Transport for NSW

Beaches Link and Gore Hill Freeway Connection

Appendix A – Middle Harbour deep water dissolved oxygen – Ecological model based assessment of potential effects of the Beaches Link immersed tube tunnel sill

November 2021

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Annexures

Glossary

Acronym	Definition
AHD	Australian height datum
Benthic	Living on or within the bed of the harbour
Cardno	Cardno (NSW/ACT) Pty Ltd
Conductivity	A measurement of salinity
Dissolved oxygen (DO)	Measurement of oxygen content in water
Epifauna	Marine biota that live on the soft sediments or reefs of the bed of the harbour
Hypoxic	Refers to a level of dissolved oxygen in the water that is not sufficient to meet the needs of marine biota
Infauna	Marine biota that live within the soft sediments of the bed of the harbour
km	Kilometres
L/s	Litres per second
m	Metres
mg/L	Milligrams per litre
MSL	Mean sea level
ppt	Parts per thousand
Project	Beaches Link and Gore Hill Freeway Connection project
RHDHV	RoyalHaskoningDHV (Haskoning Australia Pty Ltd)
SEAR	Secretary’s environmental assessment requirement
SHERM	Sydney Harbour Ecological Response Model
sill	Raised area of the bed of the harbour
SOD	Sediment oxygen demand
Oxygen	Total suspended solids

Executive Summary

The Beaches Link and Gore Hill Freeway Connection project (the project) forms a core component of the broader Western Harbour Tunnel and Beaches Link program of works. The program of works would unlock substantial travel time savings and journey time reliability for public transport, freight, services and commuters travelling between the Northern Beaches region and strategic centres across Sydney.

This report has been prepared to support the preferred infrastructure report requirements for the project.

Following exhibition of the environmental impact statement, Cardno was engaged by Transport for NSW to carry out additional assessment to address comments by the Department of Planning, Industry and Environment and Northern Beaches Council regarding the assessment of potential impacts of the project on levels of dissolved oxygen (DO) and other physio-chemical parameters, including salinity and temperature upstream of the Middle Harbour crossing. The Middle Harbour crossing would be comprised of immersed tube tunnels which form, at their highest point, a 9.2 metre high sill above the existing bed of the harbour in a water depth of 32 metres, around 1.5 kilometres upstream of the Spit Bridge. Noting that there are natural sills within Middle Harbour, the most notable one being the natural sill at the Spit Bridge, which has a depth of 10 metres below the mean sea level (MSL) surface.

The aim of the additional assessment carried out by Cardno (this assessment) was to model potential changes to DO that could occur upstream and downstream of the immersed tube tunnel due to reduced tidal flushing and mixing, and where required, update the findings of the marine ecology impact assessment that was included as part of the environmental impact statement (refer Appendix T (Technical working paper: Marine ecology)).

This assessment has utilised a high resolution 3-dimensional hydrodynamic model of Port Jackson and its tributaries which was developed and integrated with existing catchment models for the development of a model system that simulates hydrodynamics and predicts water quality under varying weather and land use management scenarios – designated as the Sydney Harbour Ecological Response Model (SHERM).

The model system was built upon an existing hydrodynamic model of the harbour and Parramatta River, and was developed using sets of winter and summer water quality data, including physical and bio-chemical parameters collected during the initial model development phases (2014-2016). These data were used previously to calibrate and verify the water quality model system for the whole of Port Jackson. The model recalibration specifically for Middle Harbour– part of the SHERM, was driven by tidal levels at its downstream end together with realistic catchment inflows, and then used to test the effect of the immersed tube tunnel on near bed of the harbour DO concentrations, and the spatial extent and durations of low DO conditions. Realistic values were adopted for parameters such as sediment oxygen demand (SOD) and re-aeration rates. These investigations also included a range of sensitivity tests, namely in terms of summer-winter meteorological influences, the effects of vertical mixing in the model and also the sensitivity of the model to SOD.

The model system was then used to model three selected three month duration hydrodynamic and water quality simulation scenarios, made up of:

- December 2017 to February 2018 (sampling period 1 from Appendix Q (Technical working paper: Marine water quality))
- April to June 2020 (sampling period 2 from Appendix Q (Technical working paper: Marine water quality))
- January to March 2012 (wet period).

The outcomes of these scenarios are as follows:

- For all of the modelled scenarios, the modelling system predicted that the immersed tube tunnel sill would reduce the near bed DO concentration by up to 0.4 milligrams per litre (mg/L) for short periods after heavy rainfall in certain areas upstream of the immersed tube tunnel sill (as indicated below)
- The area affected by the lower DO is limited to the deeper parts (depths greater than 10 metres) of Middle Harbour, which are below any identified sensitive marine habitats
- The largest decreases in near bed DO are predicted to occur immediately upstream of the immersed tube tunnel sill, in the existing deep water (greater than 27 metres deep)

- The model predicted that the deeper areas downstream of the immersed tube tunnel sill would exhibit an increase in DO levels. Increases of up to 1.0 mg/L were predicted in the deep water areas between the Spit Bridge and the immersed tube tunnel
- Each modelling time period had a range of inflow events included in the simulations, which were derived based on rainfall measurements. The time-series results indicate that the DO response is similar for various rainfall rates and volumes, with the exception of a high intensity rainfall event (greater than 100 millimetres (mm) in a day, which occurs every three to five years on average) in March 2012. This event appears to have flushed the system and resulted in rapid recovery of DO at the bed of the harbour upstream of the immersed tube tunnel.
- The immersed tube tunnel sill also has the potential to slightly change near bed salinity and temperature due to reduced mixing and flushing. However, based on the modelling results, changes to these parameters are expected to be small, and less than 0.1 degrees and 0.1 ppt upstream and downstream of the sill.

Further sensitivity testing was carried out to assess the influence of seasonality (i.e. summer versus winter), vertical mixing and the SOD. The sensitivity testing indicates that:

- Near bed DO depletion is a seasonal phenomenon, with very little depletion predicted to occur during the winter months as opposed to late summer
- Vertical mixing does play a role in the predicted near bed DO concentration. The modelling carried out for this assessment has conservatively assumed very low vertical mixing and diffusion for both the hydrodynamic and the water quality models. With the inclusion of an average (higher) vertical diffusion coefficient, the model predicts significantly more vertical mixing, resulting in less DO depletion near the bed of the harbour upstream of the immersed tube tunnel sill
- The model, and hence DO in upper Middle Harbour itself, is sensitive to SOD. Two higher values have been tested and indicate that a larger SOD results in lower oxygen levels near the bed of the harbour upstream of the immersed tube tunnel sill.

The model results indicate that the benthic infauna and epifauna (e.g. worms, molluscs, crustaceans and echinoderms) in deeper areas of Middle Harbour within the vicinity of the immersed tube tunnel sill are already subject to occasionally low concentrations of DO, in summer after heavy rainfall that reach, or become slightly less than, the threshold of 4.6 mg/L that may cause mortality to some benthic organisms.

Modelling shows, under most scenarios, that the immersed tube tunnel sill would only slightly decrease concentrations of DO near the bed of the harbour after heavy rain from what would be expected under natural conditions and not substantially increase the duration of occasionally naturally low DO concentrations. Modelling also shows that the small effects would be confined to an area of deeper water in the deep pool basin immediately upstream of the immersed tube tunnel sill. The magnitude, duration and spatial scale of the effect of the project to benthic infauna and epifauna in these areas would not be measurable beyond natural impacts from the occasionally low DO events.

Given that sensitive Type 1 or Type 2 Key Fish Habitat in the vicinity of the immersed tune tunnel sill, such as seagrass or subtidal rocky reef, are located in shallow water (less than seven metres deep) close to the shoreline of Middle Harbour, these habitats would be unaffected by the immersed tube tunnel sill.

These findings support the conclusion made in Appendix T (Technical working paper: Marine ecology) that the effect of the immersed tube tunnel sill would not be of concern given benthic assemblages are already exposed to similar disturbances that occur naturally and would be expected to be resilient, through rapid recolonisation, to slight increases to these disturbances (that is slightly decreased levels of DO during depletion events with a slightly longer duration).

However, as the modelling indicates that the near bed of the harbour dissolved oxygen levels are sensitive to the assumed SOD it is recommended that pre-construction monitoring be carried out. This should include:

- 12 months of continuous monitoring of DO, salinity (through conductivity measurements), turbidity and temperature through the water column at one location immediately upstream of the immersed tube tunnel sill. This should be located in the deep basin where the near bed of the harbour changes to DO are predicted to occur; and

- Monthly vertical profiling of DO, salinity (conductivity), turbidity and temperature upstream and downstream of the immersed tube tunnel sill at up to six locations within the estuary.

Noting that SOD is likely to vary over time due to organic loads (from catchment runoff), and water temperature, monthly sampling of SOD should also be carried out at the continuous monitoring station, and seasonally at each upstream vertical profile site. The need for further modelling or post-construction monitoring of potential DO changes should be determined following the completion of the recommended pre-construction monitoring.

1 Introduction

1.1 Previous Assessment

The Beaches Link and Gore Hill Freeway Connection project (the project) forms a core component of the broader Western Harbour Tunnel and Beaches Link program of works. The program of works would unlock substantial travel time savings and journey time reliability for public transport, freight, services and commuters travelling between the Northern Beaches region and strategic centres across Sydney.

Cardno was engaged by Transport for NSW during preparation of the project environmental impact statement to assess the potential impact of the project on levels of dissolved oxygen (DO) upstream of the Middle Harbour crossing. **Figure 1.1** shows the location of the proposed crossing.

As part of the environmental impact statement, RoyalHaskoningDHV (RHDHV) modelled hydrodynamics and tidal flushing due to the sill formed by the proposed immersed tube tunnel across Middle Harbour, as reported in Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling). Cardno combined these investigations with water quality monitoring to make predictions of potential impacts to marine water quality and benthic ecology that could arise from changes to tidal flushing (as reported in Appendix Q (Technical working paper: Marine water quality) and Appendix T (Technical working paper: Marine ecology)). These studies were carried out to comply with the updated project Secretary's environmental assessment requirements (SEARs) issued on 22 April 2020, specifically SEAR 6, Part 10 which requires that the project:

> *Identify and assess the impact of tidal flushing on the crossing of Middle Harbour. The assessment should also include details of any potential sediment accumulation and the impact this may have on marine populations that dwell on the harbour floor (SEAR 6, Part 10).*

The environmental impact statement findings were that:

- Based on water quality sampling, the water quality upstream of The Spit under existing conditions could be subject to periods of naturally low DO concentrations after rainfall
- Periods of depletion of DO near the bed of the harbour are likely to last for only a few days and the subsequent vertical mixing by the tidal currents is likely to rapidly dilute any potential effects of this deep water on the mid-depth and surface waters
- The potential for a greater duration of individual mortality events to deepwater soft sediment benthic infauna or epibiota, as a result of the immersed tube tunnel sill, is not considered to be a major impact given these assemblages are already exposed to similar disturbances naturally and would be expected to be resilient to slight increases in the longevities of these disturbances, through rapid recolonization.

Following exhibition of the environmental impact statement, comments were made by Department of Planning, Industry and Environment and Northern Beaches Council regarding the assessment of potential effects on DO from construction of the immersed tube tunnel across Middle Harbour. Subsequently, the Department of Planning, Industry and Environment requested Transport for NSW on 14 May 2021 to prepare a preferred infrastructure report that addresses several project related issues, including further assessment that:

> *b) assesses the impacts to Middle Harbour from the introduction of a sill (due to the placement of immersed tube tunnels) including appropriate measurements/monitoring data and impact assessment.*

1.2 Purpose of this assessment

The purpose of this assessment is to support the preferred infrastructure report requirements for the project and address comments by the Department of Planning, Industry and Environment and Northern Beaches Council regarding the potential impacts of the immersed tube tunnel sill.

This assessment has been designed and carried out to provide additional investigation into DO changes from the immersed tube tunnel sill, principally DO levels upstream and downstream of the sill, by using the modified and locally re-calibrated Sydney Harbour Ecological Response Model (SHERM). Predictive modelling results have then been used to assess and confirm potential impacts on benthic infauna and epifauna that dwell on the bed of the harbour. Potential changes to the near bed water temperature and salinity have also been assessed.

As noted above, this assessment has focussed on potential reductions to dissolved oxygen concentrations near the bed. Low near bed dissolved oxygen may lead to nutrient release from the sediments and subsequent vertical mixing into the photic zone, which may stimulate additional algal growth near the surface This process can then further exacerbate low near bed dissolved oxygen levels. This process has been included in the modelling.

Existing water quality data had already been collected as part of the environmental impact statement by Cardno during two sampling periods, namely Sampling Period 1 (December 2017 to January 2018) and Sampling Period 2 (April to June 2020) as reported in Section 3.3 and Annexure B of Appendix Q (Technical working paper: Marine water quality). This data is considered adequate for the DO modelling and to verify outputs from the SHERM. However, this assessment also includes recommendations on whether or not further monitoring is considered to be required, based on the modelling results.

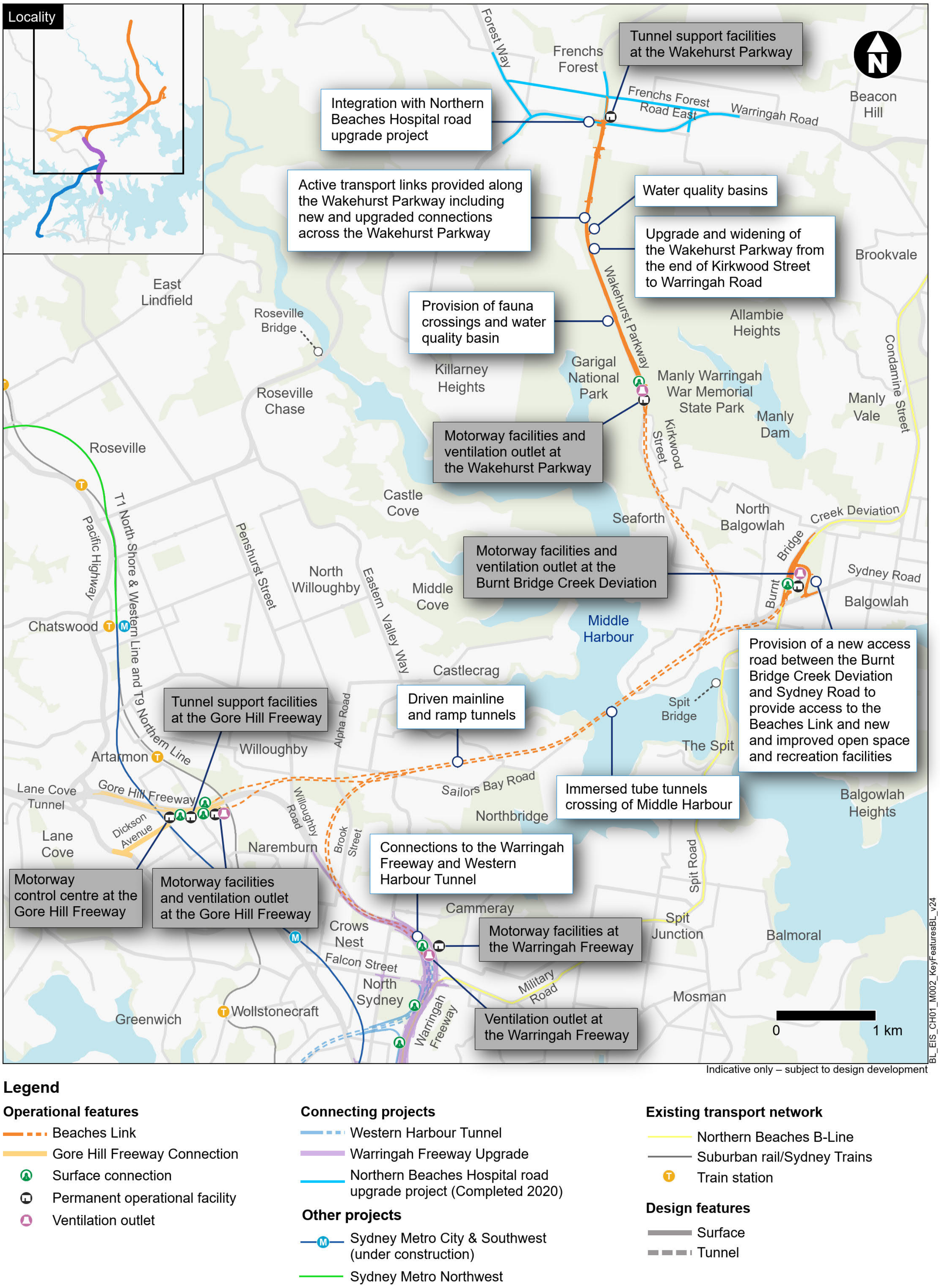


Figure 1-1 Key Features of the Project

1.3 Background

DO profiles collected during Cardno field sampling carried out for the environmental impact statement on 31 January 2018 (conductivity, temperature and depth (CTD) Profiles along Middle Harbour) and time series measurements from moored instruments during the last week of May 2020, showed the occurrence of low DO concentrations near the bed of the harbour along both the Middle Harbour main arm and Tunks Park/Willoughby Creek arm to the south of the location of the proposed crossing. The tidal flushing modelling presented in Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling) has predicted that the flushing time in the deep waters upstream of the immersed tube tunnel sill location would increase from 1.6 days for the existing conditions to 2.4 days after construction of the immersed tube tunnel.

The proposed immersed tube tunnel forms a maximum 9.2 metre high sill above the existing bed of the harbour in a water depth of 32 metres around 1.5 kilometres upstream of the Spit Bridge. The Spit Bridge currently lies on a natural sill which has a depth of 10 metres below the mean sea level (MSL) surface, whereas the sill of the immersed tube tunnel would be much deeper at 23 metres below the MSL surface. At a water depth of 23 metres, the deeper water extends from the Spit Bridge upstream for about five kilometres along the Middle Harbour main arm to near Yeoland Point. Construction of the immersed tube tunnel crossing would divide the present Middle Harbour deep waterway into two partially separated deep-water sections - 1.5 kilometres of deep water (greater than 23 metres) between the Spit Bridge and the tunnel sill, plus a distance of 3.5 kilometres of deep water upstream of the tunnel sill.

In general, flushing times greater than four days may lead to deteriorating water quality. Using a constant salinity model, the presence of the immersed tube tunnel was predicted to increase flushing times from 1.6 to 2.4 days, and because this is less than the nominal critical value of four days, it would not be likely to have significant impacts.

It is likely that the DO depletion rate would be highest in the late summer/autumn period when:

- The detritus/organic load from the catchment over the summer wet period may have accumulated more than in pre-sill conditions in the deeper benthic waters upstream of the immersed tube tunnel sill in Middle Harbour
- Water temperatures are high leading to higher rates of microbial decomposition of benthic organic matter and the associated higher DO depletion from the overlying water
- Stratification associated with warm fresh inflows causes longer water retention times in the deeper waters.

