HydroNumerics

Modelling the effects of climate change on estuarine habitats in the lower Hawkesbury estuary

Hydrodynamic modelling of climate change scenarios for the lower Hawkesbury estuary

Final Report

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Project Number

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REPORT/PROPOSAL SUMMARY

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EXECUTIVE SUMMARY

This project applied the three-dimensional hydrodynamic model ELCOM (Estuary, Lake and Coastal Ocean Model) to the lower Hawkesbury-Nepean estuary. The purpose of the hydrodynamic modelling was to assist NSW I&I to assess the vulnerability of estuarine habitats in the lower estuary to potential changes in physical conditions under scenarios of climate change. Baseline (1990) and 32 scenarios of maximum, mean and minimum projections of sea level, sea temperature and air temperature in 2030 and 2050 were then applied. Modelled water levels, salinity and temperature in the baseline and projections were output for 18 habitat locations. The output was assessed and provided to NSW I&I to assess the vulnerability of mangroves, salt marsh and seagrasses to the projected changed conditions. The results of the vulnerability assessment will be used to inform Hornsby Shire Council (HSC) strategic planning for conservation of estuarine habitats in the projected conditions of climate change.

ELCOM configuration files that had previously been applied to the Hawkesbury-Nepean estuary were assessed and improved in this project. The model extends from the tidal limit at Yarramundi to the ocean boundary at Broken Head. The improved model reproduced tidal, meteorological and catchment driven fluctuations of water height, temperature and salinity.

A summary of the differences between water height, water temperature and salinity in summer and winter periods for 15 scenarios at 18 habitat locations is presented in this report. Hourly simulated water height, temperature and salinity was provided to NSW I&I for the 18 habitat locations. This output will be further assessed by NSW I&I to report the vulnerability of the habitats to the projected physical changes. Recommendations will be made to HSC for protection or management strategies.

The results of the 2030 and 2050 scenarios indicate that habitat sites may experience increased frequencies of inundation. Water depth at submerged sites was increased by up to 0.5m, salinity was increased by up to 6 psu, and water temperature was increased by up to 1.0ºC. The locations that are likely to experience the greatest mean change in inundation, depth, temperature and salinity were:

- Brooklyn Oval, which was dry at all times during baseline conditions, experienced inundation for 2% of time during summer and 4% of time during winter in maximum projections of sea level change.
- Big Bay experienced one event of inundation in the 2030 and 2050 projections. A storm that coincided with peak spring tide resulted in an influx of estuarine waters which increased the salinity and water depth on one day.
- Cowan Creek at Bobbin Head, Cowan Creek at Smiths Creek, Pumpkin Creek, Poporan Creek and Gentlemans Halt experienced the greatest change in salinity. The salinity was increased by up to 6 psu during summer.
- Crosslands and Calna Creek, Gentlemans Halt and Mullet Creek experienced greatest change in temperature of up to 1°C. The increase was greatest during summer.

Model output will be assessed by NSW I&I to assess the vulnerability of the habitats to the changes generally described here in the hydrodynamic modelling.

Important Note

The Centre for Water Research (CWR), University of Western Australia, was commissioned to undertake this study in June 2010 through its Services Group. In April 2010 the staff of the CWR Services Group had commercialised to form HydroNumerics Pty Ltd. This project was subsequently completed by the same project team at HydroNumerics under subcontract with the University of Western Australia.

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LIST OF ABBREVIATIONS

m	metres
AHD	Australian Height Datum
BOM	Bureau of Meteorology
METOC	Royal Australian Navy Directorate of Oceanography & Meteorology
SCA	Sydney Catchment Authority
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
STP	Sewage treatment plant

1 Introduction

Estuarine habitats face increasing pressure of environmental change as populations grow and climate changes. Coastal population growth place ever-increasing demands on catchments as a backdrop for urban development and as sources of food, water and income. Added to this there is an increasing demand to maintain healthy waterways that support recreational activities such as fishing, swimming and boating and that promote social well being.

Climate change is potentially an enormous risk to estuarine ecosystems by changing the physical conditions in the estuary, most simply the dynamics of salinity and temperature. Global average air and ocean temperatures have been increasing at twice the rate of the previous 100 years, and there is the compounding effect of sea level rise by thermal expansion and melt of ice and snow (IPCC 2007). Further, ocean salinity, pH, oxygen concentrations and circulation patterns are all expected to change. These changes to air temperature, water temperature and ocean circulation patterns are expected to affect weather patterns and in New South Wales (NSW) it is projected that the number of hot days and hot nights will increase and rainfall will become more irregular (CSIRO 2007). Drought periods are expected to become longer and extreme weather events are expected to become more numerous (CSIRO 2007). As the physical environment changes the physiological processes and distribution of plants and animals will also change in response (CSIRO 2007). In estuaries, which are at the cusp of the land and ocean, habitats will therefore face and respond to numerous changes in the environment.

A three-dimensional model of the Hawkesbury-Nepean estuary was applied to estimate changed physical conditions of the estuary under projections of climate change. The Estuary, Lake and Coastal Ocean Model (ELCOM) was previously applied to the Hawkesbury-Nepean river and estuary in an initial setup (HSC 2009a). We took these model files and assessed the ability of the model to simulate estuarine dynamics by comparing model output with observed temperature, salinity and water level at various locations. We identified where improvement was required to produce more accurate reproduction of the estuarine hydrodynamics. The improved model was then applied to baseline conditions in 1990 and scenarios of sea level, water temperature and air temperature change in 2030 and 2050.

This report begins with a description of the Hawkesbury-Nepean estuary (Chapter 2). An overview of the project objective and methodology is provided (Chapters 3 and 4). The modelling methods and results follow into two parts. Firstly, the setup, assessment, modifications and verification of the model (Chapter 5); secondly, the setup and results of climate change scenarios (Chapter 6). The output of the scenarios was submitted to NSW I&I for a habitat vulnerability assessment that will be provided to Hornsby Shire Council (HSC) in an accompanying report. Model uncertainty is addressed in Chapter 7. A project summary is presented in Chapter 8 and conclusions of the model results in Chapter 9. References are listed in Chapter 10. Chapters 11, and 12 contain appendices of data, including model input data and scenario modelling results respectively.

2 Background

2.1 The Hawkesbury-Nepean Catchment

The Hawkesbury-Nepean River is approximately 225 km in length and the catchment area is 21,400 km^2 (Figure 2-1). The catchment consists of diverse terrain and land uses. National parks and state recreation areas occupy 10,000 km^2 protecting 228 threatened species and 33 endangered ecological communities. The Hawkesbury-Nepean catchment supports a population of 1 million people, and numbers are expected to increase to 1.3 million people by 2019 (HNCMA 2009).

The catchment is of enormous economic, cultural and environmental value to NSW. The upper catchment provides drinking water to Sydney and districts, and supports irrigated agriculture, boating, sand and gravel mining and electricity supply. The resources of this catchment have an annual value of $60 million (DNR 2010). The lower estuarine catchment supplies drinking water to the Central Coast, and supports commercial seafood industries, recreational fisheries, boating and tourism operations. The Hawkesbury-Nepean estuary is reported to support $6 million in commercial seafood industries and generates over $60 million annually in tourism and recreation (HNCMA 2009).

The HSC governs 510 km^2 of the catchment. The area includes 60 km^2 of bushland and 50 km of estuarine shoreline from Wiseman's Ferry to Brooklyn, and incorporates the Berowra Creek and Cowan Creek estuary branches (Figure 2-2).

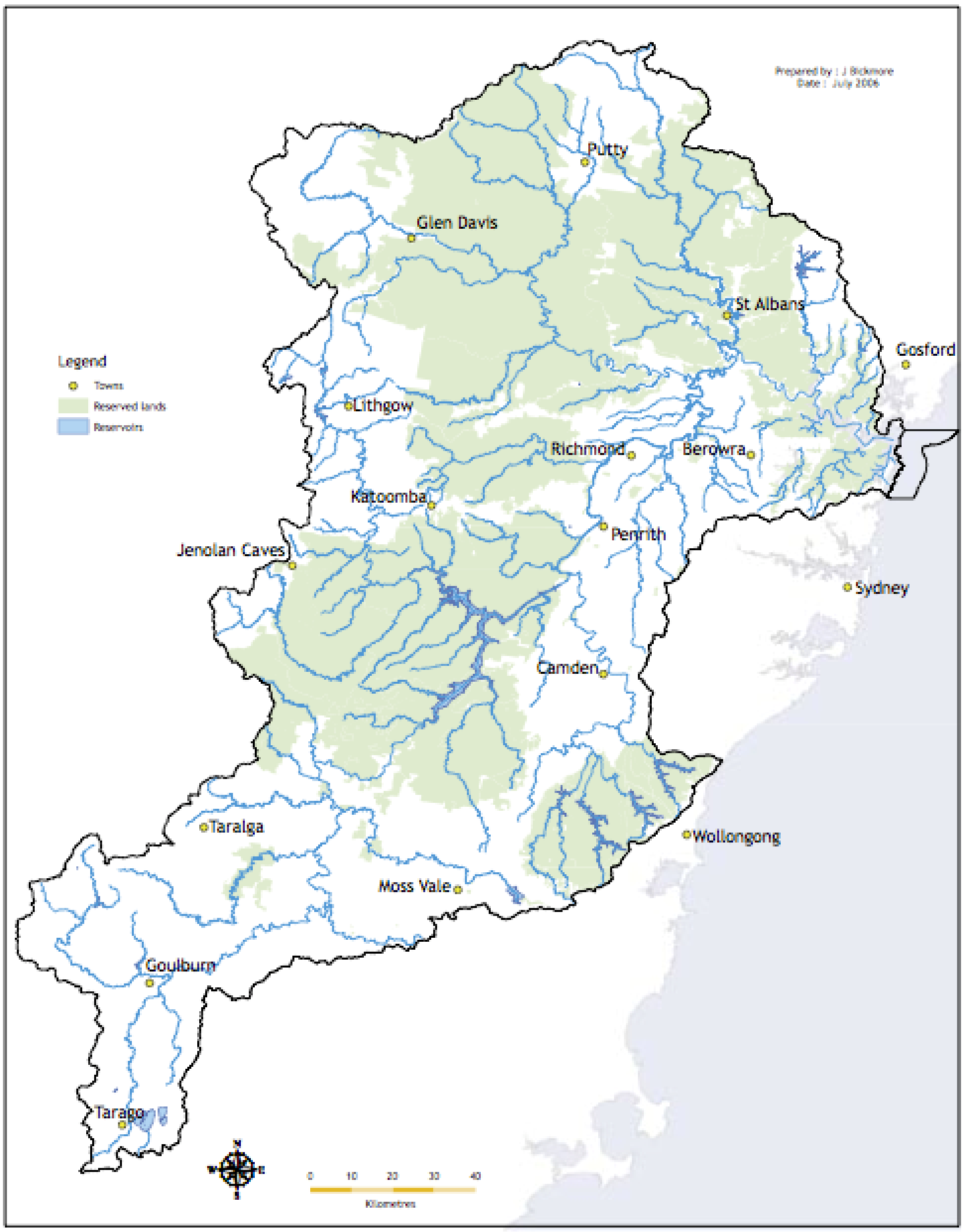


Figure 2-1: The Hawkesbury-Nepean catchment. Source HNCMA (2009).

Figure 2-2: Governing area of the Hornsby Shire Council. Source: HSC (2011).

2.2 Hawkesbury-Nepean Estuary Processes

Estuaries are water bodies that receive freshwater from the catchment and sea water from the ocean. Estuaries may be rivers, lakes or semi-enclosed embayments and they may be intermittently or permanently open to the ocean. The Hawkesbury-Nepean estuary is a 145 km drowned river valley. When sea levels were low during the last ice age the estuary was a freshwater river valley that flowed to the ocean at the continental margin. At the end of the ice age (15,000 to 6000 years ago), rising sea levels inundated the river valley and the drowned-river estuary was formed (Roy et al. 2001).

Estuaries receive water, sediment and dissolved materials from ocean and catchment sources. Tidal forcing, high mean sea levels and waves cause sea water to intrude into the estuary. Freshwater flows downstream and gradients in water quality properties occur where the freshwater and intruding sea water meet. The nature of the gradients is determined by the relative influence of the ocean, the catchment and the estuary morphometry.

Estuarine hydrodynamics may be characterised by salinity gradients. When there is significant freshwater flow from the catchment to the estuary, but the volume is not sufficient to completely expel the marine water, then freshwater flow occurs over the top of the saline water in a thin lens. The intruding sea water continues to intrude upstream in a thinly tapering wedge against the freshwater. This is referred to as a “salt-wedge” (Figure 2-3a). Salinity contours are usually horizontal and the position of the salt-wedge may move upstream and downstream with tidal or catchment forces.

When tidal energy is significant compared to the freshwater flow, the tidal oscillations break down the vertical salinity gradient by shear turbulence. A brackish region may form in between fresh and marine layers, or the vertical salinity gradient may be broken down completely and the estuary becomes partially mixed. In the case the water column is well-mixed in the vertical and a salinity gradient occurs in the horizontal length upstream. This is referred to as a partially-mixed estuary (Figure 2-3b) (Masselink and Hughes, 2003).

The Hawkesbury-Nepean estuary displays characteristics of both stratified and vertically mixed salinity gradients. During periods of high freshwater flow the estuary is stratified with freshwater flows occurring over the top of an intruding salt-wedge. During dry periods tidal energy mixes the water column vertically and a partially-mixed system is produced (NSW Government 2011). The Hawkesbury-Nepean salt-wedge or saline mixing zone is located between Wisemans Ferry and Sackville (Figure 2-4) (Cox et. al 2003, SPCC 1983).

Tidal forcing in the Hawkesbury-Nepean estuary is semi-diurnal. That is, the period of time from one high (or low) water to the next high (or low) water is on average 12 hr and 25 min. Thus two tidal periods occur in just over 24 hours.

The estuary opens to Broken Bay, Brisbane Water, Pittwater and the coastal ocean. The tidal energy of the open ocean is distorted and attenuated as it enters the boundaries of the estuary and features of tidal attenuation are observed in water level data along the course of the estuary. Figure 2-5 presents observed water levels from three regional tidal gauges: one located within the Hawkesbury-Nepean heads at Patonga, one within Sydney Harbour at Fort Denison and one at Port Hacking, a coastal embayment. The Patonga and Sydney Harbour gauges demonstrate lower water levels than the gauge at Port Hacking, which is more exposed to the coastal ocean.

Tidal dynamics in the mid and upper estuary are affected by the width and depth of the channel. Bottom friction is negligible in the mid-estuary where the channel is narrow and deep. Tidal energy is amplified here along the channel and the tidal range is greater than the coastal ocean (Figure 2-6). At Wisemans Ferry, 60km upstream of the ocean boundary, the tidal range is 16% greater than at the coastal ocean. At Windsor, 120 km upstream, the tidal range is slightly less than ocean. Upstream of Windsor the water becomes shallow and bottom friction becomes significant relative to flow. The limit of tidal influence is at Yarramundi, where the tidal signal is fully attenuated by bed friction.

Bathymetric drag produces a phase shift in the tide in the upstream. In the lower estuary the lag is 1 hr (at Peats Ferry Bridge), in the mid estuary the lag is 2 hr 15 min (at Wiseman’s Ferry) and in the upper estuary the lag is 5 hrs and 15 min (at Windsor) (NSW Maritime 2011). In shallow reaches, where bed friction becomes more significant, friction slows the drainage of water during ebb flow resulting in higher water levels at low tide than other locations in the estuary, as the water is not completely drained before the next incoming tide (Pugh 2004). To add further complexity to estuarine hydrodynamics, the lower estuary channel contains sub-estuaries, in the form of long, narrow side-branches which have water of fresh and estuarine origin. Salinity in the sub-estuaries varies with depth, and pressure gradients from tidal forcing may produce unique circulation patterns.

The lower Hawkesbury-Nepean estuary is a large, complex ecosystem in which the physical characteristics may change significantly within hours and over a range of horizontal and vertical scales. The changing gradients of temperature, salinity and water quality results in a rich biodiversity of life within the estuary.

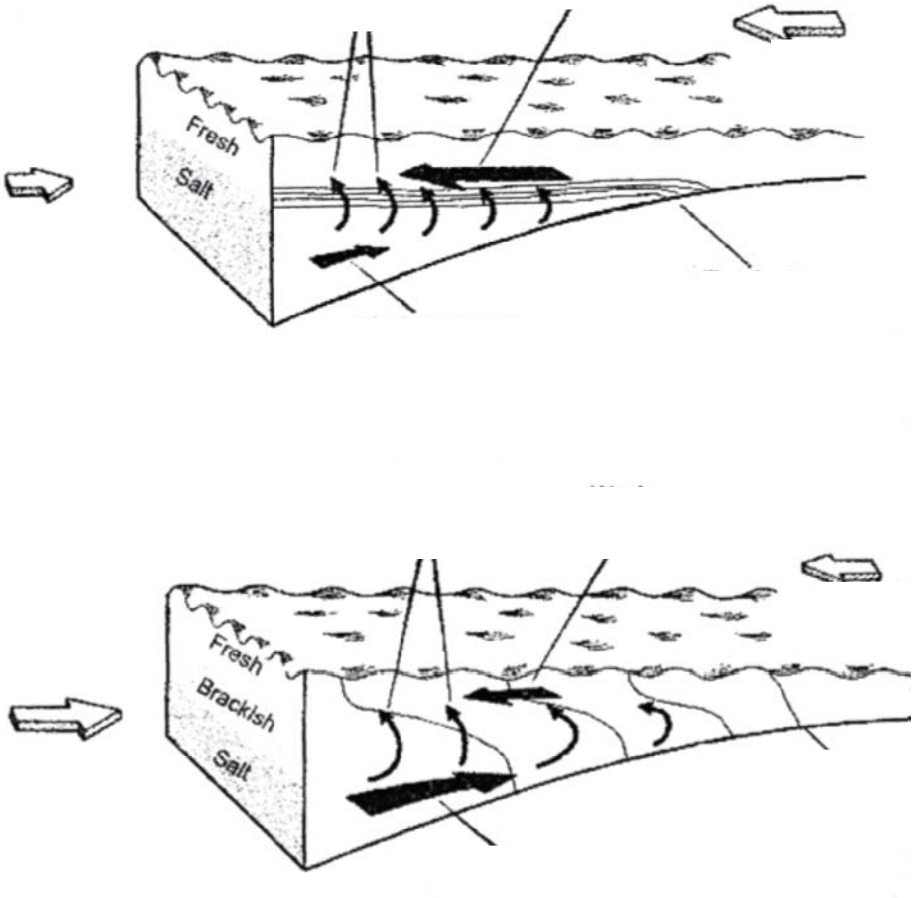


Figure 2-3: Illustration of a) a stratified “salt-wedge” salinity gradient, and b) a partially-mixed salinity gradient. Modified from Masselink and Hughes (2003).

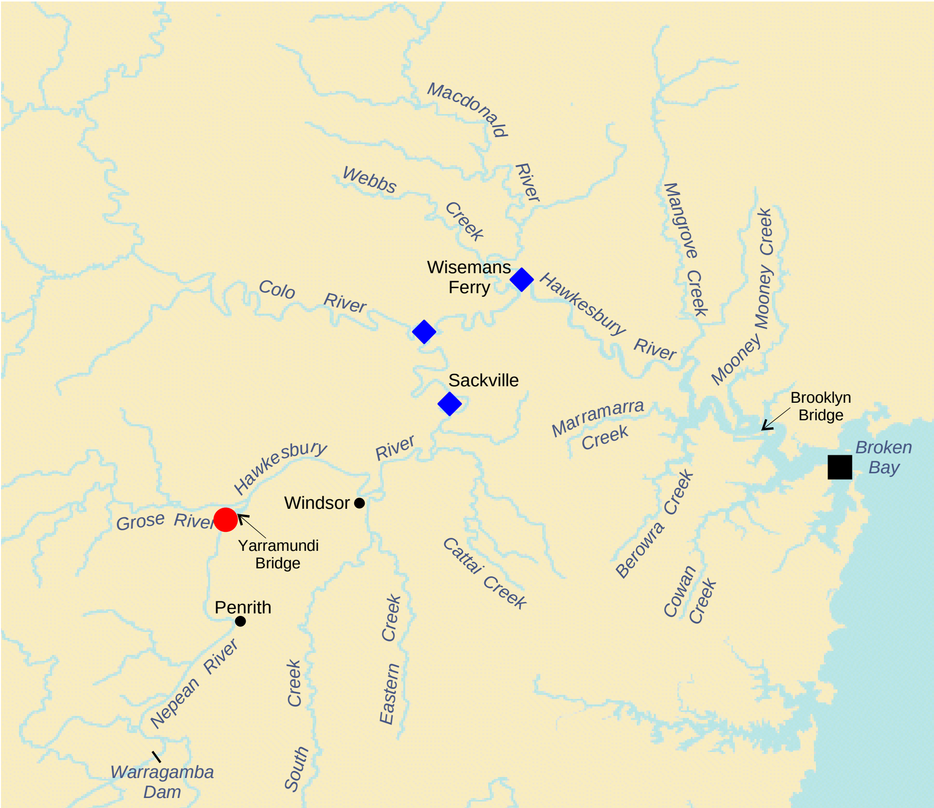


Figure 2-4: The Hawkesbury-Nepean estuary showing key locations: the limit of tidal influence at Yarramundi bridge (red circle); the saltwedge region at Colo River junction between Sackville and Wisemans Ferry (blue diamonds); and the estuary mouth at Broken Head (black square). Modified image from Cox et al. (2003).

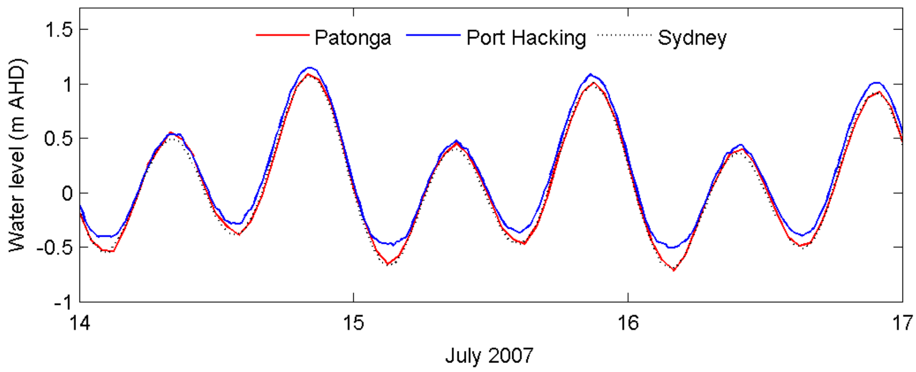


Figure 2-5: Observed water levels from the Patonga tidal gauge (red line), Port Hacking tidal gauge (blue line) and Sydney Harbour Fort Denison (dotted line) during 14 July to 17 July 2007.

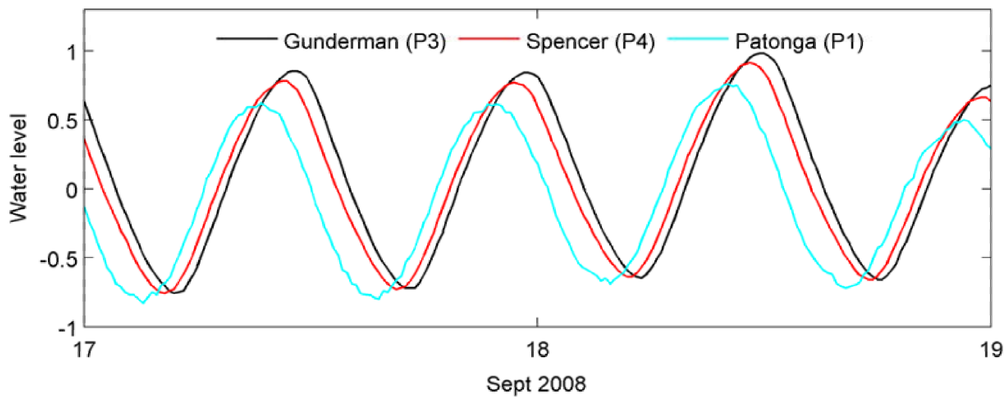


Figure 2-6: Observed water levels from Hawkesbury-Nepean gauges located at Gunderman (black line), Spencer (red line) and Patonga (blue line) during 17 Sept to 19 Sept 2008

2.3 Climate Projections in the Hawkesbury Region

Observed global average air and ocean temperatures have been increasing in the past 50 years at twice the rate of the previous 100 years (IPCC 2007). The average surface temperature of the Earth has risen 0.7°C since 1900 and sea levels have risen 1.8 mm per year since 1950 and the rate of increase is accelerating (CSIRO 2007). Rising sea levels are attributed to thermal expansion and melting of snow and ice caused by the increased Earth surface and ocean temperatures (IPCC 2007).

In Australia the average surface temperature has increased by 0.9°C from 1910 to 2004 with more hot days and nights and fewer cold days and nights. Annual total rainfall has declined by an average of 14 mm per decade (CSIRO 2007). By 2030 NSW projected conditions are:

- Warmer with more days with recorded temperatures above 35°C and less days of recorded temperatures below 0°C;
- Reduced in annual rainfall;
- Reduced volume of stream flows;
- Increased severity of droughts;
- Increased risk of bushfires; and
- Increased number of extreme rainfall events in central and south east (CSIRO 2007).

Air temperatures in the region have warmed by 0.8°C since 1950. Climate projections estimate that the average temperature will be up to 1.6°C higher than the average temperature in 1990 by 2030, and will be up to 4.8°C higher by 2070 (CSIRO 2007). Projections estimated a change in rainfall by ± 7% in 2030 and ± 20% in 2070 relative to 1990.

Projections for South-East Queensland forecast mean sea levels to potentially rise by 0.2 m in 2030 and by 0.5 m in 2070 compared to current levels (CSIRO 2010). Higher mean sea level and higher high tides will inundate riparian and low-lying inland marshes. Fresh or brackish regions may experience sudden changes in salinity during extreme weather events, such as 1-in-100 year storm surges, or may become permanently inundated by marine water. Increased sea and air temperature may induce heat stress on submerged and intertidal habitats and induce saline stress in shallow areas where evaporation rates are increased.

The threats to biodiversity in the Hawkesbury-Nepean catchment include land clearing, resource consumption by a growing population and climate change. These may alter the physical conditions of the estuary and estuarine habitats may need to physiologically adapt or migrate to survive. In the case of saltmarsh and mangroves, migration may require available space for landward progression. For seagrasses, migration may require deeper or shallower progression away from stressors.

This modelling of changed physical conditions of the estuary under projections of climate change provides a means to estimate stressors that on estuarine habitats in projected years.

3 Project Objective

The objective was to provide NSW I&I with predictions of the change in the physical conditions of the lower Hawkesbury-Nepean estuary in response to scenarios of climate change.

4 Methodology

The project was completed in stages. Each stage required ongoing consultation between the HydroNumerics and ecological scientists (NSW I&I) and managers (HSC). The methodology is described below, and the modelling report addresses each stage.

4.1 Hydrodynamic Model

In a previous project, HSC commissioned the setup of a hydrodynamic model (the Estuary, Lake and Coastal Ocean Model, ELCOM) for the Hawkesbury-Nepean river and estuary (HSC 2009a). The configured model was provided for the climate scenario modelling. Prior to scenario modelling, the model configuration and performance was assessed against measured estuary data and observed features in the lower, mid and upper estuary. Where performance of the model was poor the model input data and configuration was improved to achieve a fit-for-purpose validation.

4.2 Ecological Data

Habitat spatial data for the lower estuary was collated by NSW I&I in consultation with HSC. Key habitats were chosen according to priority areas of the HSC. The habitat locations were provided and incorporated in the setup and analysis of the model. Key physical requirements of the estuarine habitat and tolerance thresholds were identified by NSW I&I from published literature, and the hydrodynamic output will be compared against these thresholds by NSW I&I to assess the vulnerability of habitats to projected change.

4.3 Climate Change Projections

Relevant climate change literature was consulted by NSW I&I. Reported projections of air temperature, sea level and, sea surface temperature change for climate change scenario years were provided for the modelling.

4.4 Climate Change Scenario Modelling

In consultation with NSW I&I, scenarios were chosen to simulate a range of combinations of projected sea level, sea surface temperature and air temperature change in the estuary hydrodynamic model.

The climate change scenario modelling was performed after the assessment of the hydrodynamic model performance was complete and at a satisfactory standard.

4.5 Scenario Assessment

For all locations in the estuary that correspond to the habitat locations, HydroNumerics provided NSW I&I with text files of hourly simulated results of water depth, water temperature, air temperature and salinity for the climate change scenarios considered. The scenario results are provided in this report, along with the model setup, model performance assessment and climate scenario setup.

5 Hydrodynamic Model

The objective of the modelling was to capture the dynamics of the stratified or partially-mixed estuary. Vertical and horizontal gradients necessitate a three-dimensional hydrodynamic model, in order to correctly simulate the gradients in the horizontal, vertical and with time.

Model performance was assessed against field data from 2008. Comparisons of water height, salinity and temperature at five locations were assessed.

5.1 Estuary, Lake and Coastal Ocean Model

The Estuary, Lake and Coastal Ocean Model (ELCOM) is a three-dimensional hydrodynamic model that is applied to calculate the velocity, temperature and salinity distribution in water bodies that are subjected to external environmental forcing such as wind stress, surface fluxes and inflow events.

Technical descriptions of ELCOM are presented in Hodges and Dallimore (2006) and a summary follows here. ELCOM solves the equations of fluid transport (unsteady, viscous Navier-Stokes) for fluids with a constant density and changing volume (incompressible flow). Hydrostatic pressure is calculated using the hydrostatic assumption (Hodges et al. 2000). Baroclinic and barotropic responses are accounted allowing the simulation of stratified flow. Rotational effects, tidal forcing, wind stresses, surface heating and transfer, inflows, outflows, and transport of salt, heat and passive scalars are also accounted. The Euler-Lagrange method for advection of momentum is applied with a conjugate-gradient solution for the free-surface height. Passive and active scalars (i.e. tracers, salinity and temperature) are advected using a conservative ULTIMATE QUICKEST discretization.

ELCOM has been applied and proven in numerous international lake and coastal environments and has featured in peer-viewed scientific publications (Bothelo & Imberger 2007, Hodges et al. 2000, Laval et al. 2003, Laval et al. 2005, Morillio et al. 2008, Romero & Imberger 2003, Romero et al. 2004, Yeates et al. 2007).

ELCOM requires the following information:

- Bathymetry;
- Meteorology: Air temperature, relative humidity, shortwave radiation, longwave radiation, wind speed and wind direction.
- Inflow and outflows: flow rates, temperature and salinity (includes groundwater); and
- Water levels and any scalar information for calibration and validation of the model.

The above information is required in the form of measured or estimated data for the chosen periods of calibration, validation and prediction.

