Summary of Coorong hydrological, biogeochemical and ecological models

Department for Environment and Water
December, 2020

DEW Technical report 2020/39

Government
of South Australia

Department for
Environment and Water

Department for Environment and Water
Government of South Australia
December 2020

81-95 Waymouth St, ADELAIDE SA 5000
Telephone +61 (8) 8463 6946
Facsimile +61 (8) 8463 6999
ABN 36702093234

www.environment.sa.gov.au

ISBN 978-1-925964-92-9

Report prepared by:
Gareth Oerman
Environmental Science Unit
Science, Information and Technology Branch
Strategy, Science and Corporate Services Division
Department for Environment and Water

Preferred way to cite this publication

DEW (2020). *Summary of Coorong hydrological, biogeochemical and ecological models*, DEW Technical report 2020/39, Government of South Australia, Department for Environment and Water, Adelaide.

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
DEPARTMENT FOR ENVIRONMENT AND WATER

Acknowledgements

This project was developed as 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 summary of Coorong hydrological, biogeochemical and ecological models was part of *Activity 7.1 – Collation of existing tools and systems and assessment of the applicability for decision making* of the *Trial and Investigations Integration Project*. Gareth Oerman was the primary author of this report. Thank you to Matt Gibbs and Jody O'Connor for their input and reviews, which improved the report. Thank you also to Jason Higham for high-level advice on report content.

Contents

Foreword ii

Acknowledgements iii

Summary ix

1 Introduction 1

2 Model Summaries 6

2.1 TUFLOW-FV 6
2.1.1 Decription 6
2.1.2 Spatial limits and resolution 6
2.1.3 Inputs 7
2.1.4 Outputs 8
2.1.5 Former/current use 9
2.1.6 Limitations and assumptions 9
2.1.7 Improvements 9
2.2 Coorong Dynamics Model (AED2) 10
2.2.1 Description 10
2.2.2 Spatial limits and resolution 10
2.2.3 Inputs 10
2.2.4 Outputs 10
2.2.5 Former/current use 12
2.2.6 Limitations and assumptions 12
2.2.7 Improvement 13
2.3 Coorong Hydrodynamic Model 14
2.3.1 Description 14
2.3.2 Spatial limits and resolution 14
2.3.3 Inputs 14
2.3.4 Outputs 15
2.3.5 Former/current use 15
2.3.6 Limitations and assumptions 15
2.4 Nutrient Budget and Biogeochemical Model 20
2.4.1 Description 20
2.4.2 Spatial limits and resolution 20
2.4.3 Inputs 21
2.4.4 Outputs 21
2.4.5 Former/current use 22
2.4.6 Limitations and assumptions 22
2.5 Ecosystem State Model 23
2.5.1 Description 23
2.5.2 Spatial limits and resolution 25
2.5.3 Inputs 25
2.5.4 Outputs 25
2.5.5 Former/current use 25

2.5.6	Limitations and assumptions	26
2.6	Digital Elevation Model (CLLMM)	27
2.6.1	Description	27
2.6.2	Spatial limits and resolution	27
2.6.3	Inputs	27
2.6.4	Outputs	28
2.6.5	Former/current use	29
2.6.6	Limitations and assumptions	29
2.7	Digital Elevation Model (HCHB)	30
2.7.1	Description	30
2.7.2	Spatial limits and resolution	30
2.7.3	Inputs	30
2.7.4	Outputs	31
2.7.5	Former/current use	31
2.7.6	Limitations and assumptions	31
2.8	Mudflat Availability Model	33
2.8.1	Description	33
2.8.2	Spatial limits and resolution	33
2.8.3	Inputs	33
2.8.3.1	Bathymetry for reference sites	33
2.8.3.2	Water level	33
2.8.4	Outputs	33
2.8.5	Former/current use	34
2.8.6	Limitations and assumptions	34
2.9	Fish Habitat Model (CLLMM)	35
2.9.1	Description	35
2.9.2	Spatial limits and resolution	35
2.9.3	Inputs	35
2.9.4	Outputs	35
2.9.5	Former/current use	36
2.9.6	Limitations and assumptions	36
2.10	Fish Habitat Model (CSIRO)	37
2.10.1	Description	37
2.10.2	Timing	37
2.10.3	Spatial limits and resolution	37
2.10.4	Inputs	37
2.10.5	Outputs	38
2.10.6	Former/current use	39
2.10.7	Limitations and assumptions	39
2.11	*Ruppia tuberosa* Response Model	40
2.11.1	Description	40
2.11.2	Spatial limits and resolution	40
2.11.3	Inputs	40
2.11.4	Outputs	41
2.11.5	Former/Current use	41
2.11.6	Limitations and assumptions	43
2.12	Waterbird response models	44

2.12.1 Description 44
2.12.2 Timing 46
2.12.3 Spatial limits and resolution 46
2.12.4 Inputs 46
2.12.5 Outputs 46
2.12.6 Former/Current use 47
2.12.7 Limitations and assumptions 48

3 Summary 49

3.1 Hydrodynamic models 49
3.1.1 Applicable models 49
3.1.2 Rationale for preferred model 49
3.1.3 Model creation/improvement under HCHB 49
3.2 Biogeochemical models 50
3.2.1 Applicable models 50
3.2.2 Rationale for preferred model 50
3.2.3 Model creation/improvement under HCHB 50
3.3 Bathymetric models 50
3.3.1 Applicable models 50
3.3.2 Rationale for preferred model 50
3.3.3 Model creation/improvement under HCHB 50
3.4 Fish models 51
3.4.1 Applicable models 51
3.4.2 Rationale for preferred model 51
3.4.3 Model creation/improvement under HCHB 51
3.5 *Ruppia tuberosa* models 51
3.5.1 Applicable models 51
3.5.2 Rationale for preferred model 51
3.5.3 Model creation/improvement under HCHB 51
3.6 Waterbirds models 52
3.6.1 Applicable models 52
3.6.2 Rationale for preferred model 52
3.6.3 Model creation/improvement under HCHB 52

4 HCHB modelling approach 53

5 References 54

List of figures

Figure 1-2. Schematic of the TUFLOW-FV, and AED2 Biogeochemical-Habitat Model that dynamically couple to form the Coorong Dynamics Model. The arrows to and from each model demonstrate that models dynamically inform each other, rather than one model utilising the outputs of the parent model. 4

Figure 1-3. Schematic of the models that run simulations based upon the outputs of the Coorong Hydrodynamic Model. 5

Figure 2-1. Examples of mesh resolutions used in the TUFLOW-FV model. Source: Hipsey et al. (2020). 7

Figure 2-2. Salinity output of the Coorong Hydrodynamic Model with simulations commencing in 1998 and the model using a Murray Mouth depth of 2 m and horizontal salt dispersion rate of 87 m^2/s. 17

Figure 2-3. Salinity output of the Coorong Hydrodynamic Model within simulations commencing in 2010 and the model using a Murray Mouth depth of 2 m and horizontal salt dispersion rate of 40 m^2/s. 18

Figure 2-4. Salinity output of the Coorong Hydrodynamic Model within simulations commencing in 1998 and the model using a Murray Mouth depth of 2 m and horizontal salt dispersion rate of 40 m^2/s. 19

Figure 2-5. Approximate extents of each of the 14 boxes used in the Nutrient Budget and Biogeochemical Model. Source: Grigg et al. (2009). 20

Figure 2-6. The extent and resolution of the Nutrient Budget and Biogeochemical Model, showing the partition of grid cells (cells positioned around sampling sites) for different water depths (m). Source: Grigg et al. (2009). 21

Figure 2-7. Original Ecosystem State Model for the Coorong. The marine basin covers the northern Coorong and the hypersaline basin covers the southern Coorong. Where the value of a parameter is less than or equal to the threshold value specified, then the tree should be followed to the left. Where it is higher, the tree should be followed to the right. An ecosystem state is identified when a grey terminal node box is reached. Source: Lester et al. (2009a). 23

Figure 2-8. Updated Ecosystem State Model for the northern Coorong. Source: Lester et al. (2009a). 24

Figure 2-9. Updated Ecosystem State Model for the southern Coorong. Source: Lester et al. (2009a). 24

Figure 2-10. Distribution of ecosystem states for each site-year. Each bar shows the distribution of states within each site across the 114-year model run. Sites are numbered from north to south (e.g. Goolwa Channel = Site 1 and Salt Creek = Site 12). The changes in the bar colours represent transitions between states. For each bar, colours represent the following states: dark blue = Estuarine/Marine, light blue = Marine, light green = Unhealthy marine, dark green = Degraded Marine, yellow = Healthy Hypersaline, orange = Average Hypersaline, red = Unhealthy Hypersaline and purple = Degraded Hypersaline. Source: Lester et al. (2009a). 25

Figure 2-11. Final bathymetry for the Coorong, Lower Lakes and Murray Mouth (source: Sharma et al. 2009c). 28

Figure 2-12. A localised comparison of the DEM 2008 (DEM CLLMM)) (left, see section 2.6 for model summary) and the updated Coorong DEM (DEM HCHB) (right). Source: Hobbs et al. (2019). 31

Figure 2-13. Example output of the digital elevation model coupled with the Mudflat Availability Model (source: Sharma et al. 2009b). 34

Figure 2-14. Example output of the fish habitat model showing the probability of occurrence of Yellow-eyed Mullet over the Coorong at three time intervals (source: Sharma et al. 2009b). 36

Figure 2-15. Daily output of the fish habitat for Yelloweye Mullet, Congolli and Smallmouth Hardyhead from 1963–2013, noting that grey is suitable habitat and white is unsuitable habitat. Source: Jöhnk et al. (2014). 38

Figure 2-16. Annual probability output of fish habitat for Yelloweye Mullet, Congolli and Smallmouth Hardyhead. Source: Jöhnk et al. (2014). 39

Figure 2-17. Model output showing the probability of *Ruppia tuberosa* sediment propagule bank replenishment from 1963 to 2013 in the North Lagoon (lower graph) and South Lagoon (upper graph) of the Coorong between Murray Mouth channel (0 km) and Salt Creek (102 km from the Murray Mouth). The contour line on the plot represents the 25% probability of sediment propagule bank replenishment. Source: Jöhnk et al. (2014). 42
Figure 2-18. Generalised conceptual model template of waterbird habitat-use in the Coorong, Lower Lakes and Murray Mouth. Some components of this template, e.g. 'Hydrology', are broad classifications that encompass a number of more specific ecological components in species-specific models. Source: O'Connor et al. (2013a). 44
Figure 2-19. Bayesian Belief Network for Sharp-tailed Sandpiper under 'ideal' conditions. Source: O'Connor et al. (2013a). 45
Figure 2-20. Example of a spatial output of suitable Fairy Tern foraging habitat in the South Lagoon computed by the BBN model overlaid with observations of Fairy Terns during the annual waterbird census of the Coorong. Source: Kilsby (2015). 47

List of tables

Table 1.1. Hydrodynamic, biogeochemical and ecological models that have been developed for the Coorong. Coupled model are those that dynamically interact between one another, while linked model are informed by the outputs of a parent model. 1
Table 2.1. Variables and the data sources used to establish initial conditions prior to simulations of the TUFLOW-FV model. 7
Table 2.2. Variables and their data sourced used in scenario simulations of the TUFLOW-FV model. 7
Table 2.3. 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 optimal and enabled in selected simulations. Source: Hipsey et al. (2020). 11
Table 2.4. The variables used to drive the Coorong Hydrodynamic Model and their respective time resolutions, data sources and alternative data sources if available (Source: Jöhnk and Webster 2014). 14
Table 2.5. Descriptions of the daily and annual fish habitat suitability models. 37
Table 2.6. The salinity tolerance for seven species of juvenile estuarine fish in the Coorong in cold (mid-April to mid-October) and warm months (mid-October to mid-April). 38
Table 2.7. The processes, timing, condition statements and probability arguments of the *Ruppia tuberosa* Response Model. Source: Jöhnk et al. (2014). 40
Table 2.8. The probability equations specified for the successful completion of each life stage(s) or replenishment of the propagule bank within the *Ruppia tuberosa* Response Model. Source: Jöhnk et al. (2014). 41
Table 2.9. Coorong waterbird species for which Bayesian belief network models were developed by O'Connor et al. (2013a). 44
Table 2.10. Key ecological thresholds for the Sharp-tailed Sandpiper. Source: O'Connor et al. (2013a) 45
Table 2.11. The baseline ecological factors and drivers for the Bayesian Belief Networks of each key waterbird species in the Coorong. Source: O'Connor et al. (2013a). 46

Summary

Over the past 15 years, numerous models have been developed for the Coorong to simulate past and future conditions, scenario test management options and to counterfactually evaluate the impact of water for the environment provisions. Models built for the Coorong have been designed to simulate hydrodynamics, biogeochemistry, ecosystem states and habitat availability for aquatic macrophytes (*Ruppia tuberosa*), fish and waterbirds. Given the number and breadth of existing models, one of the tasks of the *Healthy Coorong Healthy Basin (HCHB) Trials and Investigations Project* is to summarise previously developed models in order to maximise investment, avoid duplication and aid adaptive management.

A total of 12 models developed for the Coorong were summarised. For each model summary, the following was detailed:

- general description
- spatial limits and resolution
- inputs
- outputs
- former/current use
- limitations and assumptions.

Models summarised were then grouped to themes, which included:

- hydrodynamics
- biogeochemistry
- bathymetry
- fish
- *Ruppia*
- waterbirds.

For each model theme, rationale was provided for the preferred model to be used to conduct (preliminary) simulations for the *Trials and Investigations Project*. It was then detailed whether the preferred model available to date is to be improved (and how) or whether a new model is to be developed under the *Phase One Trials and Investigations Project*.

The most sophisticated ecosystem model for the Coorong is the Coorong Dynamics Model, which simulates the hydrodynamic conditions, water clarity (light and turbidity), nutrients (organic and inorganic), chlorophyll-a, filamentous algae and *Ruppia* habitat quality in the Coorong at high-resolution. The HCHB program will principally use the Coorong Dynamics Model to conduct short and long simulations to forecast the response of the Coorong ecosystem to various management scenarios. Under the *Phase One Trials and Investigations Project,* the hydrodynamic, biogeochemical and habitat models that form the Coorong Dynamics Model will be updated to increase certainty in forecasted responses to management scenarios. Moreover, quantitative food web and waterbird habitat models are to be developed under the *Phase One Trials and Investigations Project,* which will be integrated with the Coorong Dynamics Model. It is envisaged that following these improvements and developments, the Coorong Dynamics Model will become a trusted tool to support management decision making.

1 Introduction

Hydrological, biogeochemical and ecological models are used by environmental managers of aquatic ecosystems to guide management decisions. Over the past 15 years, numerous models (see summary in Table 1.1) have been developed for the Coorong, South Australia (Figure 1-1) to simulate past and future conditions (e.g. Collier et al. 2017), scenario test management options (e.g. DEWNR 2017) and to counterfactually evaluate the impact of water for the environment provisions (e.g. Ye et al. 2016b). Models built for the Coorong have been designed to simulate hydrodynamics (Jöhnk and Webster 2014; BMT 2019), biogeochemistry (Grigg et al. 2009; Collier et al. 2017; Hipsey et al. 2020), ecosystem states (Lester et al. 2009a) and habitat availability for aquatic macrophytes (*Ruppia tuberosa*) (Collier et al. 2017, Jöhnk et al. 2014), fish (Sharma et al. 2009b; Jöhnk et al. 2014) and waterbirds (Sharma et al. 2009b; O'Connor et al. 2013a; Kilsby 2015) (Table 1.1). Given the number and breadth of existing models, one of the tasks of the *Healthy Coorong Healthy Basin (HCHB) Trials and Investigations Project* is to summarise previously developed models in order to maximise investment, avoid duplication and aid adaptive management. This report provides an overview of existing models that have been developed for the Coorong, and details any further use within the HCHB Program.

Table 1.1. Hydrodynamic, biogeochemical and ecological models that have been developed for the Coorong. Coupled model are those that dynamically interact between one another, while linked model are informed by the outputs of a parent model.

Model	Description	Coupled/linked models
TUFLOW-FV	A two or three-dimensional model that simulates the movement of water and predicts water level and depth, salinity, velocity, temperature, fluxes and Murray Mouth morphology in response to inflows, tides, wind, waves, evaporation and rainfall (BMT 2019).	Coupled with the Coorong Dynamics Model
Coorong Dynamics Model (AED2)	A model that simulates hydrodynamic conditions, water clarity (light and turbidity), nutrients (organic and inorganic), chlorophyll-a, filamentous algae and *Ruppia* habitat quality in the Coorong at high-resolution (Hipsey et al. 2020)	Coupled with the TUFLOW-FV model
Coorong Hydrodynamic Model	A one-dimensional model used to simulate water level and salinity conditions in the Goolwa Channel and Coorong to understand and describe the physical dynamics of the system (Jöhnk and Webster 2014).	Parent model to the Nutrient Budget and Biogeochemical Model, Ecosystem State Model, Mudflat Availability Model (Coorong, Lower Lakes and Murray Mouth (CLLMM) Recovery Project, referred to herein as CLLMM), Fish Habitat Model (CLLMM), Fish Habitat Model and *Ruppia tuberosa* Response Model.
Nutrient Budget and Biogeochemical Model	The model utilises the outputs of the Coorong Hydrodynamic Model in unison with estimated inflow nutrient concentrations to simulate the transport of nutrients and chlorophyll in the Coorong, and calculate changes in their concentration and biomass as	Linked to the Coorong Hydrodynamic Model

Model	Description	Coupled/linked models
	a result of physical and biogeochemical processes (Grigg et al. 2009).	
Ecosystem State Model	A model that identifies distinct ecosystem states of the Coorong for a given point in space and time based upon tidal influence, days since barrage flow, water level and salinity (Lester et al. 2009a).	Linked to the Coorong Hydrodynamic Model
Digital Elevation Model (CLLMM)	Digital elevation models (DEMs) were developed for the Murray Mouth and South Lagoon based on satellite data, in-situ data and existing bathymetric data. Interpolated bathymetry were already available for the Lower Lakes and North Lagoon. The DEM of the Lower Lakes, Murray estuary and Coorong were integrated in to the DEM of South Australia to produce a seamless DEM for the CLLMM region (Sharma et al. 2009c).	Used to inform the bathymetry of the Coorong Hydrodynamic Model and TUFLOW-FV model.
Digital Elevation Model (HCHB)	The DEM (HCHB) for the Murray estuary and Coorong was developed in 2019 and is an update to the DEM (CLLMM) that was developed in 2008. Updated analyses and the collection of new data (in 2018 and 2019) have provided significant improvement in the spatial mapping and precision of shallow-mid depth water areas and surrounding low-lying vegetation of the Coorong lagoons (Hobbs et al. 2019).	Proposed to inform the bathymetry of TUFLOW-FV model following model improvements.
Mudflat Availability Model	A model that predicts the availability of mudflat with water depths up to 12 cm, where the majority of waterbird foraging occurs, across 12 reference sites over the Coorong (Sharma et al. 2009b).	Linked to the Coorong Hydrodynamic Model
Fish Habitat Model (CLLMM)	The model predicts the occurrence probability of key estuarine fish species over the Coorong based upon catch data (2006–2008) and the salinity and water level conditions over the system (Sharma et al. 2009b).	Linked to the Coorong Hydrodynamic Model
Fish Habitat Model (CSIRO)	The model determines the extent of habitats for juveniles of important commercial and prey fish species over the Coorong. The model predicts fish habitat extent by comparing salinities over the Coorong against the LC_{10} of fish in aquaria held at 14°C and 23°C (Jöhnk et al. 2014).	Linked to the Coorong Hydrodynamic Model
Ruppia tuberosa Response Model	The model estimates the probability of *Ruppia tuberosa* replenishing the sediment	Linked to the Coorong Hydrodynamic Model

Model	Description	Coupled/linked models
	propagule bank based on modeled hydrological conditions (Jöhnk et al. 2014).	
Waterbird response models	Waterbird response models were developed for six waterbird species using Bayesian Belief Networks (BBNs), which are graphical probabilistic models that are used to model cause and effect relationships (i.e. conditional dependencies) between variables using both quantitative and qualitative (i.e. expert knowledge) data (O'Connor et al. 2013a).	Standalone series of models that could be linked with the TUFLOW-FV model, Coorong Dynamics Model and Coorong Hydrodynamic Model.