The findings of the environmental impact statement were that the formation of a deep basin upstream of the immersed tube tunnel sill would not lead to ongoing marine ecology issues. However, as this conclusion was not quantified, the Department of Planning, Industry and Environment, as well as Northern Beaches Council, identified that under certain conditions these findings may be incorrect and requested that additional assessment be carried out.

In considering potential effects to marine ecology, a DO level of 2.0 mg/L has been widely considered as the threshold at which hypoxic conditions would be expected to cause catastrophic mortality to marine organisms. However, taxonomic variability in behavioural and physiological adaptions to hypoxia lead to broad differences in vulnerability to oxygen depletion among taxa. The most sensitive group is fish and then benthic crustaceans, followed by worms and echinoderms (eg sea urchins), whereas at the other end of the scale cnidarians (eg jellyfish) and molluscs are the most tolerant.

In a comprehensive review of the thresholds of benthic taxa, Vaquer-Sunyer and Duarte (2008) considered 4.6 mg/L was a precautionary limit for ‘generally’ avoiding catastrophic mortality events, and hence conserving biodiversity. This concentration of DO is the 90th percentile of the distribution of mean lethal concentrations - that is the lowest concentration that would not affect populations of most species, apart from the 10% most sensitive.

1.4 Assessment approach

The approach and scope of work carried out for this assessment was as follows:

1. Develop a water quality and ecological response model using the Delft3D Water Quality (WAQ) Modelling system. The water quality model needed to be capable of modelling a range of water quality processes. Cardno applied the SHERM, which had the following water quality processes implemented for the model:
   a) Transport and dispersion of conservative and non-conservative constituents
   b) Water temperature and salinity
   c) Nutrient dynamics for nitrogen, phosphorous, silica and carbon
   d) Phytoplankton growth and mortality, including the ability to model multiple algae species
   e) Sediment/water column nutrient exchange using initial empirical process coefficients and modelled nutrient loads in the sediments, as well as being capable of modelling multiple sediment layers
   f) Spatial distribution of DO through the water column.

   The SHERM has previously been calibrated for winter and summer conditions, respectively, with data sets collected between April 2012 and February 2013 for the greater Sydney Harbour estuary system.
2. Validation of the model system with available site-specific DO data collected for the environmental impact statement within Middle Harbour.
3. Application of the calibrated model system to modelling of three selected three month duration hydrodynamic and water quality simulation scenarios, comprising:
   - December 2017 to February 2018 (Sampling period 1 from Appendix Q (Technical working paper: Marine water quality))
   - April to June 2020 (Sampling period 2 from Appendix Q (Technical working paper: Marine water quality))
   - January to March 2012 (wet period).
4. Carry out sensitivity analysis of the model for:
   - Season
   - Vertical turbulence and mixing
   - Amount of Sediment Oxygen Demand (SOD).
5. Document the outputs from the Middle Harbour water quality modelling results, compare these to appropriate DO threshold values, and where required, update the findings of the marine ecology impact assessment included as part of the environmental impact statement (refer Appendix T (Technical working paper: Marine ecology)).

The methodology applied to this assessment is outlined in the following sections.

The assessment has been carried out by Dr Craig Blount (Senior Principal, Cardno), Chris Scraggs (Principal, Coastal Engineering, Cardno) and Doug Treloar (Senior Principal, Cardno).

2 SHERM System

In partnership with the Greater Sydney Local Land Services (GSLLS) and commencing in 2012, Cardno has developed a Delft3D-based hydrodynamic and water quality model system of Port Jackson and the Parramatta River, including system-wide estuarine creeks. The Delft3D model has been refined and developed since then and has recently been extended to include high resolution spatial definition of the waterway from upstream of Parramatta to the Port Jackson entrance, including the whole of the Lane Cove River and Middle Harbour estuaries. The Delft3D hydrodynamic model developed by the study team was calibrated with available water level and current/discharge data. The model layout is shown in **Figure 2.1** and **Figure 2.2**. Model development has made use of domain decomposition to allow dynamic parallel computation of the hydrodynamic processes. These domains are shown on **Figure 2.1**.

The SHERM was designed to simulate a range of water quality and biological processes. A full description of the development history of the SHERM is presented in **Annexure A**. The water quality processes represented in the SHERM are as follows:

- Physical processes
  - Temperature
  - Salinity
  - DO and re-aeration
  - Solar radiation
  - Suspended sediments and light extinction.
- Nutrients
  - Nitrogen
    - NH_4, NO_x and two organic fractions (fast and slow decay fractions)
    - Nitrification and de-nitrification
    - Decomposition of organic nitrogen into soluble fractions
    - Sediment and water column exchange
    - Zero-and-first order nitrogen flux (release) from sediments
  - Phosphorus
    - PO_4 (absorbed and soluble) and two organic fractions (fast and slow decay fractions)
    - Decomposition of organic phosphorus into soluble fractions
    - Sediment and water column exchange
    - Zero-and-first order phosphorus flux (release) from sediments.
  - Carbon
    - Two organic fractions (fast and slow decay fractions).
- Algal processes
  - Primary production
  - Respiration
  - Mortality including grazing
  - DYNAMO option: Separation into green and diatom species
  - BLOOM option: Separation into three water column algae species (green, marine diatom, freshwater diatom) and a benthic algae species (represented by the Ulva process in Delft3D).

- Biological Contaminants
  - E-coli
  - Enterococci
  - Faecal coliforms.

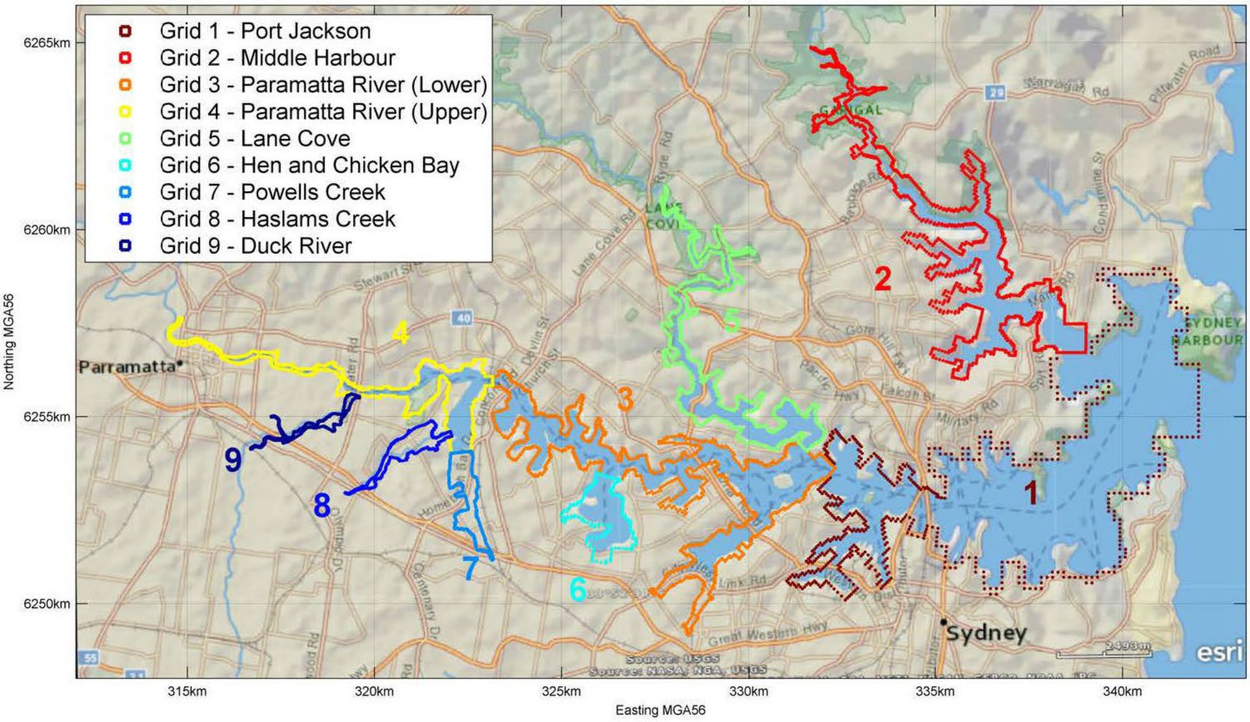


Figure 2-1 SHERM - Model Extent and Domain Decomposition Definition

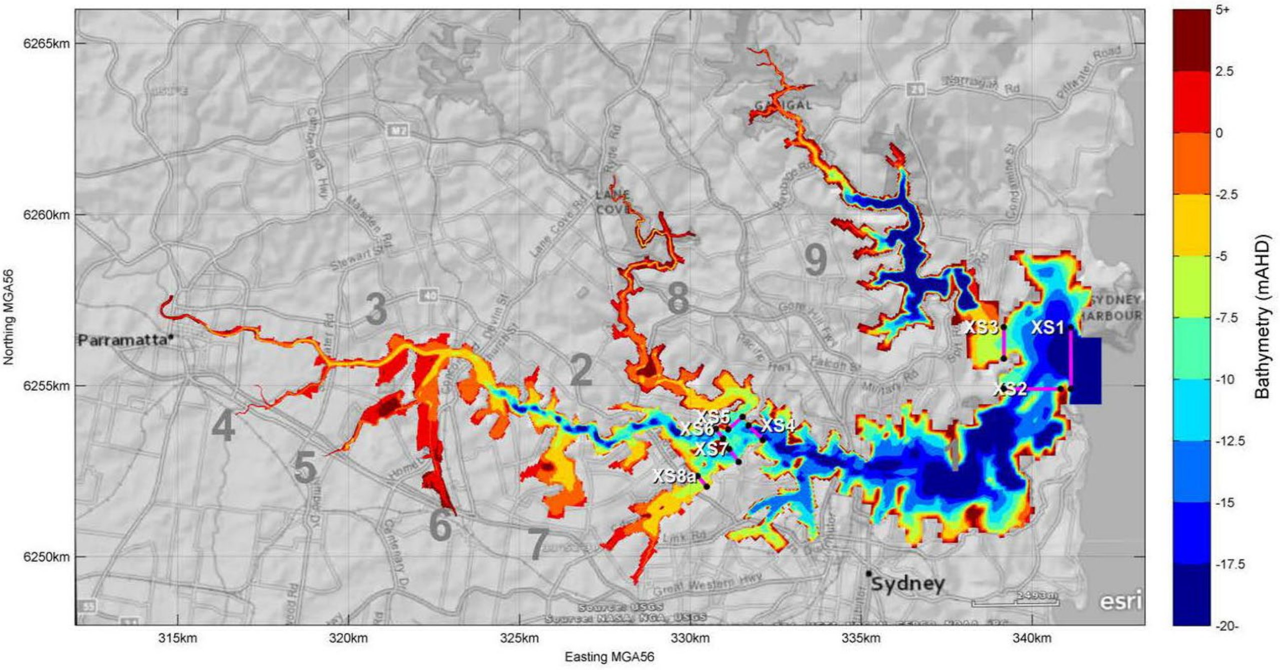


Figure 2-2 SHERM - Model Bathymetry and Discharge Calibration Cross−Section Locations

3 Methodology

In order to quantify the effect of the immersed tube tunnel sill on DO and water quality, predictive water quality modelling was carried out using the Middle Harbour grid of the existing SHERM. The existing Middle Harbour system and DO environment were simulated and compared with the results of model simulations that incorporated the immersed tube tunnel sill. Prior to carrying out this impact modelling, the model was upgraded in terms of grid alignment and plan resolution and then re-validated using the DO measurements collected during Sampling Period 1 (December 2017 to January 2018) and Sampling Period 2 (April to June 2020) as detailed in Appendix Q (Technical working paper: Marine water quality).

3.1 Model Setup and Runs

Adjustment of Model Grids

The Middle Harbour grid, Grid 2 in **Figure 2-1**, of the overall SHERM D3D model, and the WAQ model based on the same grid were applied to this investigation. To enhance accuracy of the model, the grid cells were adjusted to align with the tunnel sill. The grid was also refined to give a horizontal resolution of 30 m.

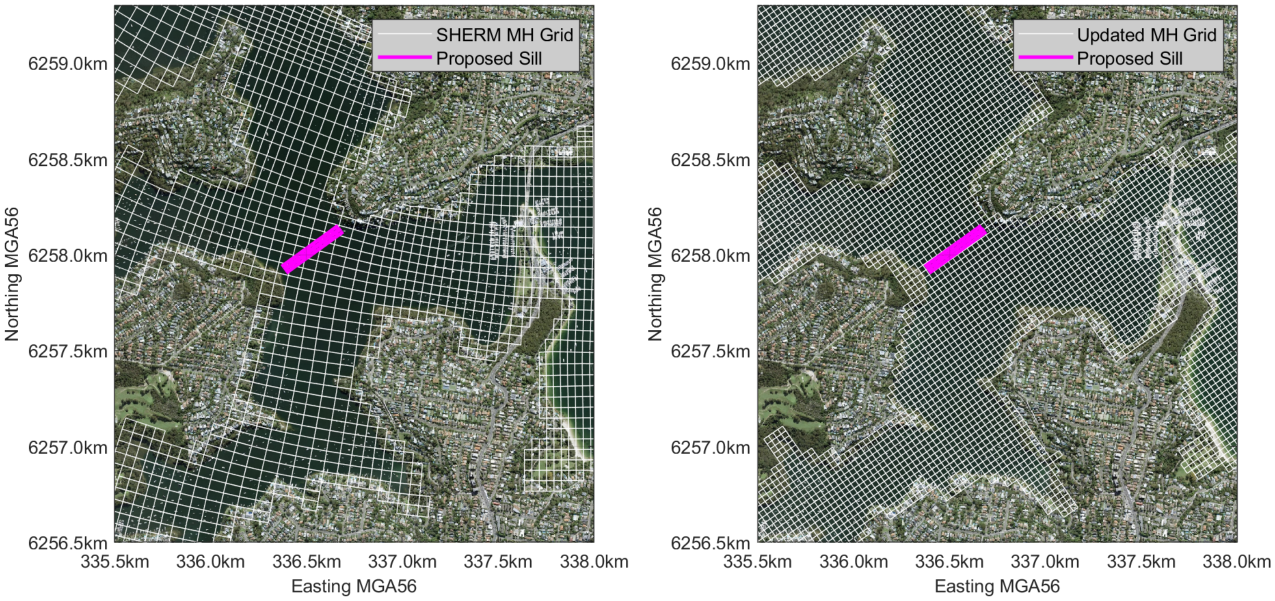


Figure 3-1 Realignment of Model Cell Boundaries to simulate the immersed tube tunnel sill. The left hand figure shows the SHERM grid, and the right hand figure shows the grid applied to this assessment

Set up of Middle Harbour Streams Boundary Conditions (BC)

Stream inputs were specified as point source boundaries to the Delft3D hydrodynamic and WAQ models. River/creek inflows applied in the model were based on an assessment aimed at selecting inflow events from the existing model record (2011 to 2014) that are most similar to the DO simulation periods. This assessment used rainfall data from Sydney Observatory Hill to compare previous periods of rainfall/inflow information, associated with existing (previous) modelled periods, with those for the simulation periods. Then, the best available estimates for nutrient and organic loads from the creeks to the WAQ Middle Harbour inflow BC module were selected, based on rainfall volume and pattern structure.

The model was re-calibrated to the current meter data for the December 2017 to March 2018 period presented in Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling), to confirm confidence in the Middle Harbour Delft3D Flow model - hydrodynamics.

Note that the WAQ model was calibrated using data collected primarily in the Port Jackson and Parramatta River arms of Sydney Harbour. At the time that the SHERM system was developed, deep water DO concentrations were not available in Middle Harbour. However, data collected during Sampling Period 1 (December 2017 to January 2018) and Sampling Period 2 (April to June 2020), provides evidence of occasional low DO levels near the Middle

Harbour bed of the harbour near the immersed tube tunnel sill, and provides the necessary additional time-series of deep water DO data to provide project-area model calibration.

Tidal and wind forcing, as well as solar input, were included.

For this assessment the Delft3D flow model was updated to simulate temperature stratification, which was directly applied to the WAQ model together with salinity.

Set up of the Open Boundary Conditions

The open boundary conditions from the Sydney Harbour model results were selected to be the same as those for the periods having similar catchment inflows.

Incorporating the Immersed Tube Tunnel Sill into the Model

The model was operated in 3D mode using the z-layer version of Delft3D. Both the sigma-layer and z-layer versions were tested, and the latter was found to provide the better description of vertical variations of salinity and water temperature. To ensure a smooth grid, and to avoid sudden expansions and contractions in the model grid, the immersed tube tunnel sill was incorporated as a sub-grid structure rather than modifying the bathymetry. This ensured that artificial vertical mixing due to the skewness of the vertical grid was minimised.

4 Data

A range of data items were required for the modelling task in order to calibrate the model in terms of hydrodynamics and transport-dispersion in the first instance, and then water quality parameters. Those items were:

- Provision of quality assured and controlled DO data for model calibration and validation
- Catchment flow time-series data from the SHERM database developed in 2014
- Boundary conditions to the flow models, including water temperature and salinity sourced from the BlueLink Reanalysis (BRAN2020) ocean model produced by the CSIRO
- Meteorological data including wind speed and direction, air temperature, relative humidity and rainfall sourced from the Bureau of Meteorology
- Hourly net solar radiation data sourced from the global ERA5 meteorological hindcast
- Bathymetric and topographic data required for model set up – available from AUS charts 200 to 203, survey data within Cardno's internal database, Transport for NSW survey data and the NSW Marine Lidar dataset.

5 Catchment Input Data

5.1 Catchment Model

A Sydney Harbour Catchment Model (SHCM) was developed for the then Hawkesbury Nepean Catchment Management Authority and is detailed in Development of the Sydney Harbour Catchment Model (Catchment Research Pty Ltd, 2014). Unlike previous catchment models of the harbour and Parramatta River, this Sydney Harbour Catchment Model simulates all Sydney Harbour Catchments in one model domain, including the Middle Harbour; Lane Cove River and Port Jackson sub-catchments (Catchment Research Pty Ltd, 2014). One of the key outcomes of the catchment model was to provide sub-daily flow and pollutant load time-series results at all specified inflow locations to Sydney Harbour and the Parramatta River for use in the Sydney Harbour hydrodynamic model, which provides the hydrodynamic basis for the SHERM.

Whilst the Sydney Harbour Catchment Model consisted of 550 sub-catchments, discharges from the approximate 195 sub-catchments, which had direct inflows to the hydrodynamic model, were used as input discharges to the hydrodynamic model, as presented in **Figure 5.1**. Data is available at 30 minute time-steps in comma separated values (csv) format for each of the catchments discharging directly to the hydrodynamic model.