ELCOM is designed to be coupled with water quality models to simulate the fate and transport of physical, chemical and biological parameters.

5.2 Modelling Approach

5.2.1 Model Assessment

The Hawkesbury-Nepean ELCOM configuration was assessed using the latest ELCOM software (Version 2.2.2 build no. 170). Estuarine data collected in 2008 from five sites was compared with a model simulation of estuarine dynamics. The compared variables were temperature, salinity and water height. The performance of the model against measured data was judged and pivots for improvement were identified. The assessment period was 1st Aug 2008 to 31st Dec 2008.

A number of modifications were made to improve the model (Table 5-1).

Table 5-1 Summary of model modifications

Model feature	Original	Updated	Effect
Software version	Version June 2009 (version number not reported).	Version 2.2.2 build no. 170, build date: Feb 16 2011.	Software developments since 2009 were incorporated and improved formatting of model files for ease of use.
Initial temperature and salinity gradients in the simulations	Model initialised with uniform temperature and salinity in the estuary.	Added horizontal gradients of salinity and temperature at initialisation.	Removed the requirement for a long spinup time by the model to simulate gradients in the estuary.
Bathymetry	Partially straightened grid.	Fully straightened grid and straightened side branches.	Improved water flow in the upstream and downstream directions in the estuary.
Inflow depths	A fixed inflow cell was selected for each inflow in the model.	INFLOW MAX DEPTH was applied.	Ensures that inflow occurs in the nearest cell with sufficient volume to receive the flow. Prevents the inhibition of inflow when cells near the inflow location become dry. Improved the estuary freshwater balance.
Inflow volumes	Gauged data from 9 inflows was applied in raw format.	Inflow events were increased by a factor of 1.6 to account for missing freshwater.	Improved freshwater balance of the upper estuary and resulted in accurate simulation of freshwater pulses through the estuary.
Bottom drag	No bottom drag was configured.	No-slip condition in all grid cells to introduce bathymetry drag	The salt-wedge dynamics were better reproduced by the model.

5.3 Model Setup

5.3.1 Bathymetry

The bathymetry for Hawkesbury-Nepean river and estuary was provided as a partially-straightened ELCOM grid. In this version the model bathymetry was straightened from Windsor to Couranga Point (HSCa 2010). The original bathymetry had been compiled from interpolation of a variety of data sources: NSW Department of Public Works soundings digitised in Broken Bay (1977/78 data), contours from Sydney Sea Bed Map series, Royal Australian Navy data, Hornsby Shire Council estuary holes data, 1952 and 1980 surveys by the NSW Department of Commerce, the Sandbrook Marina inlet at Brooklyn and high resolution SWATH map data generated by DECCW of the upper estuary and tidal river (HSC 2009a). These data sources were interpolated to a resolution of 50 by 50 m in a digital elevation map by DECCW and the result was a good coverage of datum in the lower estuary, with older (up to 40 years) and sparse (channel cross-sections at 1 km intervals) data in the mid and upper estuary (HSC 2009a). The compiled bathymetry is presented in Figure 5-1. It was recommended that new bathymetric survey data be collected from the mid and upper reaches of the Hawkesbury estuary to simulate the hydrodynamic processes with greater confidence.

The mid and upper estuary contains a highly tortuous and narrow river channel. Narrow, meandering channels modelled by an orthogonal model grid may result in a loss of momentum from the simulated flow due to the influence of bathymetric drag. To improve the flow a fine modelling grid is required however this results in restrictive computational run-times. To simulate the hydrodynamics along the extensive length and tortuosity of the Hawkesbury-Nepean estuary at efficient run-times, the model bathymetry was straightened from Windsor (point marked A in Figure 5-1) to Broken Head (point marked B in Figure 5-1). Grid straightening is a bathymetric preparation procedure to improve the simulation of flow down the meandering channel, when the size of the system or computation requirements are too large for a high resolution grid. Berowra Creek, Cowan Creek, Mangrove Creek and Mooney Mooney Creek sub-estuaries were also straightened and retained in the model grid. The width and depths of the main channel and the side branches were preserved.

A number of grid scales were trialled in the straightened grid configuration: horizontal grid resolutions of 25m^2, 50m^2, 100m^2 and 200m^2 and vertical resolutions of 0.5m, 1m and 2m were tested. The hydrodynamic output and runtimes were compared and the 100 to 200m^2 horizontal and 1m vertical scale was found to accurately depict the observed gradients at a spatial scale that was relevant to the habitat areas (which were generally of a size greater than 100m). The final bathymetry configuration was a fully straightened grid of 100 m cell length in north by 200 m cell length in the east, and 0.5 m in the vertical. The realtime-to-runtime ratio of the model was 1:80, i.e. 1 day of real time is required to simulate 80 days of model output which was an acceptable runtime for scenario modelling.

Locations of vulnerable estuarine habitats were provided by NSW I&I as hardcopy maps and geo-referenced coordinates at a 5m resolution. The coordinates and maps were used to apply fringing, emergent and submerged cells in the model bathymetry to correspond to the habitat locations.

5.3.2 Inflows

Freshwater inflows from 13 rivers and creeks (including sewage treatment plants, STPs) were applied to the model (Figure 5-1). The inflow rates were sourced from river gauging instruments of the Sydney Catchment Authority (SCA) (SCA, *pers. comm.* 2010). Where gauged data was not available, the freshwater contribution was estimated relative to gauged flows in nearby rivers of similar size and similar surrounding topography (Table 5-3). Inflow rates are presented in Appendix 1 (Chapter 11).

Effluent from discharges of 39 Sydney Water STPs were added to the inflows of 2008 to provide the model with the best available data to reproduce the influence of freshwater flows in the estuary (HSC 2009a). STP flows were added at an average daily flow rate of annually reported values in Sydney Water (2009). The Brooklyn STP was applied at a specific inflow location. All other STPs were incorporated into one of the 13 tributaries implemented in the model.

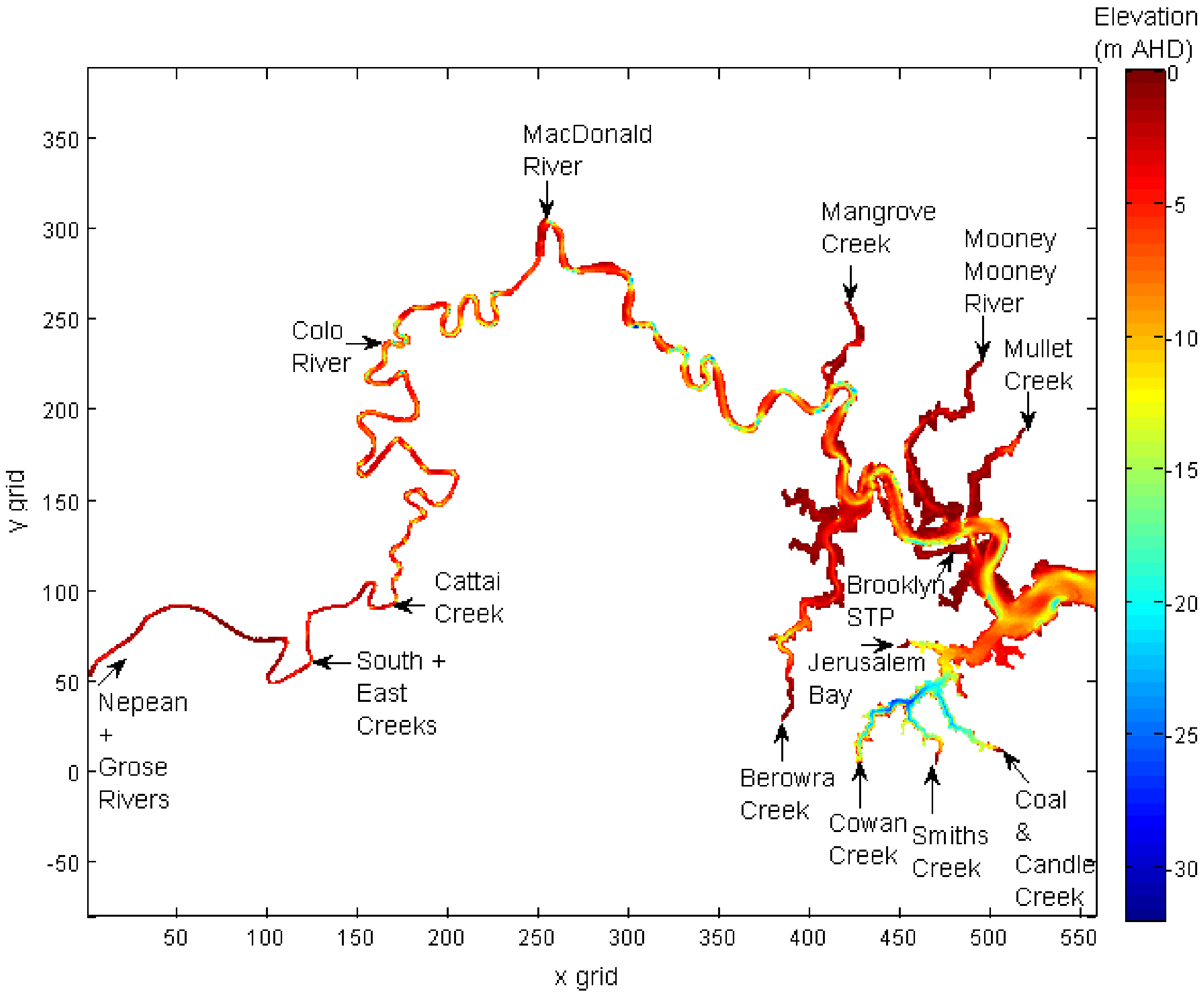


Figure 5-1: Bathymetry and inflow locations of the Hawkesbury-Nepean estuary model.

Table 5-2 Summary of freshwater inflows in the Hawkesbury-Nepean estuary model

Freshwater flow	Mean flow rate of 2008 period (m^3/s)
Penrith Weir	14
South Creek and Eastern Creek	5.8
Cattai Creek	1.2
Colo RIVER	9.2
MacDonald RIVER	4.9
Mangrove Creek	0.6
Mooney Mooney Creek	0.6*
Mullet Creek	0.3*
Berowra Creek	0.6
Smiths Creek	0.3*
Cowan Creek	0.6*
Coal & Candle Creek	0.3*
Jerusalem Bay	0.15*
Brooklyn STP	0.005**

* Ungauged assumed flows

** Average annual Brooklyn STP discharge as reported in Sydney Water (2009) applied at a constant daily rate

Table 5-3 Assumed flows of ungauged streams in the Hawkesbury-Nepean estuary model

Creek name	Calculated discharge
Mooney Mooney	1 × Berowra discharge
Mullet	0.5 × Berowra discharge
Cowan	1 × Berowra discharge
Smiths	0.5 × Berowra discharge
Coal and Candle	0.5 × Berowra discharge
Jerusalem	0.25 × Berowra discharge

5.3.3 Ocean Boundary

Ocean water levels recorded at the Patonga tidal station were applied to the model to drive tidal fluctuations from the ocean boundary (Figure 5-2). The data was applied in the model at a 15 minute interval. Ocean temperature (Figure 5-3) and salinity (Figure 5-4) were obtained from the Australian Navy and Meteorology monthly average data at Sydney (METOC, 2009).

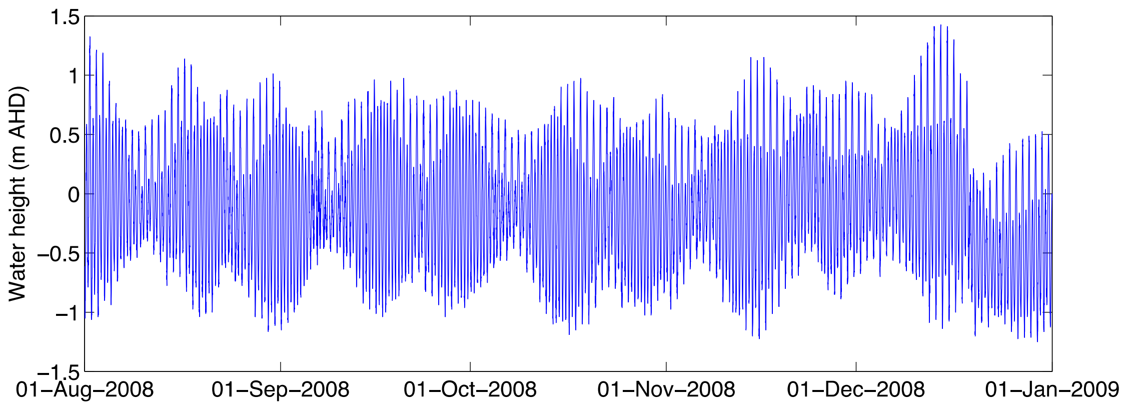


Figure 5-2: Ocean boundary hourly water level applied to the 2008 simulation.

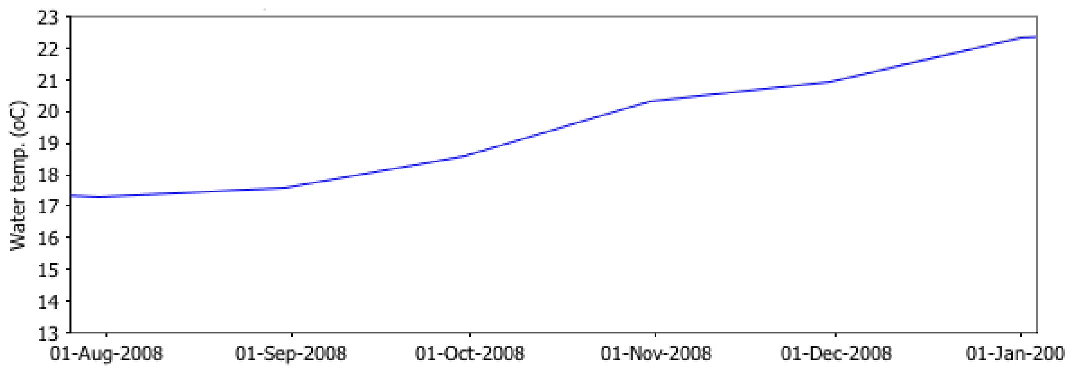


Figure 5-3: Ocean boundary water temperature applied to the 2008 simulation. Note y-axis range from 13-23°C.

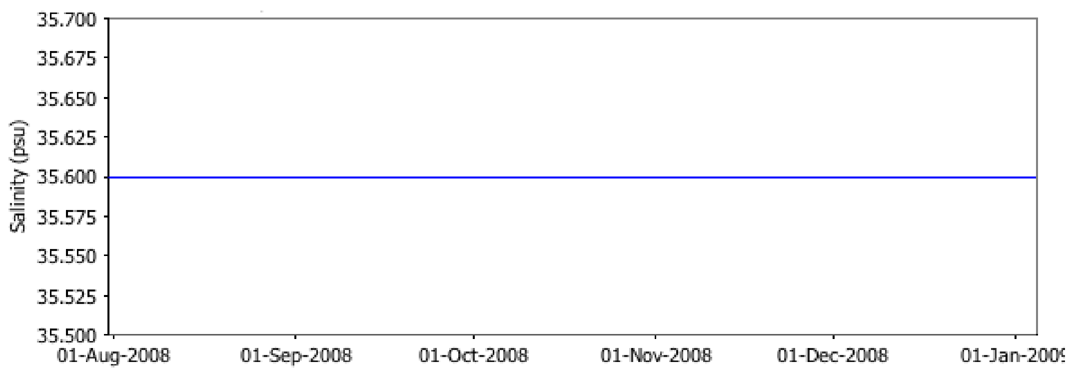


Figure 5-4: Ocean boundary salinity applied to the 2008 simulation.

5.3.4 Meteorology

Meteorological data from the BOM weather station number 061087 at Gosford was applied to the 2008 simulation period. The Gosford weather station is located 15 km to the north of the lower Hawkesbury-Nepean estuary. Observations of wind speed, wind direction, air temperature, relative humidity and rainfall were applied to the model at an hourly frequency. Cloud cover from 9 am and 3 pm observations were applied and were interpolated by the model at each timestep. Hourly solar radiation observations from Prospect Reservoir (SCA data, *pers. comm.*) were applied. The 2008 meteorological data is shown in Figure 5-5.

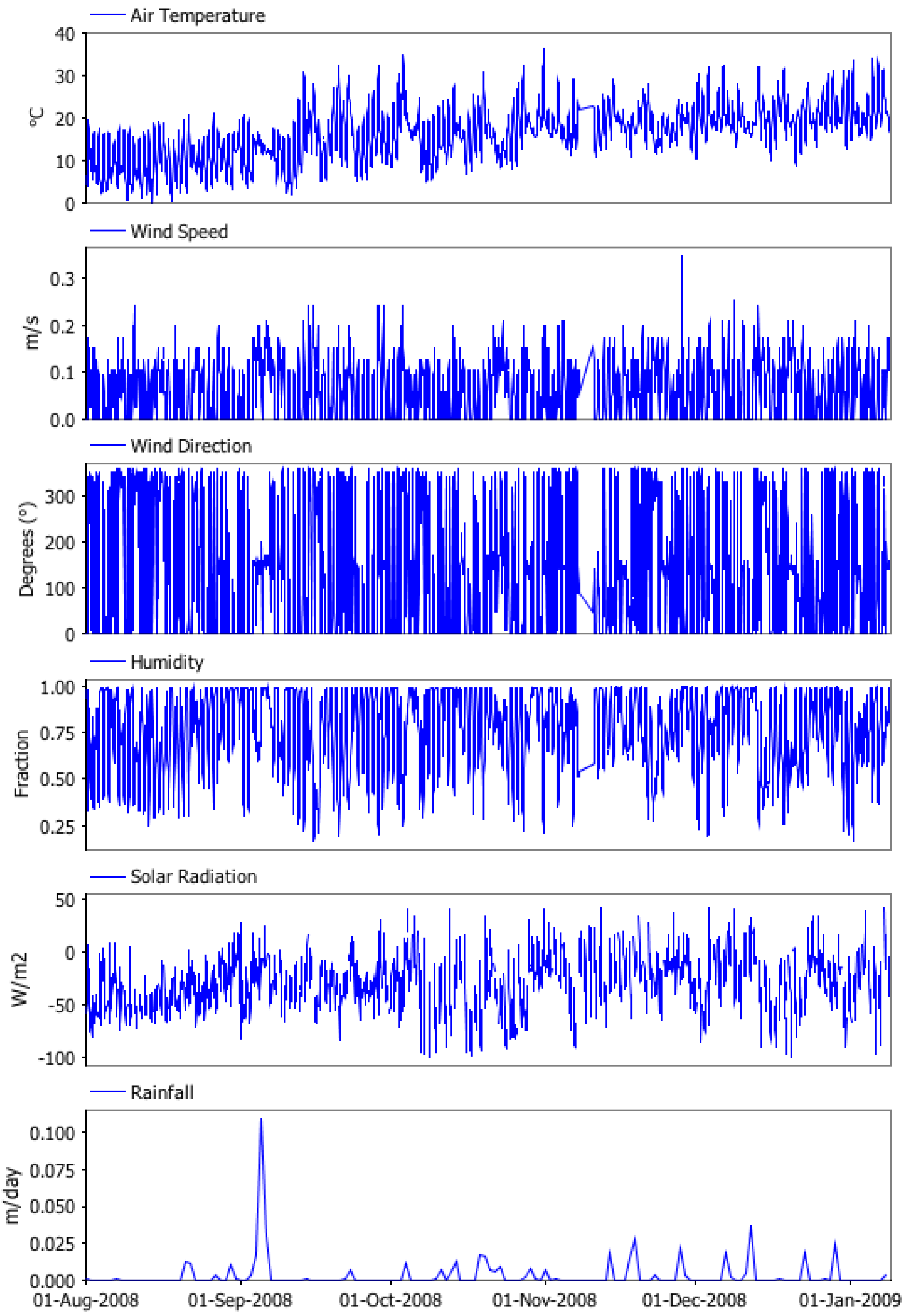


Figure 5-5: Meteorological data from Gosford weather station 067033 applied to the 2008 simulation period.

5.3.5 Model Configuration and Initial Conditions

Table 5-4 presents the applied ELCOM configuration. Initial conditions for the 2008 simulation period are presented in Table 5-5. The 2008 period was commenced at midday on 1 Aug 2008 and ceased on 31 Dec 2008. The simulation was initialised with a uniform water height at -0.5 m AHD, which was the observed water height at Gunyah Point at midday on 1 Aug 2008. Temperature was initialised with a horizontal gradient according to surface observations at the six gauges locations on 1 Aug 2008. The simulation was initialised with 0 psu uniform salinity. A spin-up period of approximately 10 simulation days was required for the model to match the observed gradients of water height, salinity of temperature in the estuary. An initial salinity of 0 psu was selected as the best starting condition from a series of configuration tests of the model, provided a spin up period was allowed. From this initial condition the model was able to arrive at the observed balance of fresh and saline water in the estuary.

Table 5-4 ELCOM configuration parameters applied to the Hawkesbury-Nepean estuary.

Description	Setting	ELCOM reference
Model timestep	60 seconds (60)	del_t
Closure model	Configuration 6 (6)	iclosure
Surface thermodynamics	On (1)	iheat_input
Inflow/outflow model	On (1)	iflow
Scalar temperature transport	On (1)	itemperature
Scalar salinity transport	On (1)	isalinity
Scalar density transport	On (1)	idensity
Rainfall input	Off (0)	irain
Atmospheric stability correction	On (1)	atmstability
Default boundary condition	No slip all (1)	DEFAULT_BC
PAR extinction coefficient	0.4	DEFAULT_PAR_EXTINCTION
UVA extinction coefficient	Default (1)	DEFAULT_UVA_EXTINCTION
UVB extinction coefficient	2.5	DEFAULT_UVB_EXTINCTION
NIR extinction coefficient	Default (1)	DEFAULT_NIR_EXTINCTION
Horizontal diffusivity	Off (0)	DEFAULT_DIFFUSIVITY
Bottom drag coefficient	0.0	drag_btm_cd

Table 5-5 Initial conditions of the 2008 simulation period.

Initial conditions	Data	Source
Start date	1 Aug 2008 12:00PM	HSC
End date	30 Dec 2008 11:00PM	HSC
Initial surface height	-0.5 m AHD	HSC gauges, Aug 2008
Initial salinity	0 psu	-
Initial temperature	6 initial profiles to set up an approximated horizontal variability. Vertical gradients not accounted for.	HSC gauges, Aug 2008

5.4 Model Application

5.4.1 Assessment of Performance

Simulated water temperature, salinity and water height were compared to data at six field gauges (Figure 5-6). The gauges at Gunderman, Spencer and Gunyah Point provided hourly water heights. The gauges at Laughtondale, Couranga Point and Gunyah Point provided surface observations of salinity and water temperature at hourly intervals. Model output at the surface was compared with the field data.

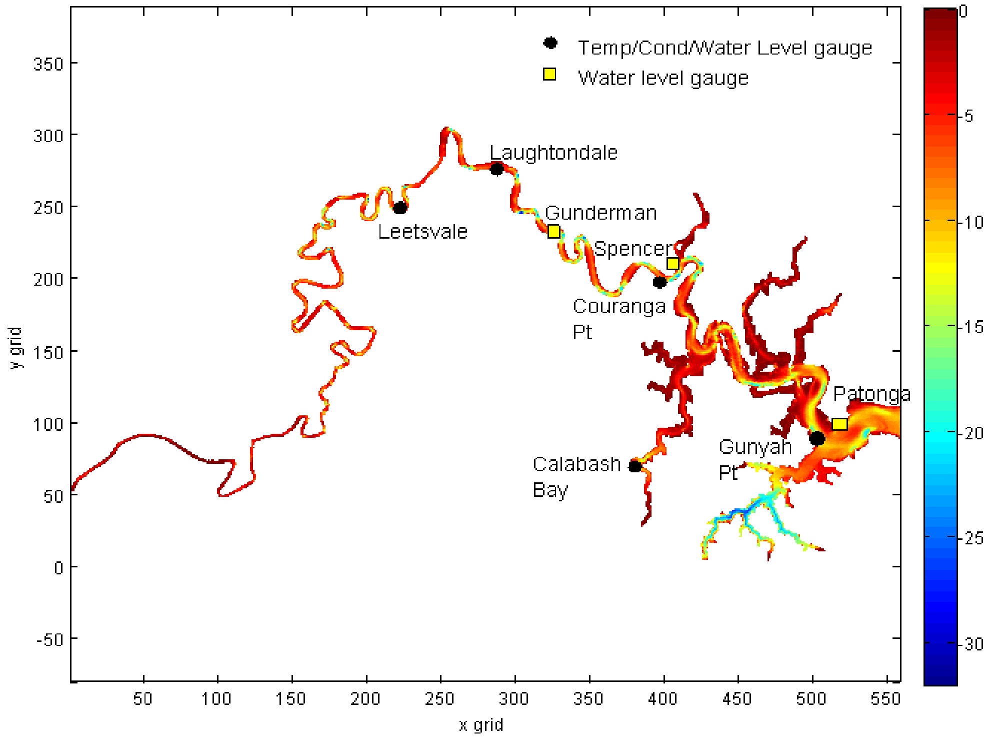


Figure 5-6:Locations of *in-situ* temperature, conductivity and water level gauges.

5.4.2 Scenario Modelling

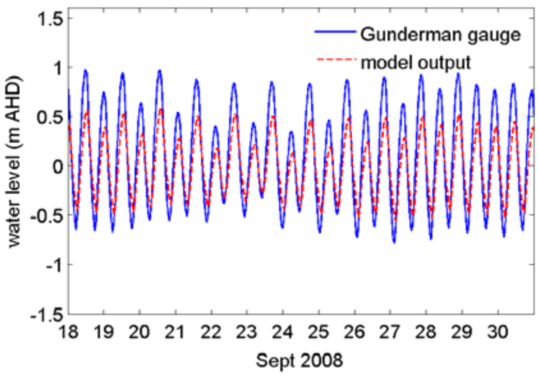
Profile outputs were produced at 18 key habitat locations. Hourly water height, surface salinity, air temperature and surface temperature (at 1m depth) were provided to the client in text files. A summary of the maximum change of water depth, salinity and temperature at each site in comparison with baseline conditions is presented in Chapter 6.4.

5.5 Model Performance Results

The model performance was compared with measured water level, salinity and temperature time series from key locations in the estuary. The model performance was further assessed in vertical transects showing the salinity profile from the head of the estuary to the estuary mouth.

5.5.1 Water levels

The original model captured the tidal oscillations and the tidal lag in the upper estuary but underestimated the amplitude by up to 50%. Modifications resulted in a marked improvement in the simulation of water levels in the upper and mid estuary (Figure 5-7 and Figure 5-8). While the modifications, namely the increase of tidal amplitude by 25% to account for forcing outside of the heads (tidal data outside of the Hawkesbury heads was not available) produced a better match inside the estuary, there was an effect of over-amplification in the lower estuary (Figure 5-9). For further modelling efforts tidal data from outside the heads should be considered.



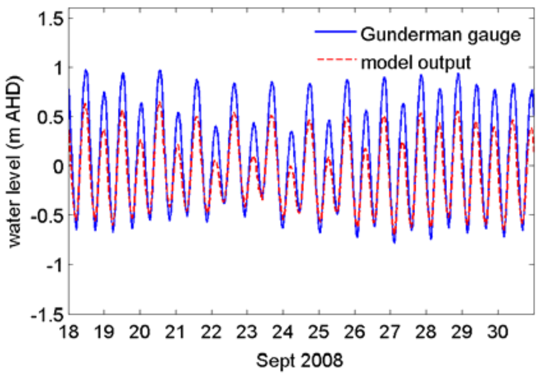


Figure 5-7: Simulated versus measured water levels in the upper estuary at Gunderman before model improvements (left panel) and after model improvements (right panel).

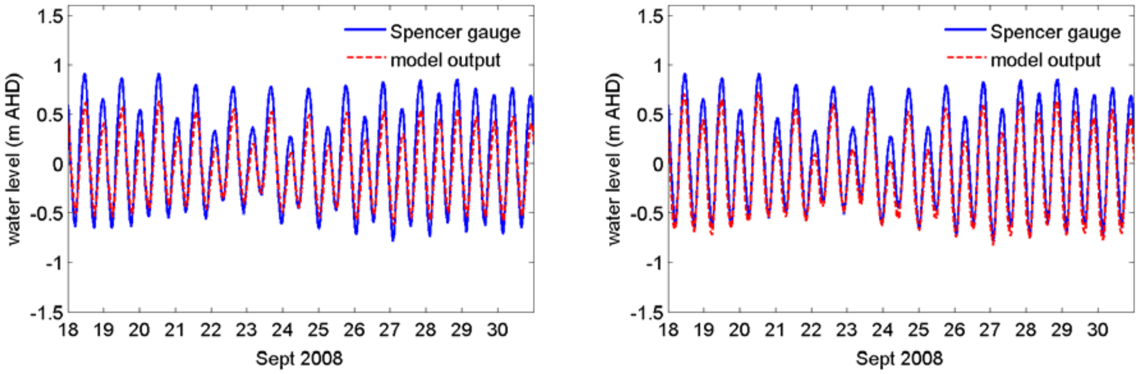


Figure 5-8: Simulated versus measured water levels in the mid estuary at Spencer before model improvements (left panel) and after model improvements (right panel).

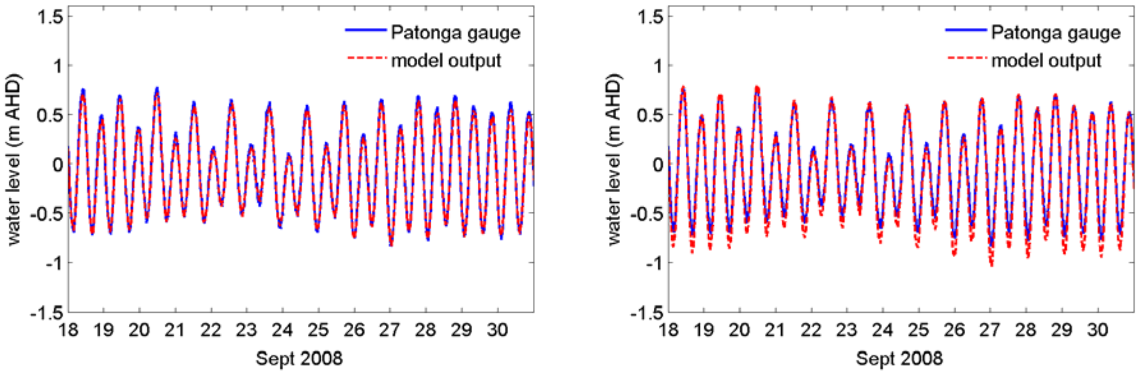


Figure 5-9: Simulated versus measured water levels in the mid estuary at Gunyah Pt. before model improvements (left panel) and after model improvements (right panel).