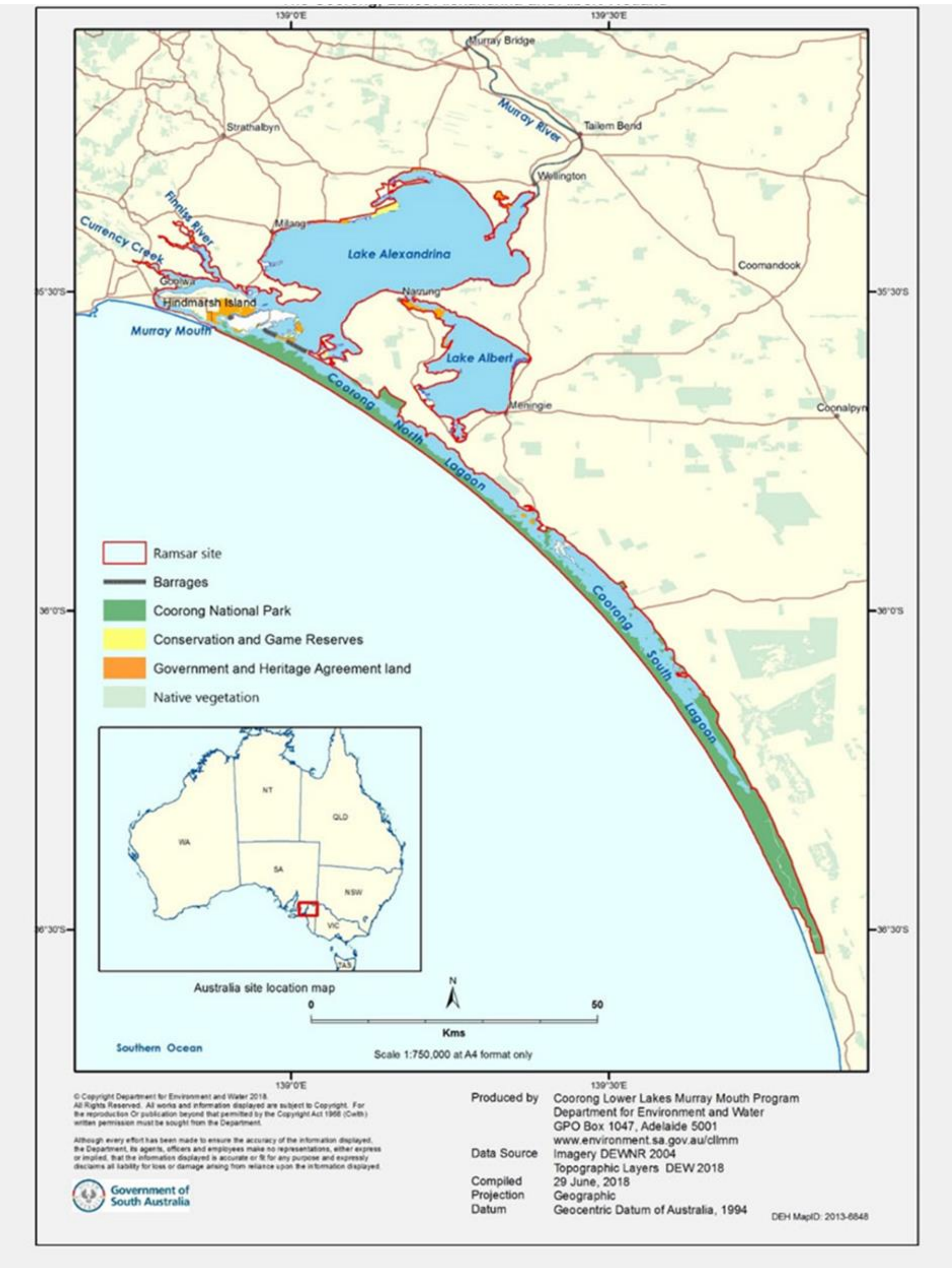

Figure 1-1. Location and extent of the Coorong, South Australia.

Models developed to help simulate the environments of the Coorong are often coupled or are extensions from a parent model. For example, the most sophisticated model developed for the Coorong is the Coorong Dynamics Model, which dynamically links the TUFLOW-FV model with the AED2 Biogeochemistry and Habitat Model (Figure 1-2). The TUFLOW-FV model can also be dynamically linked to sediment transport and the Simulating WAves Nearshore (SWAN) model to represent the interactions between flow, wave energy and sand movement at the Murray Mouth on the system.

Numerous models, typically ecological response or habitat models, built between 2009 and 2014 were extensions to the Coorong Hydrodynamic Model, meaning that the outputs of the Coorong Hydrodynamic Model were required to inform their inputs. A schematic of the Coorong Hydrodynamics Model and the model extensions is shown in Figure 1-3.

A summary of each model developed to simulate the Coorong ecosystem is provided below in section 2.

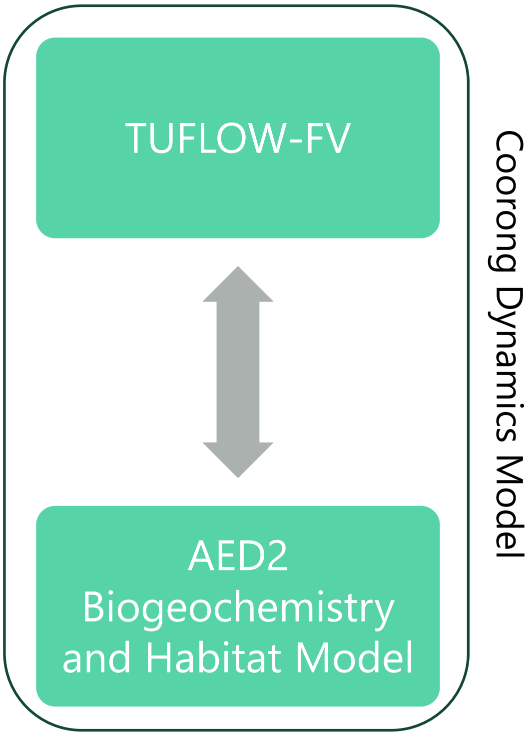

Figure 1-2. Schematic of the TUFLOW-FV, and AED2 Biogeochemical-Habitat Model that dynamically couple to form the Coorong Dynamics Model. The arrows to and from each model demonstrate that models dynamically inform each other, rather than one model utilising the outputs of the parent model.

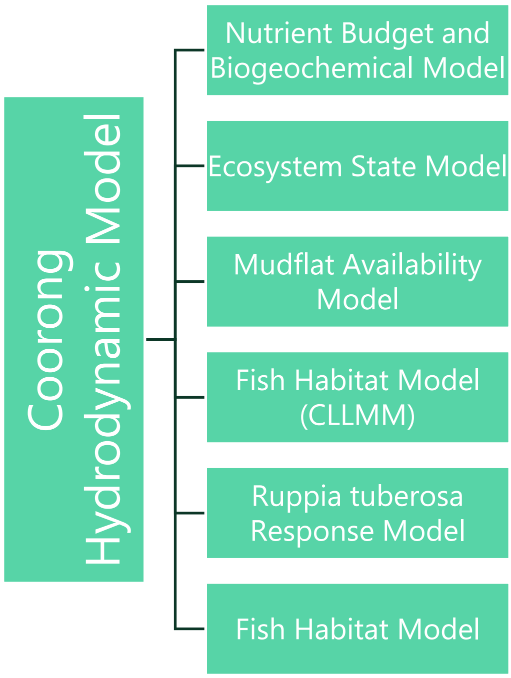

Figure 1-3. Schematic of the models that run simulations based upon the outputs of the Coorong Hydrodynamic Model.

2 Model Summaries

2.1 TUFLOW-FV

2.1.1 Decription

The TUFLOW-FV model is a two or three-dimensional model that simulates the movement of water and predicts water level and depth, salinity, velocity, temperature, fluxes and Murray Mouth morphology in response to inflows, tides, wind, waves, evaporation and rainfall (BMT 2019). The model is very flexible and to date represents the most detailed hydrodynamic model of the Coorong. A full summary of the TUFLOW-FV Model is available in BMT (2019).

2.1.2 Spatial limits and resolution

The TUFLOW-FV model of the Coorong represent the full Coorong water body, from the barrages to the southern end of the south lagoon, and also includes an 'Ocean Boundary' that extends 4 km offshore from the Murray Mouth and spreads from over 6 km north of the Murray Mouth to almost 9 km south (Figure 2-1) (BMT 2019).

Bathymetry of the TUFLOW-FV model is represented using flexible mesh cells (see Figure 2-1) (BMT 2019), with the elevations of each cell corner informed by the DEM (CLLMM) (see 2.6). This approach allows the resolution of bathymetric cells to vary depending upon elevation changes (BMT 2019). For example, coastlines, river mouths and constriction points have finer resolution (~20-40 m) than the gently sloping lagoons (~200 m). The flexible mesh allows for seamless boundary fitting along complex coastlines or open channels as well as accurately and efficiently representing complex bathymetries with a minimum number of computational elements (BMT 2020).

It should be noted that there are a number mesh domains that exist for the TUFLOW-FV model, representing:

- All of the Coorong, Lower Lakes and the River Murray up to Lock 1 (e.g. Ye et al. 2016a).
- The Coorong only, with higher resolution near the Murray Mouth to focus on sediment transport to inform dredging operations (BMT 2019).
- The Coorong only, with higher resolution on mudflats to couple with AED2+ and focus on biogeochemistry and *Ruppia* habitat suitability (Collier et al. 2017).

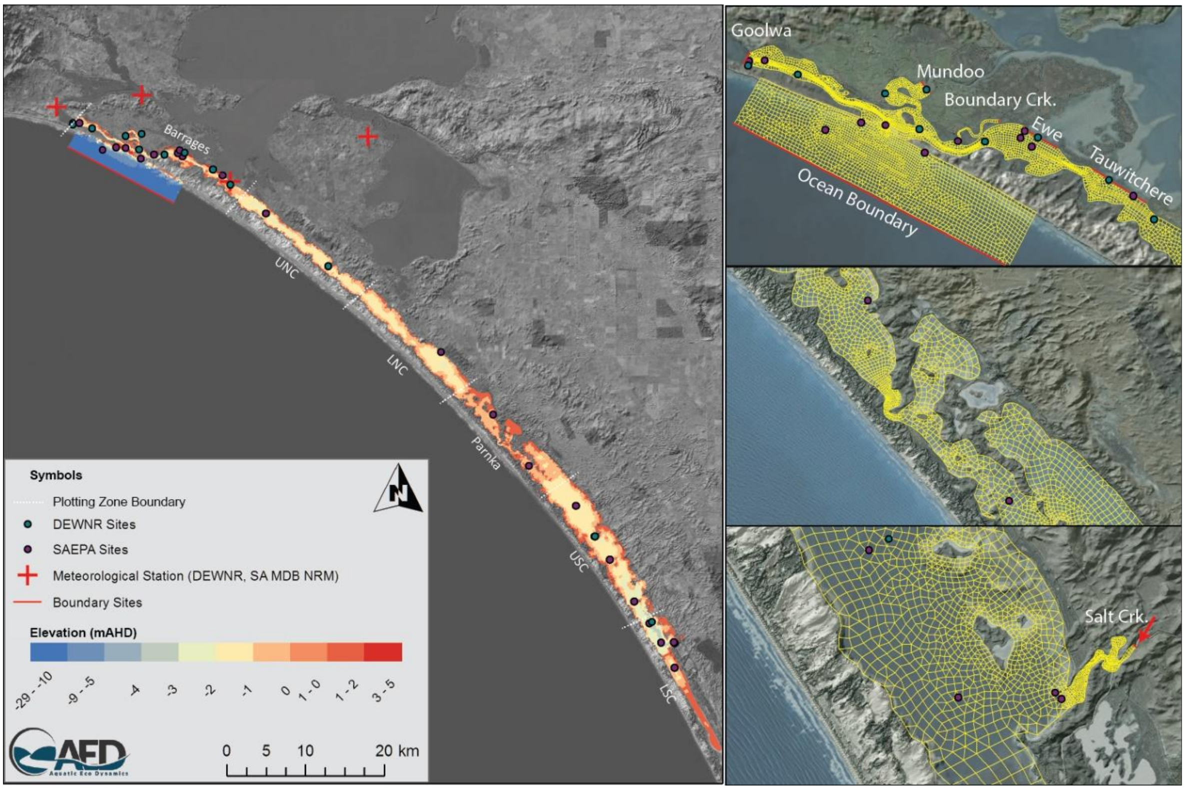

Figure 2-1. Examples of mesh resolutions used in the TUFLOW-FV model. Source: Hipsey et al. (2020).

2.1.3 Inputs

The initial conditions to be set to represent the system at the start of a simulation include water level, salinity and velocity, as well as temperature if the heat module routines are enabled (Table 2.1). Time series data (typically observed, but in some cases from other models) for tides, wind, sea level pressure, rainfall, evaporation, barrage flows and South East flows are boundary conditions that force the modelled outputs over the period of a simulation. (Table 2.2) (BMT 2019).

Table 2.1. Variables and the data sources used to establish initial conditions prior to simulations of the TUFLOW-FV model.

Variable	Source	Resolution
Water temperature Salinity Water level Velocity	Observations taken at all water monitoring gauges in the Coorong. Data available from the Department for Environment and Water (DEW). Salinity and water level data is publicly available on https://water.data.sa.gov.au/	Input data at the resolution of existing monitoring stations, interpolated to generate a value for each mesh element (e.g. Figure 2.1). Initial velocity is typically set to zero.

Table 2.2. Variables and their data sourced used in scenario simulations of the TUFLOW-FV model.

Variable	Source	Resolution
Tide	Sourced from the Victor Harbor tide gauge. Tide height data at Barker Knoll (A4261039) is available for infilling data gaps (https://water.data.sa.gov.au/Data/Location/Summary/Location/A4261039/Interval/Latest). For forecasting, tidal predictions at	15 min

Variable	Source	Resolution
	the Victor Harbor gauge are used (https://hydrotel.flindersports.com.au).	
Wind	Outputs from the National Oceanic Atmospheric Administration (NOAA) CFSv2 Forecast (Saha et al. 2014) and Reanalysis (Saha et al. 2010) models or observed wind data collected by DEW at Pelican Point (A426063) (https://water.data.sa.gov.au/Data/Location/Summary/Location/A4260603/Interval/Latest).	Hourly
Sea level pressure	Outputs from the global NOAA CFSv2 Forecast (Saha et al. 2014) and Reanalysis (Saha et al. 2010) models or sourced from the Scientific Information for Land Owners (SILO) dataset (Jeffrey et al. 2001) (https://www.longpaddock.qld.gov.au/silo/point-data/).	Hourly
Meteorology (i.e. rainfall and evaporation)	Net evaporation rate data were sourced from the SILO dataset (Jeffrey et al. 2001) (https://www.longpaddock.qld.gov.au/silo/point-data/). The rainfall and evaporation data were added together to derive a daily net source/sink term that is applied uniformly across the entire model. The heat exchange module can be used to calculate evaporation, and is required to model water temperature. Meteorological inputs for the heat module depend on the method, and can include shortwave and net longwave radiation, air temperature, wind speed and relative humidity.	Daily
Barrage flows and salinity	DEW, barrage calculator (https://water.data.sa.gov.au/Data/Location/Summary/Location/A4260603/Interval/Latest) and SA River Murray Source Model (for forecasting). Barrage salinity is typically a default value of 0.4 PSU.	Daily
South East flows and salinity	DEW, station data (A2390568) (https://water.data.sa.gov.au/Data/Location/Summary/Location/A2390568/Interval/Latest).	Daily
Waves	SWAN wave model (http://swanmodel.sourceforge.net/) output or observed values from the BOM at Cape Du Couedic (Station No. IDS65031) (http://www.bom.gov.au/products/IDS65031.shtml) or other ocean model outputs (which include wave direction)	Two hourly

2.1.4 Outputs

The outputs of the TUFLOW-FV model detailed in BMT (2019) are:

- morphology evolution of the Murray Mouth
- sediment transport
- flux (flow of salt)
- water level and depth
- salinity
- flow velocity

- water movement simulations.

Model configuration, and hence outputs available can switch between 2D and 3D representations.

2.1.5 Former/current use

The TUFLOW-FV model was used for a number of projects over the past decade and most recently to:

- inform Murray Mouth dredging operations (BMT 2019)
- serve as a hydrodynamic model platform for the Coorong Dynamics Model (Collier et al. 2017; Hipsey et al. 2020)
- conduct scenario simulations to assess the efficacy of potential infrastructure options In the Coorong (e.g. DEWNR 2017) and Lower Lakes (e.g. DEWNR 2014).

2.1.6 Limitations and assumptions

Key limitations and assumptions:

- The main limitation of the model is its long simulation times (M Gibbs, Pers. Comm. 21 February 2019), where for the current high resolution of the model mesh (See Figure 2-1) simulation periods of more than a few years have not been attempted.

2.1.7 Improvements

Key possibilities for improvement of the model include:

- Developing another coarser mesh for input of bathymetric data in to the model (currently being developed as part of the HCHB Water Resource Optimisation (WRO) Project). This update will help to reduce the long simulation times currently experienced when running long term (10–100s of years) simulations and for sensitivity analyses.
- Alignment of the different model meshes and input files into a consistent framework that is based on the same input files, and different resolutions and processes can be enabled depending on the focus of the question. TUFLOW FV Release 2019.01 has enabled this workflow through GIS integration tools.
- Data sources that could be improved to improve model accuracy include:
    - Bathymetry: acquire new survey data in critical areas to improve the distribution and representativeness of elevation data.
    - Meteorological data (i.e. rainfall and evaporation) collection closer to the South Lagoon. Recently meteorological stations have been installed at Parnka Point and Long Point to support this as part of the HCHB WRO project
    - Flow data for model calibration (particularly between the North and South Lagoons). This data was collected over July to December 2019, and model calibration and validation is currently underway as part of HCHB Trials and Investigations Activity 7.4.

2.2 Coorong Dynamics Model (AED2)

2.2.1 Description

The Coorong Dynamics Model couples the TUFLOW-FV model (see section 2.1) to the Aquatic EcoDynamics (AED2) biogeochemistry and habitat model (Hipsey et al. 2020). The model is used to simulate the hydrodynamic conditions, water clarity (light and turbidity), nutrients (organic and inorganic), chlorophyll-a, filamentous algae and *Ruppia* habitat quality in the Coorong at high-resolution (Hipsey et al. 2020). A full summary of the Coorong Dynamics Model is available in Collier et al. (2017) and Hipsey et al. (2020).

2.2.2 Spatial limits and resolution

The spatial limits and resolution of the Coorong Dynamics Model are the same as that of its base hydrodynamic model; the TUFLOW-FV model (see section 2.1), which uses flexible mesh cells to represent the bathymetry of the Murray estuary and Coorong.

2.2.3 Inputs

The inputs to the Coorong Dynamics Model include those of the TUFLOW-FV model detailed in section 2.1 and the AED2 biogeochemistry and habitat model. Additional initial and boundary conditions are required for each of the additional constituents included in the AED2 model, for example the physical and biogeochemical variables outlined in Table 2.3.

The AED2 biogeochemistry and habitat model introduces a large number of additional parameters that must be specified to represent different reaction rates and interactions. These are detailed in Collier et al. (2017) and broadly includes parameters related to light and turbidity, filamentous algae, biogeochemistry (including sediment biogeochemistry), and *Ruppia* habitat suitability. Currently, values selected for each parameter have been assigned based on previous modelling assessments, literature, expert judgement and ecological data collected in laboratory conditions, mesocosms and in-situ (Collier et al. 2017; Hipsey et al. 2020). Values for each parameter derived from literature add uncertainty to the model due to the unique (reverse estuary) nature of the Coorong and the hypersaline waters in the south of system, which are infrequently assessed in the literature (Hipsey et al. 2020). However, availability of Coorong-specific values for these parameters is recognised as a limitation of the model, and the research underway as part of the HCHB Trials and Investigations Project is aimed to update and improve the process representation and parameterization of key components of the AED2 model.

2.2.4 Outputs

The outputs of the Coorong Dynamics Model are shown in Table 2.3 as per Hipsey et al. (2020). One of the outputs of the Coorong Dynamics Model is the *Ruppia* Habitat Suitability Index (see Collier et al. 2017), which considered the sensitivity of each life stage of *Ruppia* to light, water depth, salinity, temperature and algae. The *Ruppia* Habitat Suitability Index produces maps of habitat quality that range from 0 (very low quality) to 1 (high quality), providing an understanding of where *Ruppia* would likely establish under prescribed hydro-biogeochemical conditions.

Table 2.3. 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 optimal and enabled in selected simulations. Source: Hipsey et al. (2020).

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 (400-700 nm) light intensity	Incident light, I_0, is attenuated as a function of depth
I_{UV}	mE m^{-2} s^{-1}	Shortwave (10-400 nm) 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

Variable Abbreviation	Units *	Common Name	Process Description
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 and respiration
TCHLA	mmol C m^{-3}	Total Chlorophyll-a	Sum of planktonic algal groups, converted to chlorophyll-a
Sediment and 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 and respiration.
$ULVA_{BEN}$	mmol C m^{-3}	Ulva (benthic)	Benthic photosynthesis, nutrient uptake, respiration and sloughing
Ruppia HSI	-	*Ruppia* habitat suitability	Computed from light, depth, salinity, temperature and algae

2.2.5 Former/current use

The Coorong Dynamics Model was used to:

- assess the contribution of water for the environment to the transport of matter (i.e. salt, nutrients and suspended solids) through the system (Ye et al. 2016a)
- quantitatively assess ecosystem outcomes under different management scenarios, such as weir options being considered between the North and South Lagoon (BMT WBM 2017; Hipsey et al. 2017)
- help prioritise data collection activities and other experiments by highlighting the sensitivity of important variables to modelled processes or boundary inputs (i.e. barrage flows and South East flows) (Hipsey et al. 2020).