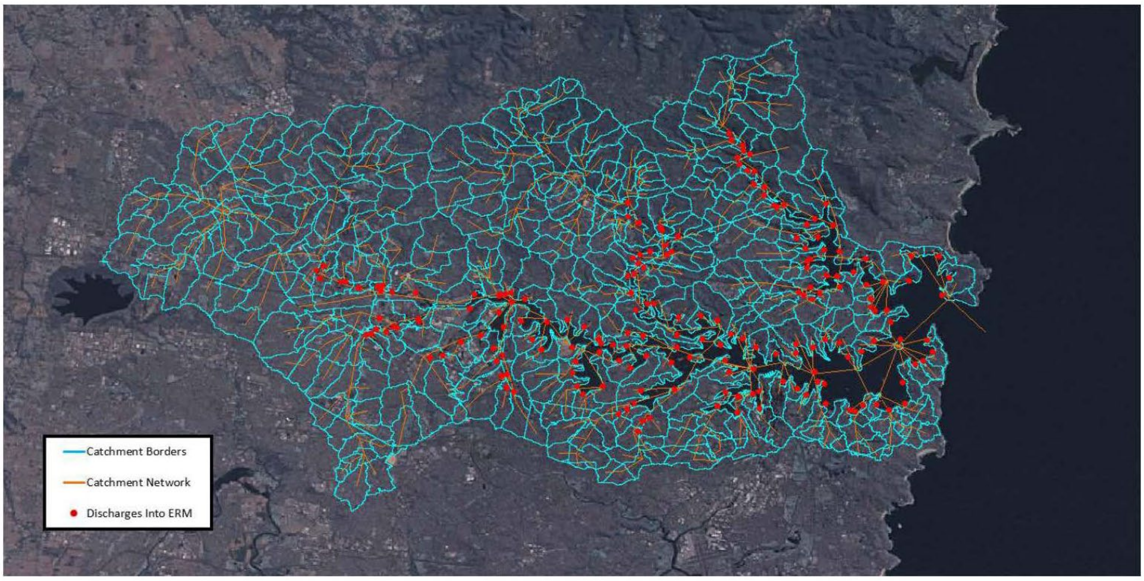


Figure 5-1 Map of Catchment Model and Inflows Discharged into the SHERM model

The catchment flow time-series, discharges and nutrient concentrations are available for the period from 1 January 2000 to 25 July 2013 and contain the following parameters:

- Flow (Q)
- Biochemical Oxygen Demand (BOD)
- E-coli (Ecoli)
- Enterococci (Enter)
- Faecal Coliforms (Fcoli)
- Total Nitrogen (TN)
- Total Organic Carbon (TOC)
- Total Phosphorous (TP)
- Total Suspended Solids (TSS).

5.2 Data Preparation for Delft3D

5.2.1 Units and Conversions

Catchment inflow data is available as time-series of daily flows. The list below summarises the units of the data and the conversions used for implementation in the Delft3D model:

- Flow: Supplied as ML/day. Divided by (1,000m^3/*86,400sec) to convert to m^3/s
- Nutrients: Supplied as kg/day. Divided by (1,000*ML/d) to convert to kg/m^3 (g/L).

5.2.2 Preparation of Input Data for Hydrodynamic and Water Quality Models

A Matlab routine was developed to load the catchment data from the comma separated values (csv) format into a Matlab structure file (mat). The routine converted the supplied data into standard units and file structures consistent with hydrodynamic and water quality model inputs as detailed in **Section 5.2.1**. The data was then prepared as Delft3D discharge input files for input to the hydrodynamic model and Delft3D time-series (tim) files for input into the Water Quality model. Discharge files were required for each simulation period, including a two week warm-up period prior to each period simulated in the model.

5.2.3 Catchment Inflow Nutrient Specifications

The most important DIN and DIP data analyses are associated with catchment inflows so that reasonable estimates of the organic and inorganic split of the catchment nutrient load can be deduced.

Based on runoff quality measurements collected in 2012 during the development of the SHERM, the ratios between the organic and inorganic fractions in that data were used to develop coefficients which could be applied to Total Nitrogen (TN) and Total Phosphorus (TP) inputs from the catchment model to provide appropriate relative inorganic and organic inflow concentrations. The DO and dissolved silica measured during this freshwater flow period were used to specify the concentrations for these variables from the catchment inflows. **Table 5-1** summarises coefficients applied to the catchment water quality inflow conditions.

Table 5-1 Summary of Coefficients Applied to Catchment Water Quality Inflow Specifications

Substance	Symbol	Coefficient	Ref. Variable from Catchment Modelling
Silica	Si	2.2	mg/L
Ammonium	NH_4	0.2	TN
Phosphate	PO_4	0.2	TP
Nitrate	NO_3	0.2	TN
Other Organic Carbon (slow decay)	OOC or POC3	0.5	TOC
Detritus Carbon (fast decay)	DetC or POC1	0.5	TOC
Oxidisable Organic Nitrogen	OON or PON3	0.3	TN
Detritus Nitrogen	DetN or PON1	0.3	TN
Oxidisable Organic Phosphorus	OOP or POP3	0.5	TP
Detritus Phosphorus	DetP or POP1	0.2	TP
Oxygen	OXY	6.5	mg/L
Inorganic Matter	IM1	1	TSS

6 Model Calibration

This section summarises the construction and development and then the recalibration of a detailed 3D hydrodynamic model of Middle Harbour. The purpose of this hydrodynamic model was to provide spatial and temporal descriptions of water levels, currents, discharges, temperature and salinity that were used to drive the detailed water quality and ecological response model for Middle Harbour – which forms part of the SHERM.

6.1 Hydrodynamic Model

The hydrodynamic model component of the SHERM solves the Navier-Stokes equations for 2D and 3D non-steady flows in the relatively shallow water of Sydney Harbour including extending upstream of the tidal limit in the Parramatta River. It incorporates the effects of tides, winds, air pressure, density differences (due to salinity and temperature), waves, turbulence (k-ε model) and drying and flooding. The following sections document the model calibration process for the hydrodynamic component of the model.

6.1.1 3D Issues

In coastal seas, estuaries and lakes, stratified flow occurs in combination with steep, deep topography and in the presence of catchment inflows of fresh water; as well as seasonal solar heating. 3D numerical modelling of the hydrodynamics and water quality in these areas requires accurate treatment of the vertical exchange processes, as well as light penetration in the water column. The existence of vertical stratification influences vertical currents and eddy structure and consequently the turbulent exchange of oxygen, heat, salinity, suspended sediments and passive contaminants; and then light. The accuracy of the discretization of the vertical exchange processes is determined by the vertical grid system.

Delft3D offers two options for 3D-FLOW models, namely 3D-Z and 3D-(S)igma layer models.

Both options have been tested to identify the more suitable method to fulfil the hydrodynamic requirements, and also the water quality modelling requirements for this investigation. Twelve vertical layers have been used in both cases.

6.1.2 3D Z-Layer Model

The Cartesian Z vertical coordinate system has horizontal coordinate lines, which are (nearly) parallel with density interfaces (isopycnals) in regions with steep bottom slopes. This is important to reduce artificial mixing of scalar properties such as suspended sediments, salinity and temperature.

The vertical grid system in the Z-model is based on horizontal layers with constant z co-ordinates (fixed vertical levels) intersecting the water column. The (maximum) layer thickness is defined as the distance between two consecutive surfaces and is independent of space and time. Near the free surface and the bed, the computational grids may be partially filled depending on the local depth and the free surface elevation – tide stage or the effect of fresh water inflow. Furthermore, the free surface in the Z grid-coordinate model is not restricted to the upper most grid cell. Consequently, the number of active grid cells may vary in space and time.

Table 6-1 presents the horizontal layer configuration adopted for the Z-layer model. Note that the 12th layer is the surface layer.

Table 6-1 Z-Layer Model Vertical Grid Structure

Z-model		Depth Extent Levels		Maximum Thickness (m)
		Bot (m AHD)	Top (m AHD)	
Layer Number	12	-0.9	1.5	2.4
	11	-3.3	-0.9	2.4
	10	-5.6	-3.3	2.4
	9	-8.0	-5.6	2.4
	8	-10.4	-8.0	2.4
	7	-13.1	-10.4	2.7
	6	-15.8	-13.1	2.7
	5	-18.9	-15.8	3.1
	4	-22.3	-18.9	3.4
	3	-25.7	-22.3	3.4
	2	-29.1	-25.7	3.4
	1	-32.5	-29.1	3.4

The upper layers were chosen to be thinner at the top (down to 10 metres depth) to improve the resolution at the depth levels in which the important vertical hydraulic and water quality gradients are expected. For example, the salinity in the water surface layer will be strongly affected by the discharge of fresh water from the catchments, more so, where the flows enter creeks, rather than in the major estuarine reaches.

6.1.3 3D-Sigma Layer Model

For the (S)igma-coordinate vertical grid model, the number of layers over the entire horizontal computational area is constant, irrespective of the local water depth. The distribution of the relative layer thicknesses is usually non-uniform. This allows for more resolution in the zones of interest such as the near surface area and the near bed area (sediment transport and benthic processes). It was adopted to be constant in this case.

The vertical sigma-grid is commonly used in Delft3D-FLOW. However, occasionally this grid may not be suitable for solving problems where stratified flow can occur in combination with steep topography. The sigma-grid, though boundary fitted, may not have enough resolution around the pycnocline, which is strictly horizontal in physical space.

One disadvantage of a sigma model is that it can induce artificial vertical mixing due to the skewness of the vertical grid. This is particularly important when investigating the effect of the immersed tube tunnel, for which it is likely to under-estimate residence times behind the immersed tube tunnel.

The sigma model was also unable to reproduce the vertical temperature and salinity structures measured after large rainfall events. For these reasons, the 3D Z-layer model was applied to this assessment.

6.2 Water Quality Model

The water quality model component of the SHERM is capable of modelling the water quality processes described in **Section 2 and Annexure A** in 2D or 3D. The Delft3D Water Quality suite utilizes the outputs from the calibrated hydrodynamic model described in **Section 6.1** to describe transport fluxes between grid cells, and then a numerical scheme is adopted to solve the process equations for selected water quality processes and the net transport-dispersions.

The following sections outline the setup and calibration of the water quality model applied to this assessment.

6.2.1 Salinity and Dispersion Calibration - WAQ

The water quality model was calibrated for salinity and dispersion by benchmarking the model against the hydrodynamic model results. During the salinity and dispersion calibration process for the water quality model, it was necessary to select the following:

- Suitable WAQ numerical scheme

- Suitable WAQ model time step
- Physically realistic dispersion coefficients.

The Delft3D WAQ model system has a number of implicit and explicit numerical solution schemes. A number of these were examined in the calibration process, with the selected scheme for the model being an implicit scheme, which provided a good trade-off between model time-step, model stability and minimizing numerical dispersion. The selected numerical scheme was 16.

Table 6-2 summarizes the dispersion coefficients and time-steps selected for the water quality model based on the salinity and dispersion calibration.

For this assessment, the WAQ model adopted the salinity, temperature, shear stress and dispersion directly from the flow model. The re-validation of the WAQ model focused on dissolved oxygen, which is described below.

Table 6-2 Water Quality Model Time Step and Dispersion Coefficient Details

Model Parameter	Full Scale Model
Vertical Schematization	3D (12 z-layers)
Time Step (min)	2
Additional Horizontal Dispersion Coefficient (m^2/s)	0 (included in hydrodynamics)
Additional Vertical Dispersion Coefficient (m^2/s)	0 (included in hydrodynamics)

6.2.2 Dissolved Oxygen Calibration - WAQ

The WAQ model was re-validated using the time-series measurements of DO collected during Sampling period 2 (April to June 2020).

As noted in **Section 5**, the catchment runoff database included in the SHERM covers the period from 1 January 2000 to 25 July 2013. As no runoff was available for the calibration period, an artificial catchment runoff time-series database was developed by selecting periods with similar rainfall volumes and shapes based on the Sydney Observatory Hill measurements.

Catchment flow, water temperature (set as 1 degree less than the corresponding air temperature) and salinity (set as 1 ppt to represent fresh water) were included in the flow model. Pollutant loads were included in the WAQ model based on the pollutant loads in the S**HERM catchment flow database.**

Figure 6-1 and Figure 6-2 present a comparison of the modelled and measured DO concentration during the re-calibration period. **Figure 6-1** indicates that the model is able to predict the near bed of the harbour DO concentration reasonably well, particularly the decay in near bed of the harbour DO after a rainfall event (late May 2020).

A comparison of the measured and modelled vertical profiles on 1 June 2020 shows that the model provided a good representation of the DO and density variation through the water column, with a slightly conservative under-estimation of DO and Salinity near the surface at the time of the profile measurement.

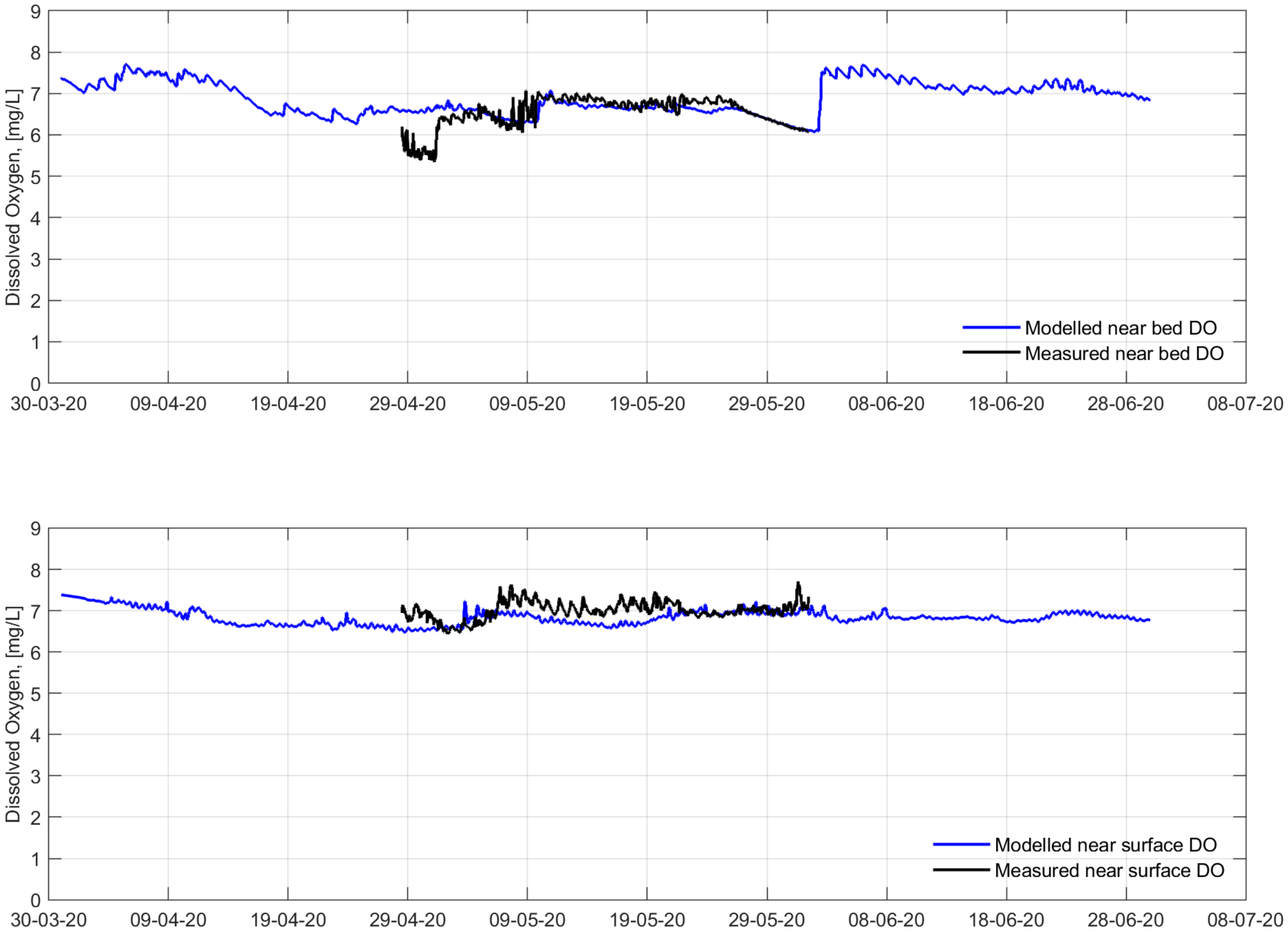


Figure 6-1 Comparison of Measured and Modelled Near-Bed (top chart) and Near-Surface (bottom chart) DO Concentration during May 2020.

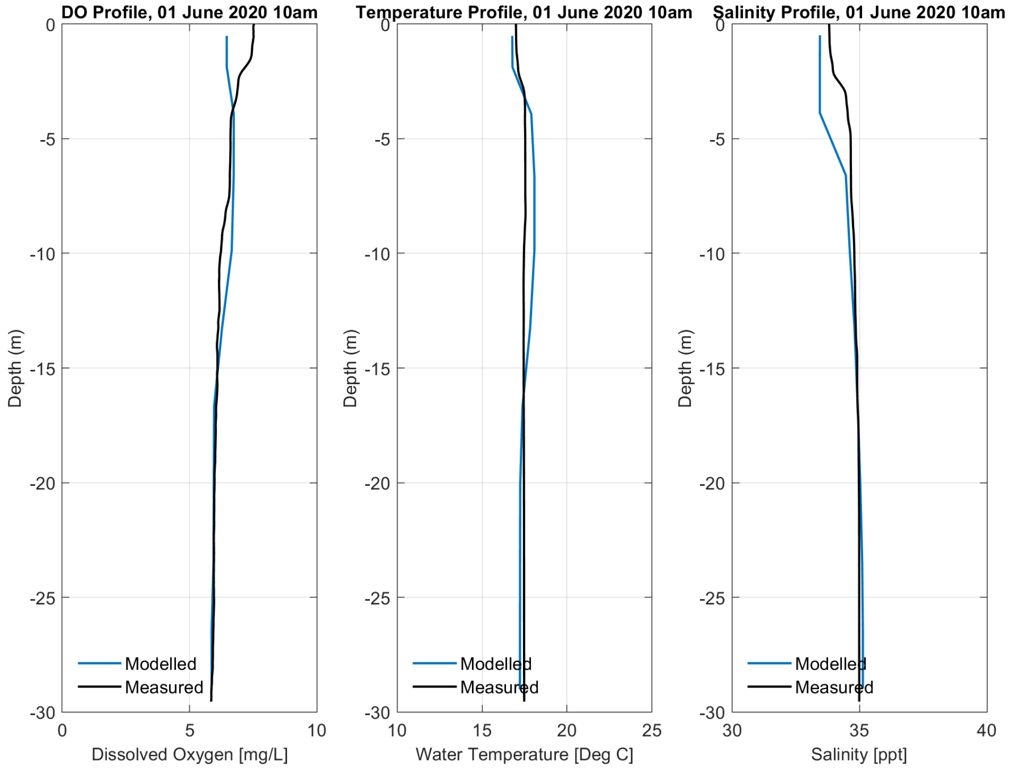


Figure 6-2 Comparison of Measured and Modelled DO, temperature and salinity Profiles – 01 June 2020

DO profiles were also collected in early 2018 during Sampling Period 1. The last set of samples, collected on the 30 January 2018, indicated that the near bed of the harbour DO concentration at the proposed crossing location dropped to approximately 4 mg/L. A comparison of the modelled and measured DO, temperature and salinity profiles are shown below in **Figure 6-3**. This figure shows that the model is predicting a decrease in DO near the bed of the harbour, however, is over-estimating the DO by approximately 1.3 mg/L (modelled 5.3 mg/L vs 4.0 mg/L measured), whereas the temperature and salinity predicted by the model are within 0.5 degrees and 0.2 ppt respectively. Given that the model is giving a reasonable estimate of DO concentration in the upper water column, the discrepancy near the bed of the harbour could be attributed to an under-estimation of the sediment oxygen demand (SOD) during this period. Delft-3D WAQ estimates the SOD based on the ambient water temperature, salinity and organic matter. It is also possible to include a user-defined SOD which has been applied in the sensitivity simulations (**Section 8**), where the model did predict a near bed DO concentration of 4 mg/L during this event.