5.5.2 Salinity and Temperature

The original model was not reproducing the observed salinity and temperature dynamics. From a series of data analyses and simulation tests it was concluded that:

- The freshwater budget was in deficit by a factor of 1.66 during high flow events, which was most likely attributed to inaccurate stream gauges in particular the Penrith Weir, which is widely regarded to contain over 50% inaccuracy (HSC 2009a); and
- Bathymetric drag resulted in an insufficient downstream flow during low water levels, which resulted in reduced flushing of salt from the upper estuary.

Modifications markedly improved salinity and temperature in the upper estuary, mid-estuary and lower estuary (Figure 5-10, Figure 5-11 and Figure 5-12). A maximum difference of 4 psu salinity occurred at times in the upper estuary, and temperature differed by up to 5°C. This is attributed to the assumed values of salinity and temperature that were applied at the ocean boundary. Further improvement of the model could be made with improved forcing data at the ocean boundary, improved gauging of freshwater flows, and an update of the bathymetry data in the upper estuary to potentially resolve the remaining differences in the estuary model.

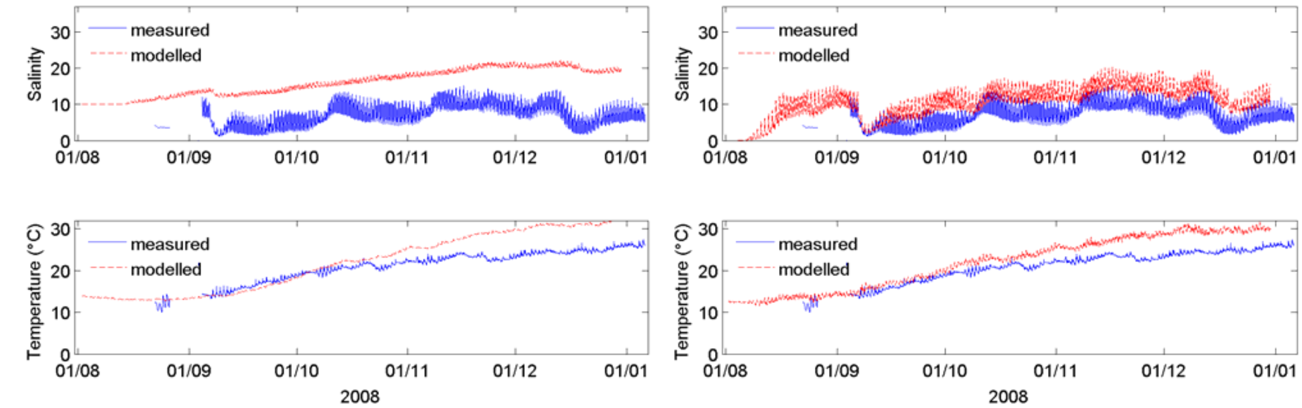


Figure 5-10: Laughtondale original and modified model output versus observed data. Top and bottom left: salinity and temperature in the original configuration, Top and bottom right: salinity and temperature in the modified configuration. Simulate output are red, observed data are blue.

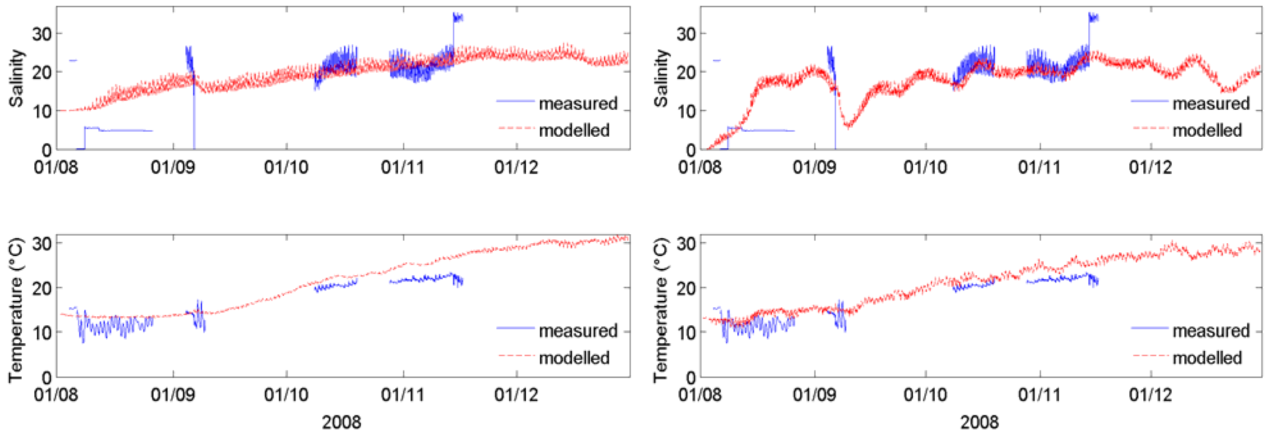


Figure 5-11: Couranga Pt original and modified model output versus observed data. Top and bottom left: salinity and temperature in the original configuration, Top and bottom right: salinity and temperature in the modified configuration. Simulate output are red, observed data are blue.

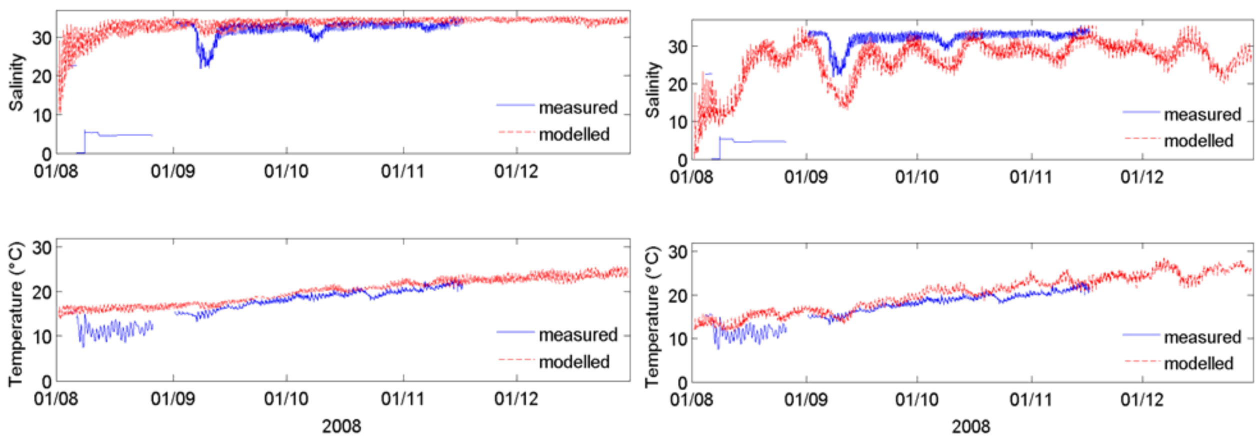


Figure 5-12: Gunyah Pt original and modified model output versus observed data. Top and bottom left: salinity and temperature in the original configuration, Top and bottom right: salinity and temperature in the modified configuration. Simulate output are red, observed data are blue.

5.5.3 Assessment of Saline Dynamics

July to October 2008 was a relatively dry period with only one notable inflow event occurring on 7 Sept (Figure 5-13). Modelled salinity transects from Windsor to Broken Head are shown for 1 Sept and 9 Sept (Figure 5-14) to demonstrate the simulated salinity profile before and after the 7 Sept inflow event. On 1 Sept 2008 the output suggests that the estuary was partially-mixed after the relatively dry conditions, with a vertically mixed and horizontally varying salinity gradient. This is consistent with reports of a partially-mixed system during dry conditions (NSW Government, 2011). After the inflow event, the simulated salinity profile suggests that freshwater from the flow event discharges over sea water in a salt-wedge formation to the ocean boundary.

Deep holes to -23 m AHD were incorporated in the model bathymetry and these can be seen in the transect from Windsor to Broken Bay. The transect salinity profile after the inflow event demonstrated that there was incomplete flushing of saline water in the deep holes around Wisemans Ferry to Couranga Point. Limited flushing may lead to anoxic conditions.

The salt-wedge was located between Colo River and Couranga Point. A time series of salinity with depth is shown at three locations in this region (Figure 5-15). The September freshwater inflow event penetrated the entire water column at Laughtondale (near Wiseman's Ferry) (left panel, Figure 5-15). Saline water of 20 psu returned as a vertically mixed front by tidal oscillations over the coming weeks. Eight kilometres downstream, at Gunderman, depicts a different salinity profile (centre panel, Figure 5-15). The salinity was vertically mixed prior to the inflow event and after the inflow event a freshwater lens was evident in the upper 5 m while saltier water remained in the lower 7m. This is indicative of the salt-wedge. A further 9 km downstream at Couranga Point, freshwater flow in the September event was confined to a lens in the upper 2m of the water column (right panel, Figure 5-15).

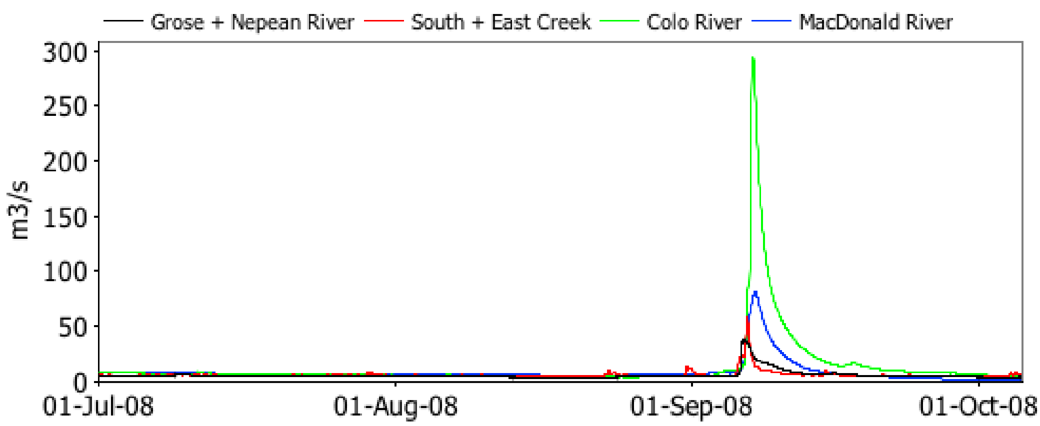


Figure 5-13: Upstream river inflow in the Hawkesbury-Nepean estuary during July to September 2008.

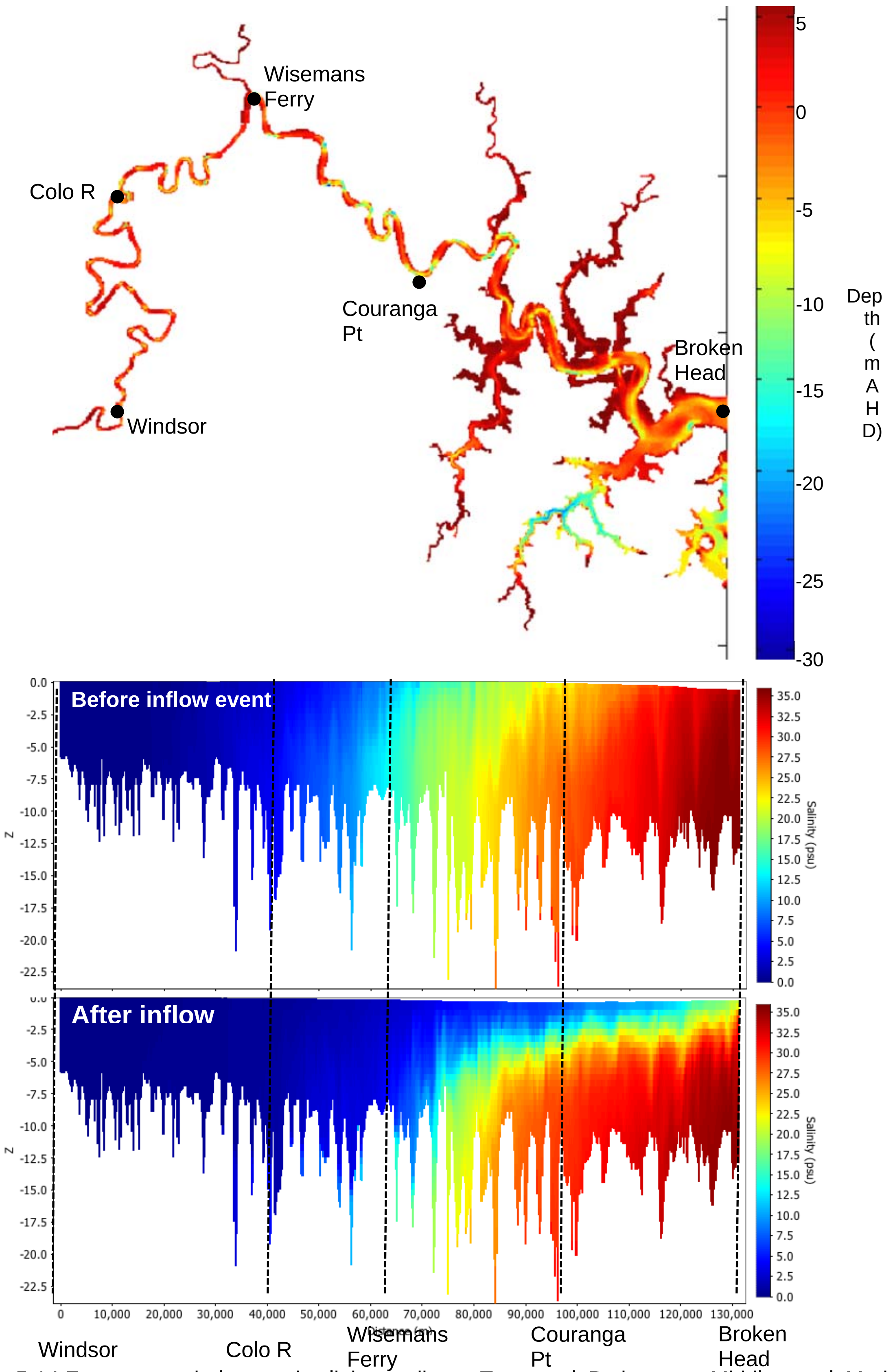


Figure 5-14 Estuary morphology and salinity gradients. Top panel: Bathymetry. Middle panel: Modelled salinity along thalweg from Windsor to Broken Head on Sept 1 2008 after minimal freshwater discharges; Bottom panel: Modelled salinity along same thalweg on Sept 9 2008 after freshwater flow event. Note the corresponding location markers in the top and bottom panels.

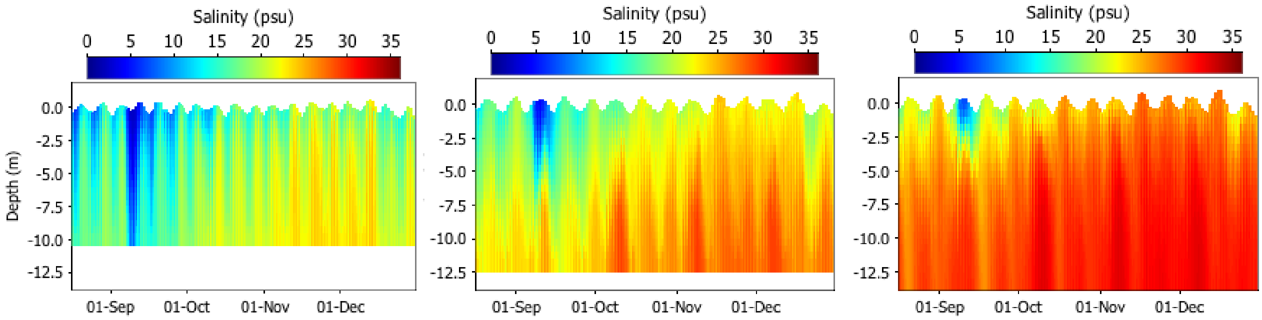


Figure 5-15: Simulated salinity with depth from 18 Aug to 31 Dec 2008 at Laughtondale (left panel), Gunderman (centre panel) and Couranga Point (right panel).

6 Scenario Modelling

6.1 Ecological Data

A list of vulnerable estuarine habitats and their locations in the Lower Hawkesbury estuary were provided by NSW I&I (Table 6-1).

Table 6-1 Locations of selected vulnerable ecological communities for the lower Hawkesbury estuary climate change vulnerability assessment.

Site name	Latitude	Longitude	Ecological description
One Tree Reach	33 25	151 02 38.61	Floodplain wetland.
Farmland	33 26	151 02 57.22	Low lying with retaining wall. Thick MANGROVES.
Couranga Point	33 27	151 07 18.14	SALTMARSH. Privately owned.
Gentlemen's Halt	33 27	151 09 34.64	Saltpan. SALTMARSH. National Park.
Pumpkin Creek	33 29	151 08 43.67	MANGROVES. SALTMARSH. HSC owned.
Seymores Creek	33 22	151 11 57.23	Floodplain forest. MANGROVES.
Brooklyn Oval	33 32	151 12 40.08	Floodplain forest. Mahogany.
Big Bay	33 30	151 07 12.05	MANGROVES. SALTMARSH.
Coba Bay	33 32	151 07 27.59	MANGROVES. SALTMARSH.
Crosslands	33 37	151 06 28.62	MANGROVES. SALTMARSH. Stressed mangroves.
Calna Creek	33 37	151 07 17.23	SALTMARSH. Extensive.
Dangar Island	33 32	151 14 22.66	SEAGRASSES.
Cowan Creek at Bobbin Head Rd.	33 39 50.32	151 09 56.19	SEAGRASSES.
Cowan Creek at Smith's Creek	33 38 49.22	151 12 37.74	SEAGRASSES.
Patonga Creek	33 33	151 15 58.91	SEAGRASSES.
Dangar Is. beach	33 32	151 14 28.34	SEAGRASSES.
Mullet Creek	33 29	151 15 45.22	SEAGRASSES.
Mangrove Creek	33 25	151 10 32.64	SALTMARSH. MANGROVES.

6.2 Physical Projections of Climate Change

Thirty-two scenarios were selected by NSW I&I for simulation. The scenarios consisted of summer and winter periods in a baseline year (1990), 12 scenarios of projected physical change in 2030 and 3 scenarios of projected physical change in 2050. The projections comprised of minimum, average and maximum projected change in mean sea level in the Hawkesbury region, air temperature in the Hawkesbury region and sea surface salinity in the Hawkesbury region (see Chapter 2.3).

The projections were modelled for both summer and winter conditions. The summer period of each year comprised 1 Dec to 1 March, and the winter period of each year was 1 May to 1 August. A total of 32 scenarios were modelled.

Baseline meteorological, oceanographic and hydrographic data was collated from local Hawkesbury locations during the years 1989 and 1990. For scenarios, the baseline observed air temperature, coastal ocean water level, ocean salinity and temperature were adjusted according to the projected change (Table 6-2). The model configuration and applied environmental data of the scenarios are presented further in the following sections.

Table 6-2 Climate change scenarios

Scenarios		**Projections (change from base case)**			
no.	**year**	**Rainfall**[1]	**Sea level (mm)** [2]	**SST (°C)** [2]	**Air Temp (°C)** [2]
1	2030	1990	Max / +362.1	Max / 1.4	Max / 1.5
2	2030	1990	Max / +362.1	Average / 0.9	Max / 1.5
3	2030	1990	Max / +362.1	Max / 1.4	Average / 0.9
4	2030	1990	Max / +362.1	Average / 0.9	Average / 0.9
5	2030	1990	Average / +138.5	Max / 1.4	Max / 1.5
6	2030	1990	Average / +138.5	Average / 0.9	Max / 1.5
7	2030	1990	Average / +138.5	Max / 1.4	Average / 0.9
8	2030	1990	Average / +138.5	Average / 0.9	Average / 0.9
9	2030	1990	Min / -33	Max / 1.4	Max / 1.5
10	2030	1990	Min / -33	Average / 0.9	Max / 1.5
11	2030	1990	Min / -33	Max / 1.4	Average / 0.9
12	2030	1990	Min / -33	Average / 0.9	Average / 0.9
13	2050	1990	Max / +400	Average / 1	Average / 1.5
14	2050	1990	Average / +185	Average / 1	Average / 1.5
15	2050	1990	Min / 120	Average / 1	Average / 1.5
16	1990	1990	Measured (mean is 0.00)	Measured (mean is 20.1°C)	Measured (mean is 17.85 °C)

[1] 1990 measured values for rainfall were applied to all climate change scenarios.

[2] the absolute change from 1990 measured values.

6.3 Climate Change Scenarios Setup

6.3.1 Bathymetry

The improved bathymetry described in Section 5.3 was applied.

6.3.2 Inflows

Gauged river flows from1990 were applied to the 13 model inflow boundaries for the 2030 and 2050 scenarios. STP discharges were not applied to the climate scenarios because of the lack of available data on STP discharges in 1990 and no information on projected wastewater plans for 2030 and 2050. Inflows were not adjusted for any projected change in rainfall or catchment runoff. A list of the inflows and the mean flow rate of the inflows in the 2008 simulation periods are presented in Table 6-3 as a summary of the mean contribution of each inflow during the scenario periods. Inflows were applied at measured daily rates. Inflow rates are shown in Chapter 11. Compared to 2008, the inflows of 1990 were of greater magnitude. This is due to a high rainfall decade occurring from 1981-1990 in the Hawkesbury region. An annual total of 1426 mm precipitation occurred in 1990 at Richmond, compared to 901 mm in 2008 (BOM, 2011). It was beyond the scope of the study to incorporate potential rainfall and catchment runoff change in the 2030 and 2050 scenarios. The 1990 inflow data was held constant across all scenarios.

Table 6-3 Mean inflow rates of the freshwater inflows in the 1990 summer and winter modelling periods.

Freshwater flow	Mean flow rate of 1990 summer period	Mean flow rate of 1990 winter period
Penrith Weir	100	98
South Creek	8.2	8.2
Cattai Creek	2.1	2.1
Colo R	37	38
MacDonald R	2.7	2.7
Mangrove	1.1	1.1
Mooney	2.2	2.2
Mullet Creek	2.2	2.2
Berowra Creek	1.1	1.1
Smiths	2.2	2.2
Cowan Creek	0.6	0.56
Coal & Candle	1.1	1.1
Jerusalem Bay	1.1	1.1
Brooklyn STP	0	0

6.3.3 Ocean Boundary

Ocean water levels recorded at Patonga tidal station in 1990 were applied to the 1990 scenario at a 15 minute interval (Figure 6-1). The 1990 data for temperature and salinity (Figure 5-3 and

Figure 5-4) was applied to the climate change scenarios with an adjustment according to the projected change listed in Table 6-2.

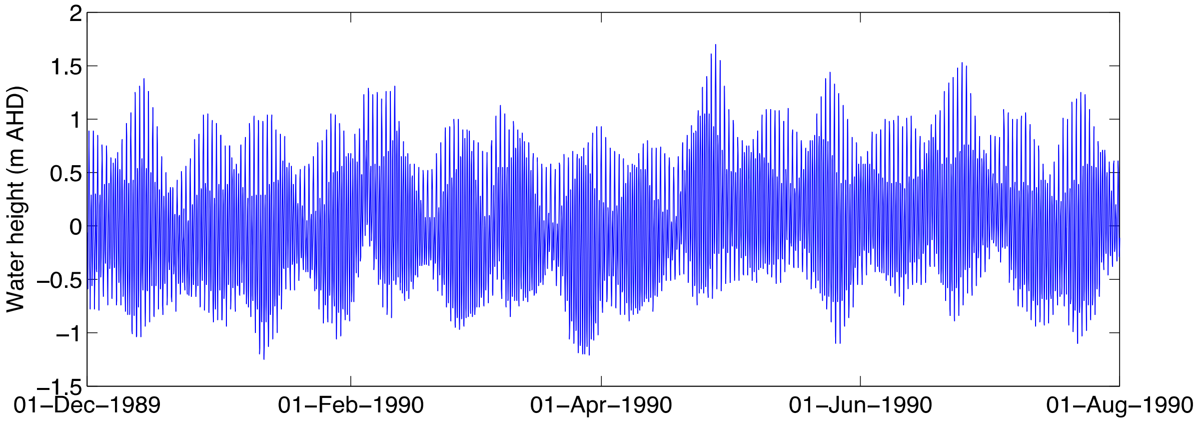


Figure 6-1: Ocean boundary hourly water level applied to the 1990 scenario model.

6.3.4 Meteorology

Meteorological data was not available at Gosford for 1990 (as was applied to the 2008 simulation). Hourly air temperature, wind speed, wind direction, relative humidity and rainfall observations were obtained from Richmond RAAF weather station 067033 for 1989-1990 and were applied to the 1990 and climate change scenarios. Richmond is located within the Hawkesbury-Nepean catchment and is 45 km to the south-west of the lower Hawkesbury-Nepean estuary. All meteorological variables from 1989-1990 were applied to 2030 and 2050 climate scenarios with the exception of air temperature. Air temperature was varied according to project climate change, as per Table 6-2. The 1989-1990 meteorological data is shown in Figure 6-2.

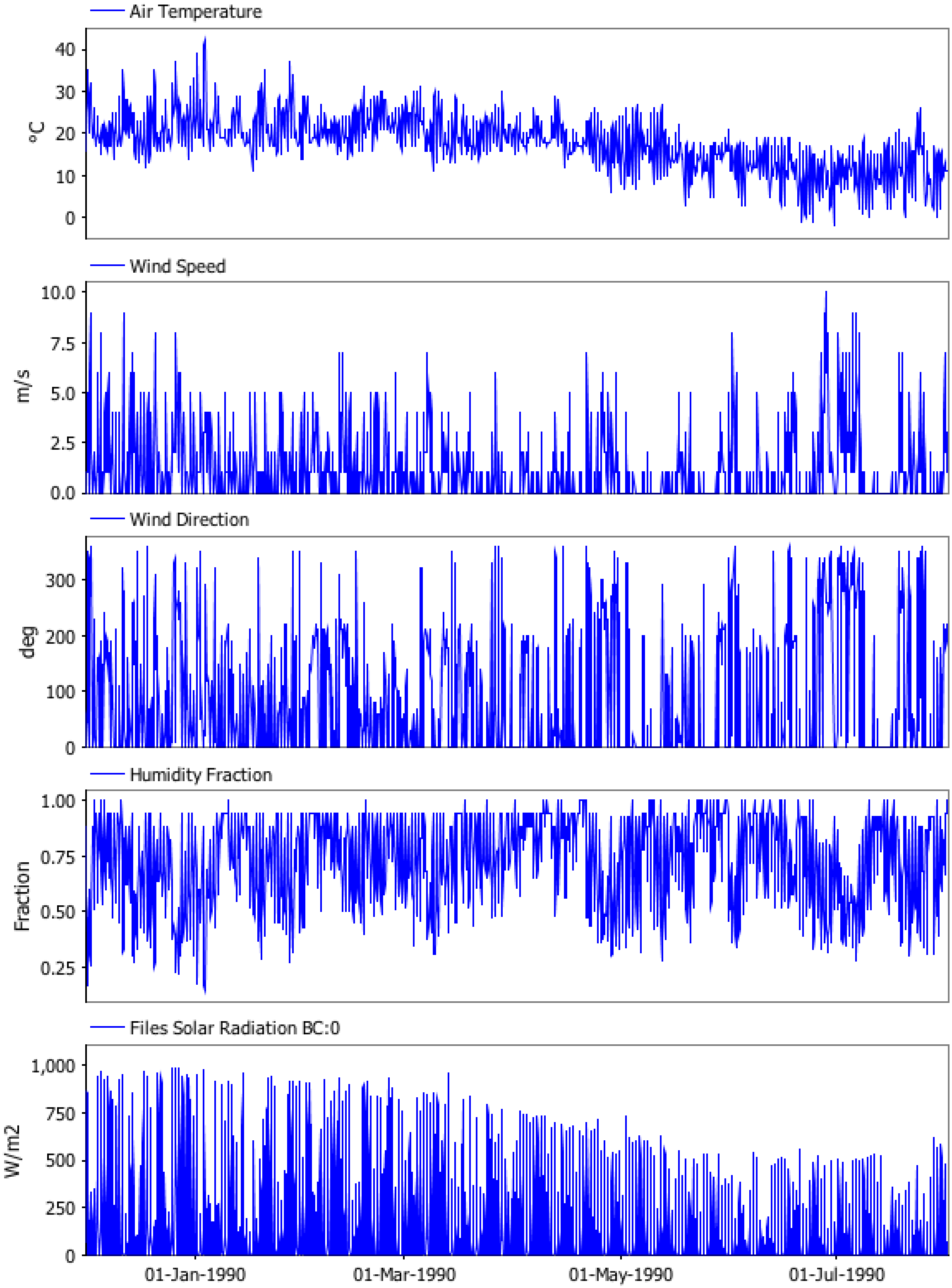


Figure 6-2: Meteorological data from Richmond weather station 067033 applied to the 1990, 2030 and 2050 scenarios, except for where air temperature was varied.

6.3.5 Model Configuration and Initial Conditions

The ELCOM configuration parameters that were applied to the 2008 verification modelling (refer to Table 5-4) were also applied here in the climate scenario modelling. Initial conditions for the 1990, 2030 and 2050 summer scenarios were different to the 2008 period, and are presented in Table 6-4. Initial conditions for the 1990, 2030 and 2050 winter scenarios are presented in Table 6-5. Summer modelling periods commenced on 1 Dec and were ended on 1 Mar for the years 2029-2030 and 2049-2050. The winter simulations commenced on 1 May and were ended on 31 Jul 2030 and 2050.

Table 6-4 Initial conditions in the 1990, 2030 and 2050 summer scenarios

Initial conditions	Data	Source
Start date	1 Dec1989 12:00PM	This project
End date	1 Mar 1990 12:00PM	This project
Initial salinity	0 psu	This project, allowing a spin-up period
Initial temperature	6 initial profiles to set up an approximated horizontal variability. Vertical gradients not accounted for.	HSC gauges, 2008

Table 6-5 Initial conditions in the 1990, 2030 and 2050 winter scenarios

Initial conditions	Data	Source
Start date	2 May 1990 12:00PM	This project
End date	31 Jul 1990 12:00PM	This project
Initial salinity	0 psu	This project, allowing a spin-up period
Initial temperature	6 initial profiles to set up an approximated horizontal variability. Vertical gradients not accounted for.	HSC gauges, 2008

6.4 Climate Change Scenarios Results

A comparison of the mean water depth, salinity, air temperature, percent inundation and water temperature in baseline and projection scenarios is presented by site in Appendix 2. Each site is presented individually and the effect of the projections on mean conditions can be compared. Graphs depicting the dynamic changes at each site are also presented by site in Appendix 2.

Raw output of the scenario results were delivered to NSW I&I for analysis in the habitat vulnerability assessment. The text files were grouped by site and contained the hourly projections of water depth, salinity, air temperature and water temperature.