2.2.6 Limitations and assumptions

Key limitations and assumptions:

- Model settings associated with biogeochemical fluxes and transformation are largely literature and expert opinion based and therefore add uncertainty to the outputs of model simulations (Hipsey et al. 2020).
- In-situ data is rather patchy and intermittent and therefore has limitations in regards to validating model simulations (Hipsey et al. 2020).
- In-situ data is lacking to help ensure that water and nutrient budgets in the Coorong are being accurately resolved (Hipsey et al. 2020).

Parameters currently limiting the accuracy and/or confidence in model simulations are listed in section 2.2.7 as priority measures for model improvement.

More specific parameter limitations that are currently limiting the accuracy and confidence in model simulations are listed in section 2.2.7 as priorities measures for model improvement.

2.2.7 Improvement

The improvements listed for the TUFLOW-FV model outlined in Section 2.1.7 are also relevant for the Coorong Dynamic Model. The sensitivity tests of the Coorong Dynamic Model identified the following list of priorities for future data collection and model improvement (Hipsey et al. 2020), which are under investigation as part of the *Trials and Investigations Project*.

Priority measure for refining model inputs:

- Salt Creek inputs of flow and nutrient concentrations
- barrage inputs of nutrients and salinity
- estimate of South Lagoon groundwater seepage
- Murray Mouth channel morphometry

Priority measures to assist model setup:

- maps depicting spatial variability of sediment type and geochemical properties
- maps depicting benthic coverage and density of seagrasses and in-fauna

Priority measures to assist model validation:

- collection of high-frequency in situ multi-parameter water quality data
- routine nutrient and chlorophyll-a sampling, including periodic algal species identification
- routine 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 filtrate rates
- benthic productivity as a function of depth/light

2.3 Coorong Hydrodynamic Model

2.3.1 Description

The Coorong Hydrodynamic Model is a one-dimensional model used to simulate water level and salinity conditions in the Goolwa Channel and Coorong to understand and describe the physical dynamics of the system (Jöhnk and Webster 2014). The model resolves water levels, salinities, and flux (flow and salt load) variables at a 1 km resolution in the Coorong and Goolwa Channel, including evolution of the Murray Mouth over time. A full summary of the Coorong Hydrodynamic Model is available in Webster (2007) and Jöhnk and Webster (2014).

2.3.2 Spatial limits and resolution

The extent of the original Coorong Hydrodynamic Model (Webster 2007; Webster 2012) extended from the start of the Tauwitchere Channel to 6 km south of Salt Creek in the southern South Lagoon. An extension to the Coorong Hydrodynamic Model to include the Goolwa Channel (from Goolwa barrage to the Murray Mouth) was added by Jöhnk and Webster (2014).

Bathymetry of the Coorong Hydrodynamics Model is represented on a spatial grid that is centered on the line connecting the lowest successive cross-sections of the Goolwa Channel and Coorong (Jöhnk and Webster 2014). The grid is comprised of cells 1 km in length, and totals 108 cells (7 cells in the Goolwa Channel and 101 cells in the Coorong (Jöhnk and Webster 2014). At the start and end of each cell, the width of the channel/lagoon and average cross-sectional depth of the channel/lagoon were informed by the DEM (CLLMM) (see 2.6), and as such each cell is represented as a rectangular box, with no change in area for change in water level.

2.3.3 Inputs

The inputs that drive the Coorong Hydrodynamic Model are time series data for wind, sea level, rainfall, evaporation, barrage flows and South East flows (Table 2.4) (Jöhnk and Webster 2014). The Murray Mouth can be input at a fixed bed elevation level to represent dredging operations, as a time series of mouth depths or can be represented dynamically using an empirical scour model to represent changes to its morphology based on the modelled velocity (i.e. scouring during higher velocity and deposition during low velocity).

Table 2.4. The variables used to drive the Coorong Hydrodynamic Model and their respective time resolutions, data sources and alternative data sources if available (Source: Jöhnk and Webster 2014).

Variable	Resolution	Source	Alternative source
Wind	Hourly	DEW, Pelican Point AWS A4260603 (https://water.data.sa.gov.au/Data/Location/Summary/Location/A4260603/Interval/Latest)	Meningie Post Office, or other meteorological stations around the Coorong
Sea level	Hourly	HydroSurvey Australia Victor Harbour (https://hydrotel.flindersports.com.au/)	
Meteorology (i.e. rainfall and evaporation)	Daily	SILO online database (Jeffrey et al. 2001) (https://www.longpaddock.qld.gov.au/silo/point-data/), Data from site 23849 at Goolwa Hindmarsh Island Marina	

Variable	Resolution	Source	Alternative source
		(Latitude: 35.51, Longitude: 138.80).	
Barrage flows	Daily	DEW, barrage calculator (https://water.data.sa.gov.au/Data/Location/Summary/Location/A4260603/Interval/Latest) and SA River Murray Source Model (for forecasting).	Murray-Darling Basin Authority (MDBA) simulated flow for different barrages using the BIGMOD model (MDBA 2014). Outputs from the BIGMOD model can be used for long-term simulations.
South East flows and salinity	Daily	DEW, station data (A2390568) (https://water.data.sa.gov.au/Data/Location/Summary/Location/A2390568/Interval/Latest)	

2.3.4 Outputs

The outputs of the model as detailed in Jöhnk and Webster (2014) include:

- water level
- salinity
- Murray Mouth depth
- flux (flow and salt load) between cells.

2.3.5 Former/current use

The Coorong Hydrodynamic Model was used by Lester et al. (2011) to set recommended barrage flow regimes to maintain adequate water levels and salinities in the Coorong to support ecosystem function. The model was used to assess Coorong responses to different water recovery volumes to inform the Basin Plan (MDBA 2012) and the Sustainable Diversion Limit Adjustment Mechanism determination (MDBA 2017).

The model is regularly used by DEW to evaluate different barrage flow delivery strategies to inform River Murray operations

The outputs of the Coorong Hydrodynamic Model are used to inform the following models:

- Nutrient Tipping Bucket Model (see section 2.4)
- Ecosystem States Model (see section 2.4.6)
- Mudflat Availability Model (see section 2.8)
- *Ruppia tuberosa* Response Model (see section 2.11)
- Fish Habitat Models (see section 2.9 and 2.10).

2.3.6 Limitations and assumptions

Key limitations and assumptions:

- As bespoke Fortran code (as opposed to an industry standard hydraulic modelling engine) is the main disadvantage of the Coorong Hydrodynamic Model in the difficulty of modifying and extending the model to represent new scenarios (e.g. infrastructure options) or to add additional functionality (e.g. biogeochemical processes).

- The model performs well compared to observed salinity and water level data given its coarse representation, and has the advantage of fast simulation times. However, the model's performance in relation to observed salinity levels deteriorates when conducting long-term hindcasts that include significant changes in salinities due to extreme drought and high flows. For example, a simulation that used a Murray Mouth dredging depth of 2m and the fixed rate of horizontal salt dispersion of $87m^2/s$ was able to accurately model salinities from 1998 to 2010 (prior to high flows), however, was unable to accurately model salinities from 2010 to 2020 (Figure 2-2). Modifying the Fortran code to change the horizontal salt dispersion from $87m^2/s$ to $40m^2/s$ improves the performance of the model to accurately simulate salinities from 2010 to 2020 (Figure 2-3), but this results in significant overestimation of the salinity during the Millennium drought period (Figure 2-4). These results are expected to be due to numerical diffusion in the model given its coarse resolution (1 km rectangular cells) (M Gibbs, Pers. Comm. 16 December 2020).
- The one-dimension of the model can lead to over-estimates for salinity in areas where haloclines (salinity stratification) exists, such as adjacent to Goolwa Channel barrage (Jöhnk and Webster 2014). This is also the case for the 2D implementation of TUFLOW FV, but this stratification is resolved by the 3D implementation of the TUFLOW model.

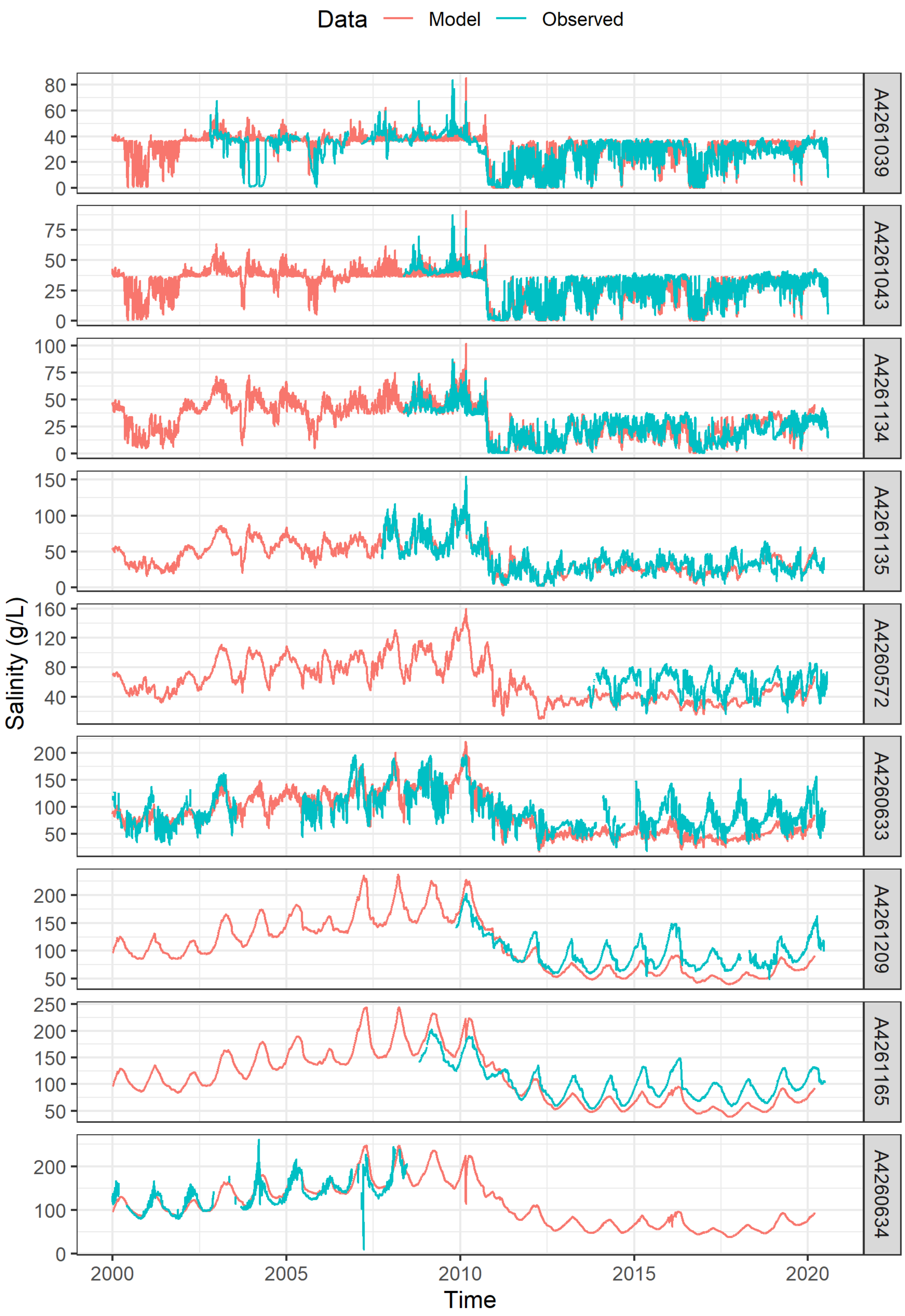

Figure 2-2. Salinity output of the Coorong Hydrodynamic Model with simulations commencing in 1998 and the model using a Murray Mouth depth of 2 m and horizontal salt dispersion rate of 87 m^2/s.

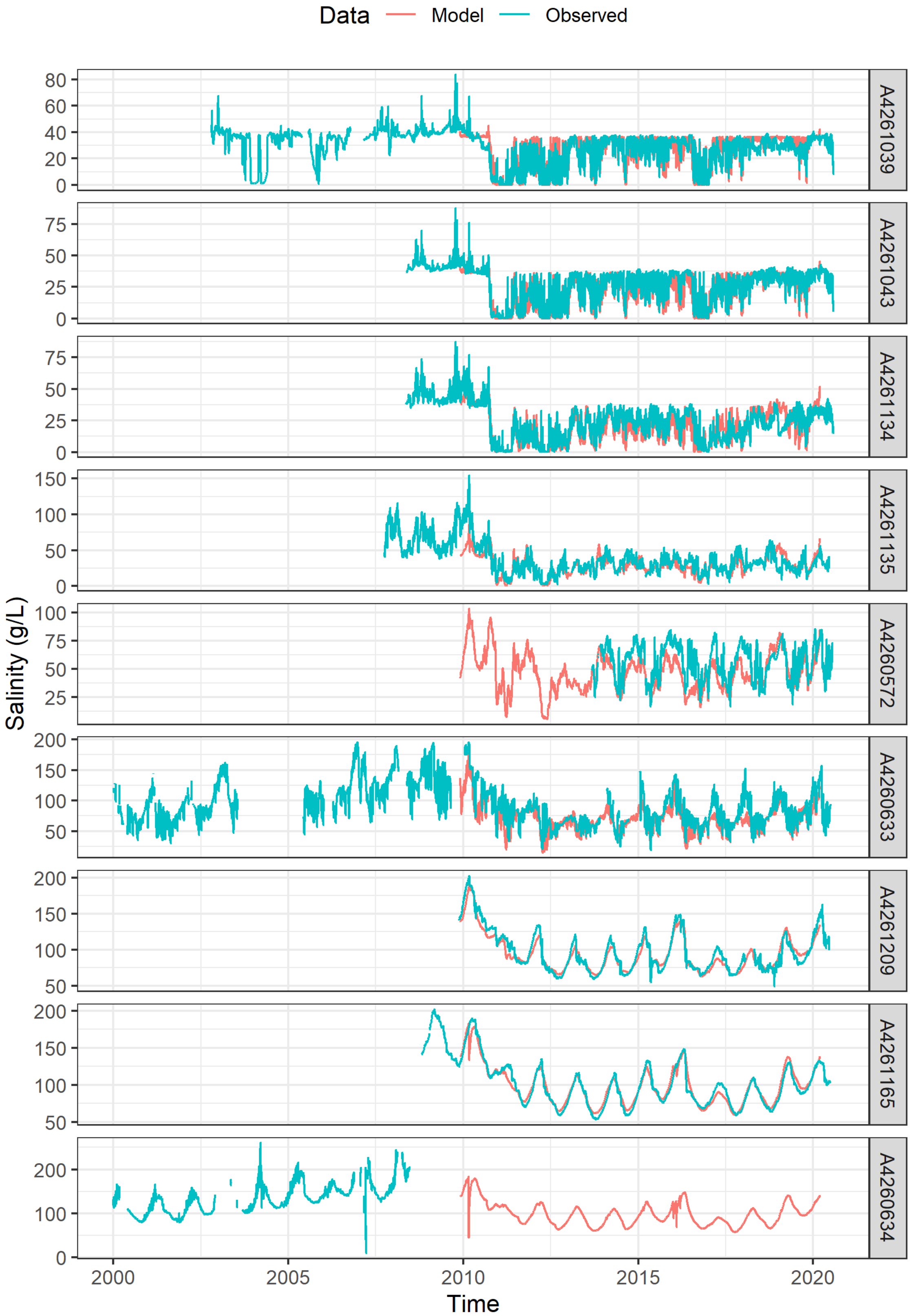

Figure 2-3. Salinity output of the Coorong Hydrodynamic Model within simulations commencing in 2010 and the model using a Murray Mouth depth of 2 m and horizontal salt dispersion rate of 40 m^2/s.

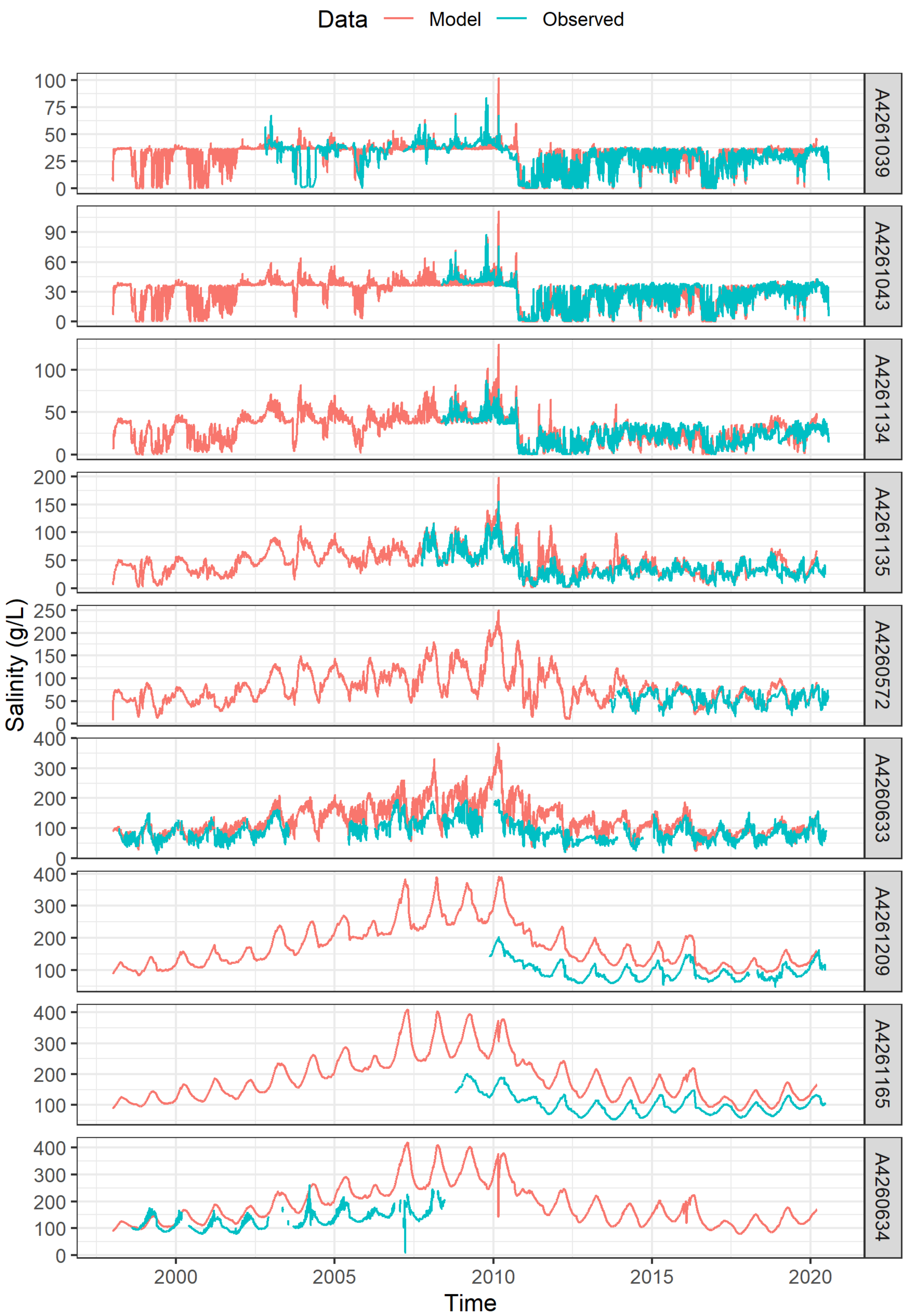

Figure 2-4. Salinity output of the Coorong Hydrodynamic Model within simulations commencing in 1998 and the model using a Murray Mouth depth of 2 m and horizontal salt dispersion rate of 40 m^2/s.

2.4 Nutrient Budget and Biogeochemical Model

2.4.1 Description

The Nutrient Budget and Biogeochemical Model was developed by Grigg et al. (2009) under the *Water for a Healthy Country National Research Flagship*. The model is one-dimensional and utilises the outputs of the Coorong Hydrodynamic Model (see section 2.3) in unison with estimated inflow nutrient concentrations to simulate the transport of nutrients and chlorophyll in the Coorong, and calculate changes in their concentration and biomass as a result of physical and biogeochemical processes (Grigg et al. 2009).

2.4.2 Spatial limits and resolution

The spatial limits and resolution of the Nutrient Budget and Biogeochemical Model reflect those in Figure 2-5. The Nutrient Budget and Biogeochemical Model has lower resolution than the Coorong Hydrodynamic Model, using 14 boxes that span the same distance (102 km) (Figure 2-5). The Nutrient Budget and Biogeochemical Model splits each of the 14 boxes in to two types of cells, (i) representing the deeper areas of the channel and lagoon and (ii) representing the shallower edges of the channel and lagoon (Figure 2-6) (Grigg et al. 2009).