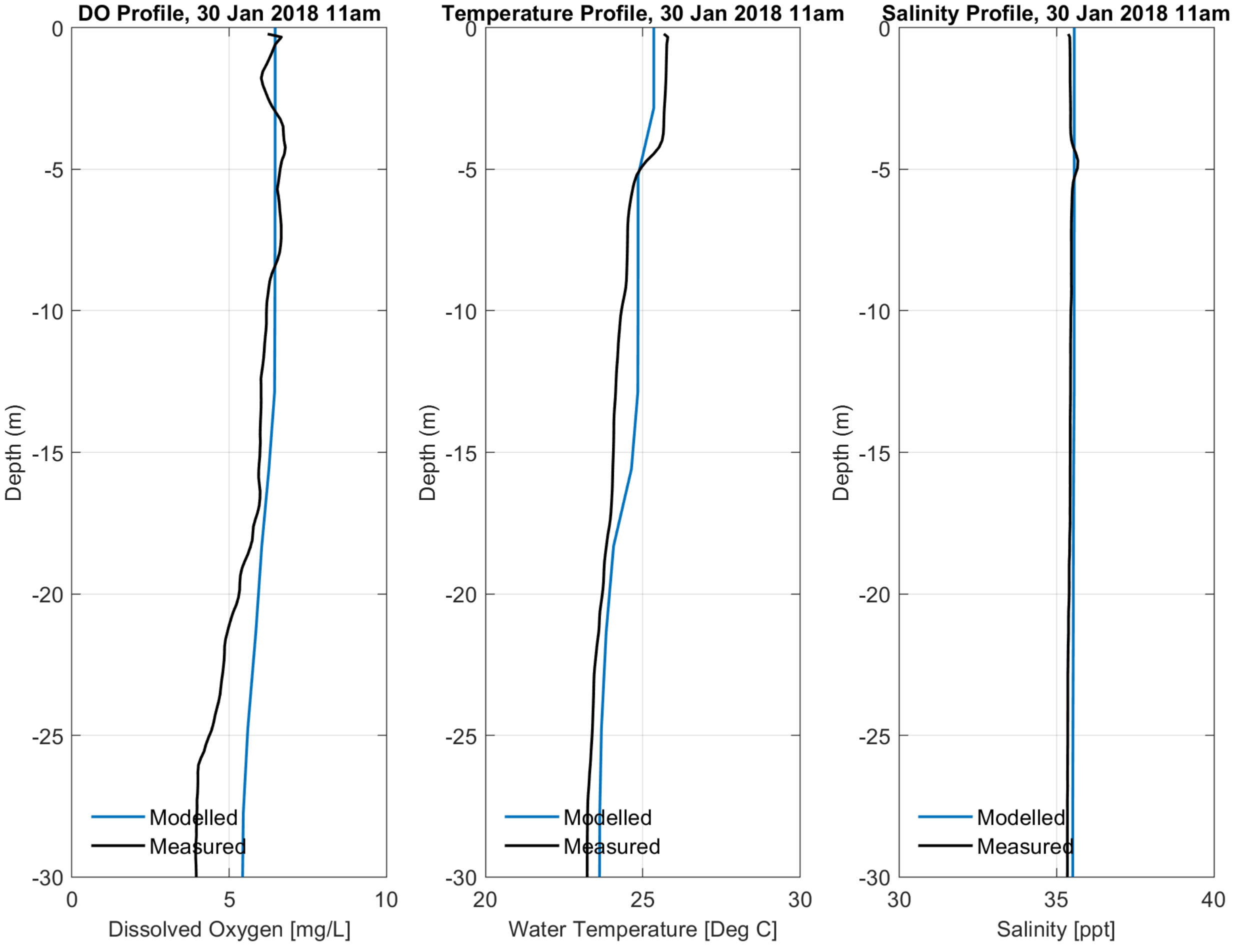


Figure 6-3 Comparison of Measured and Modelled DO Concentration Profiles – 30 January 2018

7 Dissolved Oxygen Modelling Results

The potential impact to DO levels due to the construction of the immersed tube tunnel have been investigated in the model. Three separate periods have been simulated. These included:

Simulation Period 1 – 1 December 2017 to 1 March 2018, which includes Sampling period 1

Simulation Period 2 – 1 March 2020 to 1 July 2020, which includes Sampling period 2

Simulation Period 3 –1 January 2012 to 1 April 2012, which includes a number of high rainfall events.

For each of these three periods, separate flow and water quality simulations were carried out for the existing case and additional simulations with the immersed tube tunnel sill. The immersed tube tunnel sill has been included in the model as a sub-grid structure (3D gate) that blocks horizontal flow and mixing perpendicular to the structure along the bottom four cells across Middle Harbour at the sill location.

Results from each of these simulations are presented in terms of near bed time-series plots of DO and longitudinal contours of DO with depth at select time periods. The predicted change in DO is also presented as both a longitudinal depth versus distance plot along the Middle Harbour thalweg (i.e. a long section along the deepest part of the harbour) and a 2D map showing the change in the near bed DO concentration. Charts showing the change in DO along the thalweg of Sailors Bay are also presented.

Note that absolute differences less than 0.1 mg/L are not presented on the maps as 0.1 mg/L is considered to be the limit of accuracy of the model.

The contour plots presented in the subsequent sections are a snapshot of the period when the difference between the ambient and future DO immediately upstream of the immersed tunnel sill is the largest (not including periods of delayed recovery). These snapshots give an indication of the change in minimum DO levels in the harbour.

The immersed tube tunnel sill also has the potential to slightly change near bed salinity and temperature due to reduced mixing and flushing. However, based on the time series modelling results presented in **Annexure B**, changes to these parameters are expected to be small, and less than 0.1 degrees and 0.1 ppt upstream and downstream of the immersed tube tunnel sill.

7.1 Simulation Period 1 (December 2017 to March 2018)

Figure 7-1, **Figure 7-2**, **Figure 7-3** and **Figure 7-4** present the dissolved oxygen simulation results for simulation period 1.

The time-series of near bed DO (refer to **Figure 7-1**) immediately upstream of the immersed tube tunnel sill show that the near bed DO gradually decreases from about 7 mg/L to 5 mg/L within 1-2 weeks following a rainfall event. The model predicts that the DO would reduce slightly more (approximately 0.3 mg/L) once the immersed tube tunnel is constructed. However, recovery of DO generally occurs within the same time (or within 10 hours of the existing case) and is generally very rapid. Modelling results show that DO levels would still remain within an acceptable range that is above the precautionary threshold limit of 4.6 mg/L for conserving biodiversity.

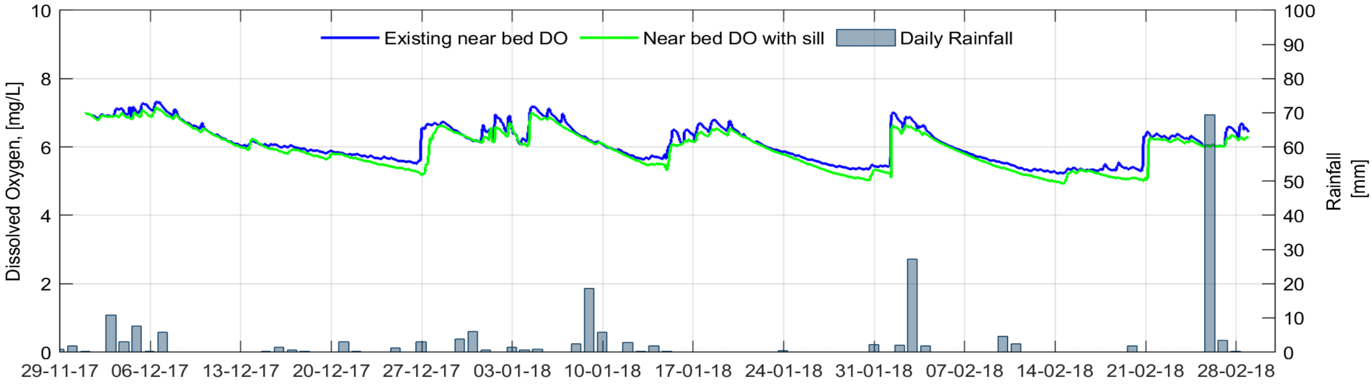
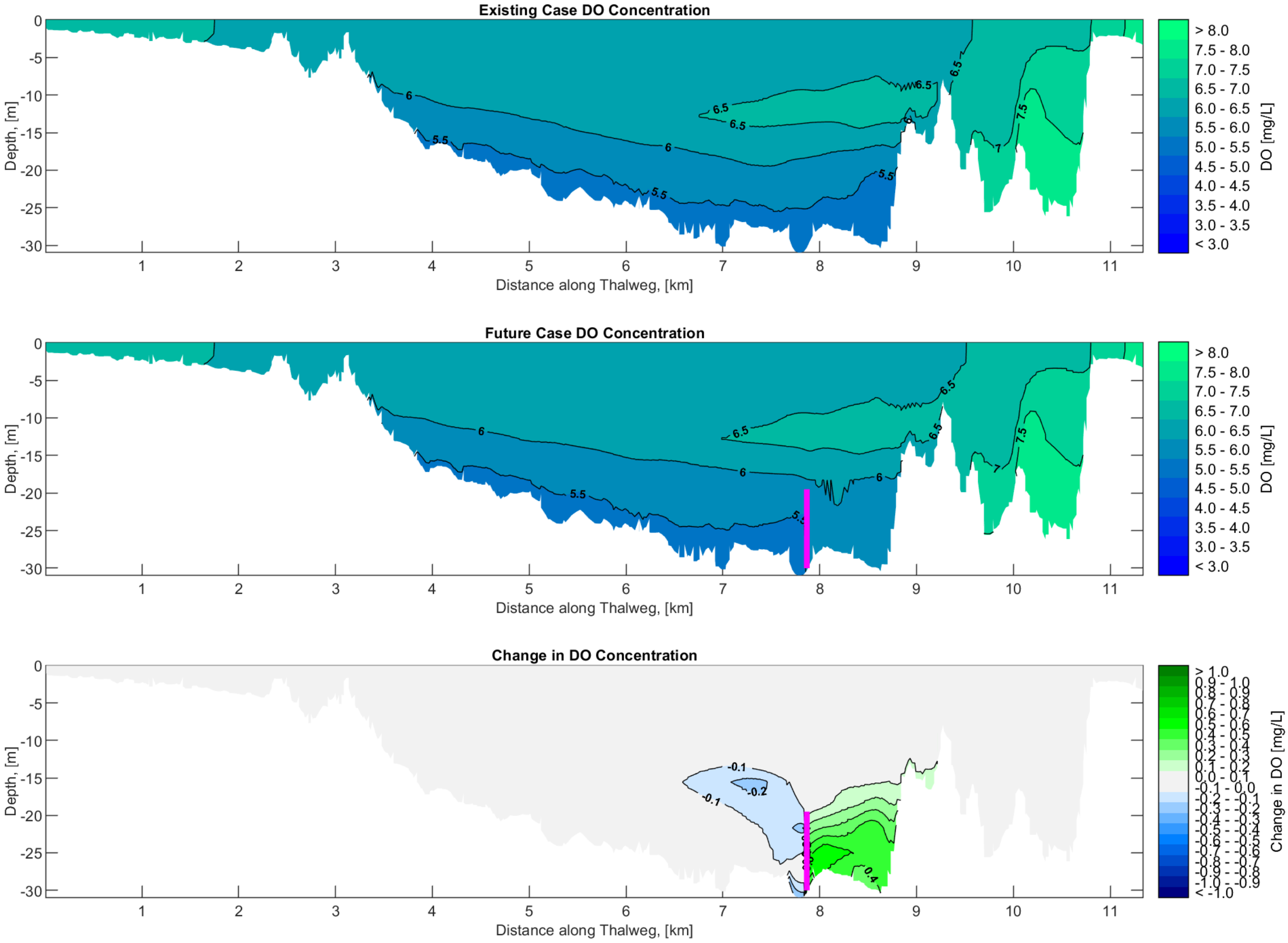


Figure 7-1 Time-Series Plot showing the Predicted Near Bed DO during Simulation Period 1

The spatial extent of the changes to DO is presented in **Figure 7-2**, **Figure 7-3** and **Figure 7-4,** which present a snapshot of the change in DO at the time when the largest change occurred. The model results indicate that DO on the bed of the harbour will be lower in an area approximately 200 to 300 metres upstream of the immersed tube tunnel sill and within Sailors Bay. Conversely, the model indicates that the DO downstream of the immersed tube tunnel sill would not drop to the extent it currently does following a rainfall event, indicating that the frequency of low DO events in this area would reduce following construction of the immersed tube tunnel sill.



Existing Case DO Concentration

Future Case DO Concentration

Change in DO Concentration

Figure 7-2 Predicted DO Concentrations for the Existing Case (top chart), with the Immersed Tube Tunnel Sill included (middle chart) and the Predicted Change in DO (bottom chart) – 30 January 2018

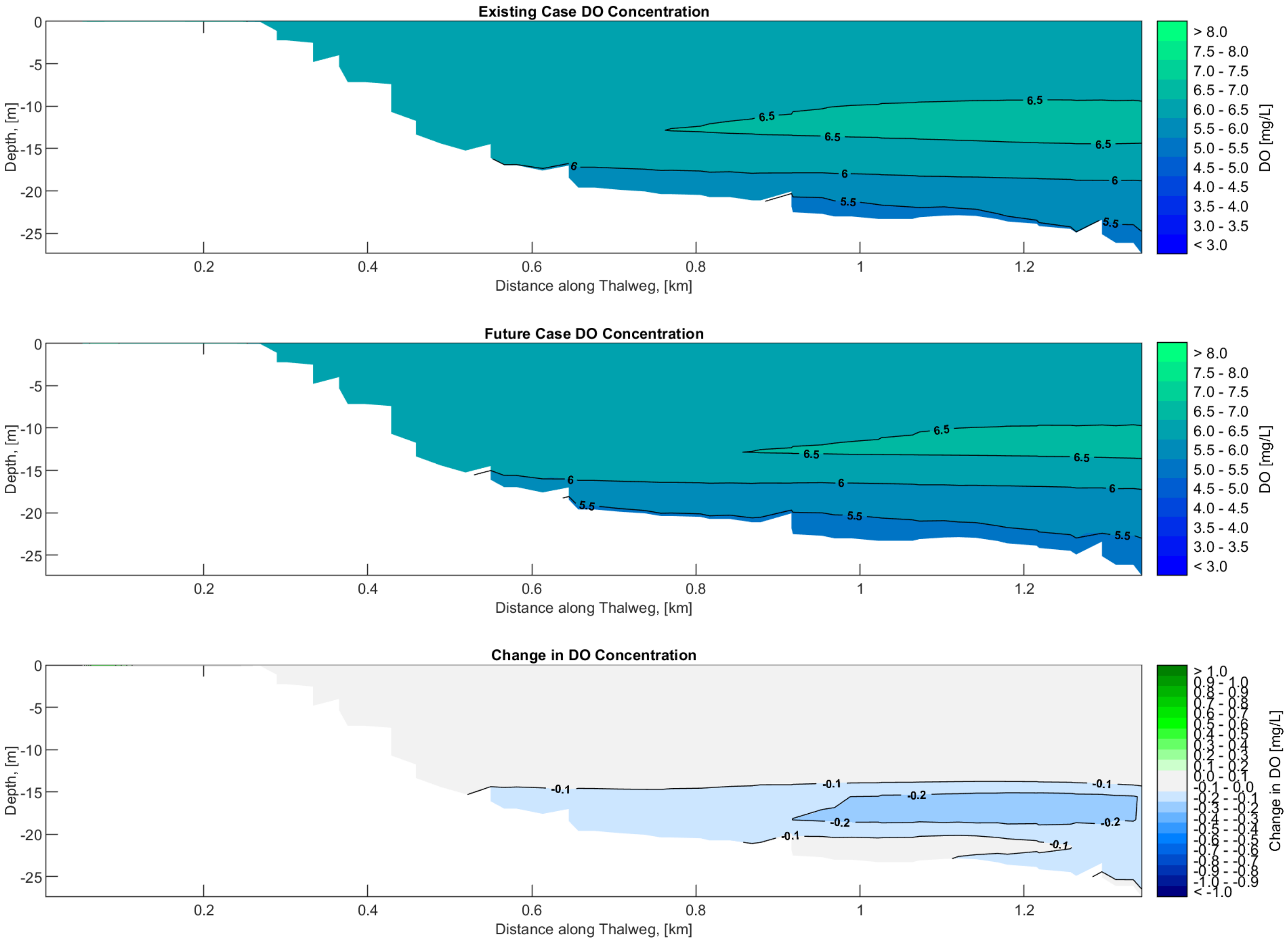


Figure 7-3 Predicted DO Concentrations in Sailors Bay for the Existing Case (top chart), with the Immersed Tube Tunnel Sill included (middle chart) and the Predicted Change in DO (bottom chart) – 30 January 2018

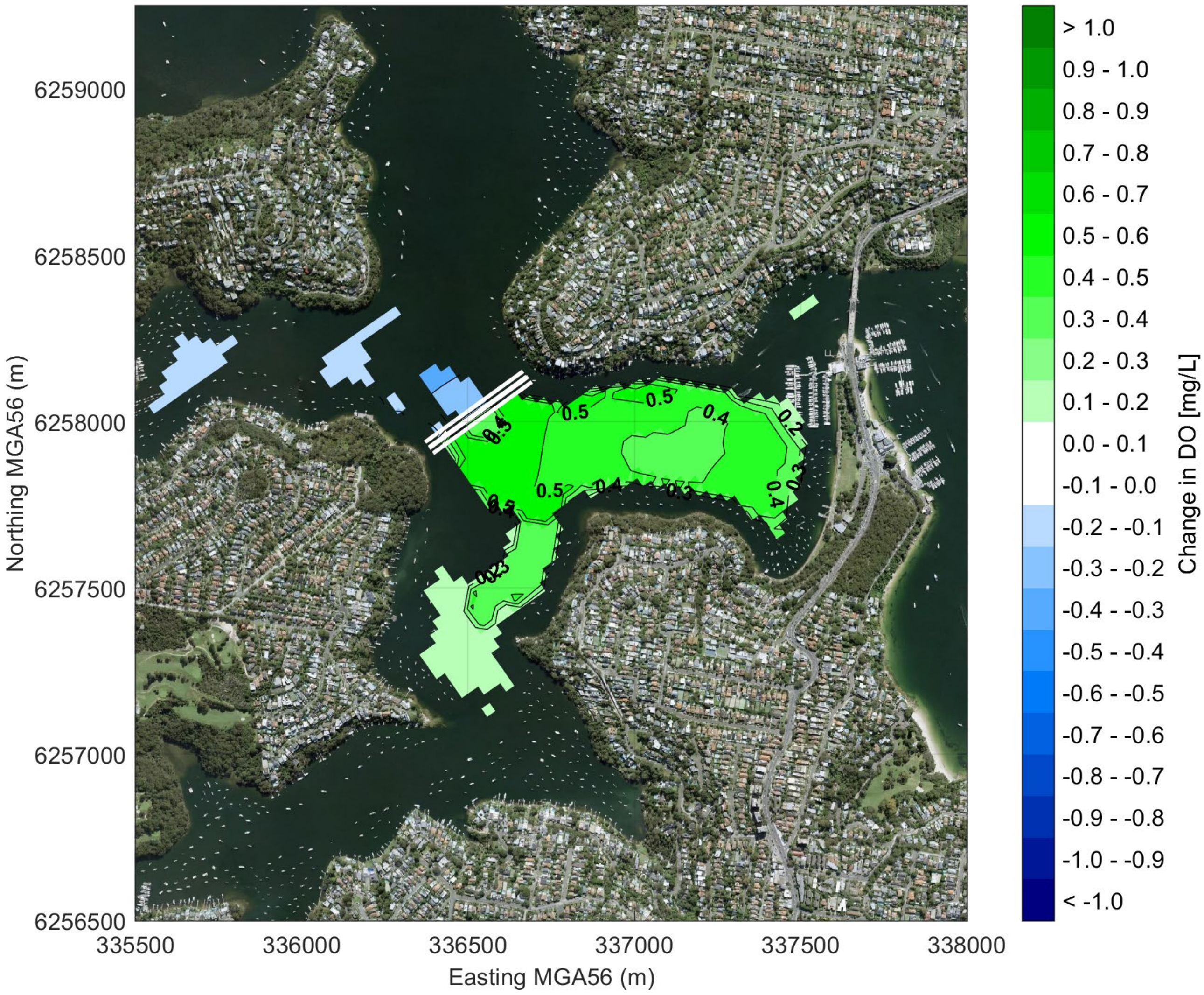


Figure 7-4 Modelled Change in Near Bed DO Concentration with the Immersed Tube Tunnel Sill – 30 January 2018

7.2 Simulation Period 2 (April 2020 to June 2020)

Figure 7-5, **Figure 7-6, Figure 7-7** and **Figure 7-8** present the DO simulation results for simulation period 2.