6.4.1 One Tree Reach

One Tree Reach (Figure 6-3) is a low-lying wetland within an escarpment and riparian zone. The site contains saltmarsh and mangroves. The model output grid cell was +0.61 m AHD at a distance of 100 m inland of the estuary channel (Figure 6-3). The habitat was inundated with water for 2% of time in the baseline scenario (Scenario 1990) to a depth of 0.36 m in summer and 0.32 m in winter (Appendix 2, Table 12-1). Inundation in climate scenarios increased to 21% of time in summer and 29% of time in winter in Scenario 13, to depths of 0.41 m in and 0.42 m respectively.

Mean summer salinity increased from 3.5 psu at baseline (Scenario 1990) to 8.9 psu in the highest sea level scenario (Scenario 13). During winter the mean baseline salinity was 8.2 psu and increased to 8.5 psu in Scenario 13. Winter salinities were less variable and higher in magnitude than summer due to the higher degree of inundation by storm surge, seasonally higher sea levels or increased river height by freshwater input upstream.

Baseline mean water temperature was 23.7ºC in summer and 15.5ºC in winter (Scenario 1990). In the climate change scenarios the mean water temperature increased up to 24.5ºC (Scenario 14) and 16.3ºC (Scenario 9) in summer and winter respectively.

Graphs depicting the range of water depth, temperature and salinity in scenarios for One Tree Reach are presented in Appendix 2, Figure 12-1.

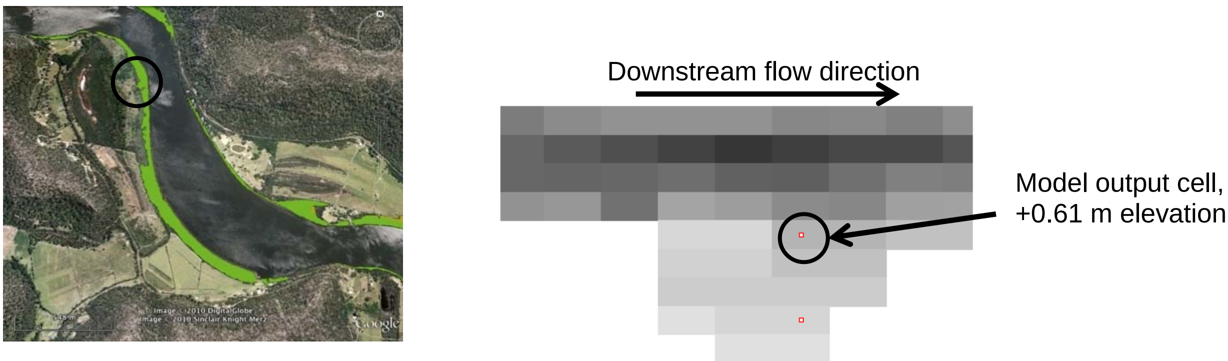


Figure 6-3: One Tree Reach and selected model output location (from Google Earth) (left) and a zoom in of the model grid at the habitat location showing the position of the output cell to represent One Tree Reach (right).

6.4.2 Farmland

Farmland (Figure 6-4) is open and low-lying with mangrove and saltmarsh habitats. The selected grid cell in the model grid was located at +1.61 m AHD elevation at a distance of 400 m inland of the main channel. This cell was dry at all times in the baseline condition (Scenario 1990) and dry in all climate scenarios (Scenarios 1-15, Appendix 2, Chapter 12.2).

Figure 6-4: Farmland and selected model output location (from Google Earth) (left) and a zoom in of the model grid at the habitat location showing the position of the output cell to represent Farmland (right).

6.4.3 Couranga Point

Couranga Pt. is a broad bend in the main river channel that contains saltmarsh and mangroves (Figure 6-5). The model grid cell was +0.61 m AHD at 300 m inland of the estuary channel (Figure 6-5). The habitat was inundated with water for 2% of time in the baseline scenario (Scenario 1990) to a depth of 0.37 m in summer and 0.33 m in winter (Appendix 2, Table 12-3). Inundation in climate scenarios increased to 23% of time in summer and 32% of time in winter (Scenario 13) to a depth of 0.44 m in summer and 0.46 m in winter.

Mean summer salinity increased from 7.6 psu at baseline (Scenario 1990) to 13.9 psu in highest sea level scenarios (Scenario 13). During winter the mean baseline salinity was 14.8 psu and increased in the low sea level scenarios (Scenarios 9, 10 and 11) to 15.5 psu in due to the low projection of minimum sea level rise. Lower sea levels may reduce the tidal flushing resulting in a smaller range of salinity variation. Mixed salinities may also be produced by increased hydrodynamic activity during winter from storm surge and river water levels.

Baseline mean water temperature was 22.5ºC in summer and 15.1ºC in winter (Scenario 1990). In climate scenarios the mean water temperature increased up to 23.9ºC (Scenario 13) and 16.3ºC (Scenario 9) in summer and winter respectively.

Graphs depicting the range of water depth, temperature and salinity in scenarios for Couranga Point are presented in Appendix 2, Figure 12-3.

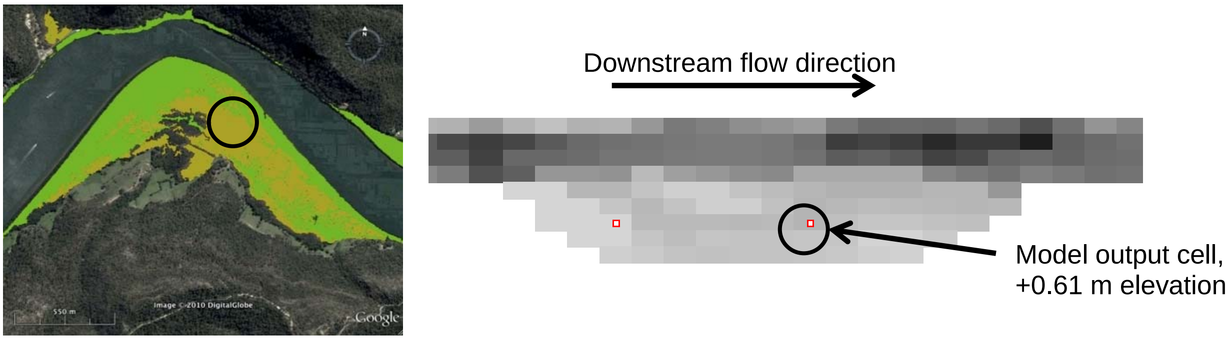


Figure 6-5: Couranga Point and selected model output location (from Google Earth) (left) and a zoom in of the model grid at the habitat location showing the position of the output cell to represent Couranga Point (right).

6.4.4 Gentlemans Halt

Gentlemans Halt (Figure 6-6) is hairpin bend of the main river channel within Marramarra National Park. The site is of a steep elevation and contains saltmarsh and mangrove habitats on the low lying areas. The model grid cell was -1.89 m AHD and was located 100 m inland from the main estuary channel (Figure 6-6). In the baseline scenario (Scenario 1990) the habitat location was always inundated with water to a mean depth of 1.86 m in summer and 1.97 m in winter (1990, Appendix 2, Table 12-4). Inundation occurred for 100% of time in climate scenarios and the mean water depth was 2.35 m in summer and 2.47 m in winter in the highest sea level scenario (Scenario 13).

Mean summer salinity increased from 16.8 psu at baseline to 18.1 psu in highest sea level scenario (Scenario 13). During winter the mean baseline salinity was 16.3 psu and increased to 18.8 psu in the highest sea level scenario (Scenario 13).

Baseline mean water temperature was 23.3ºC in summer and 15.1ºC in winter. In scenarios the mean water temperature increased to 24.5ºC in summer (Scenario 15) and 16.3ºC and winter (Scenario 1).

Graphs depicting the range of water depth, temperature and salinity in scenarios for Gentlemans Halt are presented in Appendix 2, Figure 12-4.

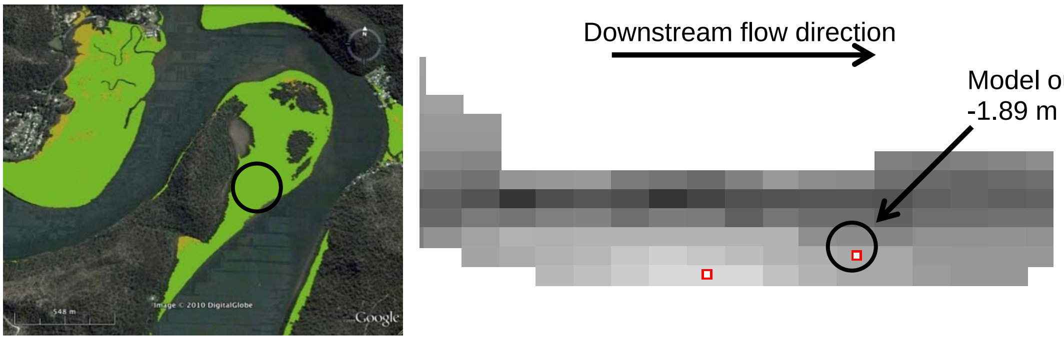


Figure 6-6: Gentlemans Halt and selected model output location (from Google Earth) (left) and a zoom in of the model grid at the habitat location showing the position of the output cell to represent Gentlemans Halt (right).

6.4.5 Pumpkin Creek

Pumpkin Creek (Figure 6-7) is a freshwater creek flowing to the main estuary channel. The surrounding land at Pumpkin Creek is owned by HSC and contains mangrove and saltmarsh habitat. The selected grid cell was-1.89 m AHD located 200 m inland of the estuary channel (Figure 6-7). The habitat was always inundated with water in the baseline at a mean depth of 1.85 m in summer and 1.97 m in winter (Appendix 2, Table 12-5). Inundation occurred for 100% of time in climate scenarios. Mean water depth increased to 2.35 m in summer and 2.46 m in winter in the highest sea level scenario (Scenario 13).

Mean summer salinity increased from 17.0 psu at baseline (Scenario 1990) to 18.2 psu in the highest sea level scenario (Scenario 13). During winter the mean baseline salinity was 16.4 psu and increased to 18.8 psu in the highest sea level scenario (Scenario 13).

Baseline mean water temperature was 23.4ºC in summer and 14.9ºC in winter. In climate scenarios the mean water temperature increased to 24.3ºC in summer (Scenarios 1, 5 and 9) and 16.0ºC in winter (Scenario 1).

Graphs depicting the range of water depth, temperature and salinity in scenarios for Pumpkin Creek are presented in Appendix 2, Figure 12-5.

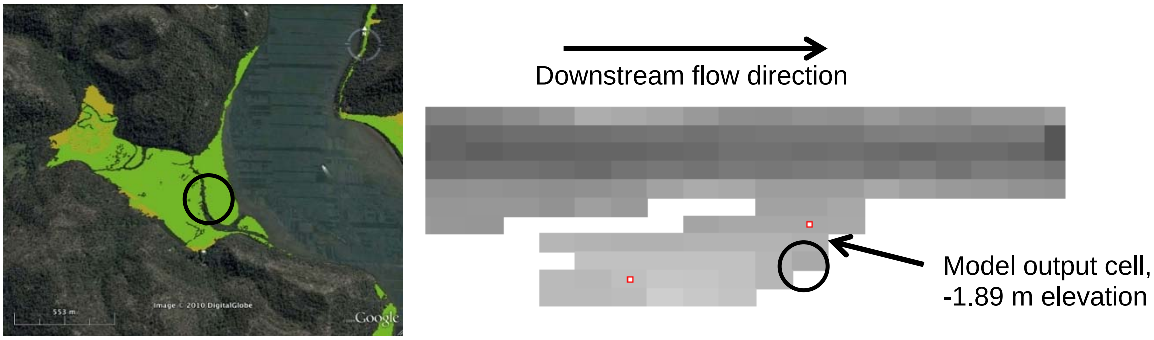


Figure 6-7: Pumpkin Creek and selected model output location (from Google Earth) (left) and a zoom in of the model grid at the habitat location showing the position of the output cell to represent Pumpkin Creek (right).

6.4.6 Seymores Creek

Seymores Creek (Figure 6-8) contains floodplain forest, saltmarsh and mangroves. The model grid cell was located at -0.87 m AHD and a distance of 200 m inland of the estuary channel (Figure 6-8). The habitat was inundated for 91% of time in the baseline with a mean depth of 0.87 m in summer and 0.95 m in winter (Scenario 1990, Appendix 2, Table 12-6). Inundation changed to 97-100% of time in higher sea level scenario (Scenarios 1-8 and Scenario 13, 14 and 15), and 89% of time in lower sea level scenarios (Scenarios 9, 10, 11, 12). The mean water depth increased to 1.30 m in summer and 1.41 m in winter in the highest sea level scenario (Scenario 13).

Mean summer salinity increased from 23.5 psu at baseline to 24.7 psu in highest sea level scenario (Scenario 13). During winter the mean baseline salinity was 24.3 psu and increased to 26.3 psu in the highest sea level scenario (Scenario 13).

Baseline mean water temperature was 23.0ºC in summer and 16.0ºC in winter. In climate scenario 1 the mean water temperature increased to 24.3ºC in summer and 17.3ºC in winter.

Graphs depicting the range of water depth, temperature and salinity in scenarios for Seymores Creek are presented in Appendix 2, Figure 12-6.

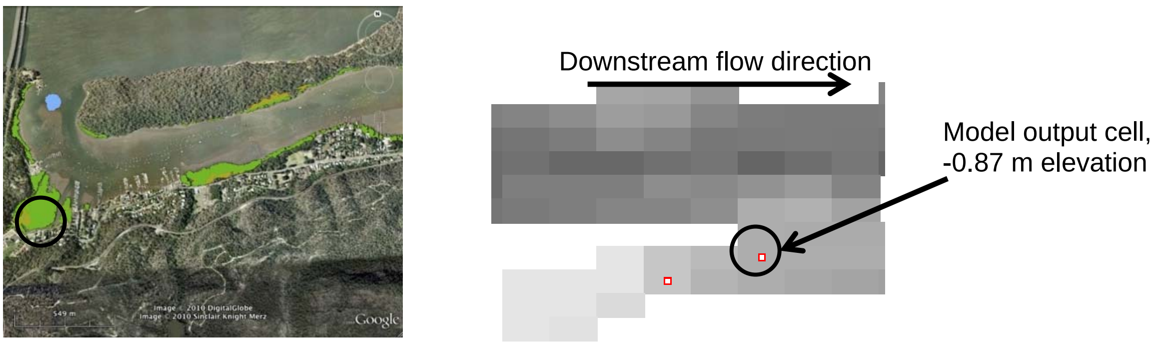


Figure 6-8: Seymores Creek and selected model output location (from Google Earth) (left) and a zoom in of the model grid at the habitat location showing the position of the output cell to represent Seymores Creek (right).

6.4.7 Brooklyn Oval

Brooklyn Oval (Figure 6-9) is a riparian region in the Sandbrook Inlet of the main river channel that is characterised by floodplain forest, mangroves and saltmarsh. The selected grid cell was +1.11 m AHD elevation at a distance of 100 m inland of the estuary channel (Figure 6-9). The site was not inundated with water at any time during baseline conditions (Scenario 1990, Appendix 2, Table 12.7). Inundation increased to 2% during summer (Scenarios 1, 2, 3 and 4) and 3-4% during winter in the highest sea level scenario of 2050 (Scenario 13). Mean water level height during inundation was 0.38 m in summer and 0.35m in winter in these scenarios.

During times of inundation the mean salinity reached 19.5 psu in summer (Scenario 13) and 33.5 psu in winter (Scenario 14).

Mean water temperature during inundation was 23.8ºC in summer (Scenario 1) and 18.9ºC in winter (Scenario 14) in the highest sea level, air temperature and water temperature scenarios of 2030 and 2050.

Graphs depicting the range of water depth, temperature and salinity in scenarios for Brooklyn Oval are presented in Appendix 2, Figure 12-7.

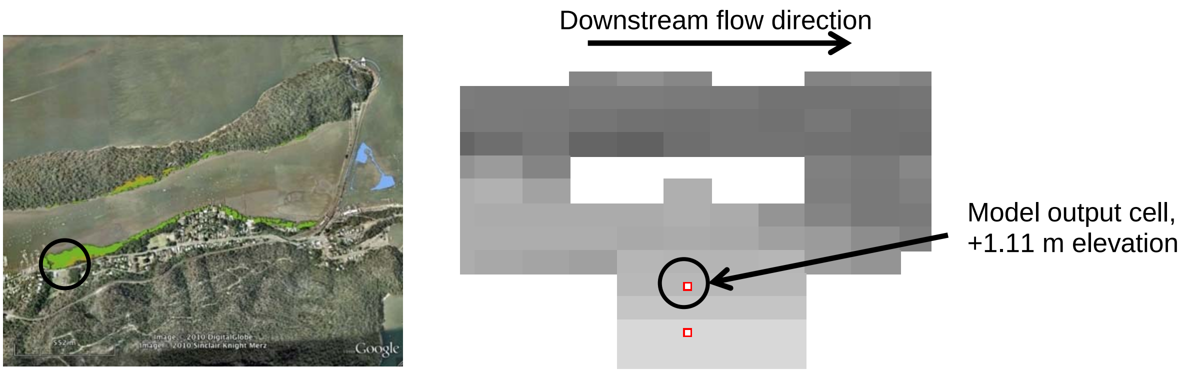


Figure 6-9: Brooklyn Oval and selected model output location (from Google Earth) (left) and a zoom in of the model grid at the habitat location showing the position of the output cell to represent Brooklyn Oval (right).

6.4.8 Big Bay

Big Bay (Figure 6-10) is a low-lying estuarine inlet of Berowra Creek containing mangrove and saltmarsh habitat. The selected grid cell was located at +1.61 m AHD elevation and a distance of 1200 m inside Big Bay from the main channel (Figure 6-10). The habitat was dry at all times during baseline conditions (Scenario 1990). In climate projection scenarios the site was dry at all times except for during one storm, when river height increased by higher upstream freshwater inflow at a time of peak high tide on 2nd Feb (refer to Appendix 1 Figure 11-3 for the inflow data and Figure 6-1 for sea levels). These conditions resulted in inundation of this site in all 2030 and 2050 scenarios (Appendix 2, Table 12-8). This was a stochastic change in the physical conditions at this site caused by storms and river flow in the projected scenarios.

Graphs depicting the range of water depth, temperature and salinity in scenarios for Big Bay are presented in Appendix 2, Figure 12-8.

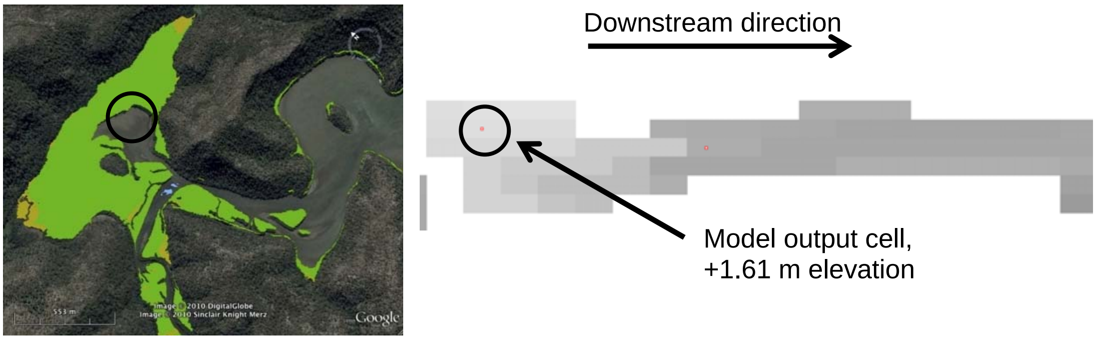


Figure 6-10: Big Bay and selected model output location (from Google Earth) (left) and a zoom in of the model grid at the habitat location showing the position of the output cell to represent Big Bay (right).

6.4.9 Coba Bay

Coba Bay is a freshwater inlet of Berowra Creek. This location contains mangrove habitats (Figure 6-11). The selected grid cell was located at -0.3 m AHD elevation at the end of the channel (Figure 6-11). The habitat was inundated for 54% of time in the baseline summer and 61% of time in the winter with a mean depth of 0.61 m in summer and 0.66 m in winter (Scenario 1990, Appendix 2, Table 12-9). Inundation increased to 93% of time and the mean water depth increased to 0.85 m in summer and 0.92 m in winter in the highest sea level scenario (Scenario 13).

Mean summer salinity increased from 15.4 psu at baseline to 17.4 psu in highest 2050 sea level scenarios (Scenario 13). During winter the mean baseline salinity was 18.0 psu and increased to 20.3 psu in the highest 2030 sea level scenario (Scenario 1).

Baseline mean water temperature was 22.4ºC in summer and 12.6ºC in winter. In climate scenarios the mean water temperature increased up to 23.9ºC in summer (Scenario 15) and 13.7ºC and winter (Scenario 1).

Graphs depicting the range of water depth, temperature and salinity in scenarios for Coba Bay are presented in Appendix 2, Figure 12-9.

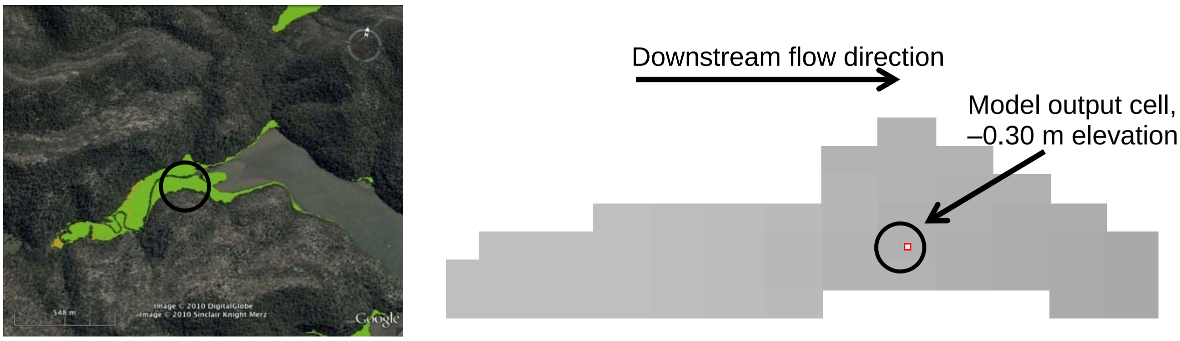


Figure 6-11: Coba Bay and selected model output location (from Google Earth) (left) and a zoom in of the model grid at the habitat location showing the position of the output cell to represent Coba Bay (right).

6.4.10 Crosslands and Calna Creek

Crosslands and Calna Creek habitats are located at the upstream end of Berowra Creek. The site contains saltmarsh and stressed mangroves (Figure 6-12). The selected grid cell was located at -0.39 m AHD elevation within the saltmarsh and mangrove region (Figure 6-12). The habitat was inundated for 60% of time in the baseline summer and 67% of time in the winter with a mean depth of 0.67 m in summer and 0.71 m in winter (Scenario 1990, Appendix 2, Table 12-10). Inundation increased to 96% of time in the highest sea level scenario (Scenario 13), and the mean water depth increased to 0.91 m in summer and 0.99 m in winter.

Mean summer salinity increased from 12.4 psu at baseline to 14.9 psu in highest sea level scenario (Scenario 13). During winter the mean baseline salinity was 17.0 psu and increased to 19.7 psu in the highest sea level scenario (Scenario 13).

Baseline mean water temperature was 22.6ºC in summer and 13.4ºC in winter. In scenarios the mean water temperature increased to 23.9ºC in summer and 14.6ºC in winter (Scenario 1 and 13).

Graphs depicting the range of water depth, temperature and salinity in scenarios for Crosslands and Calna Creek are presented in Appendix 2, Figure 12-10.

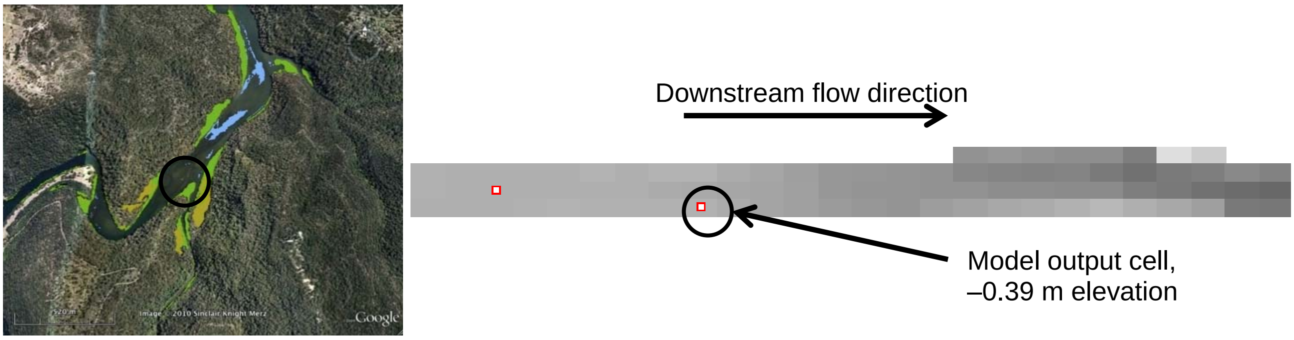


Figure 6-12: Crosslands and Calna Creek and selected model output location (from Google Earth) (left) and a zoom in of the model grid at the habitat location showing the position of the output cell to represent Crosslands and Calna Creek (right).

6.4.11 Dangar Island and Dangar Island beach

Dangar Island is located within the main channel of the lower Hawkesbury-Nepean estuary. The site contains a sandy beach that slopes downward to seagrass beds (Figure 6-13). The selected grid cell in the model was at a -2.39 m AHD elevation and 200 m distance downstream of Dangar Island (Figure 6-13). The habitat was inundated at all times in the baseline scenario with a mean depth of 2.31 m in summer and 2.42 m in winter (Scenario 1990, Appendix 2, Table 12-11). The habitats were at all times inundated during scenarios, and the mean water depth increased to 2.81 m in summer and 2.93 m in winter in the highest sea level scenarios (Scenario 13).

Mean summer salinity increased from 25.3 psu at baseline to 26.3 psu in highest sea level scenario (Scenario 13). During winter the mean baseline salinity was 26.5 psu and increased to 27.9 psu in the highest sea level scenario (Scenario 13).

Baseline mean water temperature was 22.9ºC in summer and 16.5ºC in winter (Scenario 1990). In climate scenarios the mean water temperature increased during summer to 24.1ºC in the highest air temperature scenarios (Scenarios 1, 5 and 9) and 17.8ºC in winter (Scenario 1).

Graphs depicting the range of water depth, temperature and salinity in scenarios for Dangar Island are presented in Appendix 2, Figure 12-11.

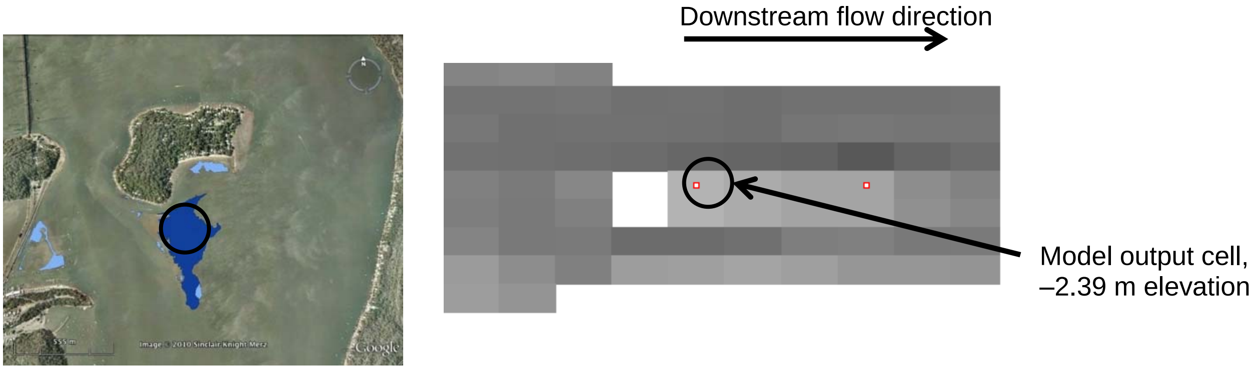


Figure 6-13: Dangar Island and selected model output location (from Google Earth) (left) and a zoom in of the model grid at the habitat location showing the position of the output cell to represent Dangar Island (right).

6.4.12 Cowan Creek at Bobbin Head Rd.

Cowan Creek at Bobbin Head Rd. contains seagrass habitat and mangroves further upstream (Figure 6-14). The selected grid cell was -0.89 m AHD elevation in the region of seagrasses (Figure 6-14). The habitat was inundated at all times in the baseline scenario with a mean depth of 1.33 m in summer and 1.43 m in winter (Scenario 1990, Appendix 2, Table 12-11). The habitats were at all times inundated during scenarios, and the mean water depth increased to 1.83 m in summer and 1.93 m in winter in the highest sea level scenario (Scenario 13).

Mean summer salinity increased from 19.0 psu at baseline to 19.9 psu in highest sea level scenario (Scenario 13). During winter the mean baseline salinity was 25.2 psu and increased to 26.4 psu in the highest sea level scenario (Scenario 13).

Baseline mean water temperature was 23.7ºC in summer and 16.2ºC in winter (Scenario 1990). In scenarios the mean water temperature increased up to 24.7ºC in summer and 17.1ºC in winter (in Scenario 15 and Scenario 1 respectively).

Graphs depicting the range of water depth, temperature and salinity in scenarios for Cowan Creek at Bobbin Head Rd. are presented in Appendix 2, Figure 12-12.

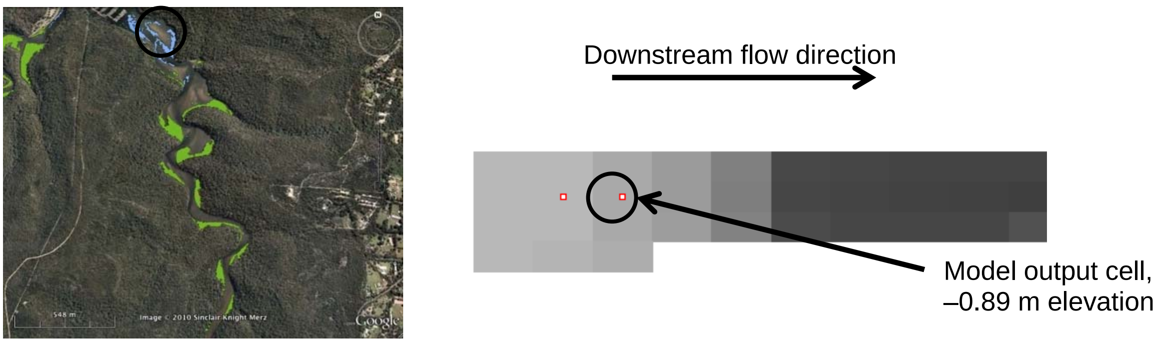


Figure 6-14: Cowan Creek at Bobbin Head Rd. and selected model output location (from Google Earth) (left) and a zoom in of the model grid at the habitat location showing the position of the output cell to represent Bobbin Head Rd (right).