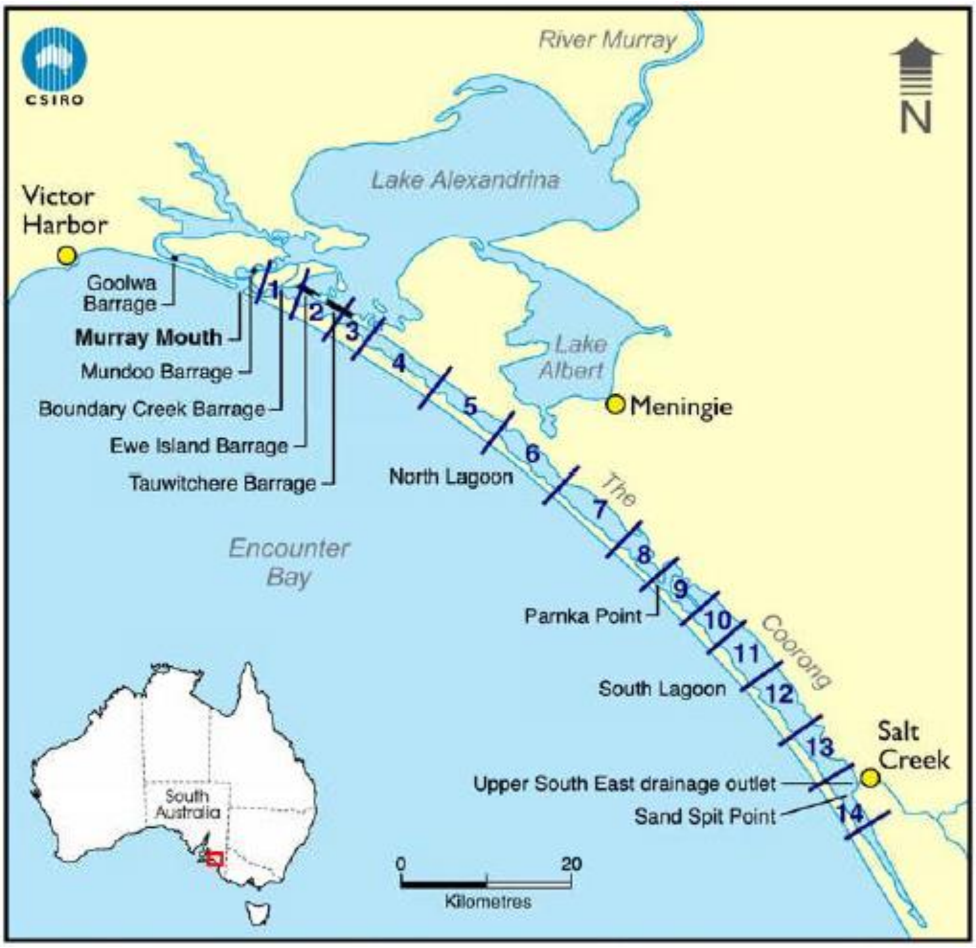

Figure 2-5. Approximate extents of each of the 14 boxes used in the Nutrient Budget and Biogeochemical Model. Source: Grigg et al. (2009).

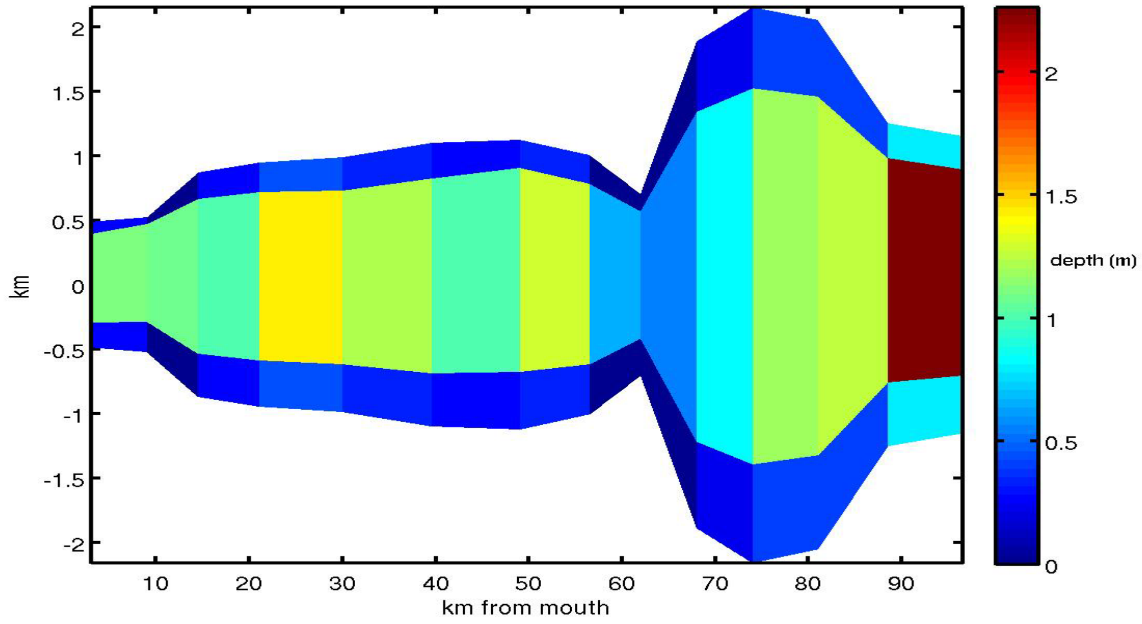

Figure 2-6. The extent and resolution of the Nutrient Budget and Biogeochemical Model, showing the partition of grid cells (cells positioned around sampling sites) for different water depths (m). Source: Grigg et al. (2009).

2.4.3 Inputs

Biogeochemical measures input in to the model corresponded to the middle of boxes where sampling sites are located, with the exception of boxes 1 and 2, which assume measures to be the same as those at box 3 (Figure 2-5). The following biogeochemical measurements are input in to the model:

- total nitrogen (TN)
- filterable reactive phosphorus (TP)
- filterable reactive phosphorus (FRP)
- ammonia (NH_4)
- nitrate (NO_{3-}) and nitrite (NO_{2-})
- dissolved silica (dSi)
- chlorophyll-a (Chla).

Interpolation was required for sites that were not sampled during a monitoring event (day) in order to create a grid array of biogeochemical concentrations for the model analysis.

The outputs of Coorong Hydrodynamic Model (see 2.3.4) were used to determine a time series (hourly) of volume exchanges between the 14 boxes over the Coorong and changes in water levels within each box.

2.4.4 Outputs

The Nutrient Budget and Biogeochemical Model estimates the source/sink flux of biogeochemical measures (see 2.4.3) from the difference in concentrations between those measured at a given location and time and those modelled from transport exchanges at a later time (Grigg et al. 2009).

2.4.5 Former/current use

The Nutrient Budget and Biogeochemical Model was used to improve our understanding of biogeochemical sources, sinks and transport over a range of simulated flow conditions (Brookes et al. 2009; Grigg et al. 2009).

2.4.6 Limitations and assumptions

Key limitations and assumptions:

- Ocean, river and South East flows biogeochemical concentrations were not sampled during the measurement period (Grigg et al. 2009).
- The contribution of *Ruppia* species in the Coorong to biogeochemical processes were not accounted for due to limited distribution and density at the time (Brookes et al. 2009).
- The frequency of in-situ biogeochemical measurements poorly matched the time scale of biogeochemical dynamics (Grigg et al. 2009).

Other key limitations and assumptions of the Nutrient Budget and Biogeochemical Model reflect those of its linked hydrodynamic model (Coorong Hydrodynamic Model) (see 2.3.6).

2.5 Ecosystem State Model

2.5.1 Description

The Ecosystem State Model developed by Lester et al. (2009a) for the Coorong determines distinct ecosystem states for a given point in space and time. There are three different models; the original model, which covers both the northern and southern Coorong (Figure 2-7) and the updated models, which are separated for the northern Coorong (Figure 2-8) and southern Coorong (Figure 2-9). The parameters used to differentiate between ecosystem states differed for each model, and overall included tides, days since barrage flow, water level and salinity. Values of each parameter are modelled by the Coorong Hydrodynamic Model (see 2.3) to forecast or hindcast transitions between ecosystem states. A full summary of the Ecosystems State Model is detailed in Lester et al. (2009a).

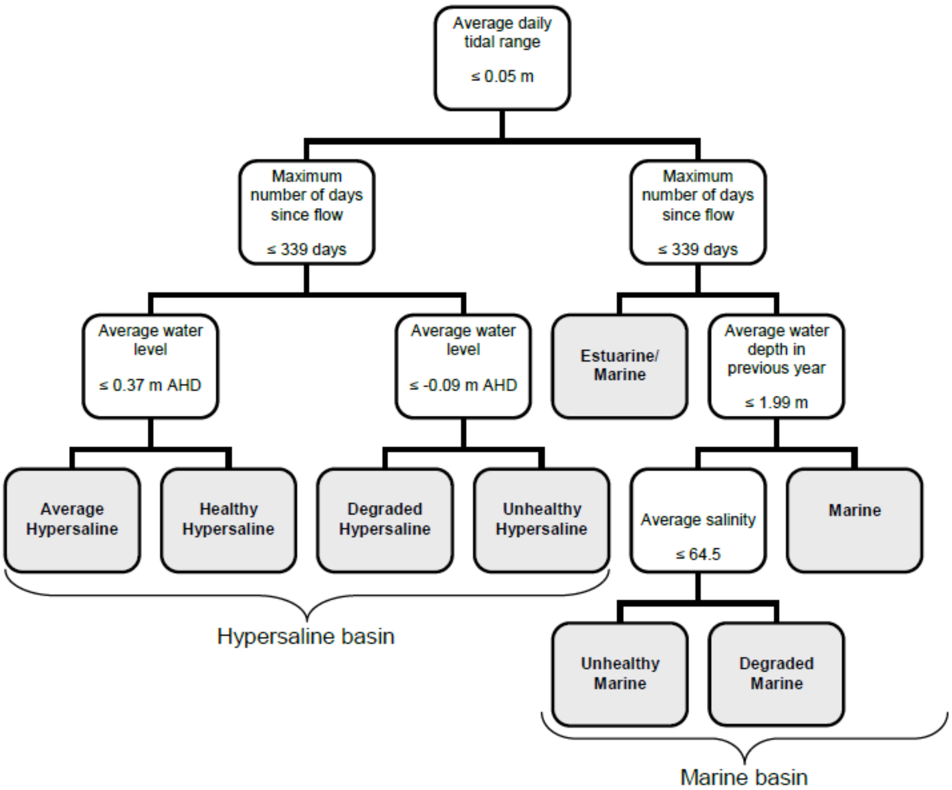

Figure 2-7. Original Ecosystem State Model for the Coorong. The marine basin covers the northern Coorong and the hypersaline basin covers the southern Coorong. Where the value of a parameter is less than or equal to the threshold value specified, then the tree should be followed to the left. Where it is higher, the tree should be followed to the right. An ecosystem state is identified when a grey terminal node box is reached. Source: Lester et al. (2009a).

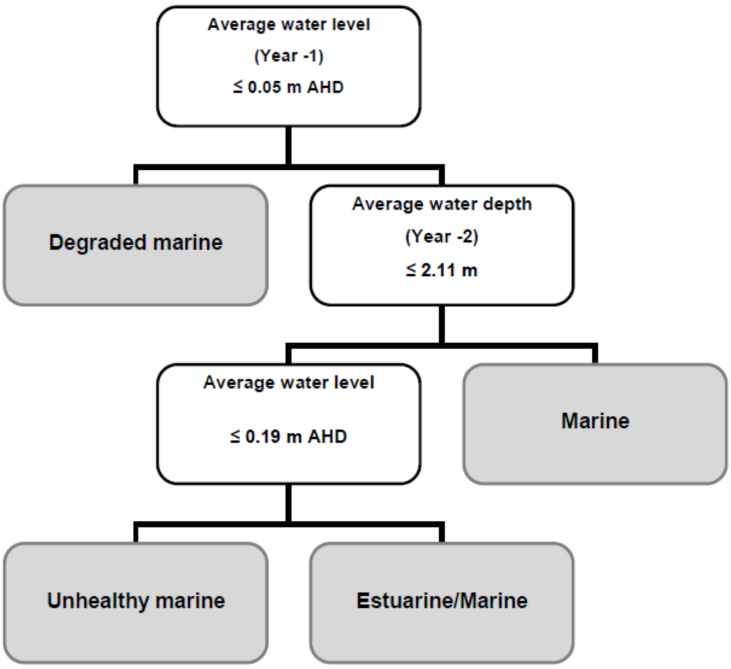

Figure 2-8. Updated Ecosystem State Model for the northern Coorong. Source: Lester et al. (2009a).

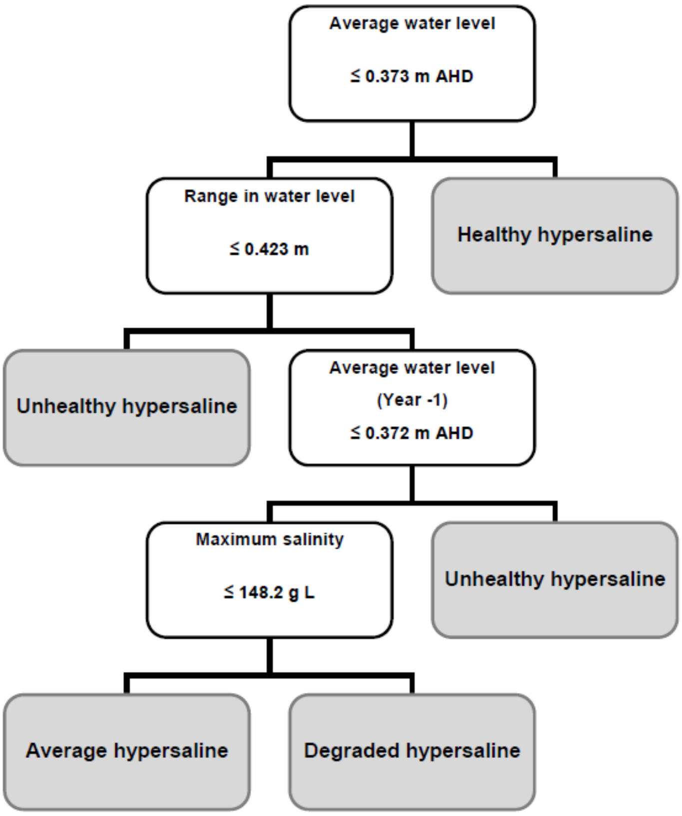

Figure 2-9. Updated Ecosystem State Model for the southern Coorong. Source: Lester et al. (2009a).

2.5.2 Spatial limits and resolution

The spatial limits of the Ecosystem State Model extend from the Murray Mouth estuary to the southernmost part of the South Lagoon (Lester et al. 2009a). The sensitivity of the original model will be limited to a divide in states from the northern and southern Coorong (Lester et al. 2009a). Whereas, the updated models can have resolution that reflects the Coorong Hydrodynamic Model (see 2.3), and therefore, have unique states for each 1 km section of the northern and southern Coorong (Lester et al. 2009a).

2.5.3 Inputs

All the parameters required for input to the Ecosystem State Model (in the original and updated models) can be calculated from either the inputs or outputs of the Coorong Hydrodynamic Model, with output data providing greater spatial resolution (see 2.3) (Lester et al. 2009a). Such data were then used to calculate the average water levels, depths and salinities for input to the Ecosystem State Model.

2.5.4 Outputs

The Ecosystem States Model (original and updated) can be used to forecast and hindcast ecosystem states for a given point in space and time for which data is available (telemetered or modelled) (Lester et al. 2009a). Below is an example output of a hindcast simulation produced when the Ecosystem States Model used the water level and salinity outputs of the Coorong Hydrodynamics Model (Figure 2-10).

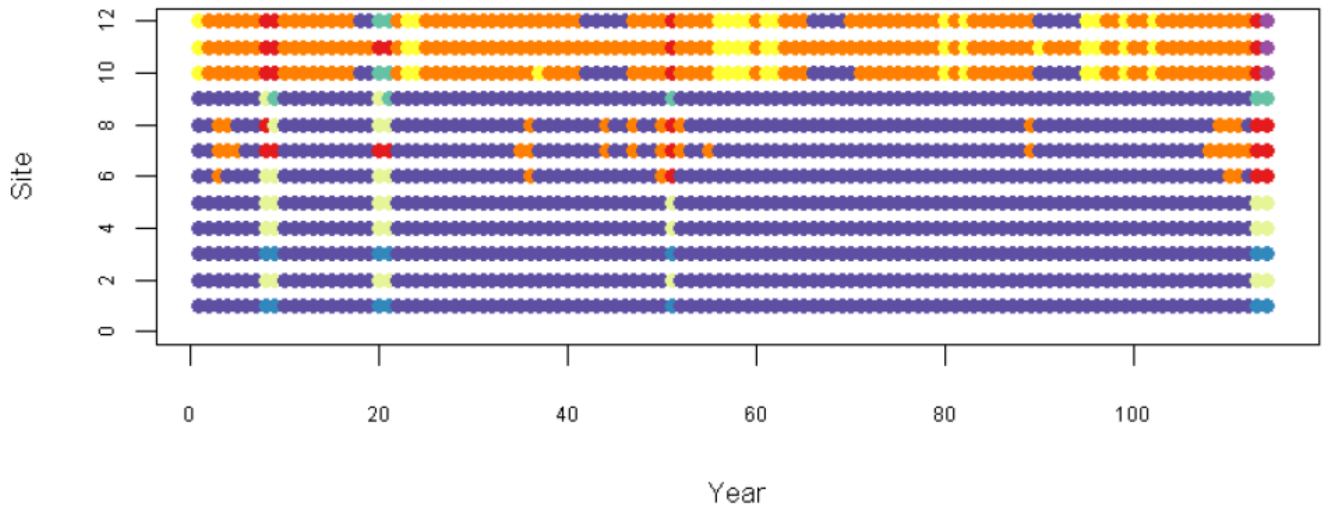

Figure 2-10. Distribution of ecosystem states for each site-year. Each bar shows the distribution of states within each site across the 114-year model run. Sites are numbered from north to south (e.g. Goolwa Channel = Site 1 and Salt Creek = Site 12). The changes in the bar colours represent transitions between states. For each bar, colours represent the following states: dark blue = Estuarine/Marine, light blue = Marine, light green = Unhealthy marine, dark green = Degraded Marine, yellow = Healthy Hypersaline, orange = Average Hypersaline, red = Unhealthy Hypersaline and purple = Degraded Hypersaline. Source: Lester et al. (2009a).

2.5.5 Former/current use

The Ecosystem State Model has been used to:

- simulate ecosystem states for sites located across the Coorong over the 114 years preceding 2009 (Lester et al. 2009a)

- scenario test proposed increased diversions from the Upper South East Drainage network (Lester et al. 2009a), the effect of Murray Mouth dredging (Lester et al. 2009a) and infrastructure in the South Lagoon to limit extremely hypersaline conditions (Lester et al. 2009b).

The Ecosystem State Model does not appear to have had extensive use since creation nor any recent use.

2.5.6 Limitations and assumptions

Key limitations and assumptions:

- The ability of the model to correctly predict the recovery of the Coorong ecosystem following drought is unknown (Lester et al. 2009a).
- Environmental factors, such as water temperature, dissolved oxygen concentration, pH, turbidity and nutrient concentrations were not included in the model, although no water chemistry variables at the time had any ability to predict the biotic composition of the Coorong with the exception of turbidity (Lester et al. 2009a).
- Our understanding of the drivers of ecosystem condition of the Coorong has changed since the development of the Ecosystem States Model. For example, new evidence for limited system-scale flushing, and subsequent effects on nutrient cycling and algal blooms will be incorporated into contemporary modelling activities (i.e. the ‘Coorong Dynamics Model’).

2.6 Digital Elevation Model (CLLMM)

2.6.1 Description

The Digital Elevation Model (DEM) for the CLLMM was developed by Sharma et al. (2009c) as part of the *CLLAMM Dynamic Habitat* report (Sharma et al. 2009a). Interpolated bathymetry for the Lower Lakes and North Lagoon was already available, however, the bathymetry for the Murray Mouth and South Lagoon had to be interpreted using satellite data, in-situ data and existing bathymetric data. The DEM of the Lower Lakes, Murray estuary and Coorong were integrated in to the DEM of South Australia to produce a seamless DEM for the CLLMM region.

2.6.2 Spatial limits and resolution

The extent of the DEM covers the entirety of the Lower Lakes, Murray estuary and Coorong at a resolution of 25 m^2 (Sharma et al. 2009c).