Similar to simulation period 1, the time-series of near bed DO (**Figure 7-5**) immediately upstream of the immersed tube tunnel sill show that the near bed DO gradually decreases from about 6.5 mg/L to 5.3 mg/L within 1 week following a rainfall event. The predicted change in DO concentration is slightly smaller than for simulation period 1; with a maximum reduction of 0.2 mg/L predicted once the immersed tube tunnel is constructed. Recovery of DO generally occurs within the same time (or within six hours of the existing case) and is generally very rapid. Modelling results show that DO levels would still remain within an acceptable range of 5.3 mg/L, which is above the precautionary threshold limit of 4.6 mg/L for conserving biodiversity.

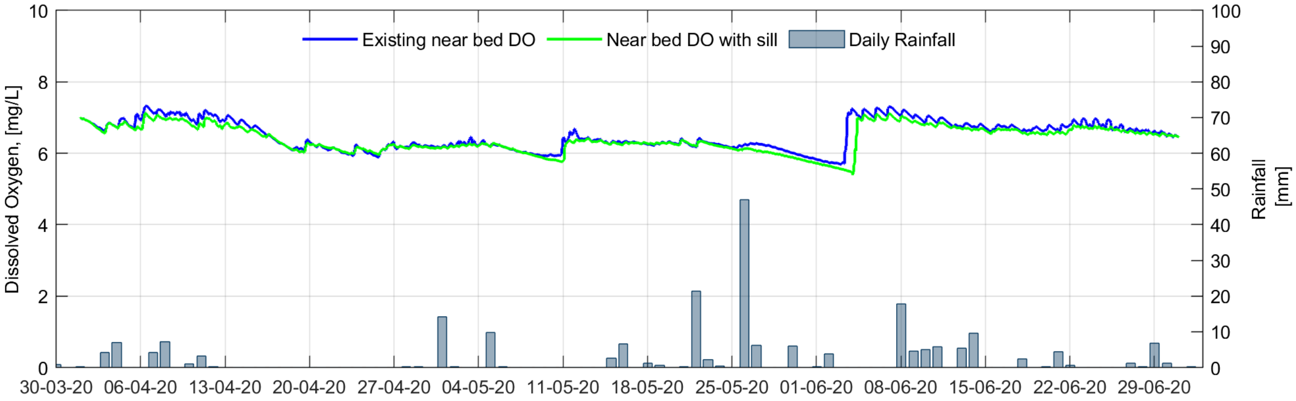


Figure 7-5 Time-Series Plot showing the Predicted Near Bed DO during Simulation Period 2

The spatial extent of the changes to DO concentration at the time of the largest change during this simulation period is presented in **Figure 7-6, Figure 7-7** and **Figure 7-8**. The model predicts a similar pattern to that of simulation period 1; however, the magnitude of predicted change is smaller. The model indicates that the near bed DO concentration would be slightly lower with the immersed tube tunnel sill in place in an area approximately 100 to 200 metres upstream of the immersed tube tunnel sill. No changes are predicted to occur in Sailors Bay as indicated in **Figure 7-7**. Downstream of the immersed tube tunnel sill, between the project and the Spit Bridge, the model indicates that the near bed DO concentration would not reduce to the extent it currently does following a rainfall event, indicating that the frequency of low DO events in this area would reduce following construction of the immersed tube tunnel sill.

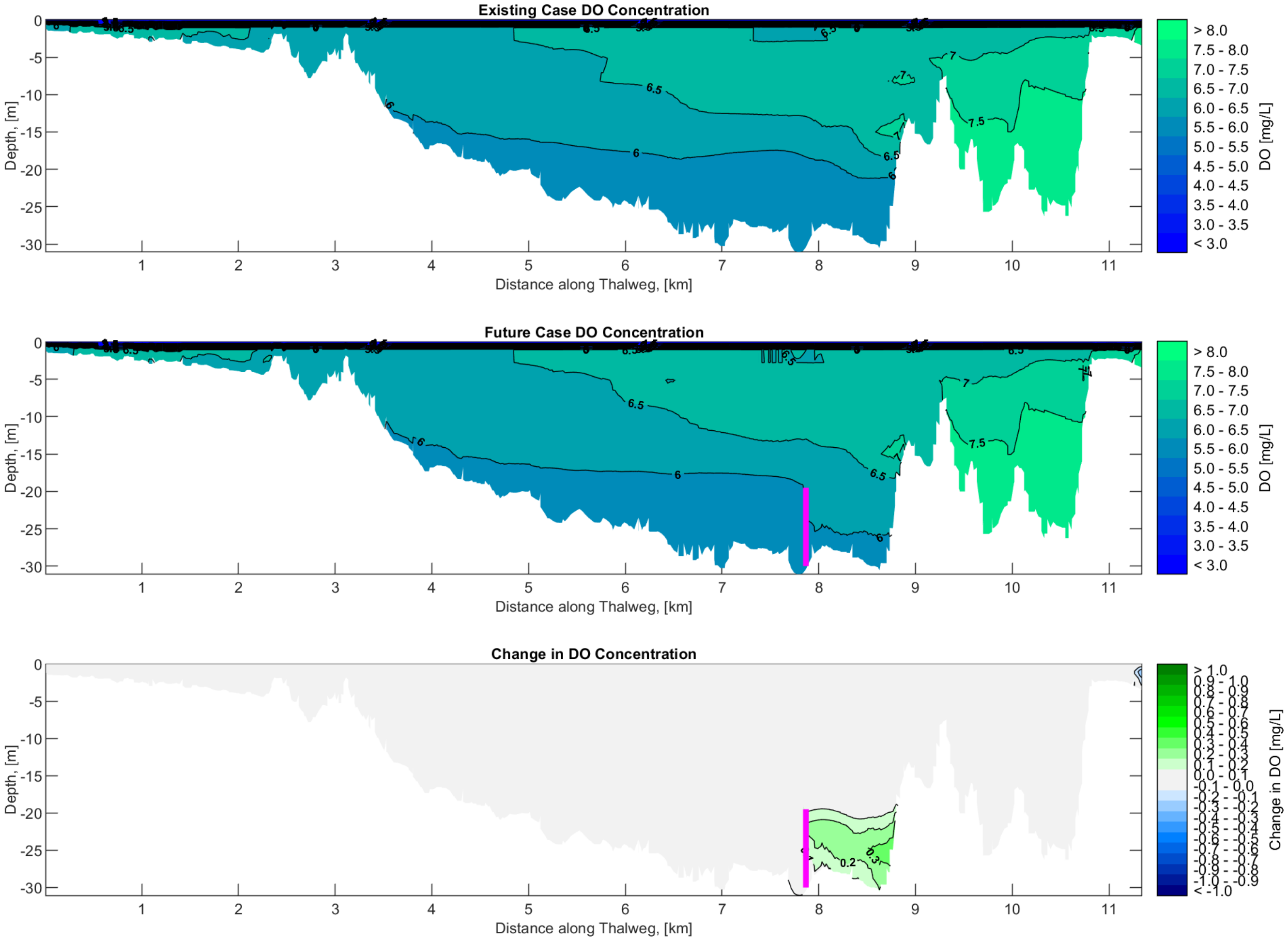


Figure 7-6 Predicted DO Concentrations for the Existing Case (top chart), with the Tunnel Sill included (middle chart) and the Predicted Change in DO (bottom chart) – 1 June 2021

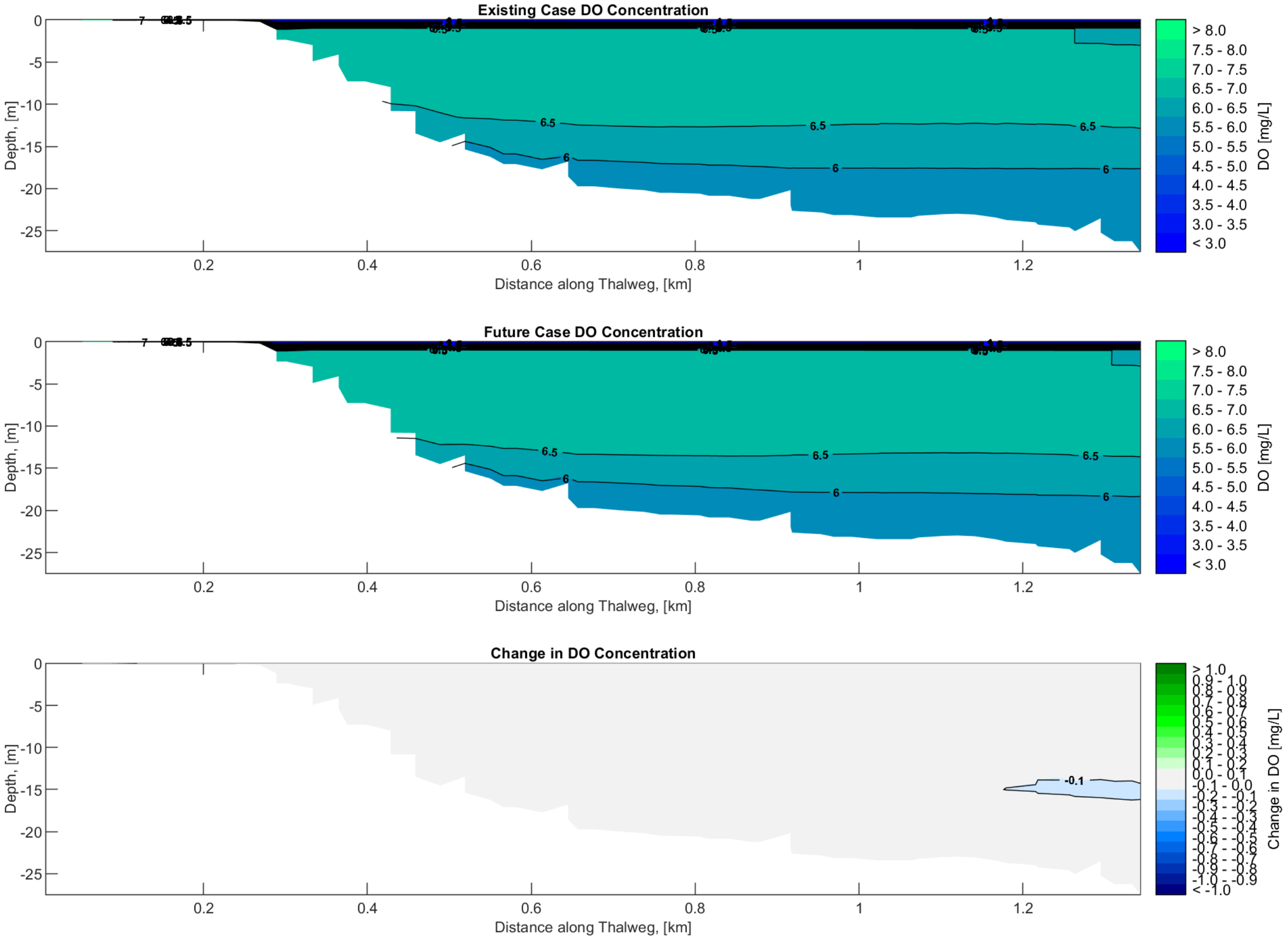


Figure 7-7 Predicted DO Concentrations in Sailors Bay for the Existing Case (top chart), with the Tunnel Sill included (middle chart) and the Predicted Change in DO (bottom chart)– 1 June 2021

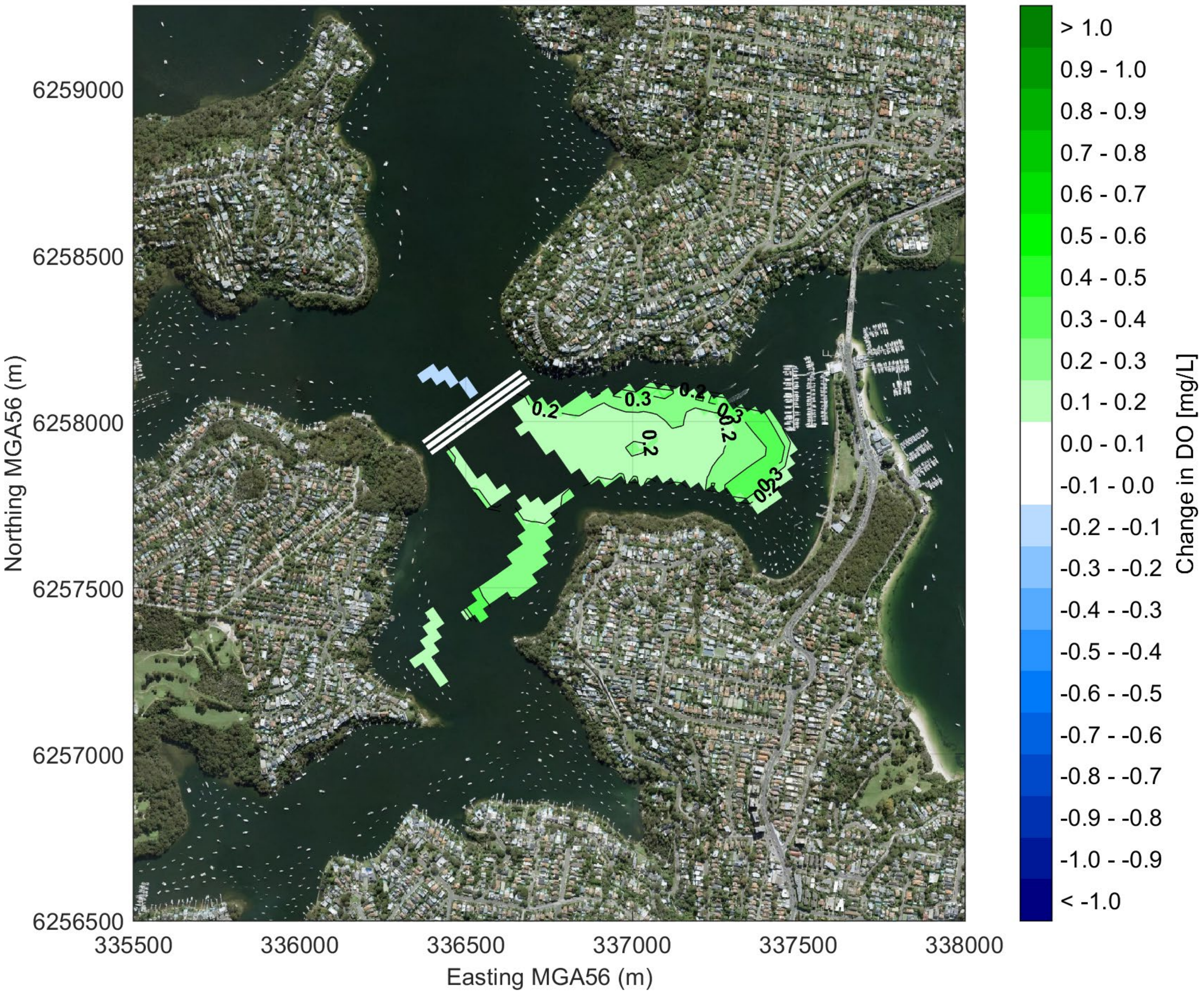


Figure 7-8 Modelled Change in Near Bed DO Concentration with the Immersed Tube Tunnel Sill – 1 June 2020

7.3 Simulation Period 3 (January to March 2012)

Figure 7-9, **Figure 7-10, Figure 7-11** and **Figure 7-12** present the DO simulation results for simulation period 3.

This period was modelled because it included a number of high rainfall events, and occurred during summer. Rainfall during this period is shown on **Figure 7-9** and totalled 140 millimetres in January 2012, 110 millimetres in February 2012 and 270 millimetres in March 2012 (including a total of 120 millimetres on 8 and 9 March 2012). The result of this rain was a period of low near bed DO starting in late January and early February, and another low DO event starting in the first week of March 2012.

A comparison of the DO results for simulations with and without the immersed tube tunnel sill indicates that the sill could reduce the near bed DO concentration by up to 0.4 mg/L. Recovery of DO generally occurs within 18 hours of the existing case. Modelling results show that DO levels would still remain within an acceptable range of 4.7 mg/L, which is above the precautionary threshold limit of 4.6 mg/L for conserving biodiversity.

