005	0.0007	0.0004	0.0006	0.0005	0.0005	0.0005	0.0005
Spring	0.0004	0.0005	0.0002	0.0005	0.0004	0.0004	0.0004	0.0004
Summer 2014	0.0006	0.0007	0.0005	0.0008	0.0007	0.0006	0.0006	0.0006
Summer 2015	0.0003	0.0003	0.0002	0.0004	0.0003	0.0003	0.0003	0.0003
Winter	0.0005	0.0005	0.0004	0.0006	0.0004	0.0005	0.0005	0.0005
North Coorong								
Autumn	0.0005	0.0004	0.0002	0.0007	0.0004	0.0005	0.0005	0.0005
Spring	0.0005	0.0004	0.0001	0.0006	0.0004	0.0005	0.0005	0.0005
Summer 2014	0.0006	0.0005	0.0002	0.0008	0.0005	0.0006	0.0006	0.0006
Summer 2015	0.0005	0.0004	0.0001	0.0007	0.0004	0.0005	0.0005	0.0005
Winter	0.0004	0.0003	0.0002	0.0006	0.0004	0.0004	0.0004	0.0004
Mid Coorong								
Autumn	0.0066	0.0015	0.0001	0.0127	0.0027	0.0066	0.0066	0.0066
Spring	0.0015	0.0006	0.0001	0.0029	0.0009	0.0015	0.0015	0.0015
Summer 2014	0.0057	0.0011	0.0002	0.0112	0.003	0.0058	0.0058	0.0058
Summer 2015	0.003	0.0008	0.0001	0.0055	0.0019	0.0033	0.0033	0.0033
Winter	0.0014	0.0012	0.0001	0.0028	0.0005	0.0014	0.0014	0.0014
Upper South Coorong								
Autumn	0.0014	0.0009	0.0001	0.0019	0.0011	0.0015	0.0014	0.0014
Spring	0.0009	0.0006	0.0001	0.0013	0.0007	0.0008	0.0008	0.0008
Summer 2014	0.0009	0.0007	0.0002	0.0014	0.0009	0.0009	0.0009	0.0009
Summer 2015	0.0012	0.0007	0.0001	0.0019	0.0011	0.0012	0.0012	0.0012
Winter	0.0011	0.0009	0.0001	0.0015	0.0009	0.0011	0.0011	0.0011
Lower South Coorong								
Autumn	0.0043	0.0007	0.0002	0.0081	0.0031	0.0043	0.0043	0.0043
Spring	0.0023	0.0008	0.0002	0.0043	0.001	0.0025	0.0025	0.0026
Summer 2014	0.0018	0.0005	0.0002	0.0032	0.0018	0.0018	0.0018	0.0018
Summer 2015	0.006	0.0011	0.0002	0.0114	0.0048	0.0064	0.0064	0.0064
Winter	0.002	0.001	0.0003	0.0034	0.0011	0.0021	0.0021	0.0021

Table A.7. Comparison of simulation average results for *Ruppia* Habitat suitability index (HSI), separated by season and region. Simulations are described in Table 2, and darker green represents higher HSI values.