2.6.3 Inputs

The DEM (CLLMM) of the Coorong utilised the following datasets:

- DEM of South Australia – derived from NASA's Shuttle Radar Topography Mission (SRTM) project. The horizontal resolution of the model is ~83 m^2 and the vertical resolution is to the nearest metre with reference to Australian Height Datum (AHD).
- Bathymetry of the Lower Lakes and the Coorong – SA Water collected depth data from the Lower Lakes and northern part of the Coorong. The northern part of the Coorong was surveyed using an echo-sounder and GPS mounted on a small boat. Methods used to survey shallow areas around the Lower Lakes are described in Sharma et al. (2009c). The horizontal resolution of data collection in the northern Coorong ranged from 25 to 50 m^2. The vertical resolution of data collected via the echo-sounder was considered to be ± 10 cm.
- Depth data for the Coorong – SA water collected depth data along 51 transects with 486 points across the North and South Lagoons of the Coorong.
- LANDSAT5 imagery – Collected over the CLLMM region in 2004 using the Thematic Mapper (TM) sensor, which captures the electromagnetic energy reflected from the earth's surface at a resolution of 25 m^2. The wavelengths of energy reflected from the earth vary dependent upon the properties of its surface, i.e. water, vegetation, rock, soil etc. These wavelengths are categorised in to seven wavelength ranges to derive information on the lands' surface cover.
- SPOT5 imagery – Multispectral imagery (captures image data within specific wavelength ranges) collected in 2004 from the high resolution geometry (HRG) optical sensor mounted on the satellite.

Interpolated bathymetry were already available for the North Lagoon, however, not available for the Murray Mouth and South Lagoon.

The dataset used to develop the DEM for the Murray Mouth combined the spectral data points of the SPOT5 imagery with the nearest LANDSAT5 data point. Each data point were joined to the nearest depth data point in the bathymetry dataset, resulting in a dataset where each data point contained 10 reflectance values and a corresponding depth value.

The dataset used to develop the DEM for the South Lagoon only utilised the LANDSAT5 imagery data as the SPOT5 imagery data had significantly different reflectance values from different dates.

To develop a DEM for the Murray Mouth and South Lagoon, Generalised Additive Modelling (GAM) was used to model the relationship between water depth and surface reflectance values.

The bathymetric point data for the Lower Lakes and North Lagoon were converted in to a DEM using the raster conversion tool in ArcGIS.

Data used to develop DEMs for the Coorong were updated following Sharma et al. (2009c), with LiDAR (light detection and ranging) surveys of the Murray estuary, North and South Lagoon in 2008 (Hobbs et al. 2019). The updated DEM for the South Lagoon utilised LiDAR data and historic DEW and SA bathymetry data, while the DEM for the Murray estuary and North Lagoon used LiDAR data and SA Water sonar data (Hobbs et al. 2019). The most up-to-date DEM for the Coorong developed by Hobbs et al. (2019) is detailed in section 2.7.

2.6.4 Outputs

The DEMs created for the Murray Mouth, Lakes and North Lagoon, and the South Lagoon were integrated with the DEM for South Australia using ArcGIS to merge the location attributed and elevation values of the models (Sharma et al. 2009c). Following integration of the DEMs, a seamless DEM of the CLLMM region was derived (Figure 2-11).

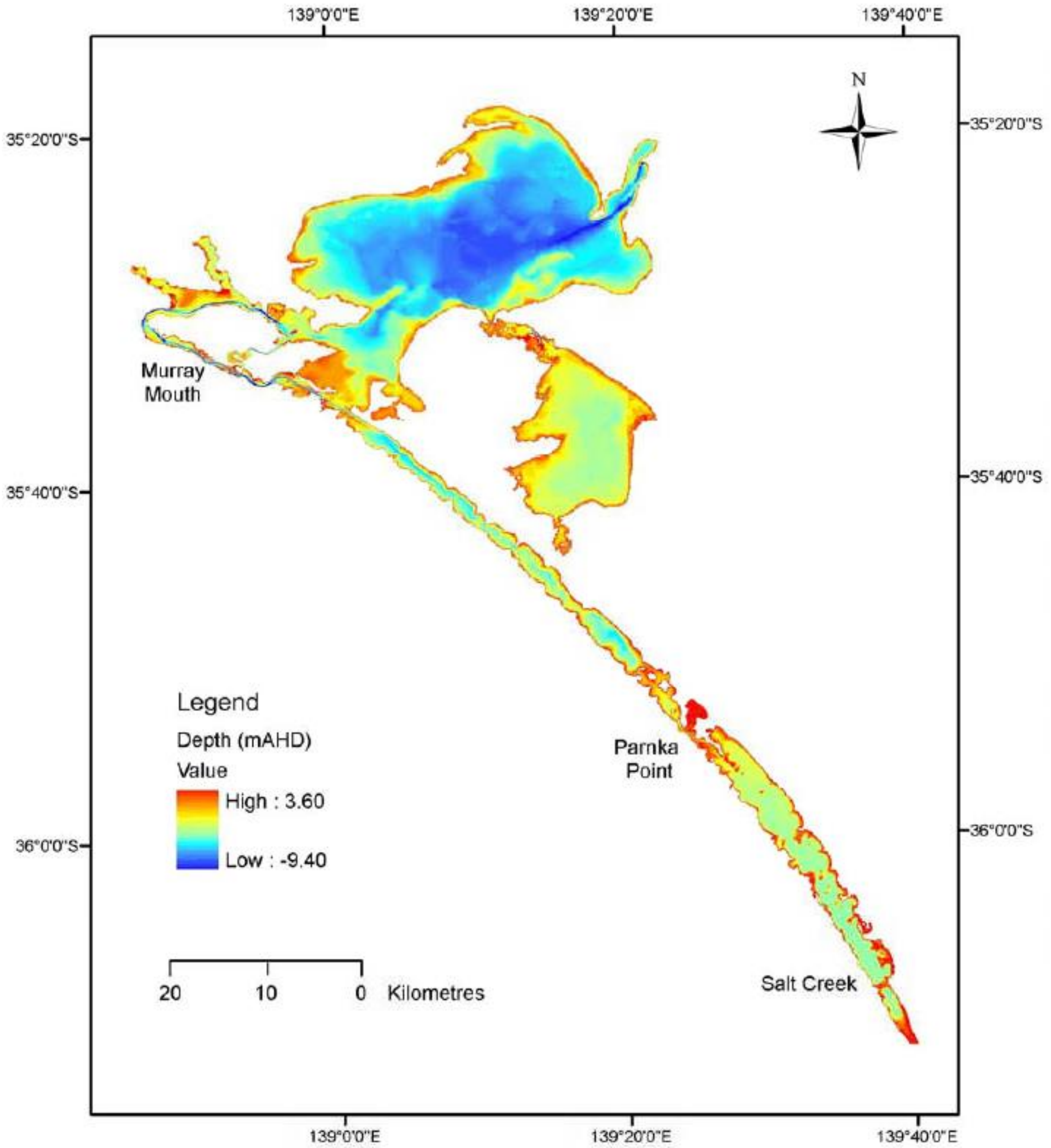

Figure 2-11. Final bathymetry for the Coorong, Lower Lakes and Murray Mouth (source: Sharma et al. 2009c).

2.6.5 Former/current use

Sharma et al. (2009c) considered the DEM (CLLMM) to be a useful modelling tool to assess habitat availability for waterbirds, fish and macro-invertebrates at difference water levels in the Coorong, which could support decision making for water management in the system. The key use of the DEM (CLLMM) was to establish the width of the channel/lagoon and average cross-sectional depth of the channel/lagoon for the Coorong and Murray estuary to inform and set-up the Coorong Hydrodynamic Model (see 2.3.2). Furthermore, the DEM (CLLMM) was used to inform the elevations of each 'mesh' corner for the flexible mesh bathymetry used in the TUFLOW-FV model (see 2.1.2).

2.6.6 Limitations and assumptions

Key limitations for the DEM (CLLMM) updated with 2008 LiDAR data were documented by Hobbs et al. (2019):

- errors in elevations from point survey data;
- poor spatial distribution of point survey data;
- flawed spatial extrapolation methods;
- absence of many shallow water, reef and island features; and
- many spatial examples of over- and under- estimation of elevation resulting from bathymetry modelling technique effects.

2.7 Digital Elevation Model (HCHB)

2.7.1 Description

The Digital Elevation Model (DEM) for the Murray estuary and Coorong was developed by Hobbs et al. (2019) as part of the HCHB program, referred to herein as DEM (HCHB). The DEM (HCHB) for the Murray estuary and Coorong was developed in 2019 and is an update to the DEM (CLLMM) that was developed in 2008. Updated analyses and the collection of new data (in 2018 and 2019) have provided significant improvement in the spatial mapping and precision of shallow-mid depth water areas and surrounding low-lying vegetation of the Coorong lagoons (Hobbs et al. 2019).

2.7.2 Spatial limits and resolution

The DEM (HCHB) extends from Goolwa Barrage to the 42 Mile Crossing and therefore covers the entirety of the Murray estuary and Coorong. The resolution of the DEM (HCHB) was 1 m^2.

2.7.3 Inputs

The data sources used in the DEM (HCHB) as listed in Hobbs et al. (2019) were:

- Digital Elevation Model 2018 (DEM, 1m grid) based on LiDAR data (22 May 2018)
- LiDAR 2008 points (~2m x, y point resolution, 6–10 April 2008)
- elevation and bathymetry points (ground and sonar surveys, various dates)
- Sentinel-2 satellite data (10m grid, 4 bands) across three time points:
    - 27 April 2018, 00:37:03 UTC (10:07:03 CST)
    - 06 June 2018, 00:44:58 UTC (10:14:58 CST)
    - 01 February 2019, 00:47:04 UTC (10:17:04 CST)
- hydrographs across 15 monitoring stations in the Coorong at the three time points above (within 5 minutes of Sentinel satellite pass-over).

Inconsistencies between the 2008 and 2018 LiDAR surveys as well as the point-based elevation and bathymetry surveys and the 2018 LiDAR surveys were resolved with correction factors. Data from the 2008 and 2018 LiDAR surveys and point-based elevation and bathymetry surveys were used to cover the terrestrial fringes and the Coorong and areas between ~0.75 and 1.0 m AHD. The bathymetry of areas covered by water over the Coorong were resolved with Sentinel-2 satellite data. Generalised Linear Models (GLMs) were used to estimate water depth based upon the reflectance values from the Sentinel-2 satellite data, and inferred elevation (m AHD) from water monitoring stations.

Three DEMs were produced from the following corrected datasets:

- 2008 LiDAR
- 2018 LiDAR
- Sentinel-2 satellite

These three DEMs were seamlessly merged and therefore the updated Coorong DEM is a composite of the satellite bathymetry model and the LiDAR DEMs.

2.7.4 Outputs

The DEM (HCHB) provided a more accurate representation of the systems bathymetry in shallow waters (<1m in depth). An example of the improvements in bathymetry detailed by the DEM (HCHB) in relation to the DEM produced in 2008 (CLLMM) (see 2.6) is shown in Figure 2-12.

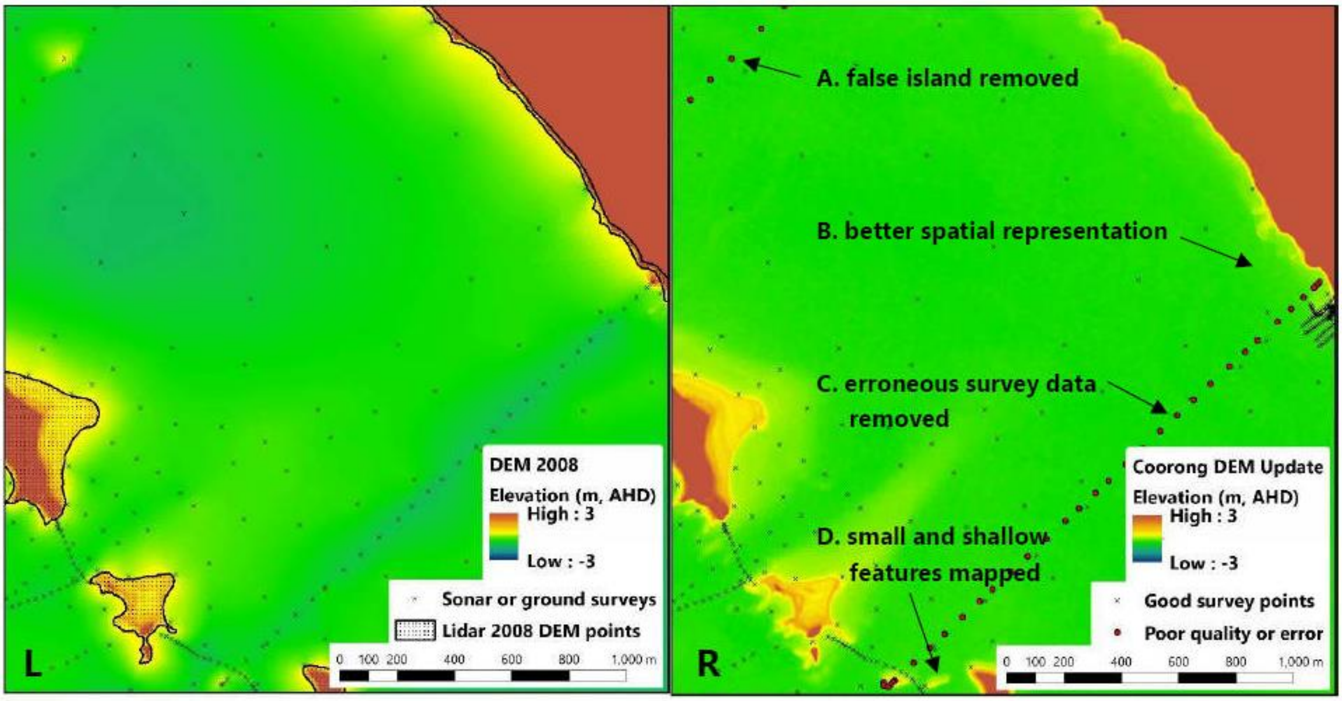

Figure 2-12. A localised comparison of the DEM 2008 (DEM CLLMM)) (left, see section 2.6 for model summary) and the updated Coorong DEM (DEM HCHB) (right). Source: Hobbs et al. (2019).

Examples of potential outputs from the DEM (HCHB) based upon water levels as produced by Hobbs et al. (2019) included:

- potential *Ruppia* habitat
- wading bird zones
- potential nesting areas - based upon the risk of foxes accessing a particular nesting island via land passage, wading through water or swimming.

2.7.5 Former/current use

The DEM (HCHB) is not yet in use due to the model's substantially different values in deeper water (>1 m deep) areas compared to the DEM (CLLMM) and it's bathymetric data inputs. However, the shallow water areas of the DEM (HCHB) could be merged with the deeper water areas of the DEM (CLLMM) to create an up-to-date DEM for the system. Investigations are being conducted as part of the *Water Resource Optimisation Project* to collate additional data and ultimately improve the performance of the DEM (HCHB) in deeper water (see 3.3.3).

2.7.6 Limitations and assumptions

Key limitation and assumptions as documented by Hobbs et al. (2019) were:

- The DEM does not perform well in deeper water areas (>1 m depth).

- Existing elevation point survey data (i.e. ground and sonar surveys) used to train or generation DEMs is unevenly distributed over the Coorong, widely variable in quality (i.e. x, y, z precision) and was collected from over 10 years ago.
- High water levels in May 2018 prevented the use of LiDAR, which collects high precision data, over more than 1,000 ha of mudflat. LiDAR data collected in 2008, which was less precise than data collected in 2018, had to be used in these mudflat areas.

2.8 Mudflat Availability Model

2.8.1 Description

The Mudflat Availability Model was developed by Sharma et al. (2009b) as part of the *CLLAMM Dynamic Habitat* report (Sharma et al. 2009a) and is an extension of the Coorong Hydrodynamic Model. The Mudflat Availability Model utilises the hourly water level outputs of the Coorong Hydrodynamic Model to predict the availability of mudflat with water depths up to 12 cm), which is where the majority of waterbird foraging occurs (Sharma et al. 2009b). The Mudflat Availability Model was generated within a GIS framework in ArcGIS (Sharma et al. 2009b). A full description of the Mudflat Availability Model is detailed in Sharma et al. (2009b).

2.8.2 Spatial limits and resolution

Twelve CLLAMMecology reference sites were identified between the Goolwa barrage in the North Lagoon and Salt Creek in the South Lagoon. Each reference site was defined as a band approximately 1.5 km wide (except for the Mundoo Channel where the channel is narrow and bends sharply), centered on the actual site selected by the CLLAMMecology research cluster (Sharma et al. 2009b). Methods for the collection of depth data at reference sites in the North and South Lagoons differed and are discussed in detail in Sharma et al. (2009a). Bathymetry for reference sites were derived by interpolating depth data collected with spatial tools in ArcGIS. Bathymetric outputs for reference sites were in Australian Height Datum with 1 m horizontal resolution and 0.001 m vertical resolution (Sharma et al. 2009b). Aerial photographs were used to digitise the high water mark to limit the spatial extent of the model (Sharma et al. 2009b).

2.8.3 Inputs

2.8.3.1 Bathymetry for reference sites

The bathymetric input to the model is discussed in section 2.8.2.

2.8.3.2 Water level

The water level input for the Mudflat Availability Model is an output of the Coorong Hydrodynamic Model (see 2.3). Water level outputs of the Coorong Hydrodynamic Model are provided at an hourly resolution and for each of the 102 cells that ranged from the Murray Mouth to 6 km past Salt Creek in the southern South Lagoon. The water level data from the Coorong Hydrodynamic Model is integrated following an inverse distance weight (IDW) interpolation to improve the 'goodness of fit' of modelled water level data (Sharma et al. 2009b).

A python script was written to automate outputs of the Mudflat Habitat Model using hourly water level data simulated by the Coorong Hydrodynamic Model (Sharma et al. 2009b).

2.8.4 Outputs

A water level raster is created following the IDW interpolation and used to output the extent of mudflat availability (up to 12 cm water depth) at a 1 cm vertical resolution (Sharma et al. 2009b). An example spatial output of the Mudflat Habitat Model is presented in Figure 2-13. These outputs provided an understanding of availability of mudflat habitat availability at a range of water levels in the Coorong.

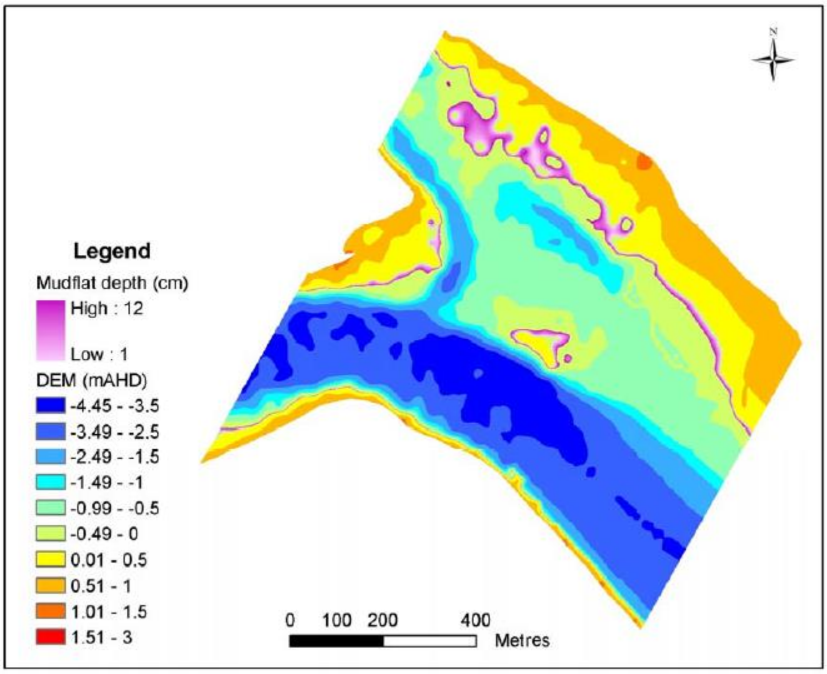

Figure 2-13. Example output of the digital elevation model coupled with the Mudflat Availability Model (source: Sharma et al. 2009b).

2.8.5 Former/current use

The Mudflat Availability Model was adapted and linked with the DEM (CLLMM) (see 2.6), Coorong Hydrodynamic Model (see 2.3) and waterbird response models (see 2.12) by Kilsby (2015) to simulate the areas of 'good' habitat for Fairy Tern, Sharp-tailed Sandpipers and Royal Spoonbills.

2.8.6 Limitations and assumptions

Key limitations and assumptions:

- Bathymetric data are restricted to 12 reference sites rather than the entirety of the Murray estuary, North and South Lagoons.
- The model was created in 2009 prior to excessive filamentous algae growth in the North Lagoon (since 2011) (Paton et al. 2011) and in the South Lagoon (since 2014) (Frahn and Gehrig 2015) that accumulate and blankets mudflat, and subsequently limit shorebird access to mudflat sediments to probe for invertebrates (Paton et al. 2019).
- The model does not take in to consideration sediment characteristics that may influence the benthic macroinvertebrate community and subsequently food resources for shorebirds (e.g. VanDusen et al. 2012).