6.4.13 Cowan Creek at Smiths Creek

Cowan Creek at Smiths Creek is a sloping sand bank that contains seagrass beds (Figure 6-15). The selected grid cell was located at -0.89 m AHD elevation at the end of the channel (Figure 6-11). The habitat was inundated for 56% of time during summer and 65% of time during winter in the baseline scenario (Scenario 1990) and was at a mean depth of 0.67 m in summer and 0.70 m in winter (Appendix 2, Table 12-13). Inundation increased up to 91% of time during summer and 95% of time during winter in the highest sea level scenario (Scenario 13), and the mean water depth increased to 0.90 m in summer and 0.98 m in winter in the highest sea level scenario (Scenario 13).

Mean summer salinity increased from 17.5 psu at baseline to 18.7 psu in highest sea level scenario (Scenario 13). During winter the mean baseline salinity was 24.0 psu and increased to 25.3 psu in the highest sea level scenario (Scenario 13).

Baseline mean water temperature was 23.2ºC in summer and 14.6ºC in winter. In climate scenarios the mean water temperature increased to 23.7ºC in summer in Scenario 10 and to 15.5ºC in winter in Scenario 1.

Graphs depicting the range of water depth, temperature and salinity in scenarios for Cowan Creek at Smiths Creek are presented in Appendix 2, Figure 12-13.

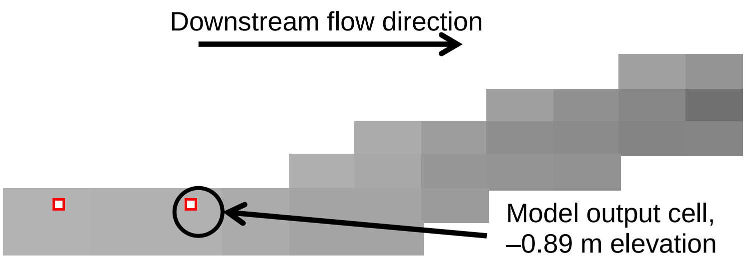


Figure 6-15: Cowan Creek at Smiths Creek and selected model output location (from Google Earth) (left) and a zoom in of the model grid at the habitat location showing the position of the output cell to represent Cowan Creek at Smiths Creek (right).

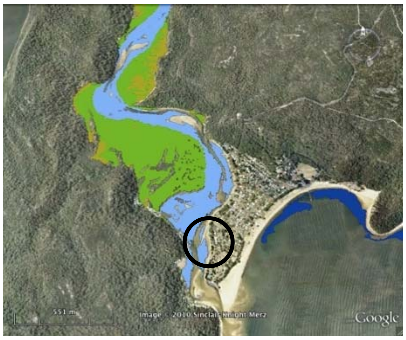
6.4.14 Patonga Creek

The Patonga Creek habitat is a sandy beach that slopes downward to seagrass beds (Figure 6-16). The selected grid cell was located 400 m inland of the main estuary body (Figure 6-16). The habitat was inundated for 91% of time during summer and 96% of time during winter in the baseline scenario with a mean depth of 0.87 m in summer and 0.96 m in winter (Scenario 1990, Appendix 2, Table 12-14). Inundation increased up to 100% of time during summer and 100% of time during winter in the highest 2030 and 2050 sea level scenarios (Scenarios 1, 2, 3, 4 and 13), and the mean water depth increased up to 1.30 m in summer and 1.42 m in winter in the highest sea level scenario (Scenario 13).

Mean summer salinity increased from 25.3 psu at baseline to 26.6 psu in highest sea level scenario (Scenario 13). During winter the mean baseline salinity was 27.6 psu and increased to 29.2 psu in the highest sea level scenario (Scenario 13).

Baseline mean water temperature was 22.7ºC in summer and 16.3ºC in winter. In climate scenarios the mean water temperature increased to 23.9ºC in summer (Scenario 15) and 17.7ºC in winter (Scenario 1).

Graphs depicting the range of water depth, temperature and salinity in scenarios for Patonga Creek are presented in Appendix 2, Figure 12-14.



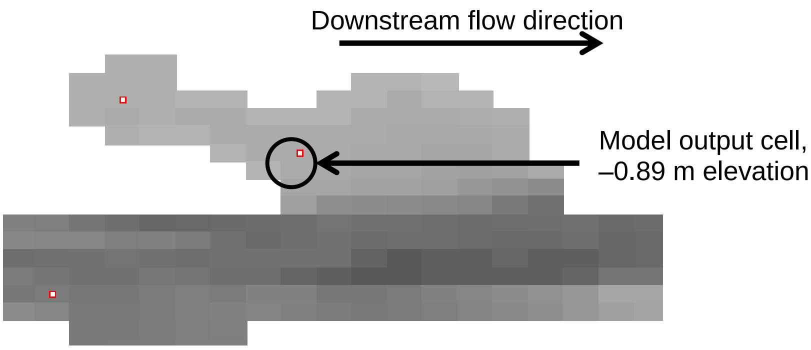


Figure 6-16: Patonga Creek and selected model output location (from Google Earth) (left) and a zoom in of the model grid at the habitat location showing the position of the output cell to represent Patonga Creek (right).

6.4.15 Upper Mullet Creek

Upper Mullet Creek contains seagrass beds, mangroves and saltmarsh (Figure 6-17). The selected grid location to represent the range of habitats was located in the fringing zone of the seagrass to mangrove region. The selected grid cell was at -0.61 m AHD elevation at the end of the channel (Figure 6-17). This location was inundated for 3% of time during summer and 5% of time during winter in the baseline scenario with a mean depth of 0.35 m in summer and 0.34 m in winter (Scenario 1990, Appendix 2, Table 12-15). Inundation increased up to 23% of time during summer and 31% of time during winter, and the mean water depth increased up to 0.46 m in summer and 0.48 m in winter in the highest sea level scenario (Scenario 13).

Mean summer salinity increased from 12.8 psu at baseline to 19.8 psu in highest sea level scenario (Scenario 13). During winter the mean baseline salinity was 23.7 psu and decreased to 22.5 psu in the lowest sea level scenarios (Scenarios 5, 6, 7 and 8). The wide range of the mean baseline salinity indicates that this was a highly variable brackish estuarine environment.

Baseline mean water temperature was 23.0ºC in summer and 15.4ºC in winter. In climate scenarios the mean water temperature increased up to 24.9ºC in summer (Scenario 15) and 16.5ºC in winter (Scenario 9).

Graphs depicting the range of water depth, temperature and salinity in scenarios for Upper Mullet Creek are presented in Appendix 2, Figure 12-15.

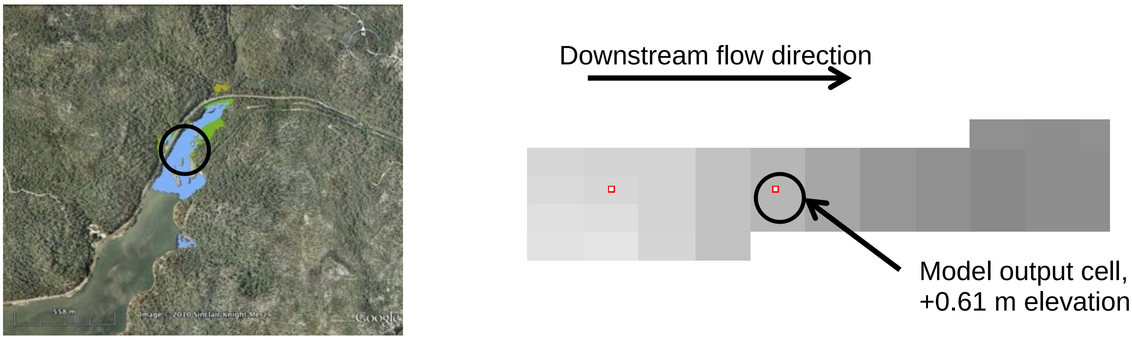


Figure 6-17: Upper Mullet Creek and selected model output location (from Google Earth) (left) and a zoom in of the model grid at the habitat location showing the position of the output cell to represent Upper Mullet Creek (right).

6.4.16 Mangrove Creek at Poporan Creek

Poporan Creek is an inlet of Mangrove Creek. The location contains mangroves and saltmarsh (Figure 6-18). The selected model output grid cell was +0.61 m AHD deep at the end of the channel (Figure 6-18). This habitat was inundated for 100% of time in the baseline scenario with a mean depth of 1.87 m in summer and 1.98 m in winter (Scenario 1990, Appendix 2, Table 12-16). Inundation of the site occurred for 100% of time in all climate scenarios and the mean water depth increased up to 2.36 m in summer and 2.47 m in winter in the highest sea level scenario (Scenario 13).

Mean summer salinity increased from 15.4 psu at baseline to 16.3 psu in highest sea level scenario (Scenario 13). During winter the mean baseline salinity was 15.0 psu and increased to 17.2 psu in the highest sea level scenario (Scenario 13).

Baseline mean water temperature was 23.7ºC in summer and 14.5ºC in winter. In climate scenarios the mean water temperature increased up to 24.9ºC in summer (Scenario 15) and 15.2ºC in winter (Scenario 1).

Graphs depicting the range of water depth, temperature and salinity in scenarios for Mangrove Creek at Poporan Creek are presented in Appendix 2, Figure 12-16.

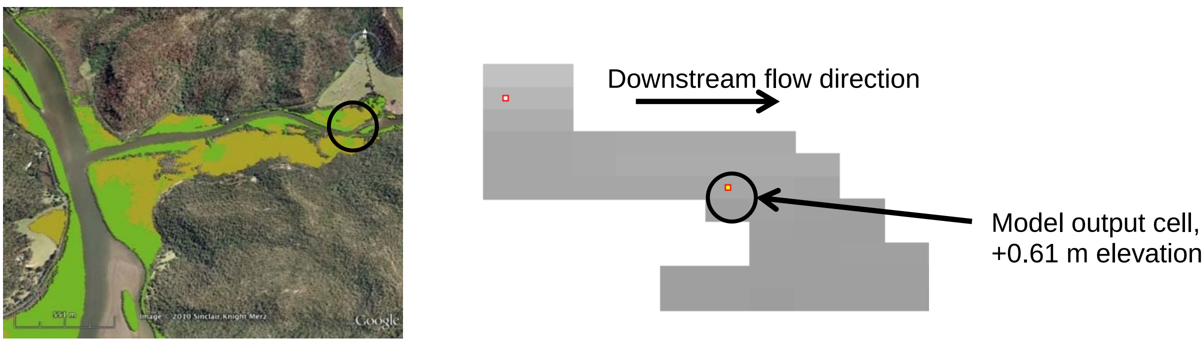


Figure 6-18: Poporan Creek and selected model output location (from Google Earth) (left) and a zoom in of the model grid at the habitat location showing the position of the output cell to represent Poporan Creek (right).

7 Model Uncertainty

7.1 Environmental Data Uncertainty

Limitations in the available environmental data for the model setup and scenario application are presented in Table 7-1.

Table 7-1 Data limitations and assumptions in the modelling procedure.

Uncertainty	Description	Solution	Assumption	Recommendation
Meteorological data in 1990	Gosford weather station data was not available for 1990	Richmond weather data used	Weather conditions at Richmond represent local estuary forcing and will not influence relative results of climate change scenarios	A scaling assessment of weather data at Richmond and Gosford is performed to assess the difference and possible effect on simulated hydrodynamic processes
Ocean boundary data in 1990	Inconsistent water level records at Hawkesbury mouth (Patonga) for the period 1989-1992	Full data record from Port Hacking acquired for this period and offset between the Patonga and Hacking data was noted for summer 1990 (at -0.0075 to -0.0011 m of Patonga water levels) and applied where Hacking data was used	Solution assumes that offset does not vary intra- and interannually	Further correction of this assumption is not recommended. The error is expected to be irrelevant when the assumption is applied consistently across all model simulations so that there is no relative effect.
Catchment landuse, runoff and rainfall change	Changed runoff and freshwater flow regimes from 1990 freshwater discharges have not been considered in this study	No adjustment		Catchment modeling and predictive water reuse modeling might be relevant to regional scope of climate change and hydrodynamic regimes in the estuary
STPs and influence of water management in	Changed freshwater flow regimes from 1990 freshwater	No adjustment		

Uncertainty	Description	Solution	Assumption	Recommendation
1990, 2030 and 2050	discharges are not considered			

7.2 Model Limitations

The following section describes the selection of appropriate scales and the limits of use of the model.

7.2.1 Spatial Scale

The hydrodynamic model ELCOM has been specifically designed to simulate hydrodynamic processes in lakes, estuaries and coastal seas. The scope of this project required a model to simulate physical dynamics at multiple locations of the mid estuary, lower estuary and sub-estuary branches. To accurately simulate oscillations of freshwater and saltwater in the estuary, the model was applied to the 145 km length of the Hawkesbury-Nepean system with sub-estuary side branches. The full estuary configuration was required to ensure accuracy of salt-wedge dynamics, tidal energy and mixing in the upper estuary. The number of grid cells that are contained in the full estuary configuration determines the computational efficiency of the model; more grid cells result in finer scales of computational analysis, less grid cells result in coarser scales and fewer necessary computations. An example of a very fine grid is $10m^2$ to $25m^2$ in the horizontal and 0.1 m layers in the vertical. Fine grids can be applied to small systems, however for large systems such as long estuaries or large lakes, a fine grid results in very long run times due to the increased number of computations that are required for all of the grid cells. Conversely, a course grid scale (e.g. $500m^2$ by 5m) produces quick run times, however the vertical or horizontal gradients of the estuary may not be sufficiently reproduced. Therefore, the balance between runtime and output quality needs to be carefully considered. A number of grid scales were trialled in this study, from $25m^2$, $50m^2$, $100m^2$ and $200m^2$ horizontal and 0.5m, 1m and 2m in the vertical. The results and runtimes were compared and $100m^2$ in the horizontal and 1m in the vertical was found to accurately depict the gradients at a spatial scale that was relevant to the habitat areas (generally of a size greater than 100m). Using this grid, the realtime-to-runtime ratio of the model was 1:80, i.e. 1 day of real time is required to simulate 80 days of model output. This was an acceptable runtime for scenario modelling.

7.2.2 Heating and Cooling

Heating and cooling of water in the model is controlled by the penetration of solar radiation into the water column and fluxes at the surface due to evaporation, sensible heat (i.e. convection of heat from the water surface to the atmosphere) and long wave radiation. Solar radiation is extinguished in the water column according to an extinction coefficient that determines the distance that radiation penetrates the water column before being extinguished to heat. A high extinction coefficient results in a high proportion of solar energy being extinguished to heat in the water column. A low extinction coefficient results in low extinction of solar energy to heat. Where excess radiation reaches the bottom of the water column the energy is reflected back into water column according to a reflectivity coefficient. The portion that is not reflected back into the water column is assumed to be lost from the system as heat into the sediments. This heat is not stored by the model and does not return to the system. Reflected radiation may be further extinguished resulting in further heating the water column on its way back through and the rate is determined by a reflective extinction coefficient.

In an estuary model inundation and recession of water may result in shallow layers of water at habitat locations. In shallow films of water the reflection and extinction coefficients must be accurately applied to ensure that the water temperature does not become unrealistic (e.g. too high if too much light is reflected by the sediments and extinguished within a thin layer of water). A test of the effect of the sediment reflectivity coefficient and reflective extinction coefficient in shallow cells was applied in four simulations. The four simulations tested low and high sediment reflectivity and extinction coefficients (Table 7-2). The effect was assessed at two grid locations to compare the effect on shallow cells: one location was deep (grid location 50, 602 and depth -1.41 mAHD) and one location was shallow (location 50, 601 and depth +0.82 m AHD) and the simulated water depth at these locations varied from 0.6-2.9 m in the deep cell, and 0-1.0 m in the shallow cell (Figure 7-1). Both locations experienced the same ambient conditions.

Test 1 assessed the effect of low (1%) solar reflection by sediments and 0% extinction in the water column. Test 2 assessed high (100%) solar reflection and 0% extinction in the water column. Test 3 assessed high (100%) solar reflection and low (1%) extinction in the water column. Test 4 assessed the effect of total (100%) solar reflection and total (100%) extinction in the water column.

Tests 1 and 2 resulted in a realistic range of simulated temperature in the deep and shallow locations (15-32°C) and the results were in agreement for both locations (Figure 7-2). In Test 3, an increase in the reflection extinction by 1% in Test 3 resulted in warmer temperatures in the shallow location by 5°C due to the higher amount of radiation that reached and was reflected at the bottom. In the deeper cell, less radiation reached the bottom of the water column. Test 4 resulted in unrealistically high temperatures (80°C) in the shallow cell, and spikes of hot water (up to 50°C) in the deep cell as the shallow cell was flushed. Tests 3 and 4 resulted in unstable thermodynamics and the simulation was unable to run to completion.

This exercise was necessary to ensure there was no excessive heating of shallow cells in the estuary model. The coefficients of Test 1 were applied in this project.

Table 7-2 Sensitivity test of sediment reflection and extinction of reflected solar radiation.

Test no.	**Test Parameter**	
	SEDIMENT_REFLECTIVITY (% of solar radiation reflected from bottom sediments)	DEFAULT_RFLCT_EXTINCTION (% of reflected solar radiation extinguished)
Test 1	1%	0%
Test 2	100%	0%
Test 3	100%	1%
Test 4	100%	100%

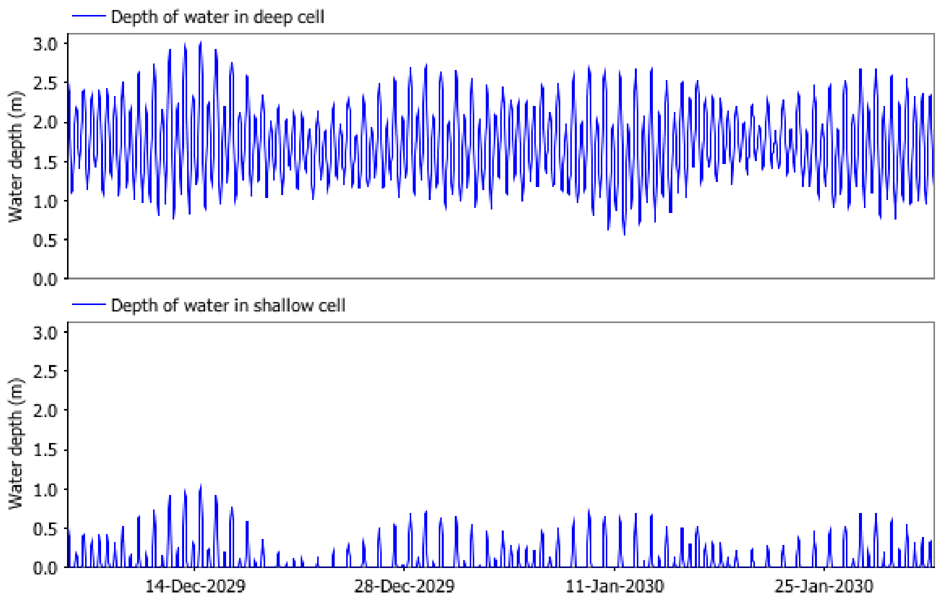


Figure 7-1: Simulated water depth in tested grid location. Top panel: deep location. Bottom panel: shallow location.

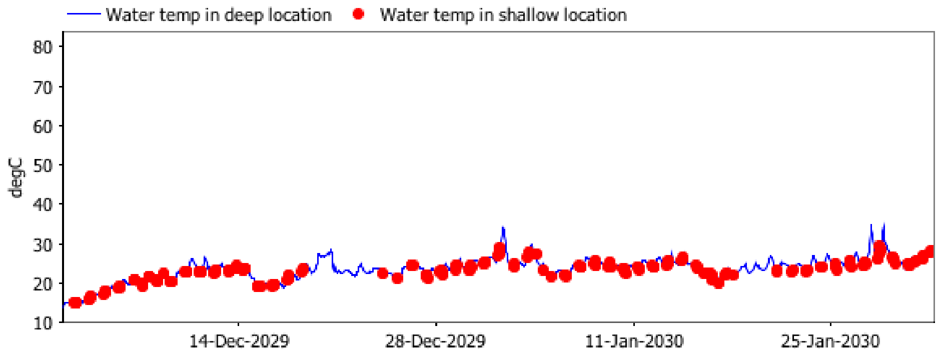


Figure 7-2: Simulated temperature in the deep and shallow locations in Test 1. Results are same for Test 2.

7.2.3 Wetting and Drying

The scale of the grid (100×200×1 m) determines the scale of inundation and water level rise in the model domain. The grid cell applies one single value for land elevation across that whole cell, so a site with variable elevation may not have the full wetting and drying accounted for when mean elevation is applied.

The model results are relevant to the scale of 100 m in the horizontal and 0.2 m in the vertical. This is an appropriate scale to simulate 3-D hydrodynamic processes in the Hawkesbury-Nepean estuary that will determine the broadscale conditions that may occur at the habitat locations. It is recommended that a spatial model is applied to more accurately represent inundation of sites by rising water levels.

8 Summary

The HSC Hawkesbury-Nepean hydrodynamic model was modified to capture the water level variation, saline dynamics and temperature gradients that were measured in field instrumentation. Water height was accurate to within 0.2 m of measured high tide. Inundation may therefore be 0.2 m higher than that reported here. Salinity was overestimated by 4 psu in the upper estuary (upstream of Wiseman's Ferry), within 2 psu in the mid estuary (between Wisemans and Spencer) and with good accuracy of < 1 psu in the lower estuary. Water temperature was within 5°C in the upper estuary above Wismans, within 2°C in the mid estuary (the Couranga Point, Farmland and possibly the Gentlemans Halt locations) and within 1°C in the lower estuary.

The model captures the expected hydrodynamics of the estuary under projected conditions of climate change. Water height and inundation estimates do not account for land-elevation gradients at scales of less than 100 m due to the model grid scale that was used.

Habitat locations were affected by projected sea levels, sea temperatures and air temperatures in a variety of ways. Some sites experienced greater inundation, increased salinity or increased water temperatures than the baseline condition. The most significant general observations were:

- The Farmland site was not inundated during baseline, 2030 or 2050 conditions (Chapter 6.4.2 and Appendix 12.2);
- Big Bay was not inundated in baseline conditions. One event of inundation occurred during summer 2030 and 2050 that corresponded to high ocean water levels and a river flow event (Chapter 6.4.8 and Appendix 12.8);
- Brooklyn Oval was not inundated in baseline conditions, and was inundated by up to 0.4 m of water in climate change scenarios (Chapter 6.4.7 and Appendix 12.7);
- The remaining 13 estuarine habitats experienced increased depths of 0.2 to 0.5 m and increased frequency of inundation;
- A greater increase of water depth occurred in the winter scenarios due to higher sea levels and higher river flows that occurred at this time.

Figure 8-1, Figure 8-2 and Figure 8-3 present the greatest change of water level, salinity and water temperature across all scenarios for the habitats. The values are presented in Table 12-17, Table 12-18 and Table 12-19 in Appendix 2, Chapter 12. The reported value in these figures is the difference between the mean of the baseline condition and the highest mean of all scenarios.

The highest increase in water depth by +0.5m occurred at the two Cowan Creek sites (Bobbin Head Rd. and Smiths Creek), Pumpkin Creek, Poporan Creek and Gentlemans Halt (Figure 8-1). The Cowan Creek sites contain seagrass habitats and the Pumpkin Creek, Poporan and Gentlemans Halt sites contain mangrove and saltmarsh habitats.

All inundated sites demonstrated an increase in mean salinity. Figure 8-2 presents the greatest change of mean salinity for all scenarios. Mullet Creek and Couranga Pt. were most affected, with mean salinity increasing by 6 psu. The greatest increases were observed during summer in scenarios of the greatest sea level rise (both 2030 and 2050). Brooklyn Oval results also indicated a large salinity change because the site was previously not inundated in the baseline conditions. The Brooklyn Oval result is marked in red in Figure 8-2.

Further, the estuary demonstrated more temporally and spatially variability salinity results during summer than winter, suggesting that summer time conditions produce a more stratified state and the system is more mixed during winter. This was observed in both the baseline and projection results. The difference between baseline salinity and 2030/2050 salinity was therefore smaller in winter than during the summer.

Water temperatures increased by 0.5-1.0ºC in the projection scenarios compared with the baseline (Figure 8-3). The scenarios with maximum projected air temperature, maximum projected water temperature and shallower water levels (i.e. the least sea level increase) resulted in the greatest temperature increase at sites. Mean water temperature at Crosslands and Calna Creek, Gentlemans Halt and Patonga Creek increased by 1.0ºC. Brooklyn Oval results also indicate a large water temperature change because the site was previously not inundated in baseline conditions. The Brooklyn Oval result is marked in red in Figure 8-3.

Overall, these results indicate that the shallow, freshwater inlets at the end of estuary side branches (Mullet Creek, Pumpkin Creek, Cowan Creek, Poporan Creek Seymores Creek) experienced the greatest change of mean water level, salinity and water temperature in the projection scenarios. Locations in the well-flushed, broader regions of the estuary, such as One Tree Reach, Coba Bay, Big Bay and Patonga, experienced relatively smaller changes of water level, salinity and temperature. These sites would naturally be more dynamic due to their exposure to more mixed conditions of the wide estuary channel. In comparison, the shallow freshwater inlets would receive less flushing and mixing by marine water. Without an increase in catchment flows, these inlets may experience a relatively larger change of mean conditions with higher sea levels.

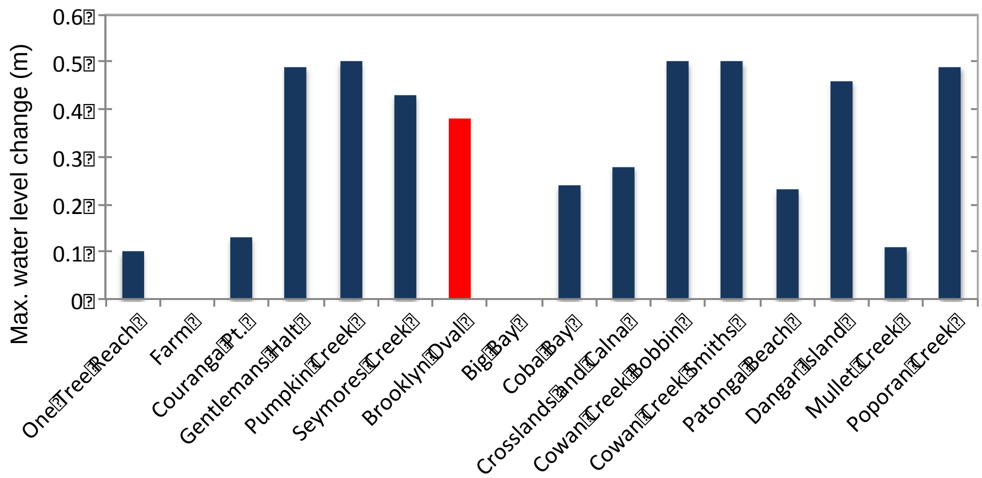


Figure 8-1: Maximum change of water level between baseline and projected scenarios at habitats. Brooklyn Oval experienced new inundation and is indicated in red.

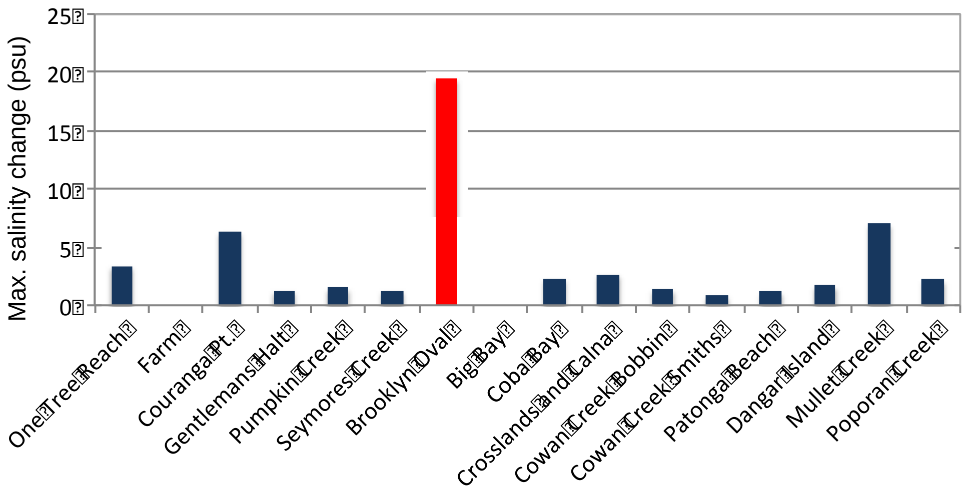


Figure 8-2: Maximum change of salinity between baseline and projected scenarios at habitats. High results caused by new inundation at Brooklyn Oval are indicated in red.

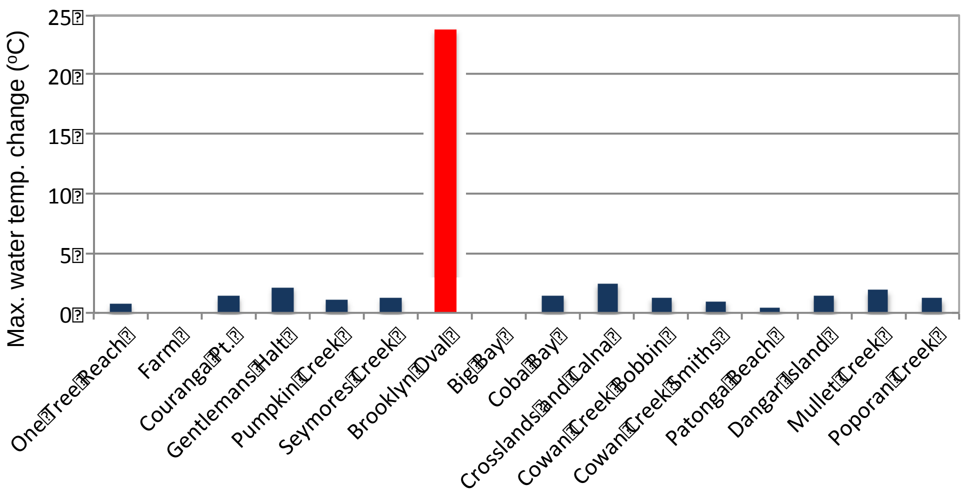


Figure 8-3: Maximum change of water temperature between baseline and projected scenarios at habitats. High results caused by new inundation at Brooklyn Oval are indicated in red.