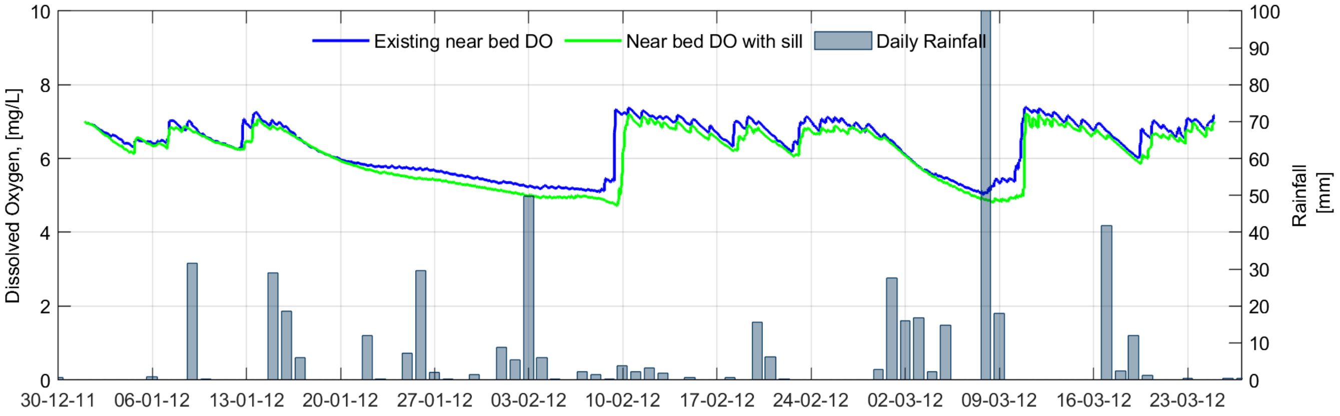


Figure 7-9 Time Series Plot showing the Predicted near Bed DO during Simulation Period 3

The spatial extent of the change to DO concentration during this period is presented in **Figure 7-10, Figure 7-11** and **Figure 7-12**. The model predicts a similar pattern to that of simulation periods 1 and 2; however, the magnitude of predicted change is higher both upstream and downstream. The model indicates that DO concentration on the bed of the harbour will be up to 0.5 mg/L lower than ambient in an area approximately 600 to 700 metres upstream of the immersed tube tunnel sill extending into Peach Tree Bay and Sailors Bay. Downstream of the immersed tube tunnel sill, between the project and the Spit Bridge, the model indicates that DO concentration could be over 1.0 mg/L higher than without the immersed tube tunnel. This indicates that the frequency of low DO events in this area would reduce following construction of the immersed tube tunnel sill.

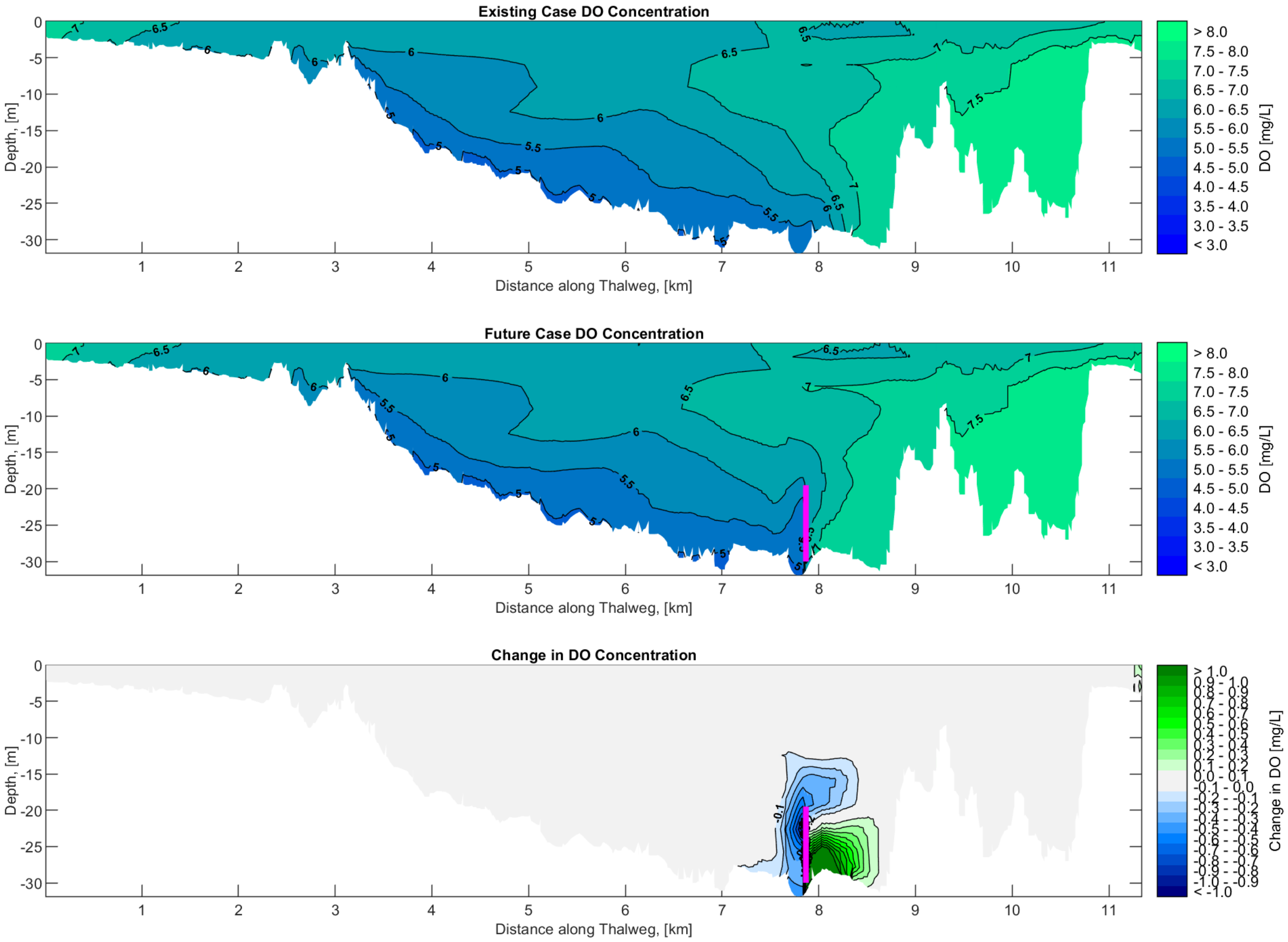


Figure 7-10 Predicted DO Concentrations for the Existing Case (top chart), with the Immersed Tube Tunnel Sill included (middle chart) and the Predicted Change in DO (bottom chart) – 10 March 2012

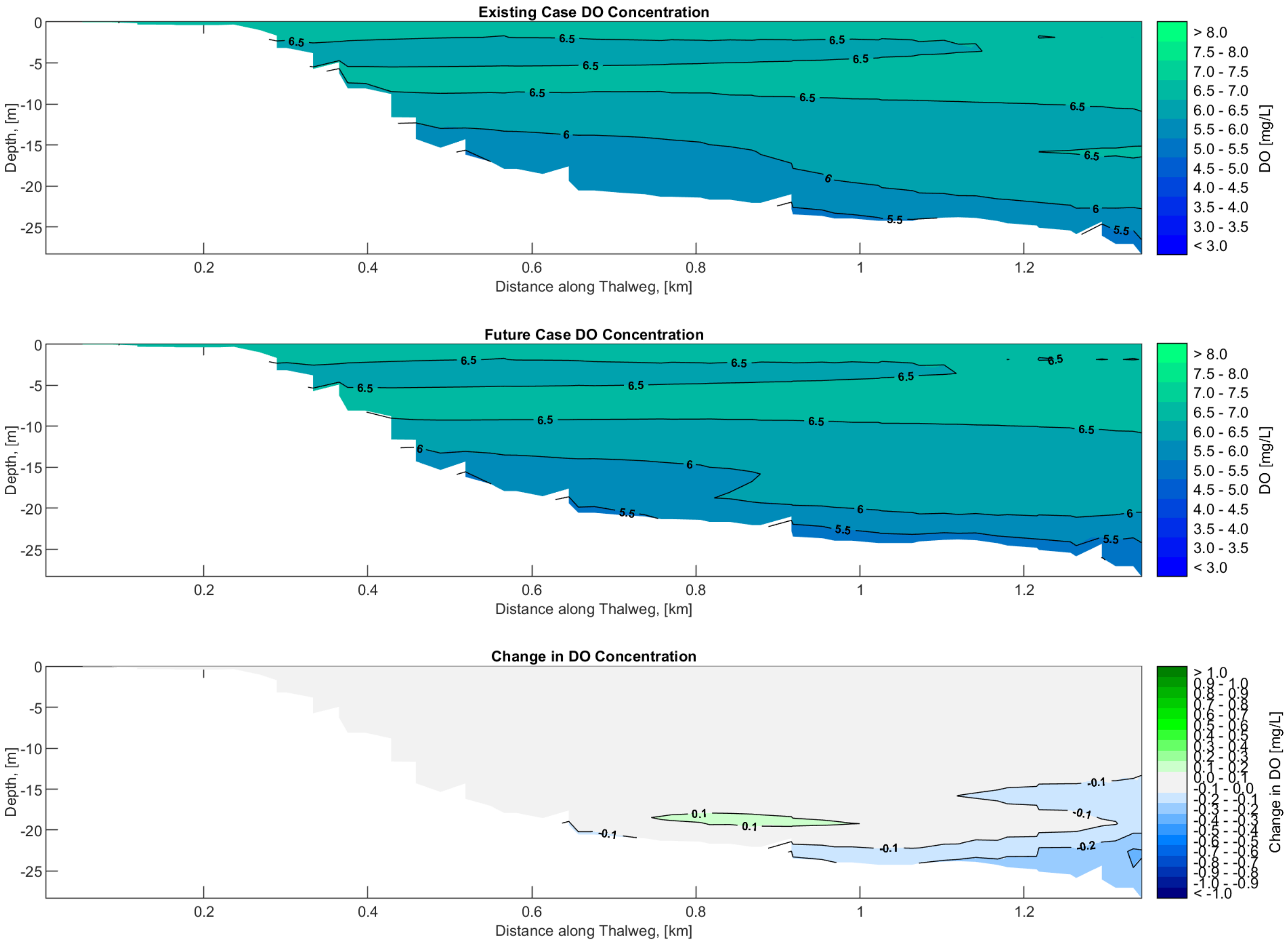


Figure 7-11 Predicted DO Concentrations in Sailors Bay for the Existing Case (top chart), with the Immersed Tube Tunnel Sill included (middle chart) and the Predicted Change in DO (bottom chart) – 10 March 2012

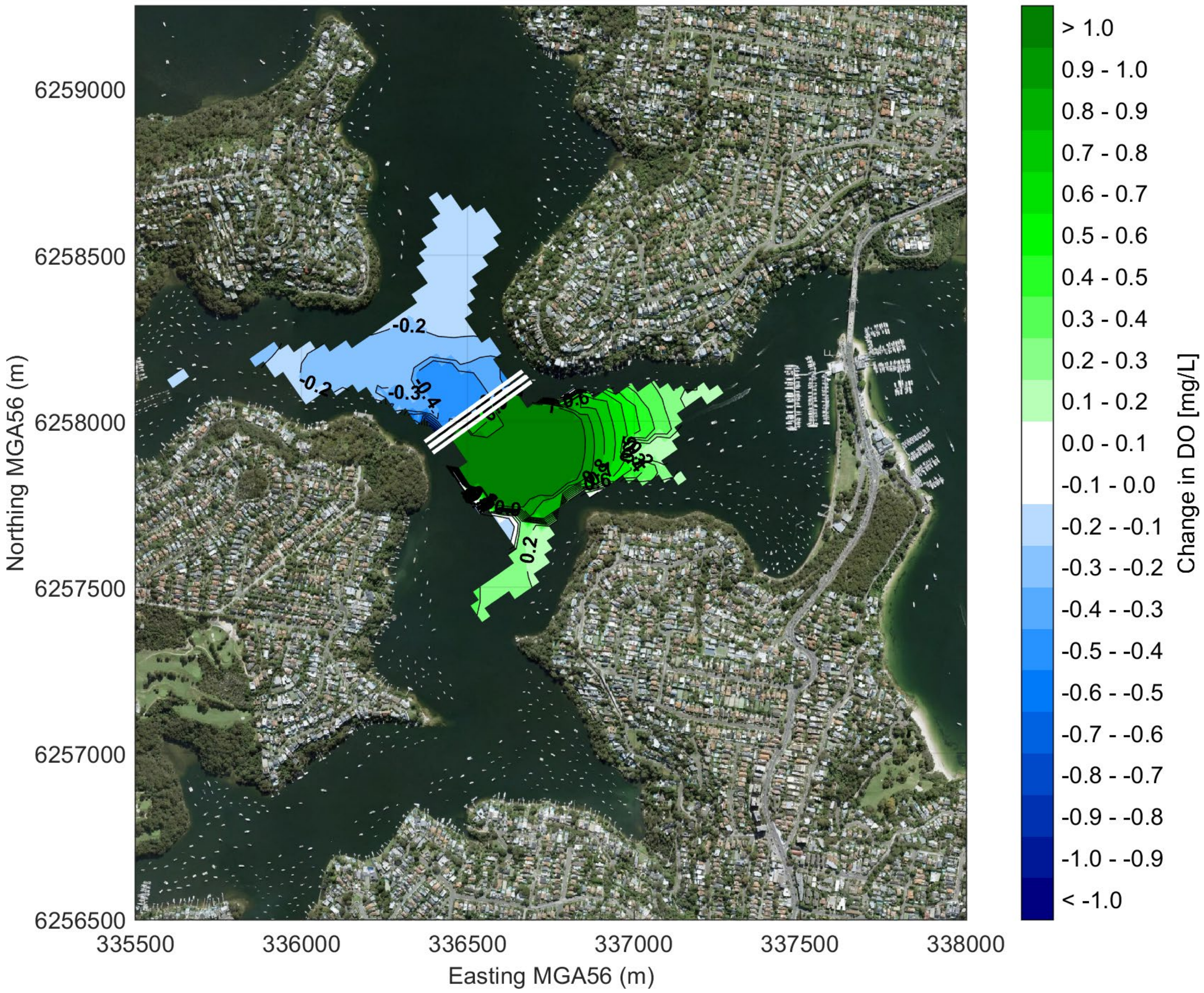


Figure 7-12 Modelled Change in near Bed DO Concentration with the Immersed Tube Tunnel Sill – 10 March 2012

8 Sensitivity Simulations

Sensitivity analysis was carried out to assess the sensitivity of the model to various input tuning coefficients and environmental variables. These included an assessment on the sensitivity to:

1. Season
2. Vertical turbulence and mixing
3. Amount of SOD.

The results of these sensitivity cases are presented below. Note that to gauge the influence, each of the sensitivity runs was simulated for simulation period 1 (December 2017-March 2018). Only physically realistic parameter changes were considered.

Although the model predicts slightly lower values of dissolved oxygen during simulation period 3 (4.7 mg/L in period 3 and 4.9 mg/L in period 1), simulation period 1 was selected for the sensitivity analysis as this period corresponds to the measured low DO event.

8.1 Season

To assess the effect of the season on near bed DO concentrations, simulation period 1 was re-simulated; however, the solar radiation, air temperature, water temperature and salinity were adjusted to be from a winter period (i.e. June-August 2018). Other parameters such as rainfall, wind speed and direction and tidal boundary conditions were unchanged in the model.

Figure 8-1, **Figure 8-2, Figure 8-3** and **Figure 8-4** present the DO simulation results for this sensitivity simulation. The time-series presented in **Figure 8-1** indicates that during winter the DO concentration at the bed of the harbour is relatively stable, and does not decrease to the same extent as it did in the summer scenario (simulation period 1 in **Section 7.1**). The modelling indicates that a small area upstream of the sill, as well as a small area within Sailors Bay would have slightly lower DO concentrations after the immersed tube tunnel is constructed, however the reductions are of the order of 0.1 mg/L at the peak of the event.

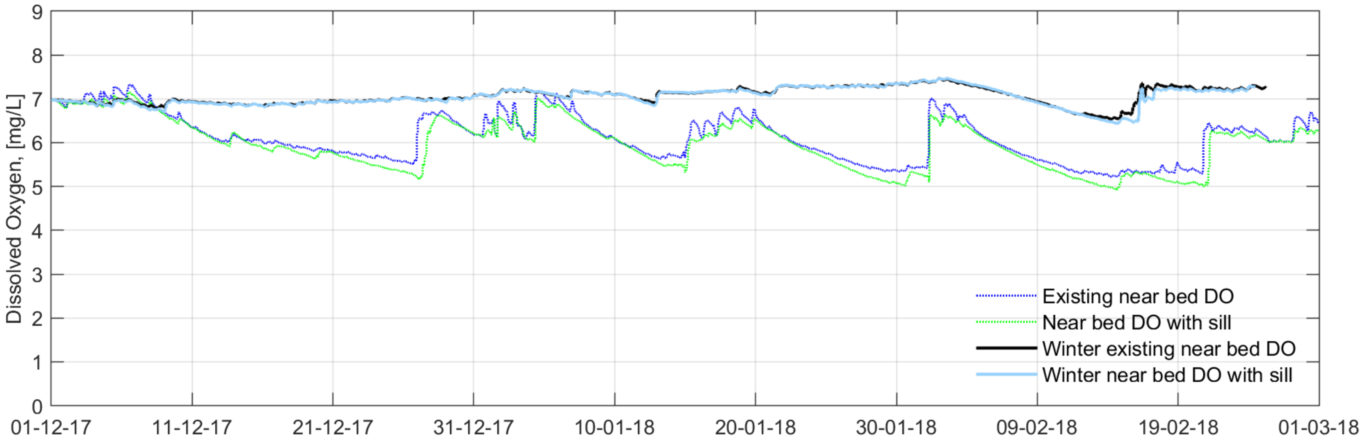


Figure 8-1 Time-Series Plot showing the Predicted near Bed DO during Simulation Period 1 and the Winter Sensitivity Simulation Results