2.9 Fish Habitat Model (CLLMM)

2.9.1 Description

The Fish Habitat Model was developed by Sharma et al. (2009b) as part of the *CLLAMM Dynamic Habitat* report (Sharma et al. 2009a) and is an extension of the Coorong Hydrodynamic Model (see 2.3). The Fish Habitat Model utilises the hourly water level and salinity outputs of the Coorong Hydrodynamic Model to predict the occurrence probability for key fish species, including Black Bream, Greenback Flounder, Yellow-eye Mullet, Mulloway, Smallmouth Hardyhead, Tamar River Goby and Congolli (Sharma et al. 2009b). The Fish Habitat Model was generated within a GIS framework in ArcGIS (Sharma et al. 2009b). A full description of the Fish Habitat Model (CLLMM) is detailed in Sharma et al. (2009b).

2.9.2 Spatial limits and resolution

The spatial limits and resolution of the Fish Habitat Model reflect those of the Coorong Hydrodynamic Model (see 2.3).

2.9.3 Inputs

The inputs to the Fish Habitat Model detailed in Sharma et al. (2009b) were:

- full Digital Elevation Model (DEM) of the Coorong
- hourly salinity and water level outputs from the Coorong Hydrodynamic Model
- logistic regression models that predicted the probability of occurrence of targeted fish species based upon salinities and fish catch data over the Coorong between October 2006 and July 2008.

Water level data were input as a binary dataset, with a 1 indicating the presence of water and a 0 indicating a dry mudflat, while salinity data informed the logistic regression model of the probability of occurrence for a particular fish species (Sharma et al. 2009b).

A python script was written to automate outputs of the Fish Habitat Model using hourly water level and salinity data simulated by the Coorong Hydrodynamic Model (Sharma et al. 2009b).

2.9.4 Outputs

Outputs of the Fish Habitat Model provide an understanding of the spatio-temporal variations in habitat availability for key fish species for a given hydrodynamic situation (Sharma et al. 2009b). An example of a spatial output of the Fish Habitat Model is provided in Figure 2-14.

The model predicted occurrence with >96% success for Yellow-eye Mullet, >89% for Greenback Flounder and >79% for Smallmouth Hardyhead and Tamar River Goby, noting that these four species out of the seven modelled species responded most strongly to salinity (Sharma et al. 2009b).

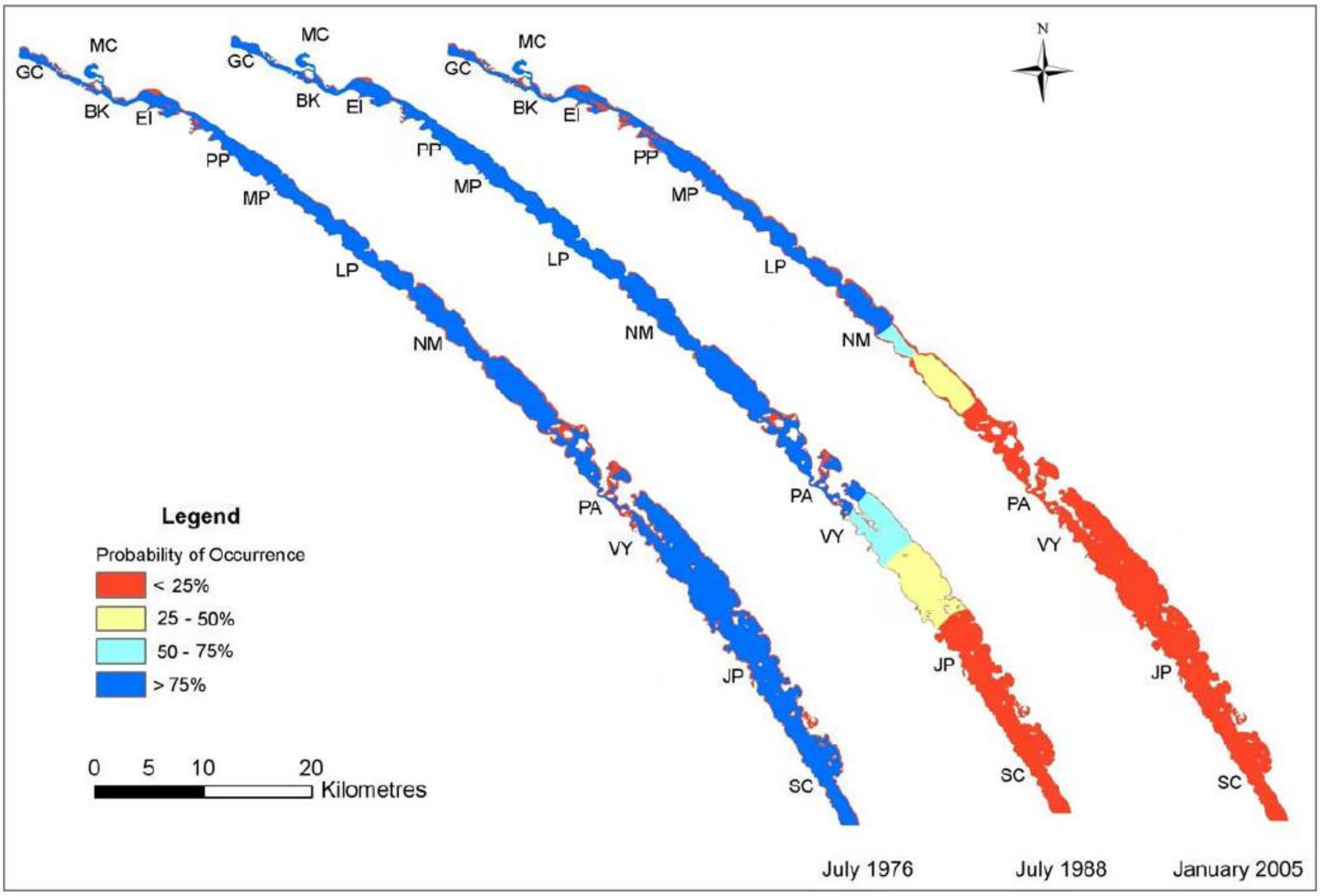

Figure 2-14. Example output of the fish habitat model showing the probability of occurrence of Yellow-eyed Mullet over the Coorong at three time intervals (source: Sharma et al. 2009b).

2.9.5 Former/current use

The Fish Habitat Model was used to:

- predict the probability of occurrence of Yelloweye Mullet, Greenback Flounder, Smallmouth Hardyhead and Tamar River Goby over the extent of the Coorong in July 1976, July 1988 and January 2005 (Sharma et al. 2009b).

2.9.6 Limitations and assumptions

Key limitations and assumptions:

- Salinity was only a significant predictor of the presence of four of the seven species of fish, with the rarity of occurrence of other targeted fish species a potential cause of salinity not being a significant predictor (Sharma et al. 2009b).
- The Fish Habitat Model is limited to estimating the extent of suitable habitat by salinity and water level (Sharma et al. 2009b) and therefore provides an estimate of potential fish distributions due to osmoregulatory constraints rather than habitat per se.
- Not all key prey species in the Coorong food web as documented in Giatas and Ye (2016) were included in the model (i.e. sandy sprat).

2.10 Fish Habitat Model (CSIRO)

2.10.1 Description

The Fish Habitat Model developed by Jöhnk et al. (2014), determines the extent of habitats for juveniles of important commercial and prey fish species in the Murray estuary, North Lagoon and South Lagoon. The fish species included in the model were: Mulloway, Tamar Goby, Black Bream, Greenback Flounder, Yellow-eye Mullet, Congolli and Smallmouth Hardyhead. The model predicts fish habitat extent by comparing salinities over the Murray estuary and Coorong against the LC_{10} of fish in aquaria held at 14ºC and 23ºC based upon research conducted by McNeil et al. (2013). Suitable habitat is considered to occur over the system where salinities are below the LC_{10} of a particular fish species. A full description of the Fish Habitat Model is detailed in Jöhnk et al. (2014).

2.10.2 Timing

The Fish Habitat Model analyses habitat suitability for estuarine fish of the Coorong on a daily and annual basis (Table 2.5). Time of year (warm months and cold months) influence salinity thresholds that need to be input to the model.

Table 2.5. Descriptions of the daily and annual fish habitat suitability models.

Model	Description
Daily	The daily calculated distance from the Murray Mouth (or the number of 1 km wide cells in the Coorong Hydrodynamic Model, see 2.3) to which a certain salinity threshold is not surpassed for a target fish species.
Annual	The annual (water year) analysis provides probabilities of habitat suitability by calculating the annual exceedance probability for a certain salinity threshold. It takes the salinity output of the Coorong Hydrodynamic Model (see 2.3) given on a 1 km grid along the Coorong with a daily resolution and counts the number of days where salinity is below a specific threshold of a fish species in one of the periods (warm months and cold months) at each spatial grid point over all available years.

2.10.3 Spatial limits and resolution

The spatial limits and resolution reflect those of the Coorong Hydrodynamic Model (see 2.3) as its salinity habitat output forms the basis for the Fish Habitat Model (Jöhnk et al. 2014). The Fish Habitat Model was, however, run using the Coorong Hydrodynamic Model prior to its spatial extension to include the Goolwa Channel (finishing at the Goolwa barrage). Therefore, Coorong Fish Model has been run from the Murray Mouth to the southern end of the South Lagoon as per the parent model of the Coorong Hydrodynamic Model (Jöhnk et al. 2014).

2.10.4 Inputs

The Fish Habitat Model operates on the outputs of the Coorong Hydrodynamic Model (see 2.3) and uses the one dimensional salinity output. The key model parameters are the salinity tolerances for seven species of juvenile estuarine fish in the Coorong in warm months (mid-October to mid-April) and in cold months (mid-April to mid-October) (Jöhnk et al. 2014). The salinity tolerances uses the LC_{10} of estuarine fish in aquaria held at 14ºC and 23ºC based upon research conducted by McNeil et al. (2013). A summary of the LC10 for each species is presented in Ye et al. (2013).

Table 2.6. The salinity tolerance for seven species of juvenile estuarine fish in the Coorong in cold (mid-April to mid-October) and warm months (mid-October to mid-April).

Species	Threshold cold month (g/L)	Threshold warm month (g/L)
Mulloway	60.3	51.1
Tamar goby	67.7	66.3
Black bream	78.6	81.8
Greenback flounder	81.1	72.9
Yelloweye mullet	83.8	68.3
Congolli	89.5	86.9
Smallmouth hardyhead	99.5	97.1

2.10.5 Outputs

The output of the Fish Habitat Model is a calculated distance from the Murray Mouth (or the number of 1 km wide cells in the Coorong Hydrodynamic Model) (Jöhnk et al. 2014). Using these calculations, a one-dimensional simplified salinity contour plot that shows the extent of suitable habitat over time (daily model) (Figure 2-15) and the probability of suitable salinities over time (annual model) (Figure 2-16) can be produced.

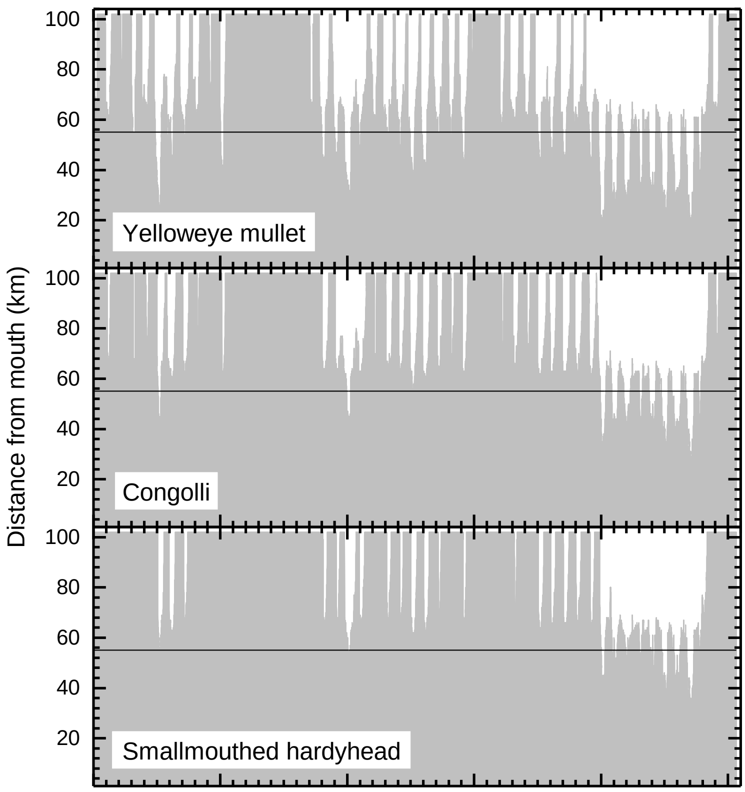

Figure 2-15. Daily output of the fish habitat for Yelloweye Mullet, Congolli and Smallmouth Hardyhead from 1963–2013, noting that grey is suitable habitat and white is unsuitable habitat. Source: Jöhnk et al. (2014).

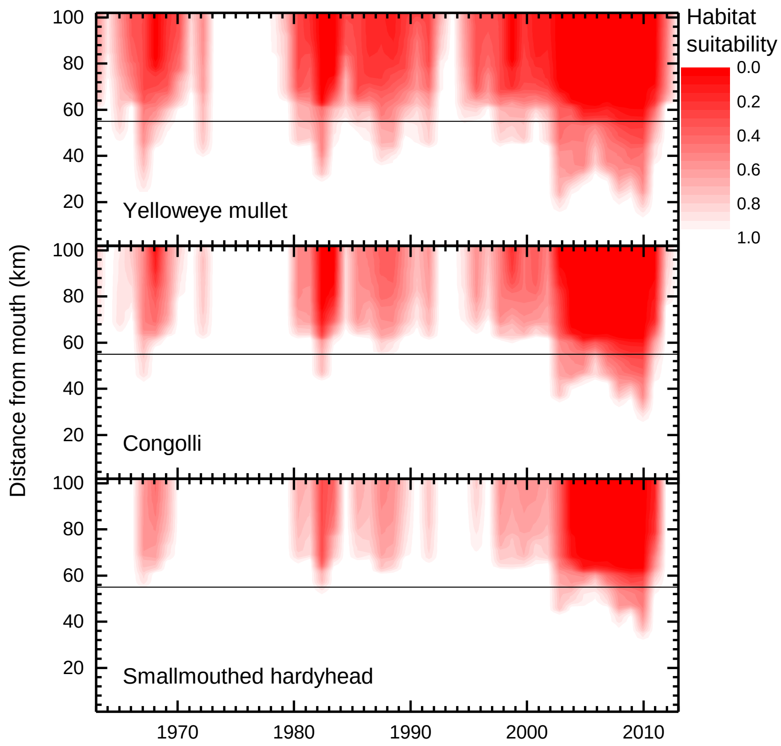

Figure 2-16. Annual probability output of fish habitat for Yelloweye Mullet, Congolli and Smallmouth Hardyhead. Source: Jöhnk et al. (2014).

2.10.6 Former/current use

The Fish Habitat Model has been used to:

- quantify differences in the extent of suitable salinity habitats for estuarine fish in the Murray estuary and Coorong with and without the provisions of water for the environment (e.g. Ye et al. 2016b)
- hindcast estimates of estuarine fish distributions in the Murray estuary and Coorong from 1963 to 2013 (Jöhnk et al. 2014)
- assess the efficacy of potential infrastructure options In the Coorong (e.g. DEWNR, 2017)
- evaluate different barrage flow delivery strategies to inform River Murray operations.

2.10.7 Limitations and assumptions

Key limitations and assumptions:

- The Fish Habitat Model is limited to estimating the extent of suitable habitat by salinity and water level (Jöhnk et al. 2014) and therefore provides an estimate of potential fish distributions due to osmoregulatory constraints rather than habitat per se.
- The model assumes that the LC_{10} of targeted estuarine fish in aquaria is reflective of their salinity tolerance in-situ within the Coorong.
- Not all key prey species in the Coorong food web as documented in Giatas and Ye (2016) were included in the model (i.e. sandy sprat).

2.11 *Ruppia tuberosa* Response Model

2.11.1 Description

The *Ruppia tuberosa* Response Model was developed by Jöhnk et al. (2014) to estimate the probability of *Ruppia tuberosa* replenishing the sediment propagule bank based on modeled hydrological conditions. The model was developed to inform barrage operations and to forecast and hindcast the effect of water for the environment provisions (Jöhnk et al. 2014). A full description of the *Ruppia tuberosa* Response Model is detailed in Jöhnk et al. (2014). The *Ruppia tuberosa* Response Model was also used to inform the development of the *Ruppia* Habitat Suitability Index (HSI) of the Coorong Dynamics Model (see 2.2).

2.11.2 Spatial limits and resolution

The spatial limits and resolution of the *Ruppia tuberosa* Response Model reflect those of the Coorong Hydrodynamic Model (see section 2.3). The spatial extents of the parent Coorong Hydrodynamic Model (i.e. without the Goolwa Channel extension) was used for the *Ruppia tuberosa* Response Model as *Ruppia* is restricted in its distribution to the North and South Lagoons of the Coorong.

2.11.3 Inputs

The model operates on the platform of the Coorong Hydrodynamic Model (see section 2.3) and uses the one dimensional daily values of salinity and water level along the 102 cells of the model geometry (Jöhnk et al. 2014). The daily values for salinity and water level along the 102 cells of the Coorong Hydrodynamic Model are compared against the conditions thought to be suitable for the successful completion of a life stage (Table 2.7).

Table 2.7. The processes, timing, condition statements and probability arguments of the *Ruppia tuberosa* Response Model. Source: Jöhnk et al. (2014).

Model processes	Timing	Condition	Probability argument
Seed germination	May 1 to June 30 (Noting that the first day of the life cycle (May 1) encompasses the preceding 15 days (April 16 to April 30).	Salinity <85 g/L and water level >+0.2 m AHD over the 15 day preceding 15 day period. If true, this day is counted as a possible germination day.	The sum of all possible germination days in the period, divided by the total number of days (61 days) gives a probability of germination (Pgerm).
Turion sprouting	May 1 to June 30 (Noting that the first day of the life cycle (May 1) encompasses the preceding 15 days (April 16 to April 30).	Salinity <125 g/L and water level >+0.2 m AHD over the 15 day preceding 15 day period. If true, this day is counted as a possible germination day.	The sum of all possible sprouting days in the period, divided by the total number of days (61 days) gives a probability of sprouting (Psprout).
Seedling development to juvenile (non-reproductive) plants	June 1 to July 31	Salinity <100 g/L and water level >+0.2 m AHD for day in time period. If true, survival =1 for this day.	The sum of all possible seedling survival days in the period, divided by the total number of days (61 days) gives a probability of seedling survival (Pseed) during this period.
Juvenile development to asexual adult plants	July 1 to October 31	Salinity <100 g/L and water level >+0.2 m AHD for day in time period. If true, survival =1 for this day.	The sum of all possible juvenile survival days in the period, divided by the total number of days (61 days)

Model processes	Timing	Condition	Probability argument
			gives a probability of juvenile survival (Pjuv).
Asexual adult development to sexual adult plant	October 1 to December 31	Salinity <100 g/L and water level >+0.2 m AHD for day in time period. If true, survival =1 for this day.	The sum of all possible seedling survival days in the period, divided by the total number of days (61 days) gives a probability of adult survival (Pjuv).

2.11.4 Outputs

The conditional probabilities calculated for the successful completion of a life stage (Table 2.7) were then used in the equations detailed in Table 2.8 to estimate the probability of an *Ruppia* plant transitioning between various life stages and ultimately estimate the probability of replenishment of the seed propagule bank in a given year in each of the 102 cells of the Coorong Hydrodynamic Model (Jöhnk et al. 2014).

Table 2.8. The probability equations specified for the successful completion of each life stage(s) or replenishment of the propagule bank within the *Ruppia tuberosa* Response Model. Source: Jöhnk et al. (2014).

Transition between life stages	Probability equation
Juvenile development to asexual adult plants	At this stage, the combined probability for a seedling to reach the adult stage is set as 0.5*(Pgerm+Psprout)*Pseed*Pjuv
Asexual adult development to sexual adult plant	At this stage, the combined probability for a seedling to reach the sexual adult stage is set as 0.5*(Pgerm+Psprout)*Pseed*Pjuv*Padult
Sediment propagule bank replenishment by turion probability	The probability the sediment propagule bank being replenished by turions (Ptb) produced by asexual adults is set to equal to the probability of cells reaching asexual adult stage: Ptb=0.5*(Pgerm+Psprout)*Pseed*Pjuv
Sediment propagule bank replenishment probability from sexual adults	The probability the sediment propagule bank being replenished by seeds (Psb) produced by sexual adults is set equal to the probability of reaching the sexual adult stage: Ps=0.5*(Pgerm+Psprout)*Pseed*Pjuv*Padult
Probability of replenishment of the seed propagule bank (Pspb) in a given year in one of the 102 cells of the hydrodynamic model	Pspb=0.5*(Ptb+Psb)

2.11.5 Former/Current use

The *Ruppia tuberosa* Response Model has been used to:

- hindcast modelled probabilities of propagule bank replenishment under historic hydrological conditions (see Jöhnk et al. 2014)

- quantify differences in the extent of suitable salinity habitats for propagule bank replenishment in the Coorong with and without the provisions of water for the environment (e.g. Ye et al. 2016b)
- assess the efficacy of potential infrastructure options in the Coorong (e.g. DEWNR 2017). DEW have used the *Ruppia tuberosa* Response Model to evaluate different barrage flow delivery strategies to inform River Murray operations.