9 Conclusions

The hydrodynamic model captured the physical dynamics and resulting gradients of the estuary in baseline and projection scenarios. The change of physical properties of the estuary in response to changed ocean and air conditions allowed an assessment of potential climate change impact from a marine perspective on 18 habitats in the estuary.

Habitats experienced increased water depths of up to 0.5 m, increased salinity of up to 6 psu and increased water temperature of up to 1.0ºC. The location with the greatest change was Brooklyn Oval, which was previously dry in baseline conditions and was inundated for up to 4% of time in projections of greatest sea level. Big Bay also demonstrated an extreme change during events of high river flow and high sea levels that produce an influx of estuarine waters onto the site. The sites with the greatest change in mean water level were Cowan Creek at Bobbin Head, Cowan Creek at Smiths Creek, Pumpkin Creek, Poporan Creek and Gentlemans Halt.

Salinity increased at most habitats in the projections. The greatest change in mean salinity was 6 psu at Mullet Creek and Couranga Pt.

Water temperature increased by up to 1°C in 2030 and 2050 projections. The sites with the greatest change in mean water temperature were Crosslands and Calna Creek, Gentlemans Halt and Patonga Creek.

It is recommended that a spatial modelling package is used to further assess flooding and inundation and build upon the results of the hydrodynamic model.

Application of catchment model scenarios to incorporate projected changes in rainfall, runoff, catchment land use and environmental flows could be further applied to this model. Coupling the hydrodynamic model with a water quality model would enable simulation of potential downstream impacts of catchment activities including changed sediment loads with catchment change and flooding, pathogens, nutrients and algae growth. Freshwater and contaminant dynamics could be further investigated to identify locations of limited flushing, hotspots of algal growth, low oxygen and poor aesthetic quality may also be considered to inform future estuary planning and management decisions.

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11 Appendix 1 Model catchment inflow data: 2008 and 1990

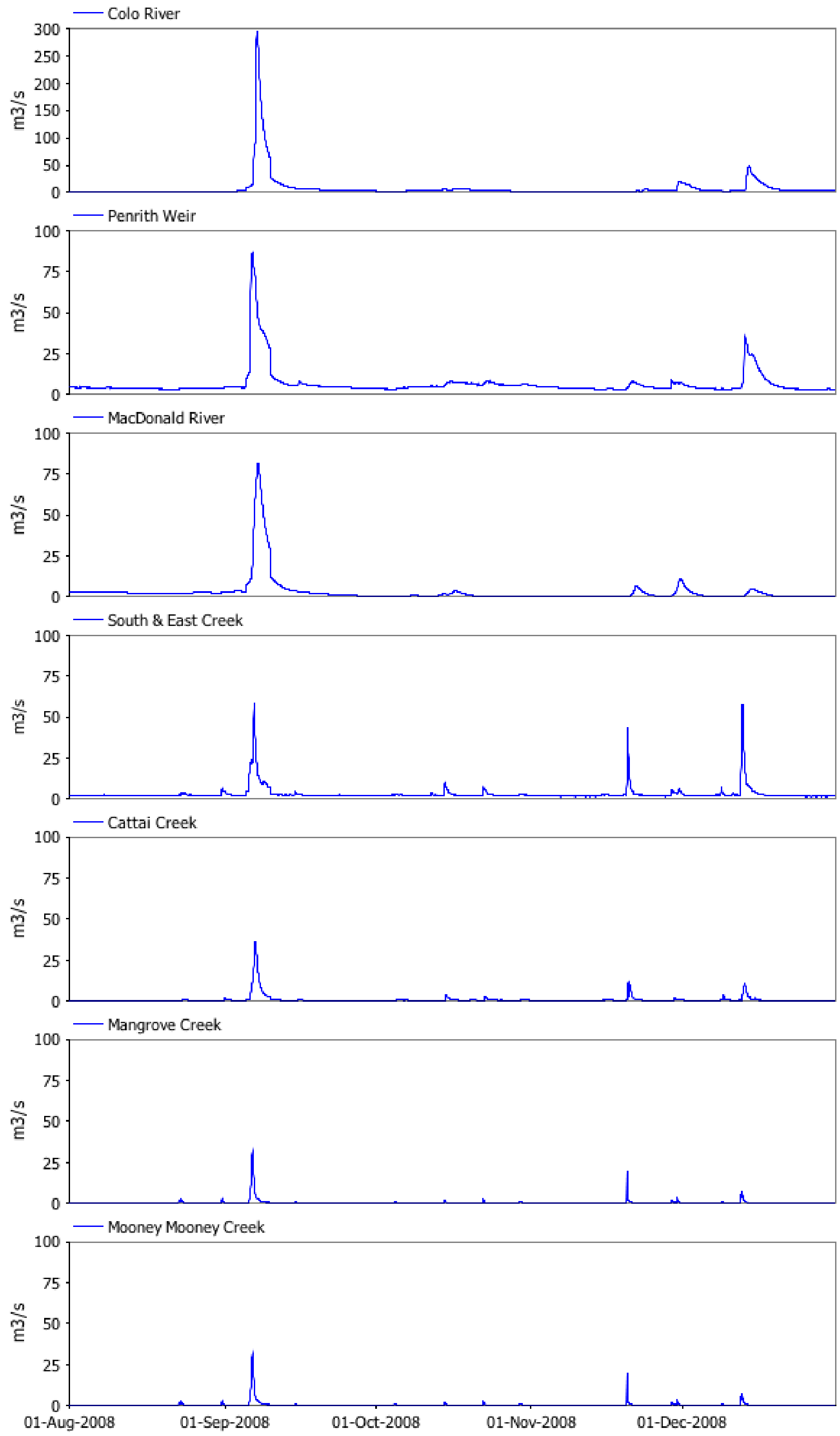

Figure 11-1: Freshwater inflows from upper and mid estuary rivers applied to the 2008 simulation. Note: y axis scales vary among locations.

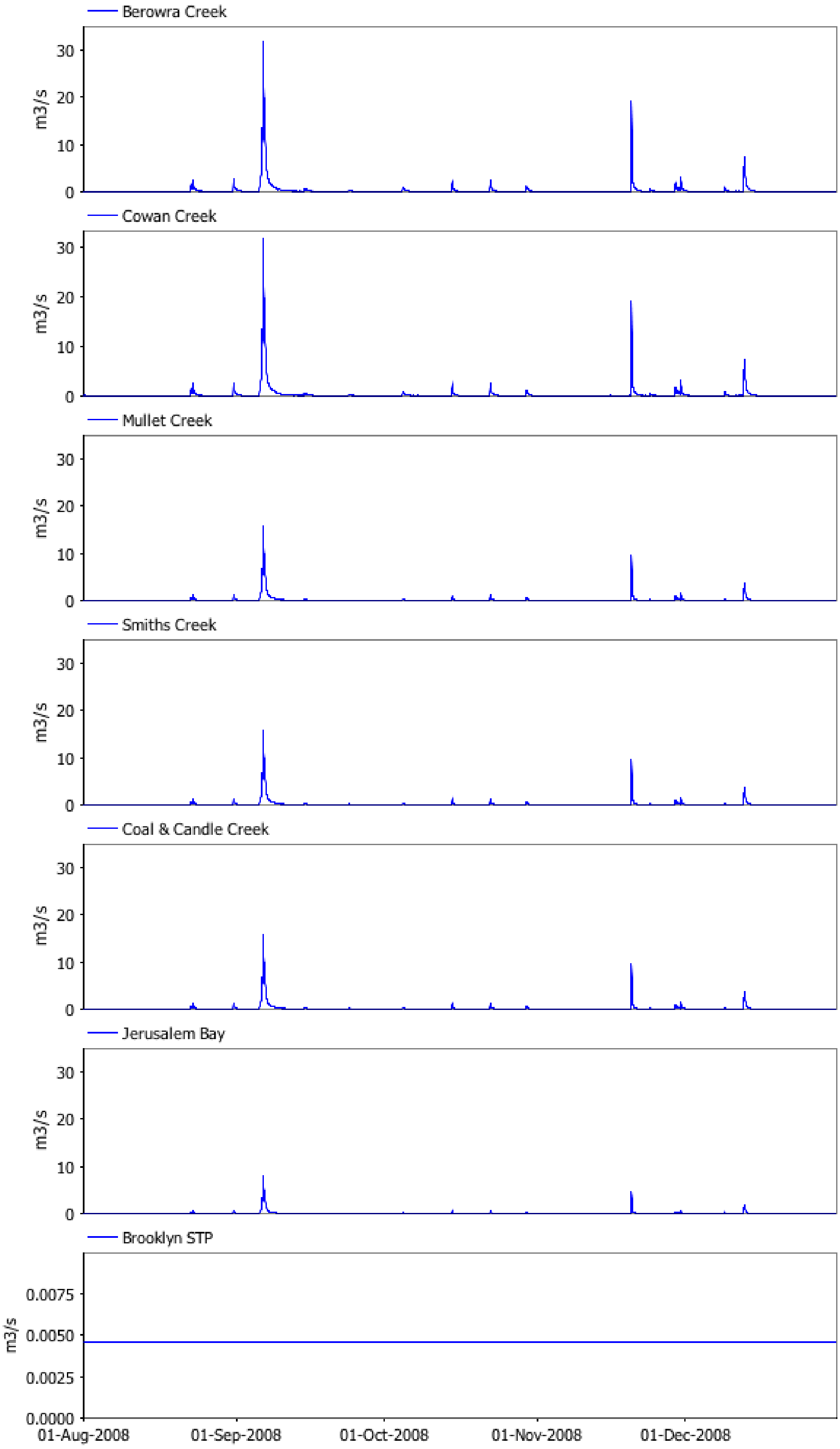

Figure 11-2: Freshwater inflows from lower estuary rivers applied to the 2008 simulation. Note y axis scales vary among locations.

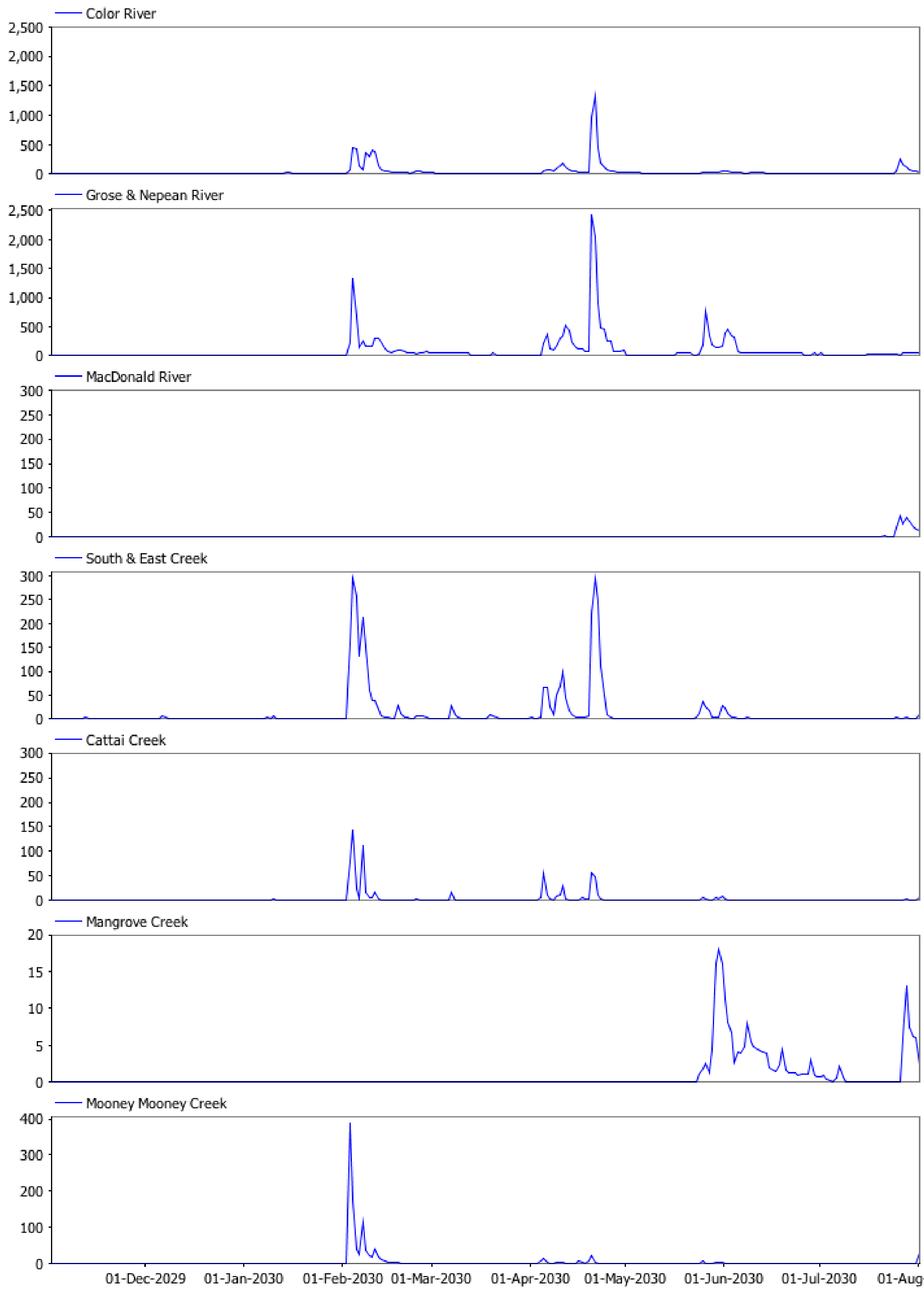

Figure 11-3: Freshwater inflows from upper and mid estuary rivers applied to the 1990, 2030 and 2050 climate change scenarios. Note: y axis scales vary among locations.

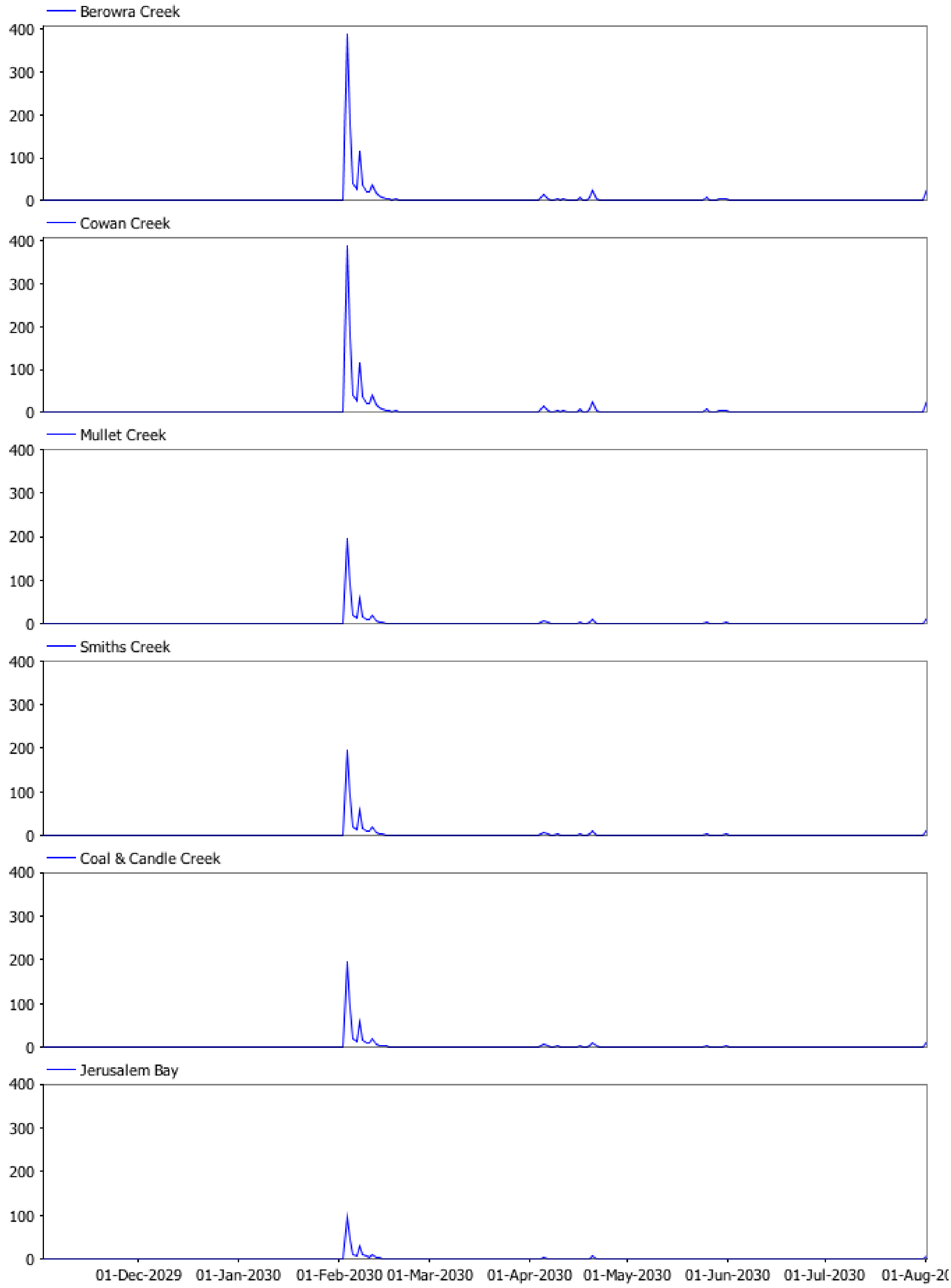

Figure 11-4: Freshwater inflows from lower estuary rivers applied to the 1990, 2030 and 2050 climate change scenarios. Note y axis scales vary among locations.

12 Appendix 2 Scenario Modelling Results

12.1 One Tree Reach

Table 12-1 Simulated mean physical conditions at One Tree Reach. Bold type shows the baseline and the most changed condition.

Scenarios	**1990**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Summer means																
Water depth (m)	**0.36**	0.41	0.41	0.41	0.40	0.40	0.40	0.40	0.40	0.36	0.36	0.36	0.36	**0.41**	0.38	0.40
Water temp. (°C)	**23.7**	24.3	24.3	23.8	23.7	23.9	23.9	23.5	23.5	24.3	24.2	23.9	23.9	24.2	**24.5**	23.9
Salinity (psu)	**3.50**	8.45	8.51	8.50	8.42	5.73	5.76	5.71	5.73	3.24	3.39	3.43	3.35	**8.89**	6.44	5.57
Inundation (%)	**2**	17	17	17	17	4	4	4	4	2	2	2	2	**21**	6	4
Air temp. (°C)	**21.7**	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	**23.2**
Winter means																
Water depth (m)	**0.32**	0.40	0.40	0.40	0.40	0.32	0.32	0.32	0.32	0.30	0.30	0.30	0.30	**0.42**	0.33	0.33
Water temp. (°C)	**15.5**	15.1	15.0	14.8	14.7	15.5	15.4	15.2	15.1	**16.3**	16.2	16.0	15.9	15.0	15.4	15.5
Salinity (psu)	**8.16**	8.33	8.34	8.29	8.32	7.79	7.82	7.78	7.81	7.85	7.88	7.83	7.87	**8.54**	8.01	7.96
Inundation (%)	**2**	26	26	26	26	7	7	7	7	1	1	1	1	**29**	9	5
Air temp. (°C)	**12.0**	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	**13.5**

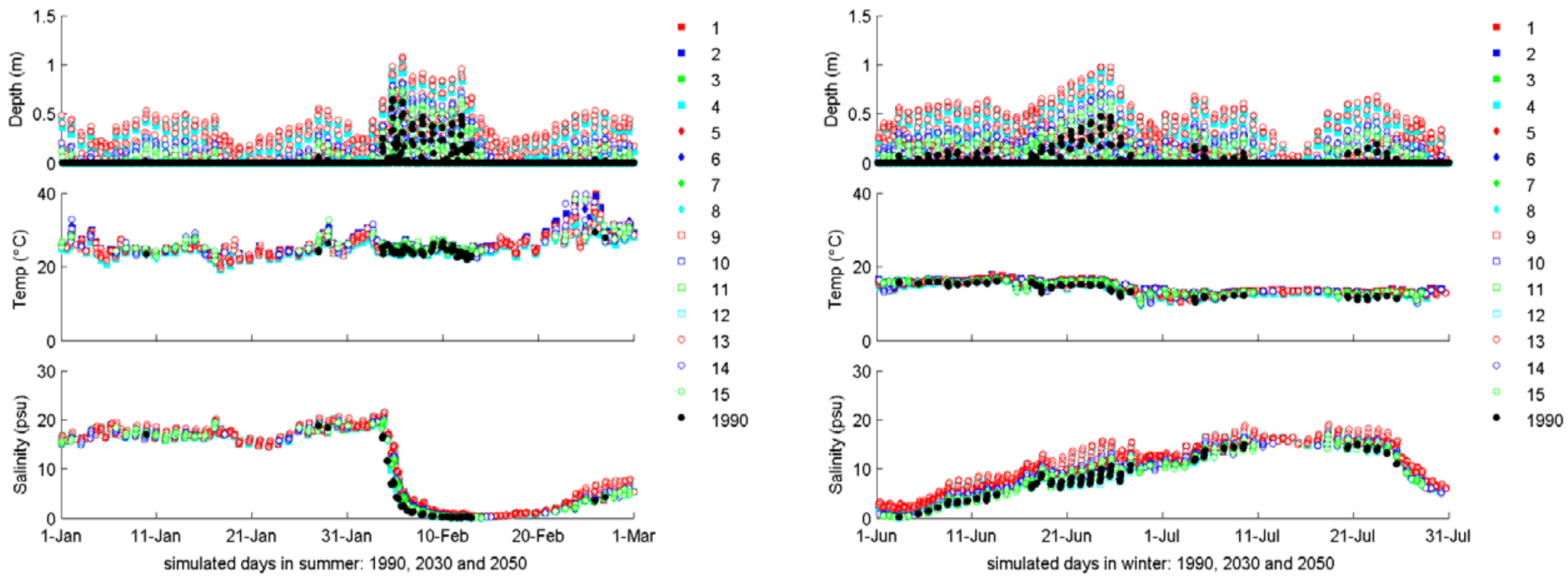

Figure 12-1: Scenario output of summer (left) and winter (right) at One Tree Reach. Figures show water height (top panel), water temperature (third panel) and salinity (bottom panel).

12.2 Farmland

Table 12-2 Simulated mean physical conditions at Farmland.

Scenarios	1990	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Summer means																
Water depth (m)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Water temp. (°C)																
Salinity (psu)																
Inundation (%)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Air temp. (°C)	21.7	23.2	23.2	22.6	22.6	23.2	23.2	22.6	22.6	23.2	23.2	22.6	22.6	23.2	23.2	23.2
Winter means																
Water depth (m)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Water temp. (°C)																
Salinity (psu)																
Inundation (%)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Air temp. (°C)	12.0	13.5	13.5	12.9	12.9	13.5	13.5	12.9	12.9	13.5	13.5	12.9	12.9	13.5	13.5	13.5

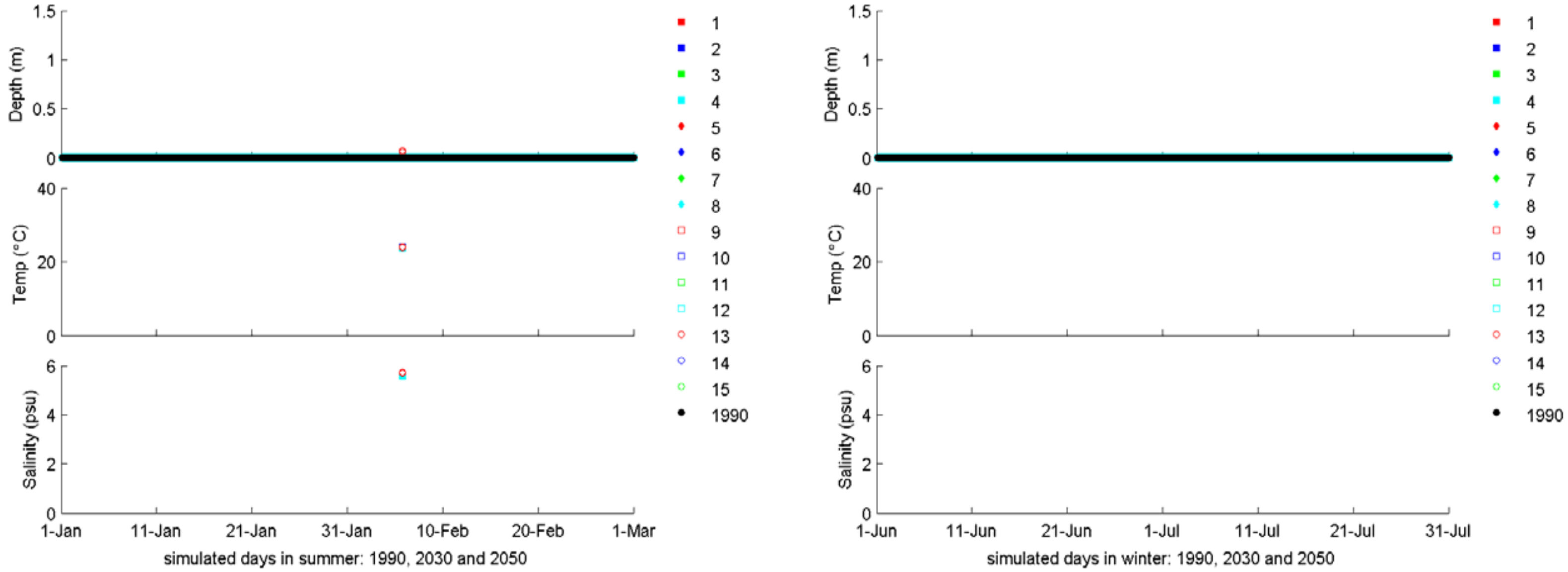

Figure 12-2: Scenario output of summer (left) and winter (right) at Farmland. Figures show water height (top panel), water temperature (third panel) and salinity (bottom panel).

12.3 Couranga Point

Table 12-3 Simulated mean physical conditions at Couranga Point. Bold type shows the baseline and the most changed condition.

Scenarios	**1990**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Summer means																
Water depth (m)	**0.37**	0.43	0.43	0.43	0.43	0.36	0.36	0.36	0.36	0.37	0.37	0.37	0.37	**0.44**	0.38	0.38
Water temp. (°C)	**22.5**	24.0	**23.9**	23.5	23.4	24.1	24.1	23.6	23.5	23.1	23.1	22.8	22.7	**23.9**	24.1	24.4
Salinity (psu)	**7.59**	13.7	13.7	13.8	13.7	12.6	12.7	12.6	12.6	8.16	8.18	8.14	8.15	**13.9**	13.2	12.1
Inundation (%)	**2**	20	20	20	20	7	7	7	7	2	2	2	2	**23**	9	6
Air temp. (°C)	**21.7**	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	**23.2**
Winter means																
Water depth (m)	**0.33**	0.44	0.44	0.44	0.44	0.35	0.35	0.35	0.35	0.34	0.34	0.34	0.34	**0.46**	0.37	0.35
Water temp. (°C)	**15.1**	15.4	15.3	15.1	15.0	15.8	15.7	15.5	15.4	**16.3**	16.2	16.0	15.9	15.3	15.6	15.7
Salinity (psu)	**14.8**	13.9	13.9	13.8	13.9	13.7	13.8	13.7	13.8	**15.5**	**15.5**	**15.5**	15.5	14.1	13.8	14.0
Inundation (%)	**3**	28	28	28	28	10	10	10	10	2	2	2	2	**32**	13	9
Air temp. (°C)	**12.0**	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	**13.5**

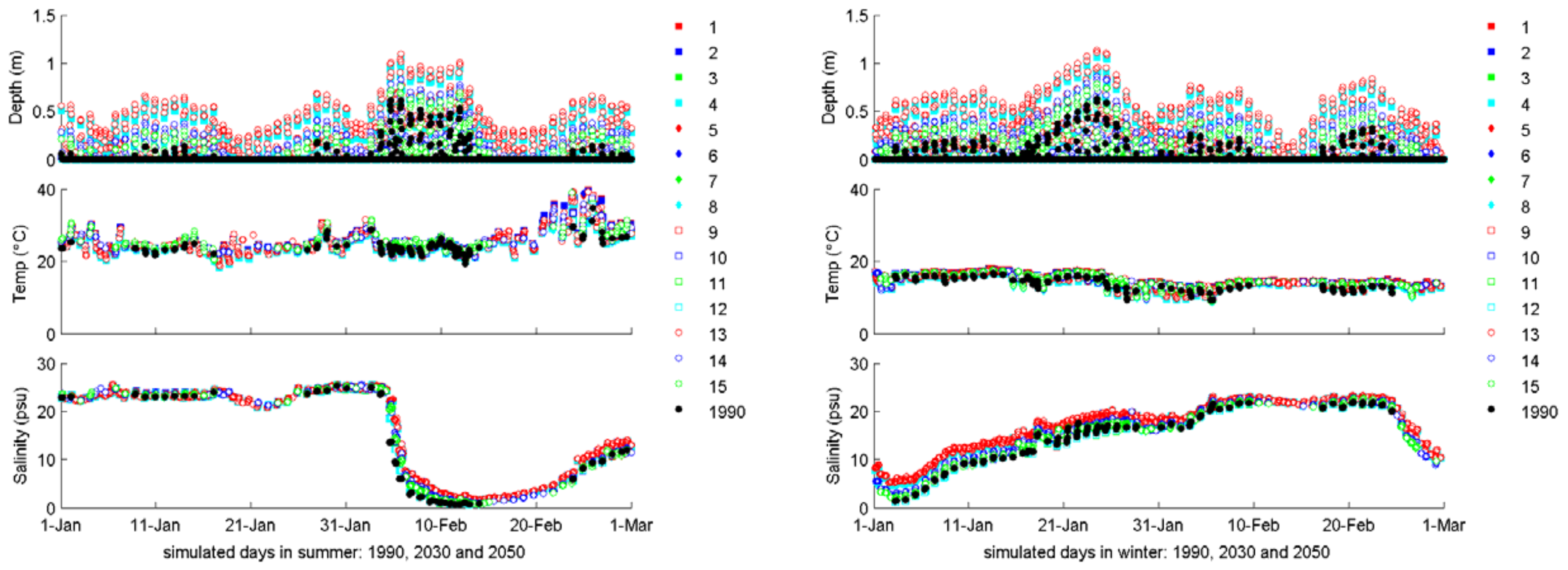

Figure 12-3: Scenario output of summer (left) and winter (right) at Couranga Pt. Figures show water height (top panel), water temperature (third panel) and salinity (bottom panel).

12.4 Gentlemans Halt

Table 12-4 Simulated mean physical conditions at Gentlemans Halt. Bold type shows the baseline and the most changed condition.