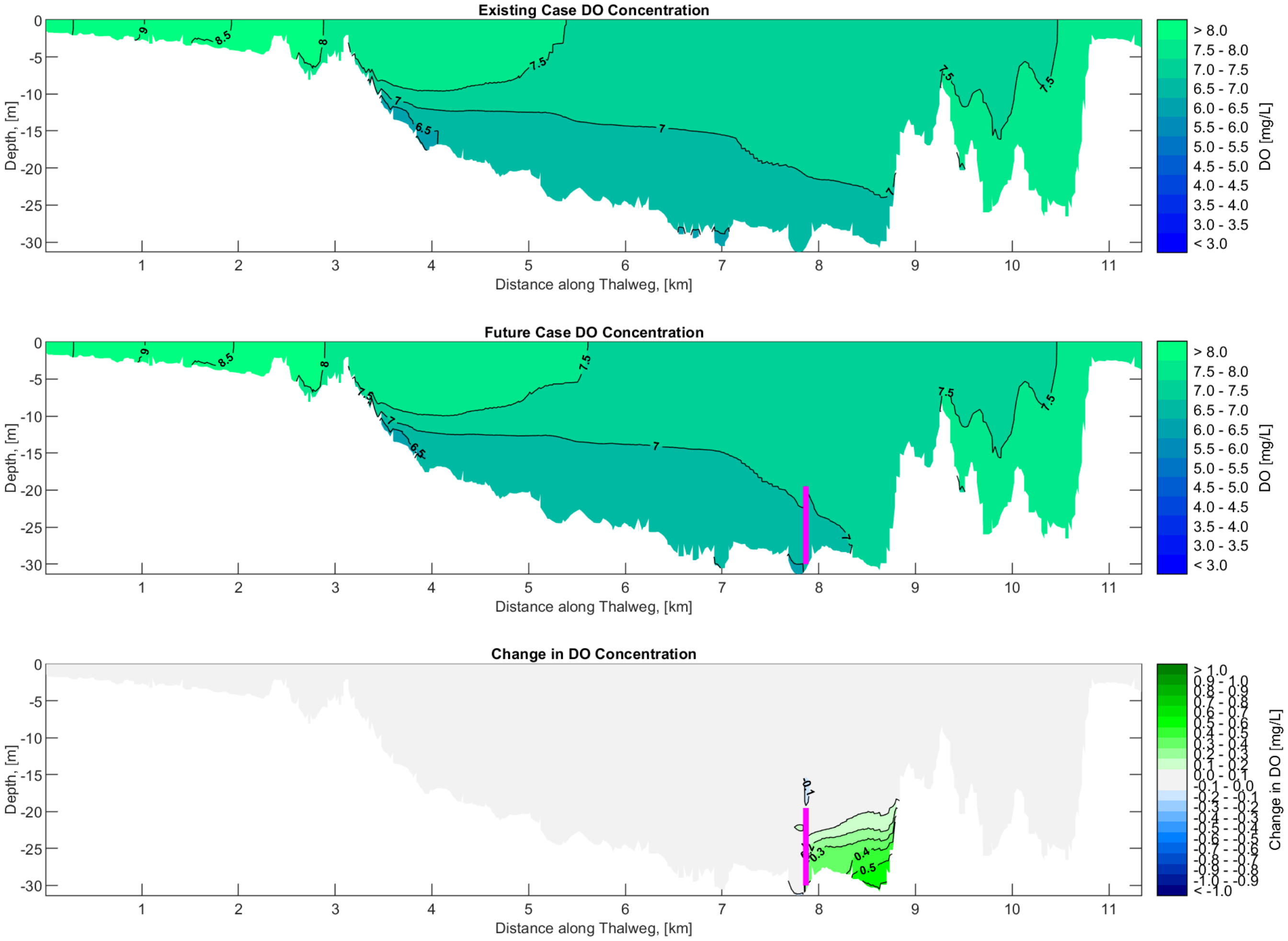


Figure 8-2 Predicted DO Concentration for the Existing Case (top chart), with the Proposed Immersed Tube Tunnel Sill included (middle chart) and the Predicted Change in DO (bottom chart) – 30 January 2017 – Winter Environmental Conditions

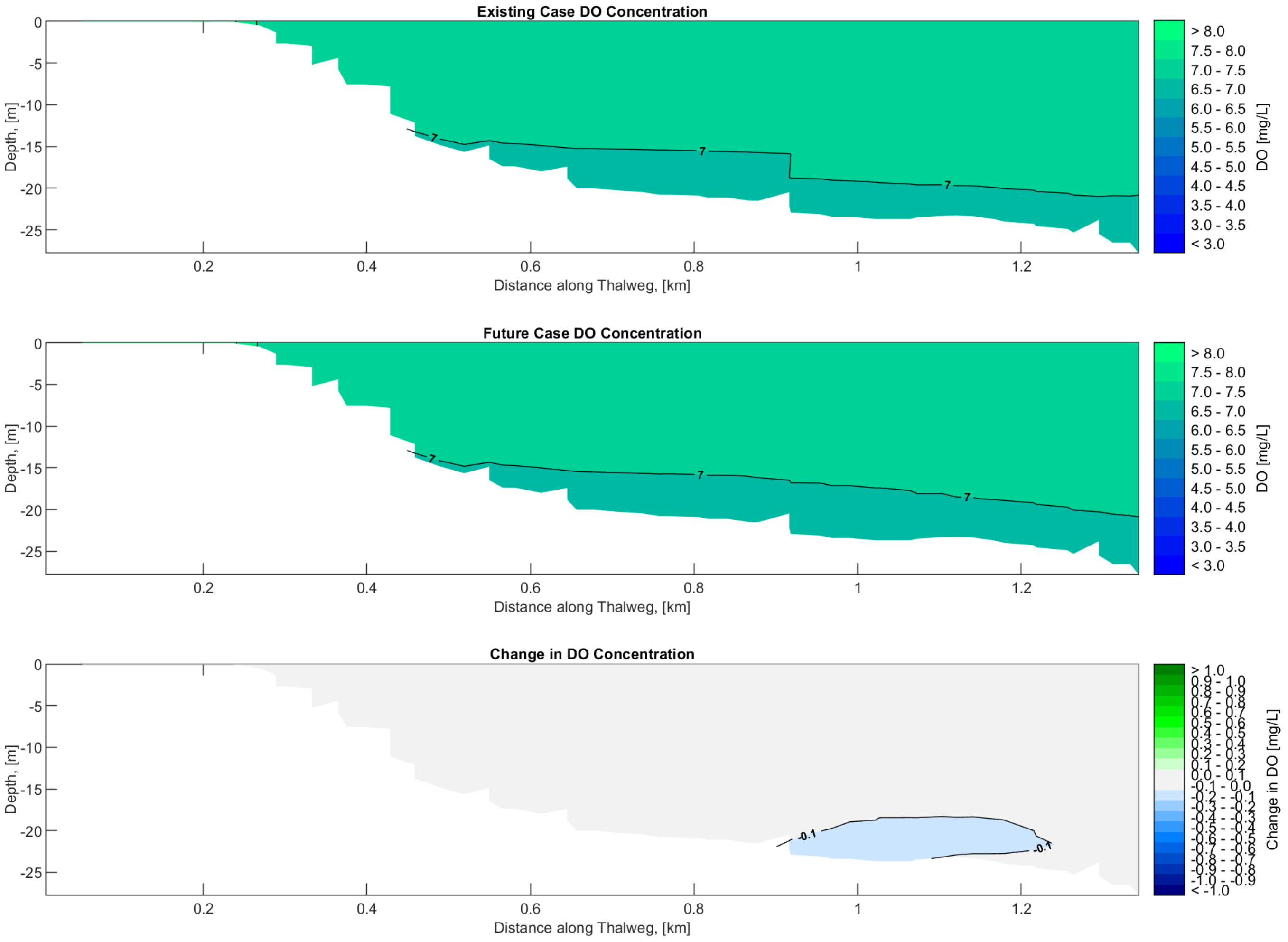


Figure 8-3 Predicted DO Concentration in Sailors Bay for the Existing Case (top chart), with the Immersed Tube Tunnel Sill included (middle chart) and the Predicted Change in DO (bottom chart) – 30 January 2017 – Winter Environmental Conditions

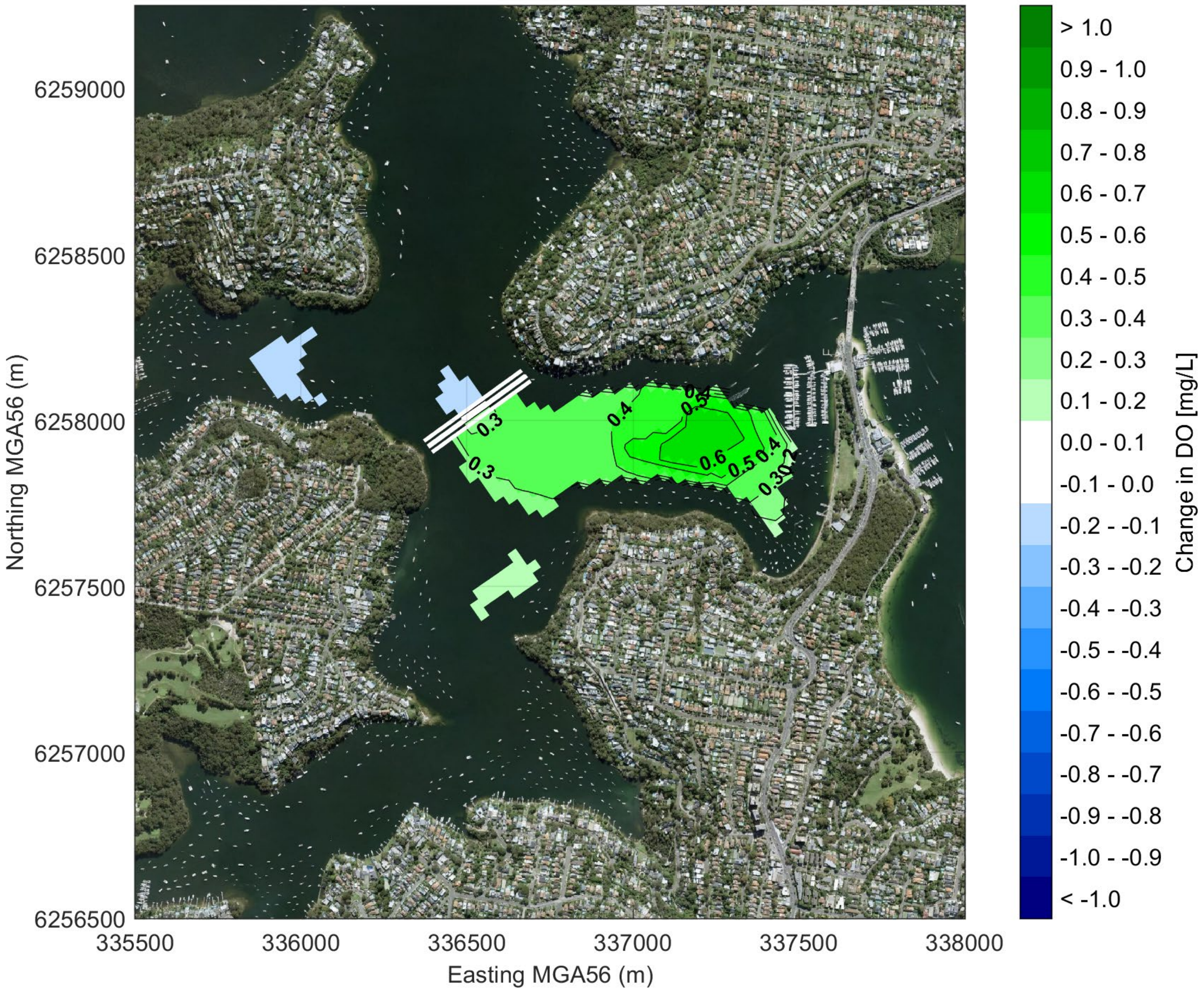


Figure 8-4 Modelled Change in near Bed DO Concentration with the Immersed Tube Tunnel Sill – 30 January 2017, Winter Environmental Conditions

8.2 Vertical Turbulence and Mixing

With the aim of being conservative, the model applied in this assessment was tuned to have as little vertical mixing as possible. Vertical mixing is influenced by factors such as turbulence due to changes in bathymetry, wind induced mixing, waves and will also be affected somewhat by vessel traffic.

This included the k-e model for vertical turbulence in the hydrodynamic model and setting the background vertical diffusion coefficients to 0 in both the hydrodynamic and the water quality models. Low values were used in the model setup to reduce the numerical dissipation of vertical stratification, which were required to match the vertical profiles of temperature and salinity.

To assess the effect of vertical mixing on the near bed DO, an additional water quality simulation was carried out using a vertical diffusion coefficient of $5x10^{-6}$. This represents a value that is in the middle of the typical range of values ($1x10^{-6}$ to $1x10^{-7}$). Other than the vertical diffusion coefficient, all of the other model parameters and inputs were unchanged in the model.

Figure 8-5, **Figure 8-6, Figure 8-7** and **Figure 8-8** present the DO simulation results for this sensitivity scenario. The model results indicate that the predicted near bed DO is relatively sensitive to the vertical diffusion coefficient, with the results showing a well-mixed waterbody and less variability in the near bed DO levels.

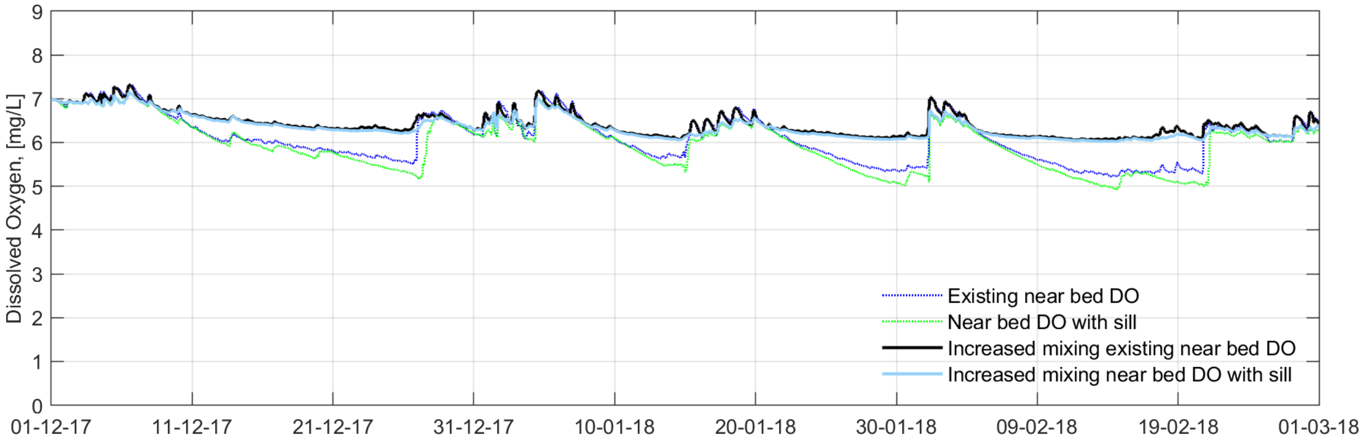


Figure 8-5 Time series plot showing the predicted near bed DO during simulation period 1 and the increased vertical mixing sensitivity simulation results

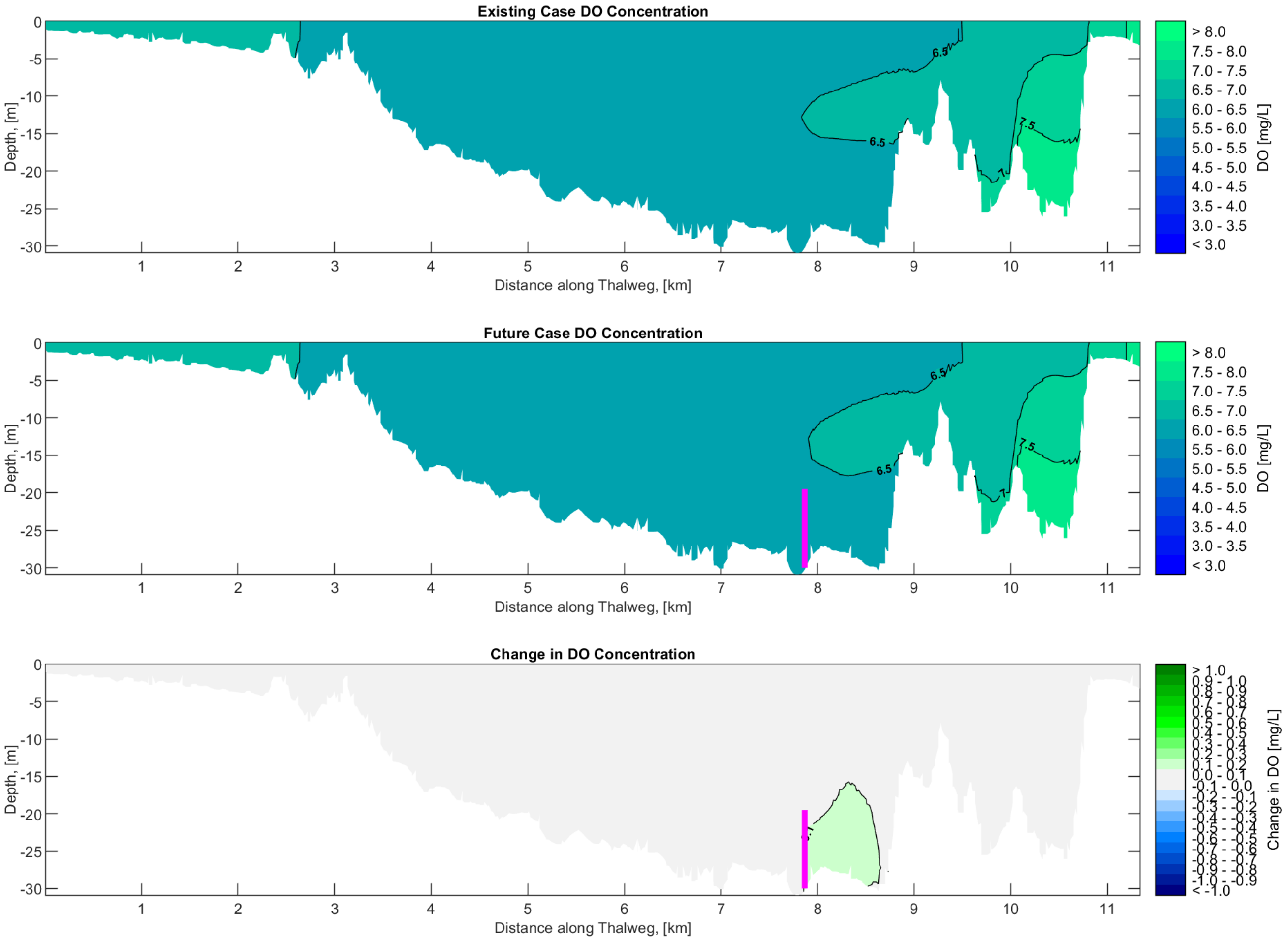


Figure 8-6 Predicted DO concentration for the existing case (top chart), with the Immersed Tube Tunnel Sill included (middle chart) and the predicted change in DO (bottom chart) – 30 January 2017 – increased vertical mixing sensitivity results