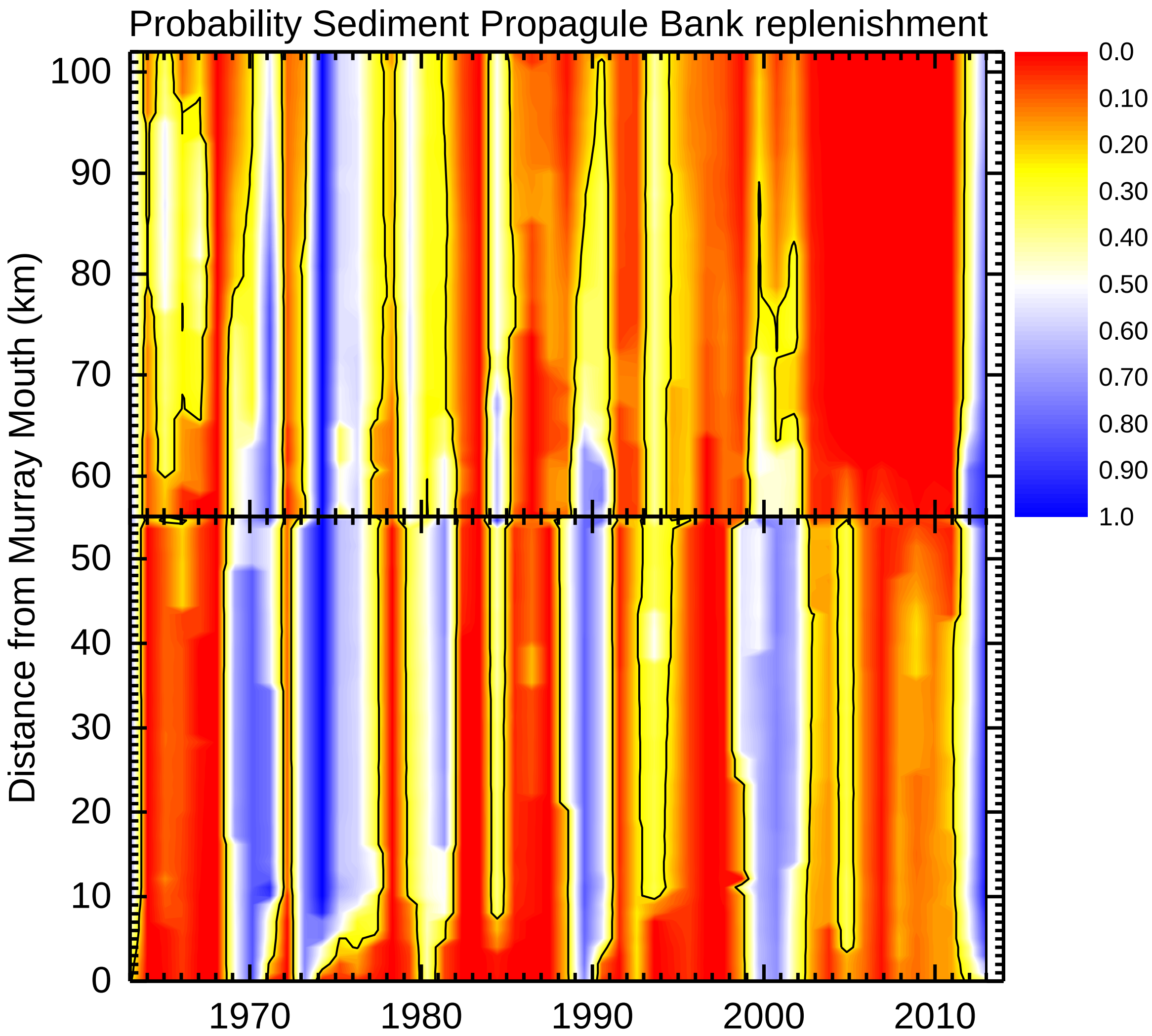

Figure 2-17. Model output showing the probability of *Ruppia tuberosa* sediment propagule bank replenishment from 1963 to 2013 in the North Lagoon (lower graph) and South Lagoon (upper graph) of the Coorong between Murray Mouth channel (0 km) and Salt Creek (102 km from the Murray Mouth). The contour line on the plot represents the 25% probability of sediment propagule bank replenishment. Source: Jöhnk et al. (2014).

2.11.6 Limitations and assumptions

Key limitations and assumptions:

- Nutrient and excessive filamentous algae growth were not factored in to the model, however, these drivers are now known to have significant influence over *Ruppia* condition and reproductive output (Collier et al. 2017).
- Water level and salinity thresholds used in the model do not reflect our most contemporary understanding of the *Ruppia* lifecycle, including the optimal, suitable and unsuitable values presented in Collier et al. (2017).
- The model assumes that a life stage will be successfully completed provided that the conditions of the met are met.
- The accuracy of the model outputs is limited by plants that successfully complete a life stage outside the time limits defined by the model, which has been documented to occur (see Collier et al. 2017).

2.12 Waterbird response models

2.12.1 Description

Waterbird response models were developed by O'Connor et al. (2013a) for ten waterbird species that use the Coorong, Lower Lakes and Murray Mouth habitats. The Coorong plays an important role in providing key habitat for six of these species (Table 2.9). The models were developed using Bayesian Belief Networks (BBNs), which are graphical probabilistic models that are used to model cause and effect relationships (i.e. conditional dependencies) between variables using both quantitative and qualitative (i.e. expert knowledge) data. All expert opinion data was elicited using transparent, structured protocols, which captured best estimates, estimated ranges in possible value and uncertainty (O'Connor et al. 2013a)

A conceptual model template (Figure 2-18) was developed in order to to encourage consistency in structure and content between species-specific models. This template assisted the model development process by identifying conceptual model categories (baseline ecological factors, drivers and limiting factors) and components that formed the basis of species-specific models.

Table 2.9. Coorong waterbird species for which Bayesian belief network models were developed by O'Connor et al. (2013a).

Common name
Australian Fairy Tern
Common Greenshank
Sharp-tailed Sandpiper
Red-necked Avocet
Black Swan
Chestnut Teal

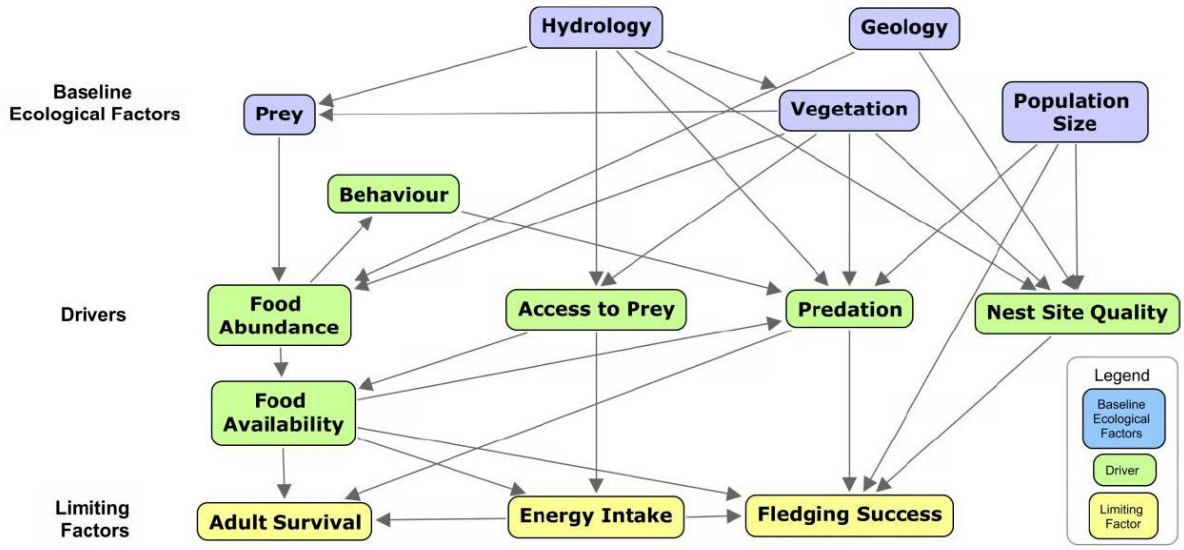

Figure 2-18. Generalised conceptual model template of waterbird habitat-use in the Coorong, Lower Lakes and Murray Mouth. Some components of this template, e.g. 'Hydrology', are broad classifications that encompass a number of more specific ecological components in species-specific models. Source: O'Connor et al. (2013a).

An example BBN model for the Sharp-tailed Sandpiper is shown below in Figure 2-19. These BBNs form graphical models of the relationships/ causal links, between a series of predictor and response variables. Each node can be parameterised using a combination of data and expert knowledge. The relationship between a child node and all its parents is described by a Conditional Probability Table (CPT). The CPT describes the probability of being in a particular state, given a combination of values. Each node in the waterbird BBNs represent an observable or measurable process that was represented as 'continuous' (i.e. % cover of vegetation) or categorised into discrete states (i.e. high, medium or low fledging success). Sensitivity analysis characterised uncertainties so that key causal factors and knowledge gaps could be identified (O'Connor et al. 2013a).

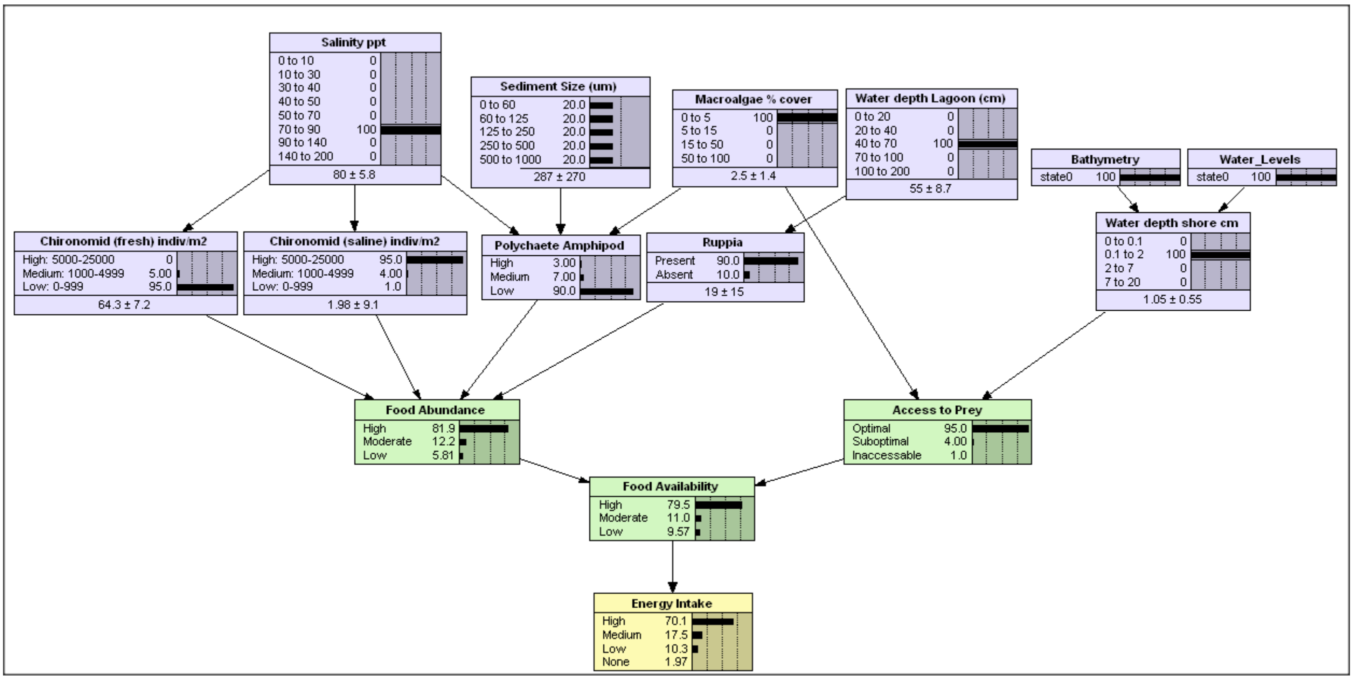

Figure 2-19. Bayesian Belief Network for Sharp-tailed Sandpiper under 'ideal' conditions. Source: O'Connor et al. (2013a).

O'Connor et al. (2013a) also summarised key ecological thresholds for each targets species (Table 2.10). This information was used to define 'states' within nodes, and could be further tested/utilised within updated Coorong waterbird models (i.e. those being developed under the HCHB program).

Table 2.10. Key ecological thresholds for the Sharp-tailed Sandpiper. Source: O'Connor et al. (2013a)

			Thresholds			
Indicator	**Knowledge**	**Unit**	**Ideal**	**Fair**	**Poor**	**Confidence**
Salinity	Expert opinion/data	ppt	70-90	<70, 90-140	>140	95%
Water depth (shoreline)	Expert opinion	cm	0.1-2	0-0.1,2-7	>7	90%
Macroalgal cover (% cover over sediment)	Expert opinion	% cover	0-5	5-50	>50	60%
Sediment size	Expert opinion/data	um	125-250	60-125, 250-500	<60, >500	95%

2.12.2 Timing

The importance of Coorong habitats varies seasonally for different waterbird guilds, depending on their critical life-history requirements. For example, the Coorong supports a greater abundance and diversity of waterbirds over summer and autumn, when migratory shorebirds arrive at the site to utililise mudflat foraging habitats (Paton 2010). Waterbird species that breed in the Coorong (i.e. terns, pelicans and beach-nesting birds) typically do so during summer (O'Connor 2013b). Waterbird response models presented in O'Connor et al (2013a) should therefore be applied with consideration to seasonally-dependent life-history requirements.

2.12.3 Spatial limits and resolution

The spatial extent of the waterbird response models for selected waterbird species is inclusive of the Murray estuary and Coorong (O'Connor et al. 2013a) as per the data collected during annual censuses (Paton et al. 2017). The spatial and temporal resolution of the model was any given point in space and time, and therefore, would vary dependent upon whether modelled or observed data were used as inputs to the model.

2.12.4 Inputs

The input parameters to the response model differed by waterbird species as described in O'Connor et al. (2013a). These inputs were tiered as 'baseline ecological factors' and 'drivers' as broadly shown in Figure 2-13. Baseline ecological factors included specific hydrological inputs such as salinity, water level and bathymetry, which can be used to determine the probability of conditions for drivers such as food abundance (Table 2.11).

Table 2.11. The baseline ecological factors and drivers for the Bayesian Belief Networks of each key waterbird species in the Coorong. Source: O'Connor et al. (2013a).

Common name	Baseline Ecological factors	Drivers
Australian Fairy Tern	Bathymetry, salinity, water levels (AHD), water depth, nest site cover, nest site inundation, connection of nest site to mainland, colony size, previous year's population size	Proximity to food, Access to prey, food abundance, nest site
Common Greenshank	Bathymetry, salinity, water levels (AHD), water depth, turbidity, prey abundance (snails, crabs, chironomids, fish)	Access to prey, overall food abundance and availability (preferred and non-preferred prey)
Sharp-tailed Sandpiper	Bathymetry, salinity, water levels (AHD), water depth, turbidity, prey abundance (Polychaete/Amphipod, chironomids, *Ruppia*)	Access to prey, overall food abundance and availability

Values for these parameters were derived from expert opinion and observed data sourced from the University of Adelaide.

2.12.5 Outputs

The waterbird response models determine the probability of conditions that affect a particular component (or 'limiting factor') of a specie's life history. For example, these models predict the probability of a particular fledging success, foraging habitat or energy intake outcome given the conditions (see section 2.12.4) experienced at that point in time (O'Connor et al. 2013).

2.12.6 Former/Current use

The BBN models described in O'Connor et al. (2013a) were designed to determine the probability of a particular point in space being considered suitable habitat for a species, given the conditions that the site is experiencing at a point in time. Ultimately, the model could be applied to continuous environmental surfaces to determine the area of the Coorong that could be considered 'suitable habitat' under given conditions. This spatial extrapolation was tested by Kilsby (2015) who linked spatially explicit models to GIS data.

Kilsby (2015) linked the BBN models with spatial water depth and salinity data extracted from the Mudflat Availability Model (see 2.8) that was linked with the DEM (CLLMM) (see 2.8) rather than bathymetry of the 12 *CLLAMMecology* reference sites. The BBN models were linked with ArcGIS using the *Bayesian Network Classification (BNC) tool* that reads in the spatial layers of ArcGIS to process them through the BBN models and subsequently presents outputs back in ArcGIS (Figure 2-20). Kilsby (2015) determined that:

- coarser temporal and spatial predictions produced better predictions than finer-scale predictions
- the correlation between good quality habitat extent and bird abundance varied between species, indicating that other factors affected the abundance.

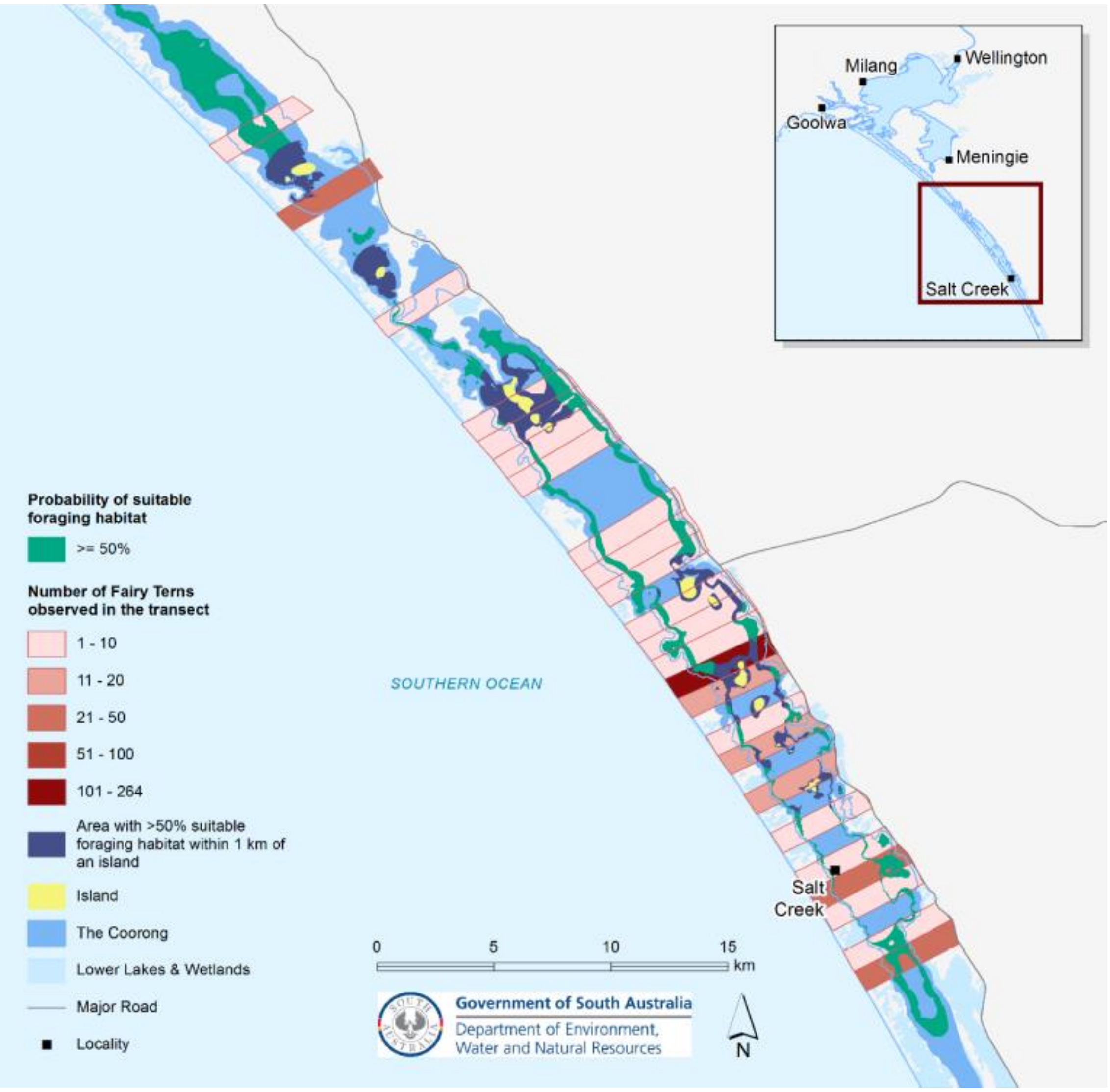

Figure 2-20. Example of a spatial output of suitable Fairy Tern foraging habitat in the South Lagoon computed by the BBN model overlaid with observations of Fairy Terns during the annual waterbird census of the Coorong. Source: Kilsby (2015).