Scenarios	**1990**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Summer means																
Water depth (m)	**1.86**	2.31	2.31	2.30	2.31	2.03	2.03	2.03	2.03	1.82	1.82	1.82	1.82	**2.35**	2.09	2.01
Water temp. (°C)	**23.3**	24.3	24.2	23.9	23.8	24.3	24.2	23.9	23.8	24.4	24.3	23.9	23.8	24.2	24.2	**24.5**
Salinity (psu)	**16.8**	17.9	18.0	18.0	17.9	17.2	17.2	17.2	17.2	16.7	16.7	16.7	16.7	**18.1**	17.4	17.2
Inundation (%)	**100**	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Air temp. (°C)	**21.7**	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	**23.2**
Winter means																
Water depth (m)	**1.97**	2.42	2.42	2.42	2.42	2.14	2.14	2.14	2.14	1.93	1.93	1.93	1.93	**2.47**	2.20	2.12
Water temp. (°C)	**15.1**	**16.3**	16.1	16.0	15.8	16.1	16.0	15.9	15.7	16.0	15.9	15.8	15.6	16.1	16.0	16.0
Salinity (psu)	**16.3**	18.6	18.6	18.5	18.6	17.0	17.0	17.0	17.0	15.9	15.9	15.9	15.9	**18.8**	17.3	16.9
Inundation (%)	**100**	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Air temp. (°C)	**12.0**	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	**13.5**

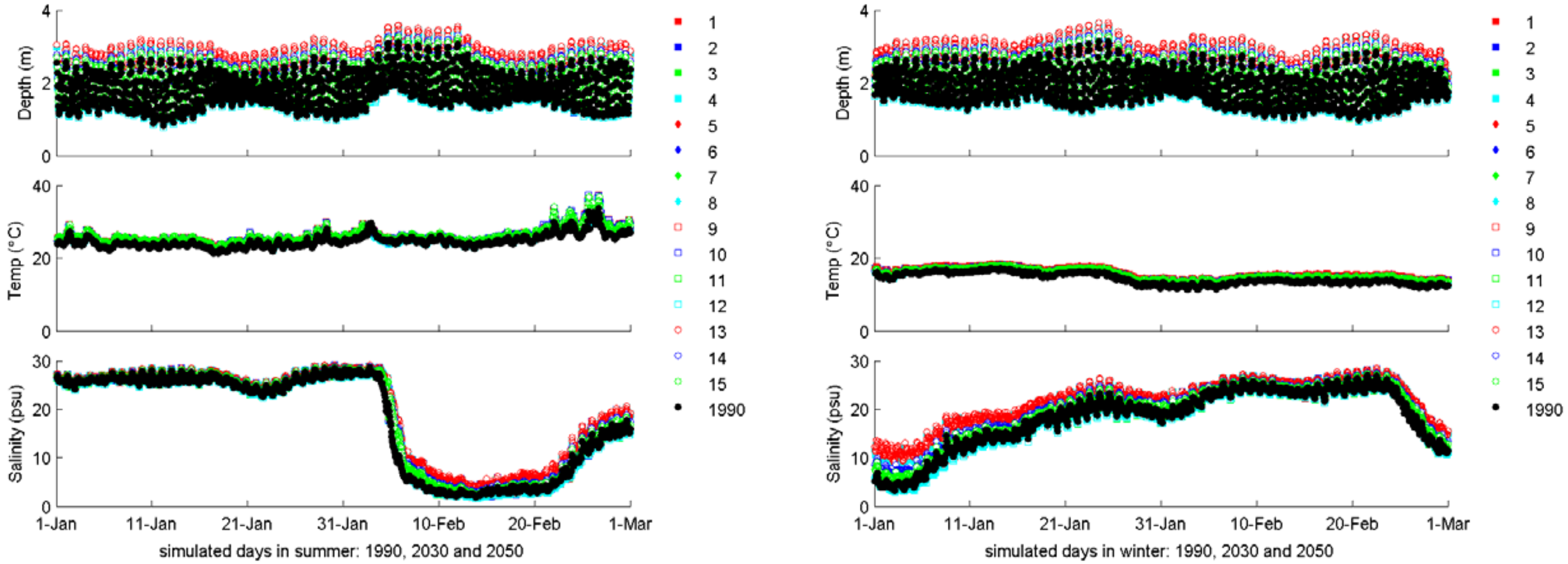

Figure 12-4: Scenario output of summer (left) and winter (right) at Gentlemans Halt. Figures show water height (top panel), water temperature (third panel) and salinity (bottom panel).

12.5 Pumpkin Creek

Table 12-5 Simulated mean physical conditions at Pumpkin Creek. Bold type shows the baseline and the most changed condition.

Scenarios	**1990**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Summer means																
Water depth (m)	**1.85**	2.30	2.30	2.30	2.30	2.03	2.03	2.03	2.03	1.81	1.81	1.81	1.81	**2.35**	2.08	2.00
Water temp. (°C)	**23.4**	**24.3**	24.1	23.8	23.7	**24.3**	24.2	23.8	23.7	**24.3**	24.2	23.9	23.8	24.2	24.2	24.6
Salinity (psu)	**17.0**	18.0	18.1	18.1	18.0	17.3	17.3	17.3	17.3	16.8	16.9	16.8	16.8	**18.2**	17.5	17.4
Inundation (%)	**100**	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Air temp. (°C)	**21.7**	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	**23.2**
Winter means																
Water depth (m)	**1.97**	2.42	2.42	2.42	2.42	2.14	2.14	2.14	2.14	1.93	1.93	1.93	1.93	**2.46**	2.20	2.12
Water temp. (°C)	**14.9**	**16.0**	15.8	15.7	15.6	15.9	15.7	15.6	15.4	15.8	15.6	15.5	15.3	15.9	15.8	15.7
Salinity (psu)	**16.4**	18.5	18.6	18.5	18.5	17.0	17.0	17.0	17.0	15.9	15.9	15.9	15.9	**18.8**	17.3	16.9
Inundation (%)	**100**	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Air temp. (°C)	**12.0**	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	**13.5**

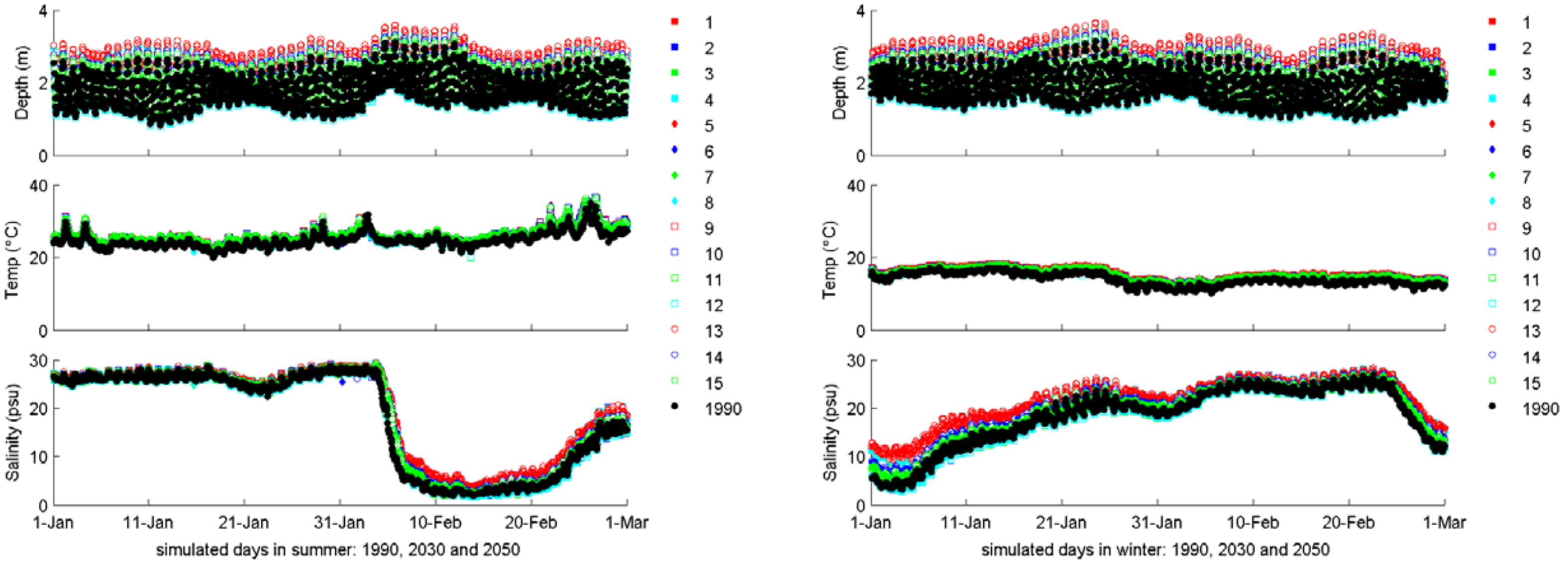

Figure 12-5: Scenario output of summer (left) and winter (right) at Pumkin Creek Figures show water height (top panel), water temperature (third panel) and salinity (bottom panel).

12.6 Seymores Creek

Table 12-6 Simulated mean physical conditions at Seymores Creek. Bold type shows the baseline and the most changed condition.

Scenarios	1990	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Summer means																
Water depth (m)	**0.87**	1.25	1.25	1.25	1.25	0.99	0.99	0.99	0.99	0.84	0.84	0.84	0.84	**1.30**	1.04	0.97
Water temp. (°C)	**23.0**	**24.3**	24.0	23.9	23.7	24.2	24.0	23.8	23.6	24.1	23.9	23.8	23.6	24.1	24.1	**24.3**
Salinity (psu)	**23.5**	24.6	24.6	24.6	24.5	23.9	23.9	23.9	23.9	23.4	23.4	23.4	23.4	**24.7**	24.1	23.9
Inundation (%)	**91**	**100**	**100**	**100**	**100**	98	98	98	98	89	89	89	89	**100**	99	97
Air temp. (°C)	**21.7**	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	**23.2**
Winter means																
Water depth (m)	**0.95**	1.37	1.37	1.37	1.37	1.10	1.10	1.10	1.10	0.92	0.92	0.92	0.92	**1.41**	1.15	1.08
Water temp. (°C)	**16.0**	**17.3**	17.0	17.2	16.9	17.2	16.9	17.0	16.7	17.1	16.8	16.9	16.6	17.1	17.0	17.0
Salinity (psu)	**24.3**	26.1	26.1	26.1	26.1	24.9	24.9	24.9	24.9	23.8	23.8	23.8	23.8	**26.3**	25.2	24.8
Inundation (%)	**96**	**100**	**100**	**100**	**100**	99	99	99	99	94	94	94	94	**100**	99	99
Air temp. (°C)	**12.0**	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	**13.5**

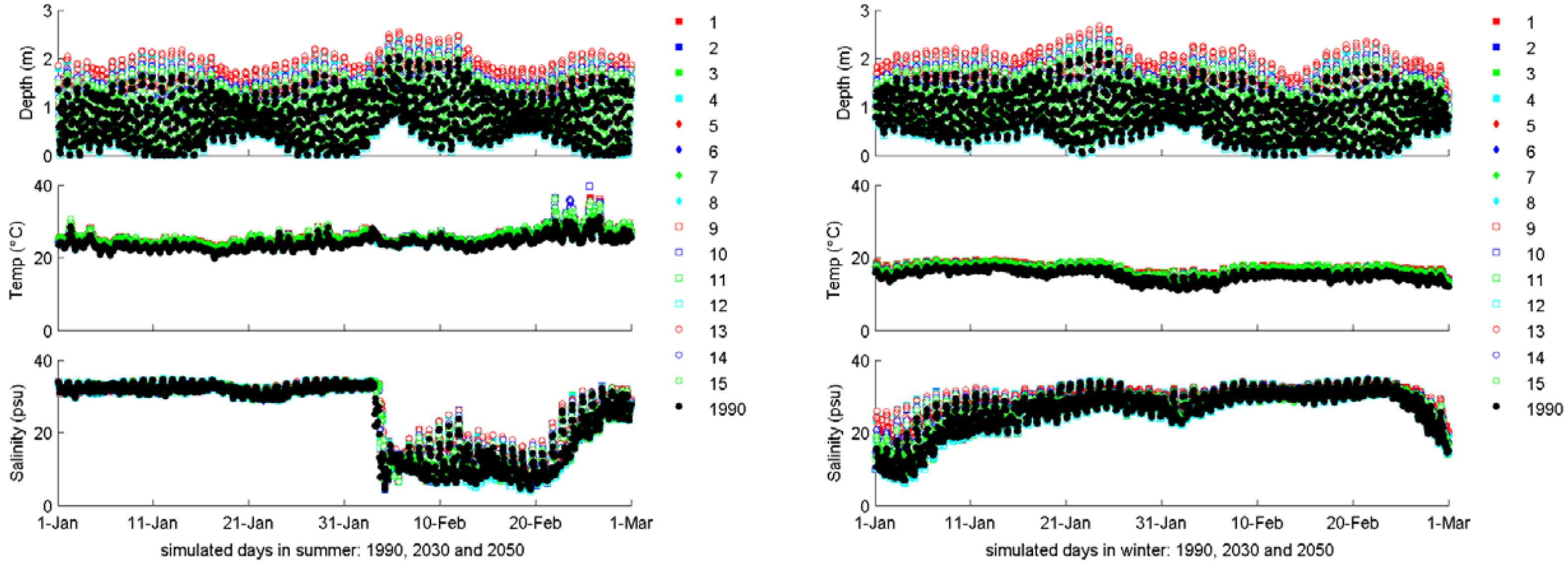

Figure 12-6: Scenario output of summer (left) and winter (right) at Seymores Creek Figures show water height (top panel), water temperature (third panel) and salinity (bottom panel).

12.7 Brooklyn Oval

Table 12-7 Simulated mean physical conditions at Brooklyn Oval. Bold type shows the baseline and the most changed condition.

Scenarios	**1990**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Summer means																
Water depth (m)	**0**	0.36	0.36	0.36	0.36	0.26	0.26	0.26	0.26	0	0	0	0	**0.38**	0.24	0.24
Water temp. (°C)		**23.8**	23.6	23.6	23.4	22.6	22.6	22.3	22.3					23.6	23.2	22.7
Salinity (psu)		18.6	18.6	18.6	18.6	6.01	6.07	6.03	6.03					**19.5**	13.5	6.19
Inundation (%)	**0**	**2**	**2**	**2**	**2**	0	0	0	0	0	0	0	0	**2**	0	0
Air temp. (°C)	**21.7**	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	**23.2**
Winter means																
Water depth (m)	**0**	0.34	0.34	0.34	0.34	0.27	0.27	0.27	0.27	0	0	0	0	**0.35**	0.28	0.27
Water temp. (°C)		18.5	18.1	18.4	18.0	18.8	18.4	18.7	18.3					18.2	**18.9**	18.5
Salinity (psu)		31.4	31.4	31.4	31.4	33.2	33.2	33.2	33.2					30.5	**33.4**	33.3
Inundation (%)	**0**	3	3	3	3	0	0	0	0	0	0	0	0	**4**	1	0
Air temp. (°C)	**12.0**	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	**13.5**

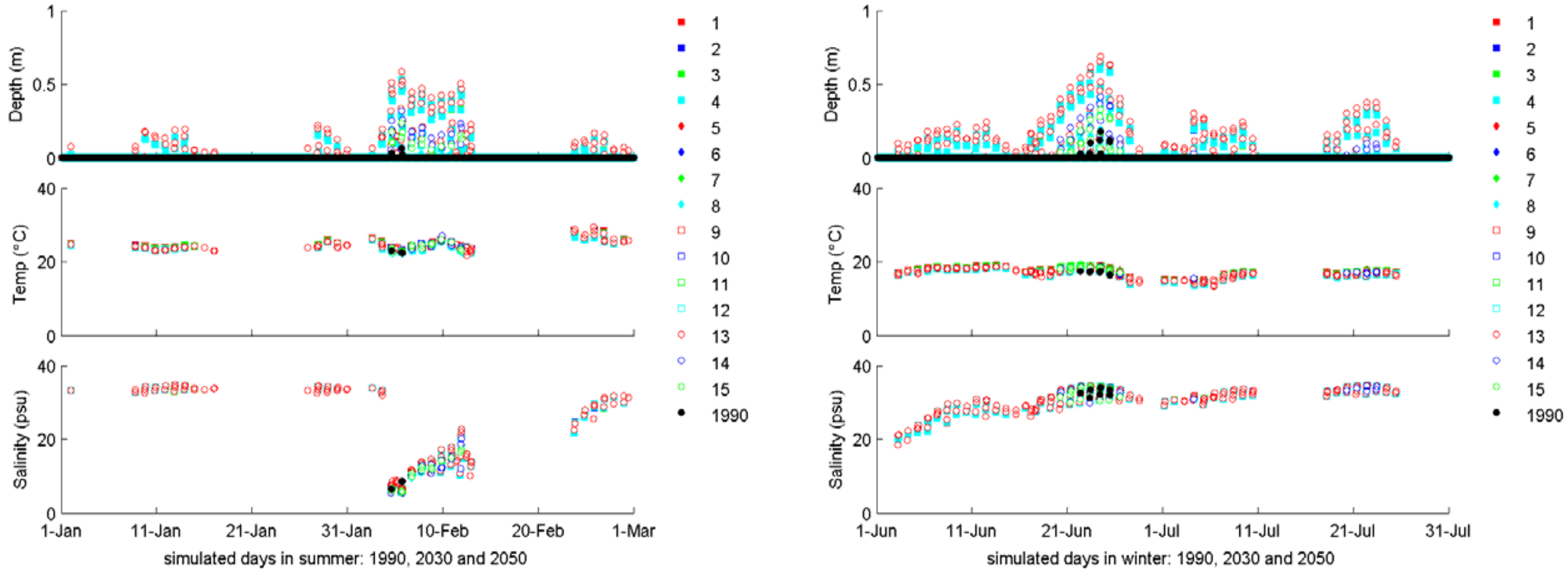

Figure 12-7: Scenario output of summer (left) and winter (right) at Brooklyn Oval. Figures show water height (top panel), water temperature (third panel) and salinity (bottom panel).

12.8 Big Bay

Table 12-8 Simulated mean physical conditions at Big Bay.

Scenarios	1990	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Summer means																
Water depth (m)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Water temp. (°C)																
Salinity (psu)																
Inundation (%)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Air temp. (°C)	21.7	23.2	23.2	22.6	22.6	23.2	23.2	22.6	22.6	23.2	23.2	22.6	22.6	23.2	23.2	23.2
Winter means																
Water depth (m)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Water temp. (°C)																
Salinity (psu)																
Inundation (%)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Air temp. (°C)	12.0	13.5	13.5	12.9	12.9	13.5	13.5	12.9	12.9	13.5	13.5	12.9	12.9	13.5	13.5	13.5

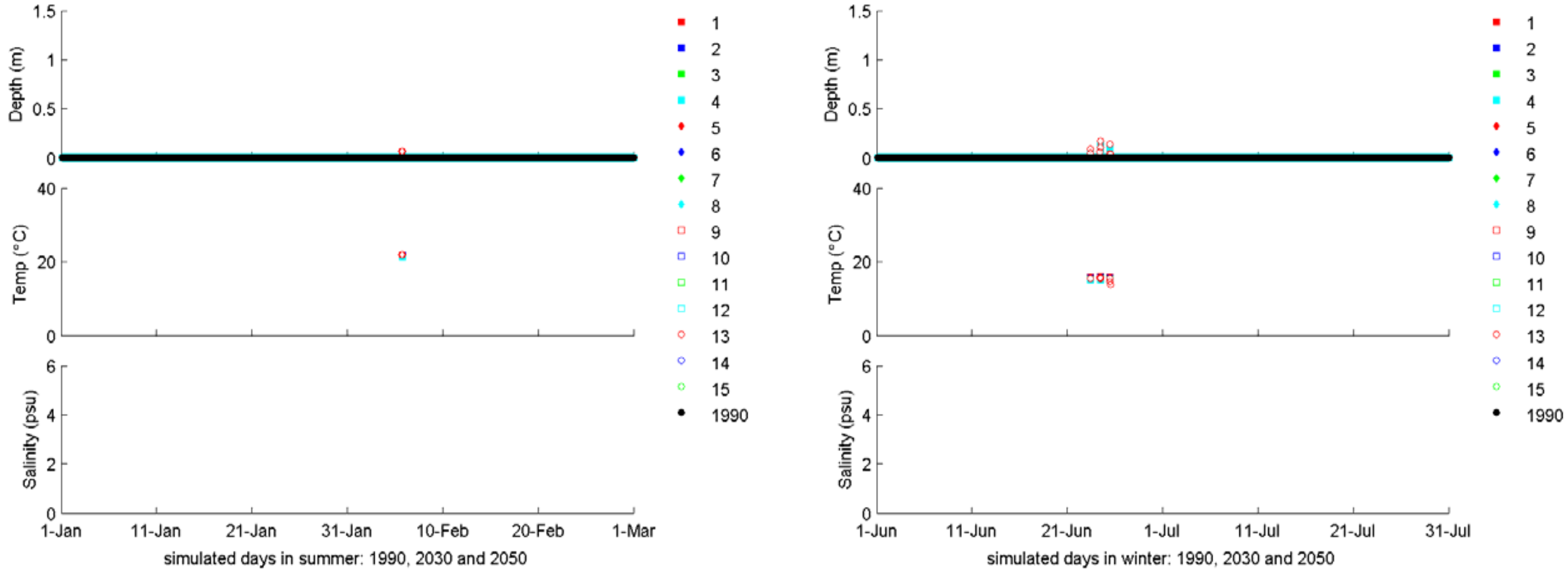

Figure 12-8: Scenario output of summer (left) and winter (right) at Big Bay. Figures show water height (top panel), water temperature (third panel) and salinity (bottom panel).

12.9 Coba Bay

Table 12-9 Simulated mean physical conditions at Coba Bay. Bold type shows the baseline and the most changed condition.

Scenarios	**1990**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Summer means																
Water depth (m)	**0.61**	0.83	0.83	0.83	0.83	0.70	0.70	0.70	0.70	0.59	0.59	0.59	0.59	**0.85**	0.72	0.69
Water temp. (°C)	**22.4**	23.3	23.3	22.7	22.7	23.2	23.2	22.6	22.6	23.1	23.1	22.5	22.5	23.3	23.2	**23.9**
Salinity (psu)	**15.4**	17.2	17.2	17.2	17.1	16.2	16.2	16.1	16.2	15.2	15.2	15.2	15.2	**17.4**	16.4	16.2
Inundation (%)	**54**	84	84	84	84	65	65	65	65	50	51	50	50	**87**	69	63
Air temp. (°C)	**21.7**	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	**23.2**
Winter means																
Water depth (m)	**0.66**	0.89	0.89	0.89	0.89	0.73	0.73	0.73	0.73	0.64	0.64	0.64	0.64	**0.92**	0.77	0.73
Water temp. (°C)	**12.6**	**13.7**	13.5	13.2	13.1	13.4	13.3	12.9	12.8	13.2	13.1	12.7	12.6	13.6	13.4	13.3
Salinity (psu)	**18.0**	20.0	20.0	20.0	20.0	18.6	18.6	18.5	18.6	17.3	17.3	17.3	17.3	**20.3**	18.9	18.5
Inundation (%)	**61**	92	92	92	92	74	74	74	74	58	58	58	58	**93**	78	72
Air temp. (°C)	**12.0**	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	**13.5**

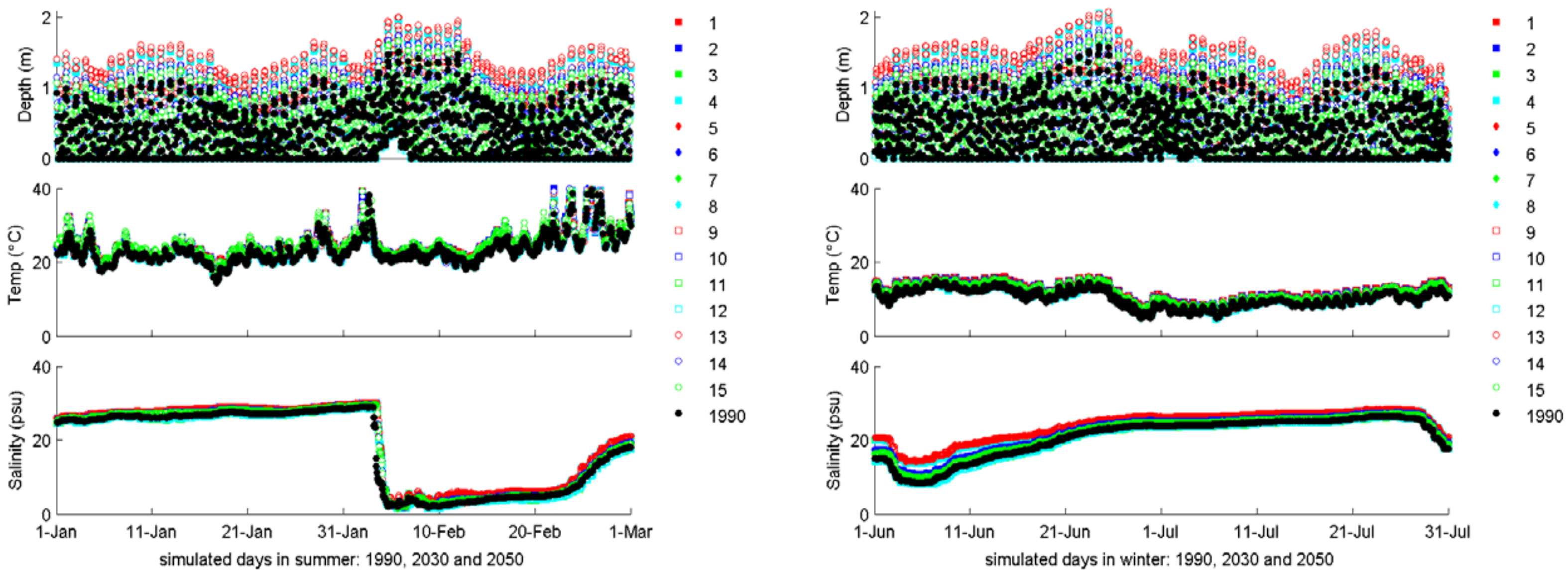

Figure 12-9: Scenario output of summer (left) and winter (right) at Coba Bay. Figures show water height (top panel), water temperature (third panel) and salinity (bottom panel).

12.10 Crosslands and Calna Creek

Table 12-10 Simulated mean physical conditions at Crosslands and Calna Creek. Bold type shows the baseline and the most changed condition.

Scenarios	1990	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Summer means																
Water depth (m)	**0.67**	0.89	0.89	0.89	0.89	0.74	0.74	0.74	0.74	0.64	0.64	0.64	0.64	**0.91**	0.77	0.74
Water temp. (°C)	**22.6**	**23.9**	23.9	23.4	23.4	23.7	23.7	23.2	23.2	23.4	23.4	22.9	22.9	**23.9**	23.8	24.3
Salinity (psu)	**12.4**	14.7	14.7	14.7	14.7	13.3	13.3	13.3	13.3	12.0	12.1	12.0	12.0	**14.9**	13.7	13.3
Inundation (%)	**60**	90	90	90	90	72	72	72	72	57	57	57	57	**92**	76	70
Air temp. (°C)	**21.7**	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	**23.2**
Winter means																
Water depth (m)	**0.71**	0.96	0.96	0.96	0.96	0.79	0.79	0.79	0.79	0.69	0.69	0.69	0.69	**0.99**	0.81	0.78
Water temp. (°C)	**13.4**	**14.6**	14.5	14.3	14.2	14.4	14.3	14.0	13.9	14.2	14.1	13.8	13.7	**14.6**	14.4	14.3
Salinity (psu)	**17.0**	19.4	19.4	19.3	19.4	17.8	17.8	17.8	17.8	16.4	16.5	16.4	16.5	**19.7**	18.1	17.7
Inundation (%)	**67**	95	95	95	95	80	80	80	80	65	65	65	65	**96**	84	78
Air temp. (°C)	**12.0**	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	**13.5**

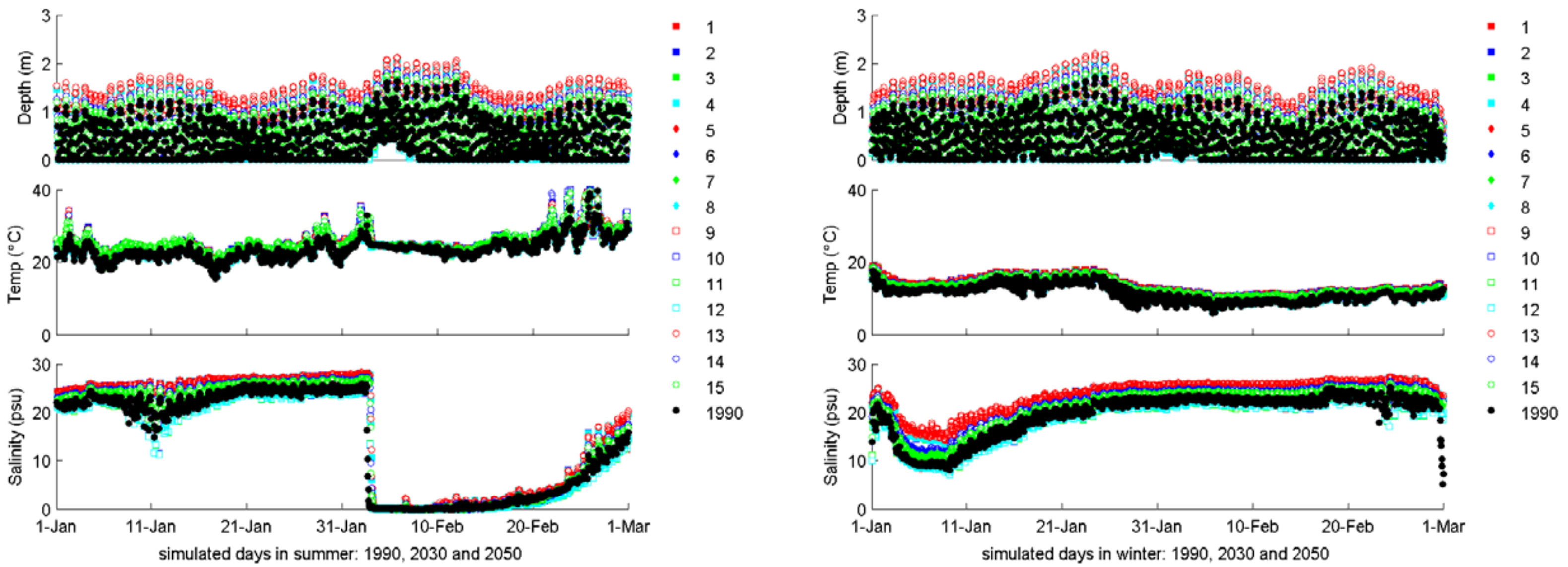

Figure 12-10: Scenario output of summer (left) and winter (right) at Crosslands and Calna Creek Figures show water height (top panel), water temperature (third panel) and salinity (bottom panel).