	ORH	FSED 0	FSED 2	SLR 0.2m	SC40	SC40 x 1.5	SC40 x 2
Mouth/Barrages							
Autumn	29.0	29.1	29.0	37.1	29.0	29.0	29.0
Spring	23.1	23.1	22.9	33.0	23.7	23.7	23.7
Summer 2014	52.3	52.4	52.2	62.3	52.3	52.3	52.3
Summer 2015	22.5	22.6	22.1	36.4	22.8	22.8	22.8
Winter	41.2	41.2	41.2	49.4	39.1	39.1	39.0
North Coorong							
Autumn	59.1	59.3	59.0	74.0	59.2	59.2	59.2
Spring	78.0	78.1	77.9	84.0	82.6	82.6	82.6
Summer 2014	80.1	80.3	79.9	84.4	80.1	80.1	80.1
Summer 2015	47.4	47.8	46.8	59.1	53.4	53.4	53.4
Winter	81.8	81.9	81.6	91.8	78.8	78.8	78.7
Mid Coorong							
Autumn	71.2	71.2	70.9	85.4	71.2	71.2	71.2
Spring	71.0	71.5	68.8	81.3	70.9	70.9	70.9
Summer 2014	46.1	46.4	45.8	60.2	46.1	46.1	46.1
Summer 2015	56.6	57.0	55.5	67.7	55.1	55.1	55.1
Winter	85.5	85.6	84.5	91.5	85.4	85.4	85.4
Upper South Coorong							
Autumn	88.7	88.7	88.7	91.6	88.7	88.7	88.7
Spring	86.2	86.7	84.8	89.9	86.3	86.3	86.3
Summer 2014	68.9	69.5	68.2	73.9	68.9	68.9	68.9
Summer 2015	73.5	74.3	72.3	78.1	73.0	73.0	73.0
Winter	91.5	91.5	91.5	92.9	91.5	91.5	91.5
Lower South Coorong							
Autumn	82.9	83.0	70.3	88.3	83.0	83.0	83.0
Spring	81.2	81.4	74.9	86.4	81.9	81.9	81.9
Summer 2014	61.7	62.9	50.9	65.5	61.7	61.7	61.7
Summer 2015	66.7	68.0	51.0	71.7	72.0	72.0	72.0
Winter	89.2	89.2	87.1	91.5	89.0	89.0	89.0

Table A.8. Comparison of simulation average results for Macroalgal Habitat Suitability Index (HSI), separated by season and region. Simulations are described in Table 2, and darker green represents higher HSI values.

	ORH	FSED 0	FSED 2	SLR 0.2m	SC40	SC40 x 1.5	SC40 x 2
Mouth/Barrages							
Autumn	0.8	0.6	1.5	0.9	0.8	0.8	0.8
Spring	6.6	1.2	6.1	4.3	6.5	6.5	6.6
Summer 2014	13.8	0.4	15.9	12.6	13.7	13.7	13.8
Summer 2015	5.6	0.5	7.1	3.4	4.6	4.6	4.7
Winter	6.4	4.8	6.9	6.6	6.5	6.4	6.6
North Coorong							
Autumn	1.9	0.2	3.5	0.3	1.9	1.9	1.9
Spring	3.2	0.0	3.7	0.5	4.3	4.3	4.3
Summer 2014	24.6	0.0	25.0	19.0	24.6	24.6	24.7
Summer 2015	8.3	0.0	8.5	6.3	12.6	12.6	12.7
Winter	1.4	0.8	1.9	0.9	1.4	1.4	1.4
Mid Coorong							
Autumn	13.4	0.1	14.3	9.7	13.5	13.4	13.5
Spring	8.7	0.0	10.0	5.3	12.0	11.7	11.8
Summer 2014	13.9	0.2	14.3	19.8	14.0	14.0	13.8
Summer 2015	8.8	0.5	9.8	10.5	10.9	10.4	10.5
Winter	14.5	0.0	15.2	5.5	13.9	13.7	13.8
Upper South Coorong							
Autumn	12.0	0.0	11.1	17.4	11.9	11.9	11.9
Spring	22.4	0.0	21.7	24.7	24.7	24.6	24.8
Summer 2014	2.1	0.0	3.1	10.6	2.2	2.2	2.1
Summer 2015	4.5	0.0	4.7	6.1	3.1	3.0	3.2
Winter	22.3	0.0	21.4	20.5	22.4	22.4	22.4
Lower South Coorong							
Autumn	1.3	0.0	1.3	3.5	1.3	1.4	1.3
Spring	28.0	0.0	26.2	33.0	32.1	32.2	32.4
Summer 2014	7.9	0.0	9.5	8.1	7.9	7.9	7.9
Summer 2015	2.0	0.0	2.0	1.7	7.2	7.1	7.3
Winter	17.3	0.0	15.8	18.6	11.6	11.7	11.7

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