2.12.7 Limitations and assumptions

Key limitations and assumptions for each species-specific model are described in O'Connor et al. (2013a). Overarching limitations include:

- Model predictions are primarily driven by expert-derived probability data, rather than observational data, and could benefit from further application/testing (see Kilsby 2015).
- Specific Coorong waterbird diets, and relative contributions of each food resource to overall diets, are generalized based on literature reviews and anecdotal observations.
- The accuracy of Waterbird Models would be improved through the development of separate response models for key food resources (e.g. *Ruppia*, macroinvertebrates and Smallmouth Hardyhead response models).
- Links between model components were not always included if they were too complex and required the inclusion of separate models (e.g. the link between water level and salinity).
- Hydrological nodes of the model did not include water levels (m AHD) and bathymetry, which potentially impact waterbird food availability and foraging behaviour.

3 Summary

The review of existing models for the Coorong identified significant overlap in their aims and/or outputs. Models reviewed have been grouped in to themes below based these similarities. The themes for models were:

- hydrodynamics
- biogeochemistry
- bathymetry
- fish
- *Ruppia tuberosa*
- waterbirds.

For each model theme, rationale has been provided for the preferred model to be used to conduct *Step 1* (preliminary) simulations for the *Trials and Investigations Project*. It is then detailed whether the preferred model available to date is to be improved (and how) or whether a new model is to be developed.

3.1 Hydrodynamic models

3.1.1 Applicable models

Hydrodynamic models developed for the Coorong include:

- TUFLOW-FV (see 2.1)
- Coorong Hydrodynamic Model (see 2.3).

3.1.2 Rationale for preferred model

The TUFLOW-FV model is the most flexible and detailed hydrodynamic model of the Coorong to date, and therefore, in the long-term will be the preferred model for use. However, in the immediate to short-term, the Coorong Hydrodynamic Model may be used to conduct long-term (decades) forecasts and hindcasts due to its fast simulation times, which are currently a limitation of the TUFLOW-FV model. However, the Coorong Hydrodynamic Model results in Figure 2-2 to Figure 2-4 that indicate the model does not have one parameterisation to accurately represent both the during and post Millennium drought periods accurately, creating some uncertainty in the accuracy of the results from the Coorong Hydrodynamic Model over long term simulations. This indicates a model with resolution between the 1 km of Coorong Hydrodynamic Model, and the 20-50 m of the TUFLOW-FV model would be advantageous for long term simulations.

3.1.3 Model creation/improvement under HCHB

The development of a coarser flexible mesh is currently underway to address the main limitation of the TUFLOW-FV model (long simulation times), and enable multi-decadal simulations to be undertaken in practical timeframes with the necessary accuracy, it is expected the TUFLOW-FV model will become the preferred hydrodynamic modelling tool available for the Coorong in all applications. Furthermore, the TUFLOW-FV model will serve as the hydrodynamic platform for the Coorong Dynamics Model, which will be refined and expanded upon in the *Phase One Trials and Investigations Project*.

3.2 Biogeochemical models

3.2.1 Applicable models

Biogeochemical models developed for the Coorong include:

- AED2 biogeochemical and habitat model in the Coorong Dynamics Model (AED2) (see 2.2)
- Nutrient Budget and Biogeochemical Model (see 2.4).

3.2.2 Rationale for preferred model

The Coorong Dynamics Model represents the most flexible and detailed biogeochemical model of the Coorong to date. The ability to model biogeochemistry and ecological responses of the Coorong has advanced significantly in the past 5 years, and as such, updating the Nutrient Budget and Biogeochemical Model to consider these advances would require significant effort.

3.2.3 Model creation/improvement under HCHB

The Coorong Dynamics Model is the main model to be improved and used as part of the HCHB program. The HCHB Trials and Investigations project has been structured to progress the improvements outlined in Section 2.2.7, through collection of necessary field data, experimental investigations and improvements to the model. The caveat outlined in Section 2.1.8 is relevant, where current development is expected to produce a coarser, faster version of the model compatible with the AED2 biogeochemical and habitat model, suitable for long term simulations.

3.3 Bathymetric models

3.3.1 Applicable models

Bathymetric models developed for the Coorong were:

- Digital Elevation Model (CLLMM) (see 2.6)
- Digital Elevation Model (HCHB) (see 2.7)
- Mudflat Availability Model (see 2.8).

3.3.2 Rationale for preferred model

The bathymetric data of the Mudflat Availability Model has very high resolution, however it is restricted to 12 reference sites, and as such, cannot be used to detail the bathymetry of the entire Murray estuary and Coorong. The DEM (CLLMM) and DEM (HCHB) both cover the entirety of the Murray estuary and Coorong. The DEM (CLLMM) currently in use to inform the bathymetry of the Coorong Hydrodynamic Model (see 2.3) and TUFLOW-FV model (see 2.1). However, the DEM (HCHB) has been shown to provide a more accurate representation of the systems bathymetry in shallow waters (<1m in depth) (Figure 2-12). As the DEM (HCHB) is based on contemporary and higher resolution LiDAR data, it is considered the preferred model for investigations following improvement in the representation of deeper areas.

3.3.3 Model creation/improvement under HCHB

To improve the performance of the DEM (HCHB) in deeper waters (>1m), a LiDAR survey that uses a more powerful sensor is being trialed over a small section of the Coorong as part of the *Water Resource Optimisation Project*. The LiDAR survey will use a sensor that is capable of determining bathymetry in clear water up to 50 m in depth. As the Coorong is relatively turbid, the trial will ascertain the depths to which the sensor can record the bathymetry of system. The results of the trial will determine whether a LiDAR survey is replicated over the entire Coorong. Future iterations of the DEM (HCHB) may be validated with the very high resolution spatial data across the 12 reference sites of the Mudflat Availability Model, and boat based bathymetric surveys.

3.4 Fish models

3.4.1 Applicable models

Fish models developed for the Coorong were:

- Fish Habitat Model (CLLMM) (see 2.9)
- Fish Habitat Model (CSIRO) (see 2.10).

3.4.2 Rationale for preferred model

The Fish Habitat Model (CSIRO) is the preferred model to simulate fish habitat for estuarine fish in the Coorong as it can be integrated into the Coorong Dynamics Model in its current form. The Fish Habitat Model (CLLMM) used fish catch data from October 2006 to July 2008 in its logistic regression models for each target fish species, and therefore, significant effort would be required to update these models with fish catch data since 2008.

3.4.3 Model creation/improvement under HCHB

The Fish Habitat Model (CSIRO) is proposed to be used to operationalise the Coorong Dynamics Model for the aforementioned reasons. Rather than improve the Fish Habitat Model (CSIRO), an integrated quantitative food web model for the Coorong ecosystem will be developed under the *Phase One Trials and Investigations Project; Component 3 – Restoring a functioning Coorong food web*. Due to the importance of fish in the Coorong food web (e.g. Giatas and Ye 2016), they will form a critical part of the Coorong food web model to be developed.

3.5 *Ruppia tuberosa* models

3.5.1 Applicable models

Ruppia tuberosa models developed for the Coorong were:

- *Ruppia* Habitat Suitability Index (HSI) of the Coorong Dynamics Model (see 2.2)
- *Ruppia tuberosa* Response Model (see 2.11).

3.5.2 Rationale for preferred model

The *Ruppia* HSI of the Coorong Dynamics Model is an updated iteration of the *Ruppia tuberosa* Response Model, and therefore, the inputs to the Coorong Dynamics Model reflect our current understanding of the optimal, suitable and unsuitable conditions for each *Ruppia* life stage as detailed in Collier et al. (2017). Furthermore, the *Ruppia* HSI takes in to consideration temperature, light and algal biomass (Collier et al. 2017) which are not accounted for in the *Ruppia tuberosa* Response Model (Jöhnk et al. 2014).

3.5.3 Model creation/improvement under HCHB

Thresholds for optimal, suitable and unsuitable conditions for each *Ruppia* life stage used in the *Ruppia* HSI may be updated based on the findings of *Phase One Trials and Investigations Project; Component 2 – Investigating the drivers and control of filamentous algae and restoration of aquatic plants in the Coorong*.

3.6 Waterbirds models

3.6.1 Applicable models

The only statistical waterbirds models for the Coorong were the BBNs developed for key species by O'Connor et al. (2013) (see 2.12).

3.6.2 Rationale for preferred model

The models developed by O'Connor et al. (2013) are the only existing waterbird response models for the Coorong.

3.6.3 Model creation/improvement under HCHB

The waterbird response models developed by O'Connor et al. (2013) will be used to inform the development of updated quantitative response models under the HCHB program, These updated models will utilise the conceptual model development and key thresholds from O'Connor et al. (2013) provide a contemporary understanding of how the distribution and abundance of key waterbird species changes in response to variation in local conditions within the Coorong (Prowse 2020). This information will be used to predict the response of key waterbird species under different management scenarios.

4 HCHB modelling approach

The HCHB program will principally use the Coorong Dynamics Model to conduct short and long simulations to forecast the response of the Coorong ecosystem to various management scenarios. The approach to improving and further developing the Coorong Dynamics Model involves three steps:

1. *Integration of existing models and datasets in to the Coorong Dynamics Model*

The waterbird response models and Fish Habitat Model (CSIRO) are to be integrated in to the Coorong Dynamics Model in association with sediment mapping data to extend its habitat simulation capabilities to include key components (i.e. waterbirds and fish) of the Coorong ecosystem.

2. *Improve and validate the Coorong Dynamics Model*

The hydrodynamic, biogeochemical and habitat models that form the Coorong Dynamics Model will be updated to increase certainty in forecasted responses to management scenarios.

3. *Integration of quantitative models developed through the Phase One Trials and Investigations Project*

The quantitative food web model and waterbird habitat model that are to be developed under the *Phase One Trials and Investigations Project* will be integrated in to the Coorong Dynamics Model in replacement of the waterbird response models and Fish Habitat Model (CSIRO). The models to be developed under the *Phase One Trials and Investigations Project* will represent our most contemporary understanding of the Coorong food web and habitat requirements for key waterbird species. It is envisaged that following these three steps that the Coorong Dynamics Model will accurately model ecosystem responses to management scenarios, and therefore, become a trusted tool to support management decision making.

5 References

BMT (2019) *Murray Mouth Model Status Report*, BMT Eastern Australia Pty Ltd.

—— (2020) *TUFLOW FV User Manual Build 2020.01*, viewed 26 November 2020, <https://www.tuflow.com/Download/TUFLOW_FV/Manual/TUFLOW_FV_User_Manual_2020.pdf>.

BMT WBM (2017) *Coorong Options Assessment*, Brisbane BMT WBM Pty Ltd.

Brookes J, Lamontagne S, Aldridge K, Benger S, Bissett A, Bucater L, Cheshire A, Cook P, Deegan B, Dittmann S, Fairweather P, Fernandes M, Ford P, Geddes M, Gillanders B, Grigg N, Haese R, Krull E, Langley R, Lester R, Loo M, Munro A, Noell C, Nayar S, Paton D, Revill A, Rogers D, Rolston A, Sharma S, Short D, Tanner J, Webster I, Wellman N and Ye Q (2009) *An Ecosystem Assessment Framework to Guide Management of the Coorong*, Final Report of the CLLAMMecology Research Cluster, CSIRO: Water for a Healthy Country National Research Flagship, Canberra.

Collier C, van Dijk K, Erftemeijer P, Foster N, Hipsey M, O'Loughlin E, Ticli K and Waycott M (2017) Optimising Coorong *Ruppia* habitat, *Strategies to improve habitat conditions for* Ruppia tuberosa *in the Coorong (South Australia) based on literature review, manipulative experiments and predictive modelling,* University of Adelaide, DEWNR, University of Western Australian and DAMCO Consulting.

DEW (2020) *South Australian River Murray Basin Plan Environmental Outcome Evaluation: Coorong, Lower Lakes and Murray Mouth (CLLMM) Priority Environmental Asset*, DEW Technical report 2020/18, Government of South Australia, Department for Environment and Water, Adelaide.

DEWNR (2014) *Lake Albert Scoping Study Options Paper*, River Murray Operations and Major Projects, Government of South Australia, Department of Environment, Water and Natural Resources, Adelaide.

—— (2017) *Coorong Investigations Study: Feasibility Assessment Report*. Government of South Australia Department of Environment, Water and Natural Resources, Adelaide

Frahn K and Gehrig S (2015) *Distribution and abundance of* Ruppia tuberosa *in the Coorong,* December 2014, SARDI (Aquatic Sciences).

Giatas G and Ye Q (2016) *Conceptual food-web models for the Coorong: A focus on fishes and the influence of freshwater inflows*, South Australian Research and Development Institute (Aquatic Sciences), Adelaide, SARDI Publication No. F2016/000124-1, SARDI Research Report Series No. 892.

Grigg N, Robson B, Webster I and Ford P (2009) *Nutrient Budgets and Biogeochemical Modelling of the Coorong*, CSIRO: Water for a Healthy Country National Research Flagship.

Hipsey M, Busch B and Aldridge K (2017) *Coorong Investigations Project: Ruppia habitat changes in response to augmented South East Flows scenarios and a regulating structure*, AED Report #R39, The University of Western Australia, Perth, Australia.

Hipsey M, Busch B, Huang P and Gibbs M (2020) *Coorong Dynamics Model sensitivity tests and gap identification*, Goyder Institute for Water Research Technical Report Series No. 19/35.

Hobbs T, O'Connor J and Gibbs M (2019) *Improved elevation and bathymetry models for the Coorong*. A Healthy Coorong, Healthy Basin project, DEW Technical report 2019/23, Government of South Australia, Department for Environment and Water, Adelaide.

Jeffrey S, Carter J, Moodie K and Beswick A (2001) 'Using spatial interpolation to construct a comprehensive archive of Australian climate data', *Environmental Modelling and Software*, 16: 309-330.

Jöhnk K and Webster I (2014) *Hydrodynamic Investigations of the Coorong* - Development and application strategy: Water for a Healthy Country National Research Flagship.

Jöhnk K, Nicol J and Ye Q (2014) *Hydrodynamic modelling and impact of environmental watering on Ruppia tuberosa and fish habitats in the Coorong*, South Australian Research and Development Institute (Aquatic Sciences), Adelaide.

Kilsby N (2015) *Using spatially-explicit Bayesian belief networks to modelling the spatial distribution of waterbird habitat in the Coorong, Lakes Alexandrina and Albert Wetland,* DEWNR Technical report 2015/47, Government of South Australia, through Department of Environment, Water and Natural Resources, Adelaide

Lester R, Fairweather P, Higham J, Muller K and Heneker T (2011) *Specifying an environmental water requirement for the Coorong and Lakes Alexandrina and Albert: A first iteration*, A report prepared for the South Australian Department for Environment and Heritage, Flinders University, Adelaide.

Lester R, Webster I, Fairweather P and Langley R (2009a) *Predicting the future ecological condition of the Coorong. Effects of management and climate change scenarios*. CSIRO: Water for a Healthy Country National Research Flagship.

—— (2009b) *Predicting the ecosystem response of the Coorong to the South Lagoon Salinity Reduction Scheme*. A report prepared for the South Australian Murray-Darling Basin Natural Resources Management Board, Flinders University, Adelaide.

MDBA (2012) *Hydrologic modelling to inform the proposed Basin Plan – methods and results*, MDBA publication no: 17/12, Murray-Darling Basin Authority, Canberra.

—— (2014) *2014 status of the MSM-BIGMOD modelling suite for the River Murray system*, technical report 2014/01.

—— (2017) *Modelling assessment to determine SDL Adjustment Volume*, MDBA publication no: 35/17, Murray-Darling Basin Authority, Canberra.

O'Connor J, Rogers D and Pisanu P (2013a) *Modelling waterbird responses to ecological conditions in the Coorong, Lower Lakes, and Murray Mouth Ramsar site*, South Australian Department for Environment, Water and Natural Resources, Adelaide.

—— (2013b). Cryptic and colonial-nesting waterbirds in the Coorong, Lower Lakes and Murray Mouth: distribution, abundance and habitat associations, South Australian Department for Environment, Water and Natural Resources, Adelaide.

Paton D (2010) *At the End of the River: the Coorong and Lower Lakes*, ATF Press, Hindmarsh SA.

Paton D, McKillop T and Bailey C (2011) *Developing ecological knowledge to inform the re-establishment of* Ruppia tuberosa *in the southern Coorong*, University of Adelaide

Paton D, Paton F and Bailey C (2017) 'Birds', in *Condition Monitoring Plan (Revised) 2017. The Living Murray – Lower Lakes, Coorong and Murray Mouth Icon Site*, DEWNR Technical report 2016–17, Adelaide: Government of South Australia, through Department of Environment, Water and Natural Resources, p. 17-25.

—— (2019) *Condition monitoring of the Lower Lakes, Murray Mouth and Coorong Icon Site: Waterbirds in the Coorong and Lower Lakes 2019*, The University of Adelaide, Adelaide.

Prowse T (2020) *Review of the ecology, status and modelling of waterbird populations of the Coorong South Lagoon*. Goyder Institute for Water Research Technical Report Series No. 20/12.

Saha S, Moorthi S, Wu X, Wang J, Nadiga S, Tripp P, Behringer D, Hou Y-T, Chuang H-Y, Iredell M, Ek M, Meng J, Yang R, Mendez M, van den Dool H, Zhang Q, Wang W, Chen M and Becker E (2014) 'The NCEP climate forecast system version 2', Journal of Climate, 27: 2185-2208.

Saha S, Moorthi S, Pan H-L, Wu X, Wang J, Nadiga S, Tripp P, Kistler R, Woollen J, Behringer D, Liu H, Stokes D, Grumbine R, Gayno G, Wang J, Hou Y-T, Chuang H-y, Juang H-M, Sela J, Iredell M, Treadon R, Kleist D, Van Delst P, Keyser D, Derber J, Ek M, Meng J, Wei H, Yang R, Lord S, van den Dool H, Kumar A, Wang W, Long C, Chelliah M, Xue Y, Huang B, Schemm J-K, Ebisuzaki W, Lin R, Xie P, Chen M, Zhou S, Higgins W, Zou C-Z, Liu Q, Chen Y, Han Y, Cucurull L, Reynolds R, Rutledge G and Goldberg M (2010) 'The NCEP climate forecast system reanalysis', *Bulletin of the American Meteorological Society*, 91(8): 1015-1058.

Sharma S, Benger S, Fernandes M, Webster I and Tanner J (2009a) *The CLLAMM Dynamic Habitat: Habitat mapping and dynamic modelling of species distributions*, CSIRO: Water for a Healthy Country National Research Flagship and South Australian Research and Development Institute (Aquatic Sciences), Adelaide.

Sharma S, Benger S, Tanner J and Webster I (2009b) 'Spatial modelling of mudflat availability and fish habitat in the Coorong', in *The CLLAMM Dynamic Habitat: Habitat mapping and dynamic modelling of species distributions*, CSIRO: Water for a Healthy Country National Research Flagship and South Australian Research and Development Institute (Aquatic Sciences), Adelaide.

Sharma S, Tanner J and Benger S (2009c). '*Digital elevation model of the Coorong and surrounds*', in *The CLLAMM Dynamic Habitat: Habitat mapping and dynamic modelling of species distributions*, CSIRO: Water for a Healthy Country National Research Flagship and South Australian Research and Development Institute (Aquatic Sciences), Adelaide.

VanDusen B, Fegley S and Peterson C (2012) '*Prey distribution, physical habitat features, and guild traits interact to produce contrasting shorebird assemblages among foraging patches*'. PLoS ONE 7(12): e52694. doi:10.1371/journal.pone.0052694

Webster I (2007) *Hydrodynamic Modelling of the Coorong*, Water for a Healthy Country National Research Flagship, CSIRO, Canberra. http://www.csiro.au/files/files/pd9z.pdf.

—— (2012) *The application of hydrodynamic modelling to assess the impact of supplementary flow releases on Coorong water levels and salinities*, Water for a Healthy Country National Research Flagship.

Ye Q, Giatas G, Aldridge K, Busch B, Gibbs M, Hipsey MR, Lorenz Z, Oliver R and Zampatti B (2016a) *Long-term intervention monitoring for the ecological responses of Commonwealth environmental water delivered to the Lower Murray River Selected Area in 2014/15*, Prepared for Commonwealth Environmental Water Office, South Australian Research and Development Institute, Aquatic Sciences, Adelaide, Australia.

Ye Q, Livore J, Aldridge K, Giatas G, Hipsey M, Joehnk K, Nicol K, Wilson P and Zampatti B (2016b) *Monitoring ecological response to Commonwealth environmental water delivered to the Lower Murray River in 2013-14*, Final Report prepared for the Commonwealth Environmental Water Office, South Australian Research and Development Institute.

Ye Q, Giatas G, Dittmann S, Baring R, Bucater L, Deane D and Rogers D (2020) *A synthesis of current knowledge of the food web and food resources for waterbird and fish populations in the Coorong*. Goyder Institute for Water Research Technical Report Series No. 20/11.

Government
of South Australia

Department for
Environment and Water