12.11 Dangar Island

Table 12-11 Simulated mean physical conditions at Dangar Island. Bold type shows the baseline and the most changed condition.

Scenarios	**1990**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Summer means																
Water depth (m)	**2.31**	2.76	2.76	2.76	2.76	2.48	2.48	2.48	2.48	2.26	2.26	2.26	2.26	**2.81**	2.54	2.46
Water temp. (°C)	**22.9**	**24.1**	23.8	23.8	23.6	**24.1**	23.8	23.8	23.6	**24.1**	23.9	23.8	23.6	23.9	23.9	24.0
Salinity (psu)	**25.3**	26.2	26.2	**26.3**	26.2	25.6	25.6	25.6	25.6	25.2	25.2	25.2	25.2	**26.3**	25.7	25.6
Inundation (%)	**100**	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Air temp. (°C)	**21.7**	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	**23.2**
Winter means																
Water depth (m)	**2.42**	2.88	2.88	2.88	2.88	2.60	2.60	2.60	2.60	2.38	2.38	2.38	2.38	**2.93**	2.66	2.57
Water temp. (°C)	**16.5**	**17.8**	17.5	17.7	17.4	17.7	17.4	17.6	17.3	17.6	17.3	17.5	17.2	17.6	17.5	17.5
Salinity (psu)	**26.5**	27.7	27.7	27.7	27.7	26.8	26.8	26.8	26.8	26.0	26.0	26.0	26.0	**27.9**	27.0	26.7
Inundation (%)	**100**	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Air temp. (°C)	**12.0**	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	**13.5**

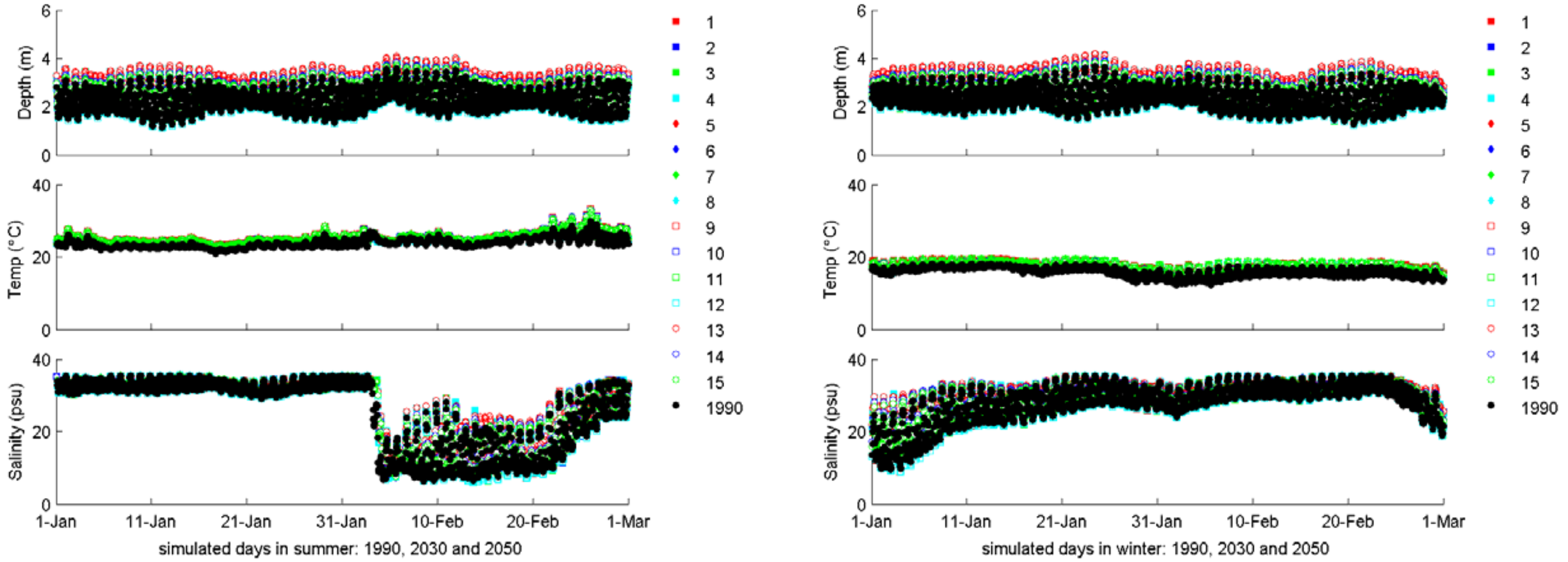

Figure 12-11: Scenario output of summer (left) and winter (right) at Dangar Island. Figures show water height (top panel), water temperature (third panel) and salinity (bottom panel).

12.12 Cowan Creek at Bobbin Head Rd.

Table 12-12 Simulated mean physical conditions at Cowan Creek at Bobbin Head Rd. Bold type shows the baseline and the most changed condition.

Scenarios	**1990**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Summer means																
Water depth (m)	**1.33**	1.78	1.78	1.78	1.78	1.50	1.50	1.50	1.50	1.29	1.29	1.29	1.29	**1.83**	1.56	1.48
Water temp. (°C)	**23.7**	24.4	24.3	24.1	24.0	24.4	24.3	24.0	23.9	24.4	24.3	24.0	23.9	24.3	24.3	**24.7**
Salinity (psu)	**19.0**	19.8	19.8	**19.9**	19.8	19.2	19.2	19.2	19.2	18.8	18.8	18.8	18.8	**19.9**	19.3	19.2
Inundation (%)	**100**	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Air temp. (°C)	**21.7**	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	**23.2**
Winter means																
Water depth (m)	**1.43**	1.89	1.89	1.89	1.89	1.61	1.61	1.61	1.61	1.39	1.39	1.39	1.39	**1.93**	1.66	1.58
Water temp. (°C)	**16.2**	**17.1**	16.9	16.8	16.6	17.0	16.8	16.8	16.6	16.9	16.7	16.7	16.5	16.9	16.9	16.8
Salinity (psu)	**25.2**	26.3	26.3	26.3	26.3	25.4	25.5	25.4	25.5	24.8	24.8	24.8	24.8	**26.4**	25.6	25.4
Inundation (%)	**100**	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Air temp. (°C)	**12.0**	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	**13.5**

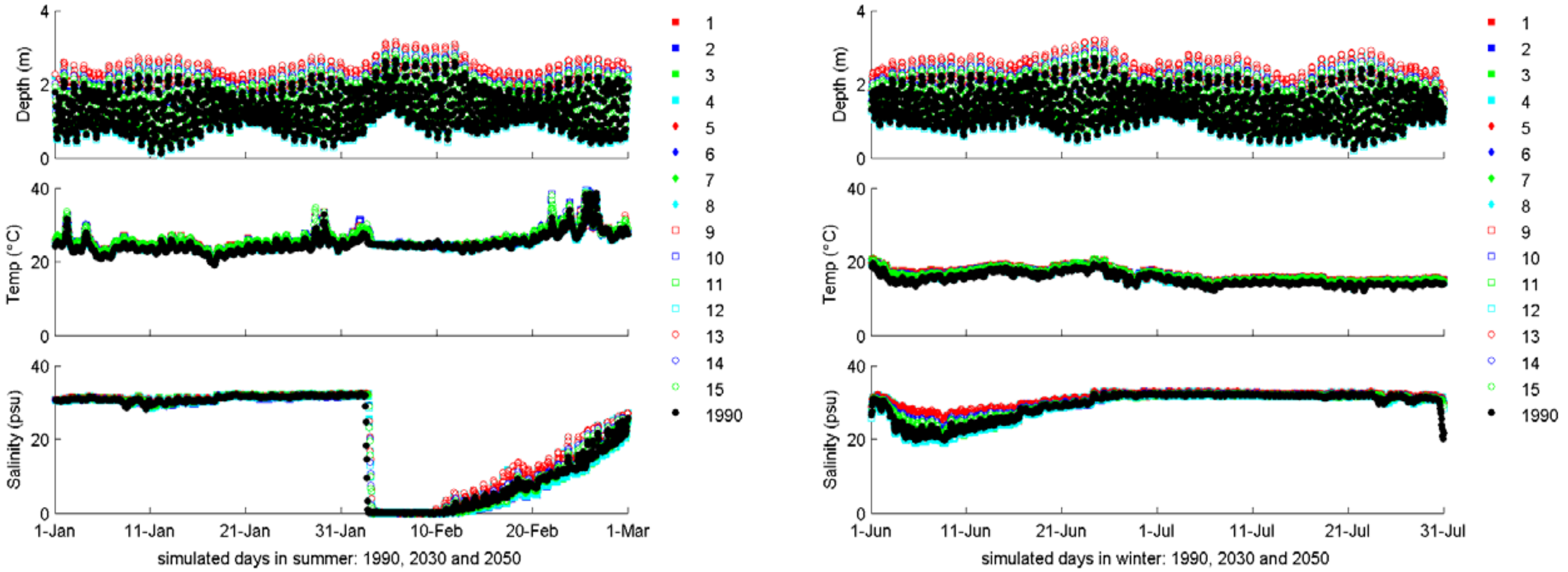

Figure 12-12: Scenario output of summer (left) and winter (right) at Cowan Creek at Bobbin Head Rd. Figures show water height (top panel), water temperature (third panel) and salinity (bottom panel).

12.13 Cowan Creek at Smiths Creek

Table 12-13 Simulated mean physical conditions at Cowan Creek at Smiths Creek Bold type shows the baseline and the most changed condition.

Scenarios	**1990**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Summer means																
Water depth (m)	**0.67**	0.88	0.88	0.88	0.88	0.73	0.73	0.73	0.73	0.65	0.65	0.65	0.65	**0.90**	0.76	0.73
Water temp. (°C)	**23.2**	23.6	23.5	23.1	23.0	23.6	23.6	23.2	23.1	23.8	**23.7**	23.3	23.3	23.5	23.5	24.1
Salinity (psu)	**17.5**	18.5	18.5	18.6	18.5	17.9	17.9	17.9	17.9	17.3	17.3	17.3	17.3	**18.7**	17.9	17.9
Inundation (%)	**56**	87	87	87	87	70	70	70	70	53	53	53	53	**91**	74	68
Air temp. (°C)	**21.7**	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	**23.2**
Winter means																
Water depth (m)	**0.70**	0.94	0.94	0.94	0.94	0.78	0.78	0.78	0.78	0.68	0.68	0.68	0.68	**0.98**	0.80	0.77
Water temp. (°C)	**14.6**	**15.5**	15.3	15.2	15.0	15.2	15.1	14.9	14.8	15.3	15.1	14.9	14.8	15.4	15.1	15.1
Salinity (psu)	**24.0**	25.1	25.1	25.1	25.1	24.1	24.1	24.1	24.1	23.5	23.5	23.5	23.5	**25.3**	24.2	24.1
Inundation (%)	**65**	94	94	94	94	78	78	78	78	62	62	62	62	**95**	83	77
Air temp. (°C)	**12.0**	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	**13.5**

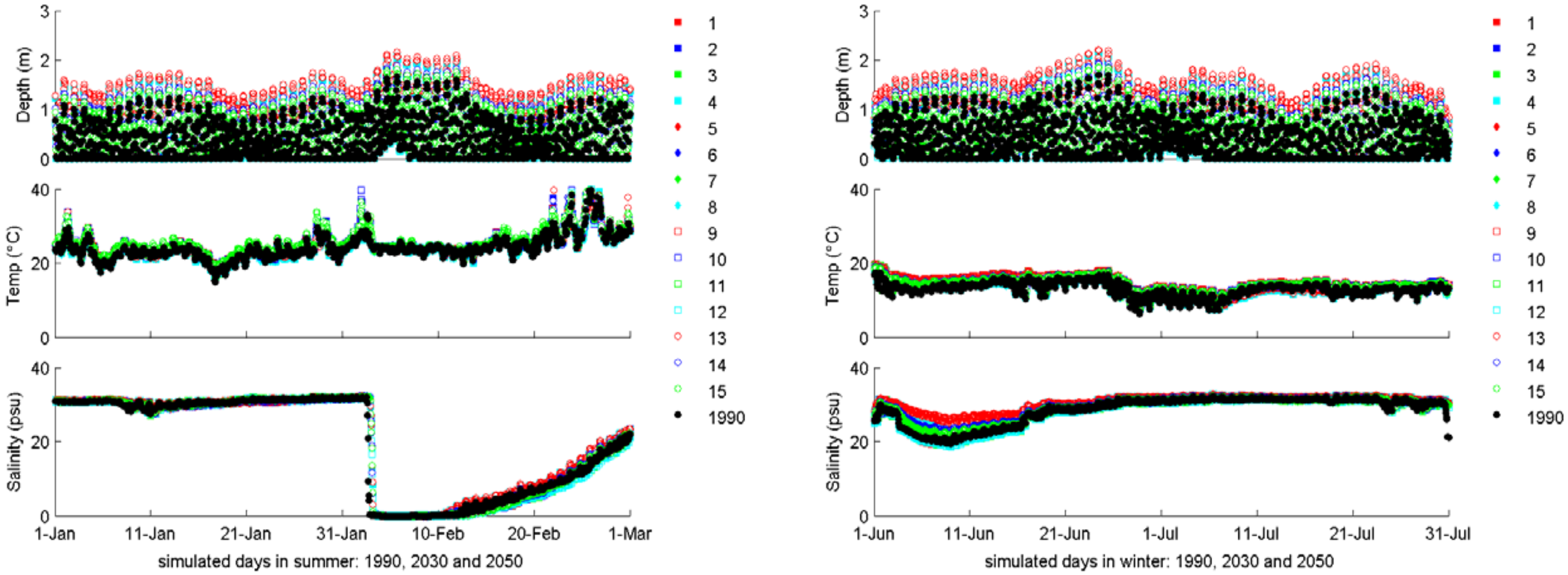

Figure 12-13: Scenario output of summer (left) and winter (right) at Cowan Creek at Smiths Creek Figures show water height (top panel), water temperature (third panel) and salinity (bottom panel).

12.14 Patonga Creek

Table 12-14 Simulated mean physical conditions at Patonga Creek. Bold type shows the baseline and the most changed condition.

Scenarios	**1990**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Summer means																
Water depth (m)	**0.87**	1.26	1.26	1.26	1.26	1.00	1.00	1.00	1.00	0.85	0.85	0.85	0.85	**1.30**	1.05	0.98
Water temp. (°C)	**22.7**	**23.9**	23.6	23.6	23.3	23.8	23.5	23.4	23.2	23.6	23.4	23.3	23.1	23.7	23.6	**23.9**
Salinity (psu)	**25.3**	**26.6**	26.5	**26.6**	26.5	25.9	25.8	25.9	25.9	25.1	25.1	25.1	25.1	**26.6**	26.0	25.8
Inundation (%)	**91**	**100**	**100**	**100**	**100**	98	98	98	98	89	89	89	89	**100**	99	97
Air temp. (°C)	**21.7**	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	**23.2**
Winter means																
Water depth (m)	**0.96**	1.38	1.38	1.38	1.38	1.11	1.11	1.11	1.11	0.93	0.93	0.93	0.93	**1.42**	1.16	1.09
Water temp. (°C)	**16.3**	**17.7**	17.3	17.5	17.2	17.5	17.1	17.3	17.0	17.3	16.9	17.1	16.8	17.4	17.2	17.2
Salinity (psu)	**27.6**	29.1	29.1	29.1	29.1	28.1	28.0	28.1	28.1	27.1	27.0	27.1	27.1	**29.2**	28.3	28.0
Inundation (%)	**96**	**100**	**100**	**100**	**100**	99	99	99	99	94	94	94	94	**100**	99	98
Air temp. (°C)	**12.0**	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	**13.5**

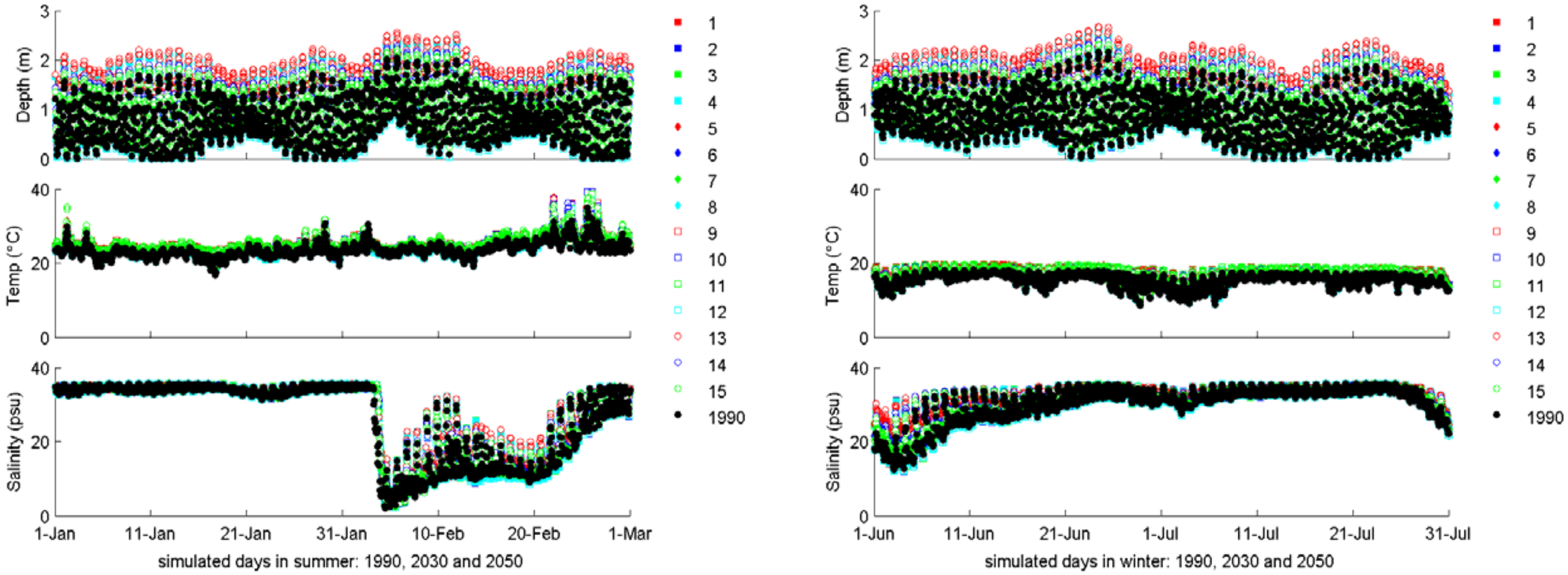

Figure 12-14: Scenario output of summer (left) and winter (right) at Patonga Creek. Figures show water height (top panel), water temperature (third panel) and salinity (bottom panel).

12.15 Upper Mullet Creek

Table 12-15 Simulated mean physical conditions at Upper Mullet Creek.

Scenarios	**1990**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Summer means																
Water depth (m)	**0.35**	0.45	0.45	0.45	0.45	0.37	0.37	0.37	0.37	0.38	0.38	0.38	0.38	**0.46**	0.40	0.37
Water temp. (°C)	**23.0**	24.4	24.4	24.0	23.9	24.4	24.3	24.0	23.9	23.1	23.0	22.8	22.7	24.3	24.2	**24.9**
Salinity (psu)	**12.8**	19.6	19.6	19.7	19.6	18.0	18.0	18.0	18.0	9.98	9.99	10.0	10.0	**19.8**	18.7	17.4
Inundation (%)	**3**	20	20	20	20	8	8	8	8	2	2	2	2	**23**	9	7
Air temp. (°C)	**21.7**	23.2	23.2	22.6	22.6	23.2	23.2	22.6	22.6	23.2	23.2	22.6	22.6	23.2	23.2	23.2
Winter means																
Water depth (m)	**0.34**	0.47	0.47	0.47	0.47	0.37	0.37	0.37	0.37	0.33	0.33	0.33	0.33	**0.48**	0.39	0.37
Water temp. (°C)	**15.4**	15.6	15.4	15.2	15.0	15.7	15.5	15.4	15.2	**16.5**	16.3	16.2	16.0	15.4	15.4	15.6
Salinity (psu)	**23.7**	22.8	22.8	22.8	22.8	**22.5**	**22.5**	**22.5**	**22.5**	23.6	23.6	23.6	23.6	23.2	22.8	22.6
Inundation (%)	**5**	27	27	27	27	12	12	12	12	4	4	4	4	**31**	14	10
Air temp. (°C)	**12.0**	13.5	13.5	12.9	12.9	13.5	13.5	12.9	12.9	13.5	13.5	12.9	12.9	13.5	13.5	13.5

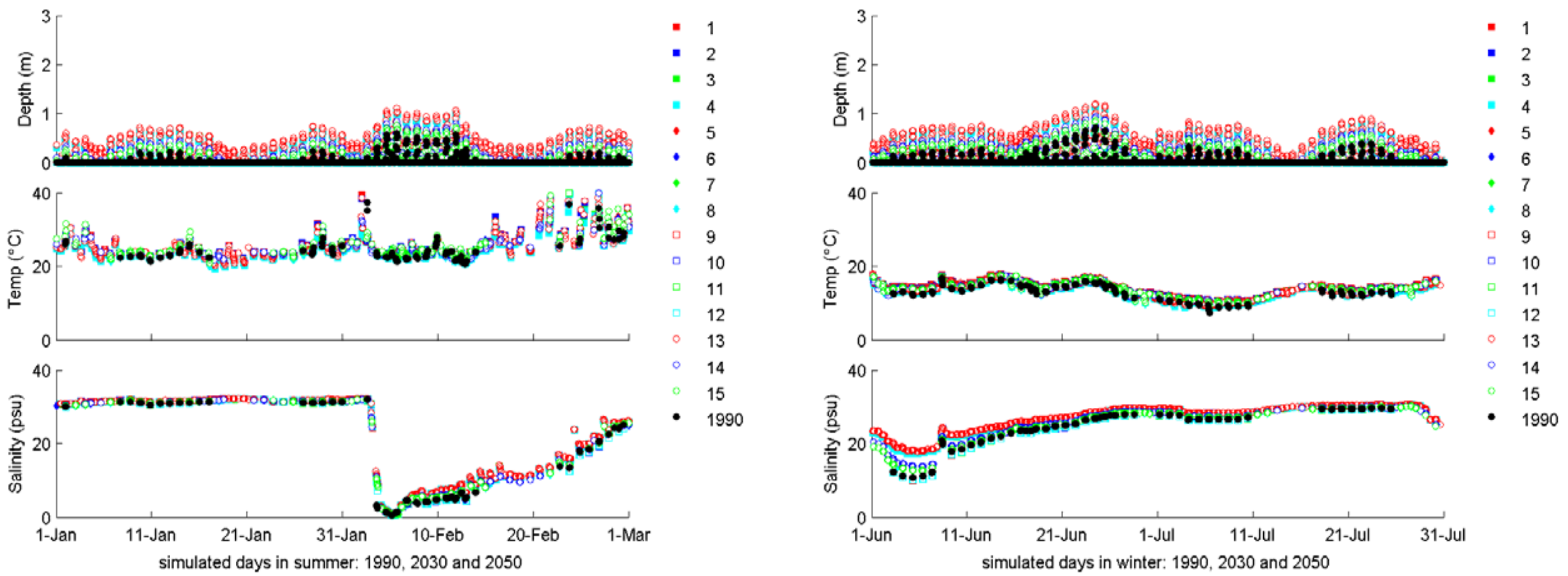

Figure 12-15: Scenario output of summer (left) and winter (right) at Upper Mullet Creek Figures show water height (top panel), water temperature (third panel) and salinity (bottom panel).

12.16 Mangrove Creek at Poporan Creek

Table 12-16 Simulated mean physical conditions at Mangrove Creek at Poporan Creek. Bold type shows the baseline and the most changed condition.

Scenarios	**1990**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Summer means																
Water depth (m)	**1.87**	2.32	2.32	2.31	2.32	2.04	2.04	2.04	2.04	1.83	1.83	1.83	1.83	**2.36**	2.10	2.02
Water temp. (°C)	**23.7**	24.2	24.2	23.7	23.7	24.2	24.1	23.7	23.6	24.2	24.1	23.6	23.6	24.2	24.2	**24.9**
Salinity (psu)	**15.4**	16.2	16.2	16.2	16.2	15.5	15.6	15.5	15.5	15.1	15.1	15.1	15.1	**16.3**	15.7	15.7
Inundation (%)	**100**	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Air temp. (°C)	**21.7**	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	22.6	22.6	**23.2**	**23.2**	**23.2**
Winter means																
Water depth (m)	**1.98**	2.43	2.43	2.43	2.43	2.15	2.15	2.15	2.15	1.94	1.94	1.94	1.94	**2.47**	2.21	2.13
Water temp. (°C)	**14.5**	**15.2**	15.1	14.9	14.7	15.0	14.9	14.6	14.5	14.8	14.7	14.5	14.4	15.1	14.9	14.9
Salinity (psu)	**15.0**	17.0	17.0	16.9	17.0	15.5	15.5	15.5	15.5	14.5	14.5	14.5	14.5	**17.2**	15.8	15.4
Inundation (%)	**100**	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Air temp. (°C)	**12.0**	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	12.9	12.9	**13.5**	**13.5**	**13.5**

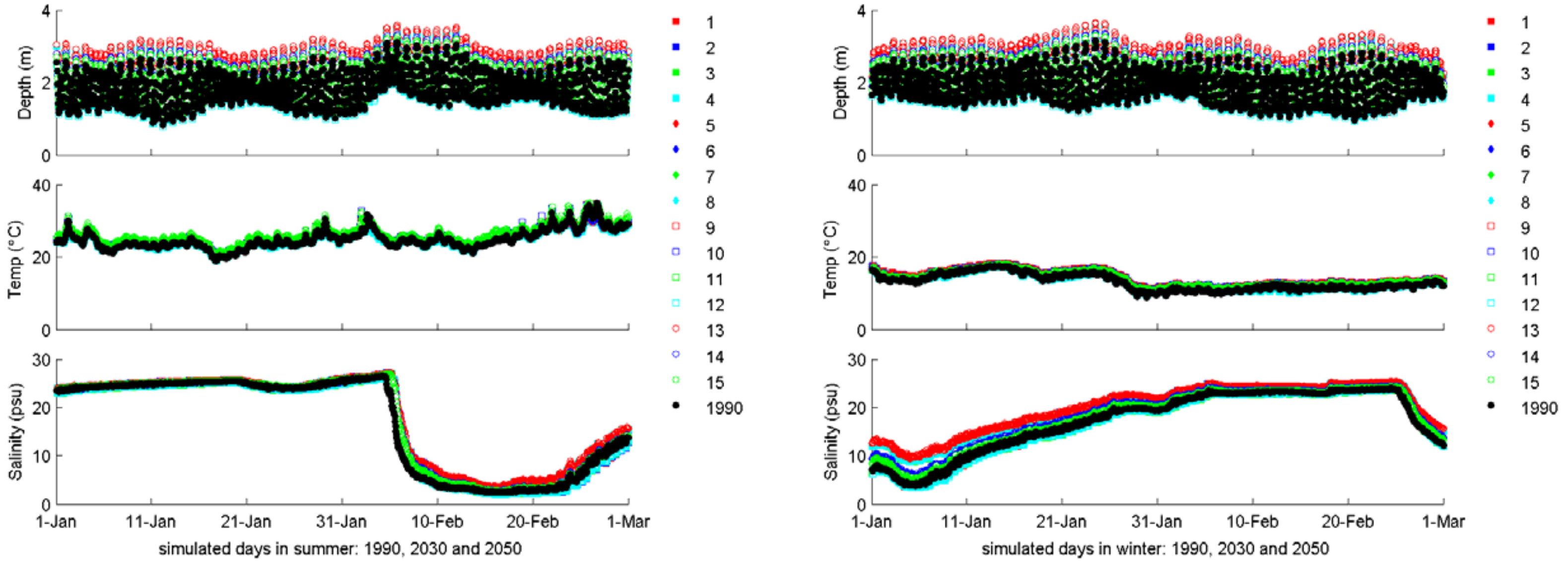

Figure 12-16: Scenario output of summer (left) and winter (right) at Mangrove Creek at Poporan Creek Figures show water height (top panel), water temperature (third panel) and salinity (bottom panel).

Table 12-17 Greatest simulated change in water height at habitat locations under climate projection scenarios. Results denote the largest difference in simulated water height from the baseline condition and the scenario in which that difference occurred.

Site	Water Level difference (m)	Scenario
One Tree Reach	0.1	13
Farm	0	none
Couranga Pt.	0.13	13
Gentlemans Halt	0.49	13
Pumpkin Creek	0.5	13
Seymores Creek	0.43	13
Brooklyn Oval	0.38	13
Big Bay	0	none
Coba Bay	0.24	13
Crosslands and Calna Creek	0.28	13
Cowan Creek Bobbin Head	0.5	13
Cowan Creek Smiths Creek	0.5	13
Patonga Beach	0.23	13
Dangar Island	0.46	13
Mullet Creek	0.11	13
Poporan Creek	0.49	13

Table 12-18 Greatest simulated change in salinity at habitat locations under climate projection scenarios. Results denote the largest difference in simulated water salinity from the baseline condition and the scenario in which that difference occurred.

Site	Salinity difference (psu)	Scenario
One Tree Reach	3.4	13
Farm	0	none
Couranga Pt.	6.3	13
Gentlemans Halt	1.3	13
Pumpkin Creek	1.5	13
Seymores Creek	1.3	13
Brooklyn Oval	19.5	13
Big Bay	0	none
Coba Bay	2.3	13
Crosslands and Calna Creek	2.7	13
Cowan Creek Bobbin Head	1.4	13
Cowan Creek Smiths Creek	0.9	13
Patonga Beach	1.2	1
Dangar Island	1.7	13
Mullet Creek	7	13
Poporan Creek	2.2	13

Table 12-19 Greatest simulated change in water temperature at habitat locations under climate projection scenarios. Results denote the largest difference in simulated water temperature from the baseline condition and the scenario in which that difference occurred.

Site	Water temperature difference (psu)	Scenarios
One Tree Reach	0.8	9, 14
Farm	0	none
Couranga Pt.	1.4	13
Gentlemans Halt	2.2	15
Pumpkin Creek	1.1	1
Seymores Creek	1.3	1, 13
Brooklyn Oval	23.8	1
Big Bay	0	none
Coba Bay	1.5	15
Crosslands and Calna Creek	2.5	13
Cowan Creek Bobbin Head	1.3	1, 5, 9
Cowan Creek Smiths Creek	1	15
Patonga Beach	0.5	10, 1
Dangar Island	1.5	1
Mullet Creek	1.9	15
Poporan Creek	1.2	13