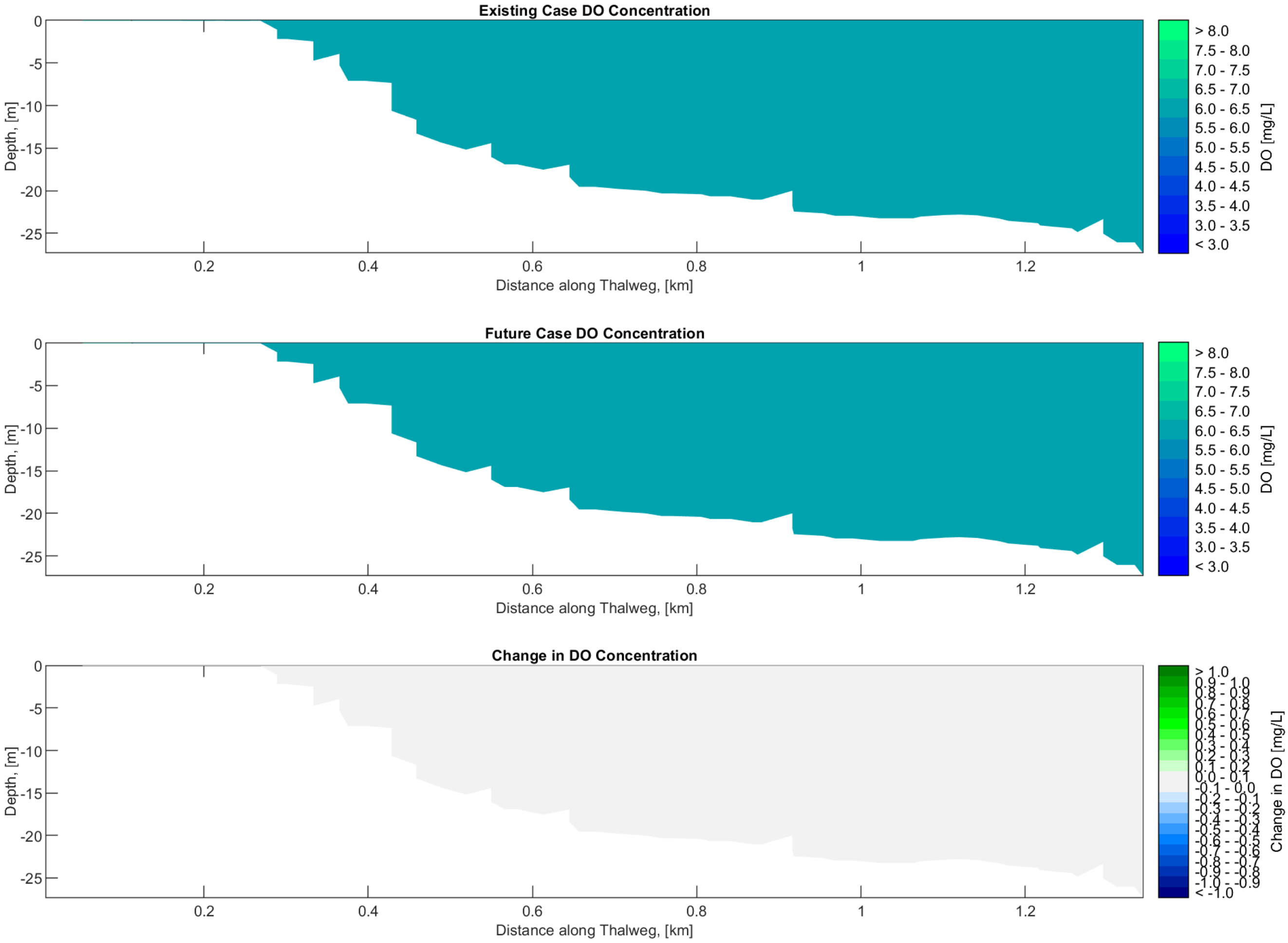


Figure 8-7 Predicted DO concentration in Sailors Bay for the existing case (top chart), with the Immersed Tube Tunnel Sill included (middle chart) and the predicted change in DO (bottom chart) – 30 January 2017 – increased vertical mixing sensitivity results

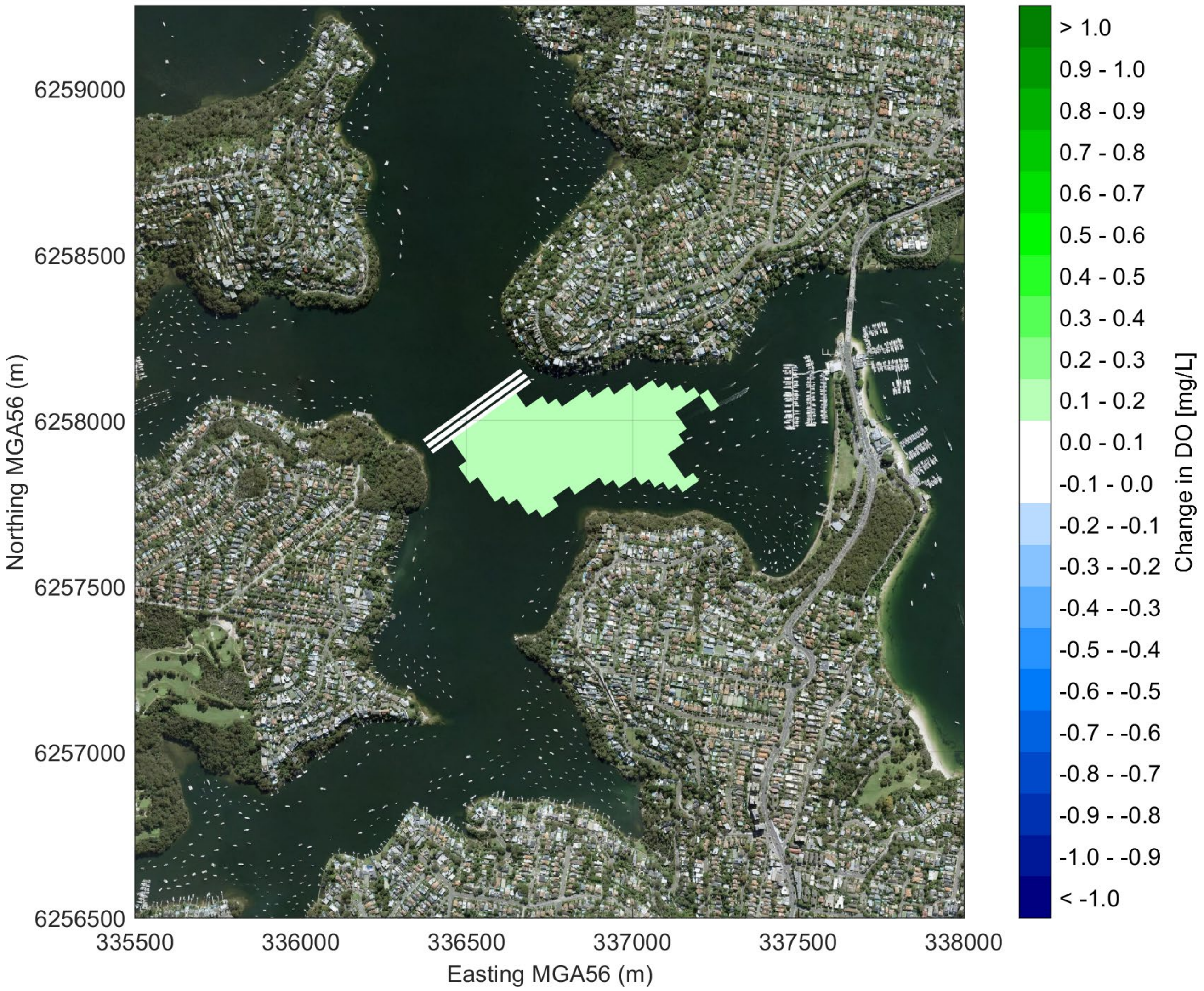


Figure 8-8 Modelled change in near bed DO concentration with the Immersed Tube Tunnel Sill – 30 January 2017, increased vertical mixing sensitivity runs

8.3 Sediment Oxygen Demand (SOD)

8.3.1 SOD Sensitivity Test 1

SOD is a measure of the rate of DO that is consumed by the bed of the harbour. This includes the DO used by benthic organisms as well as by biochemical decomposition of organic matter. Key factors that can affect the SOD are water temperature as well as the amount of organic matter deposited on the bed of the harbour.

The SHERM was originally calibrated with a SOD value of 0.5 g/m^2/day, however this value is scaled in the model depending on the amount of organic matter and water temperature (i.e. ranges from 0 to 0.5 g/m^2/day). This is a typical value applied to healthy tidal rivers and has a typical range between 0.2 g/m^2/day and 1.0 g/m^2/day based on Thomson and Mueller (1987). To assess the sensitivity of the model to the assumed SOD value, an additional simulation was carried out using a constant (i.e. independent of temperature and organic matter) SOD of 1.0 g/m^2/day, which is at the uppermost limit of this range.

The effect of increased SOD is shown below in **Figure 8-9**, **Figure 8-10, Figure 8-11** and **Figure 8-12**. With a higher SOD rate, the near bed DO levels tend to reduce further. With a higher SOD, the model is predicting that the near bed DO upstream of the tunnel sill would be up to 0.9 mg/L lower once the immersed tube tunnel is constructed, however recovery of DO is still predicted to occur rapidly and within 12 hours of the case without the immersed tube tunnel sill included. The area with lower DO is generally similar to the simulations presented in **Section 7.1**, with the largest reduction predicted to occur within 200 metres upstream of the immersed tube tunnel sill.

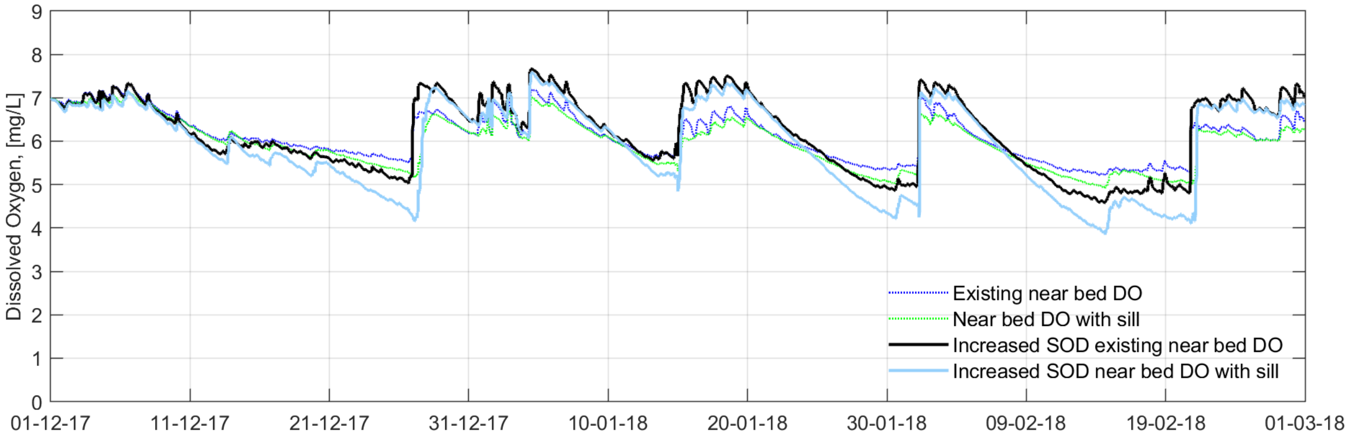


Figure 8-9 **Time series plot showing the predicted near bed DO during simulation period 1 and the increased SOD (1 g/m^2/day) sensitivity runs**

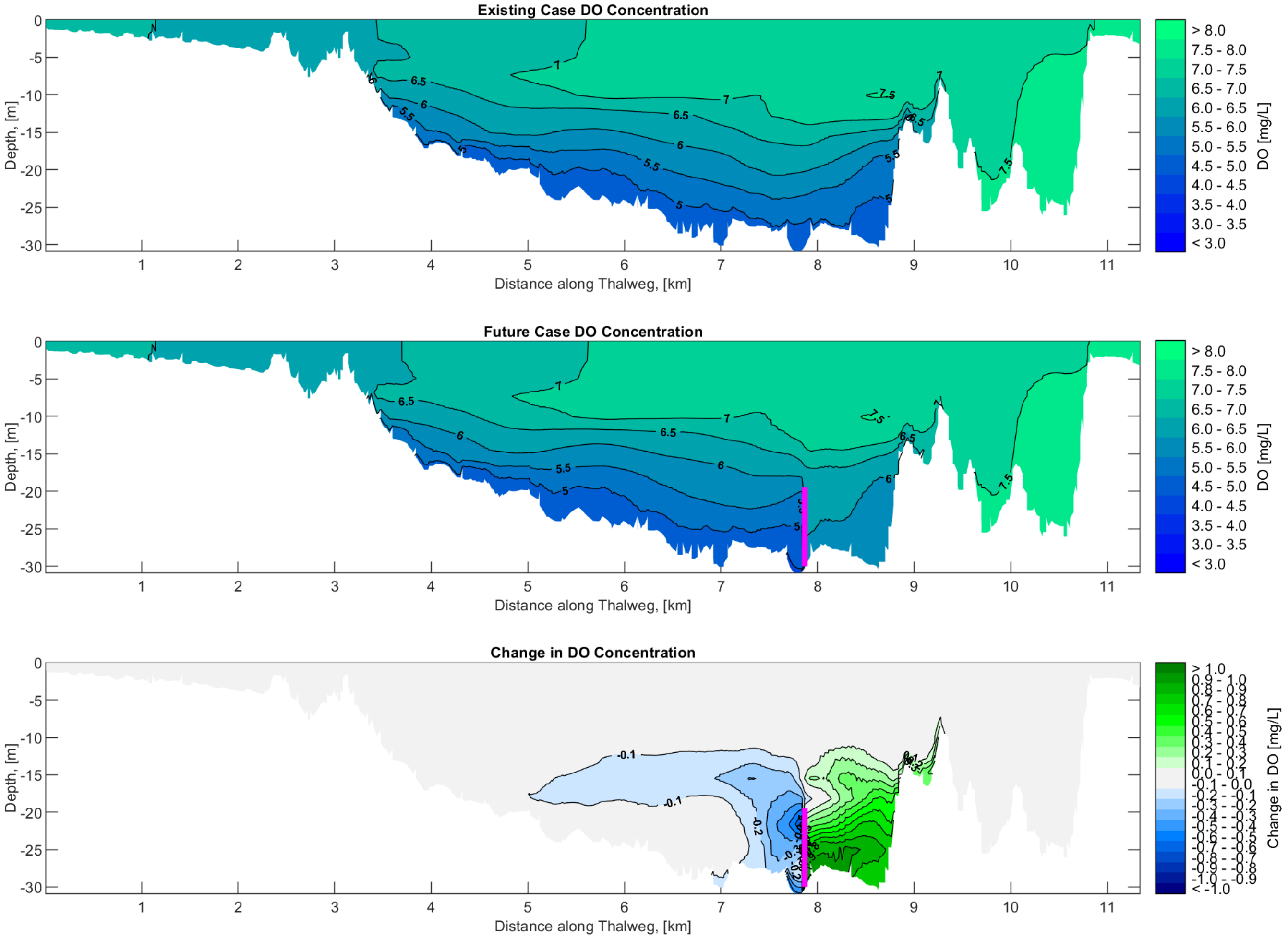


Figure 8-10 Predicted DO concentration for the existing case (top), with the Immersed Tube Tunnel sill included (middle) and the predicted change in DO (bottom) – 30 January 2017 – increased SOD (1 g/m^2/day) sensitivity runs

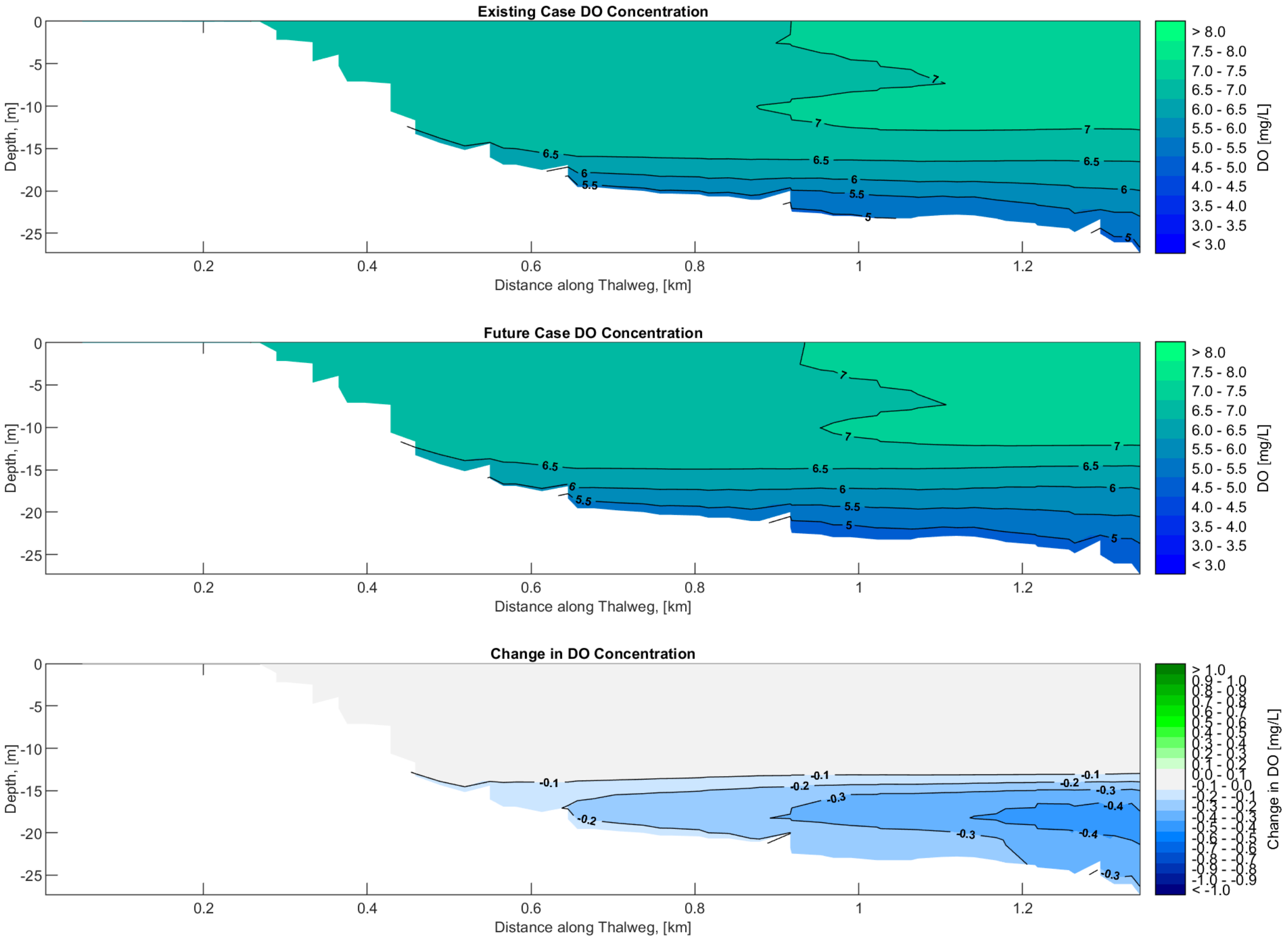


Figure 8-11 Predicted DO concentration in Sailors Bay for the existing case (top), with the Immersed Tube Tunnel sill included (middle) and the predicted change in DO (bottom) – 30 January 2017 – increased SOD (1 g/m^2/day) sensitivity runs

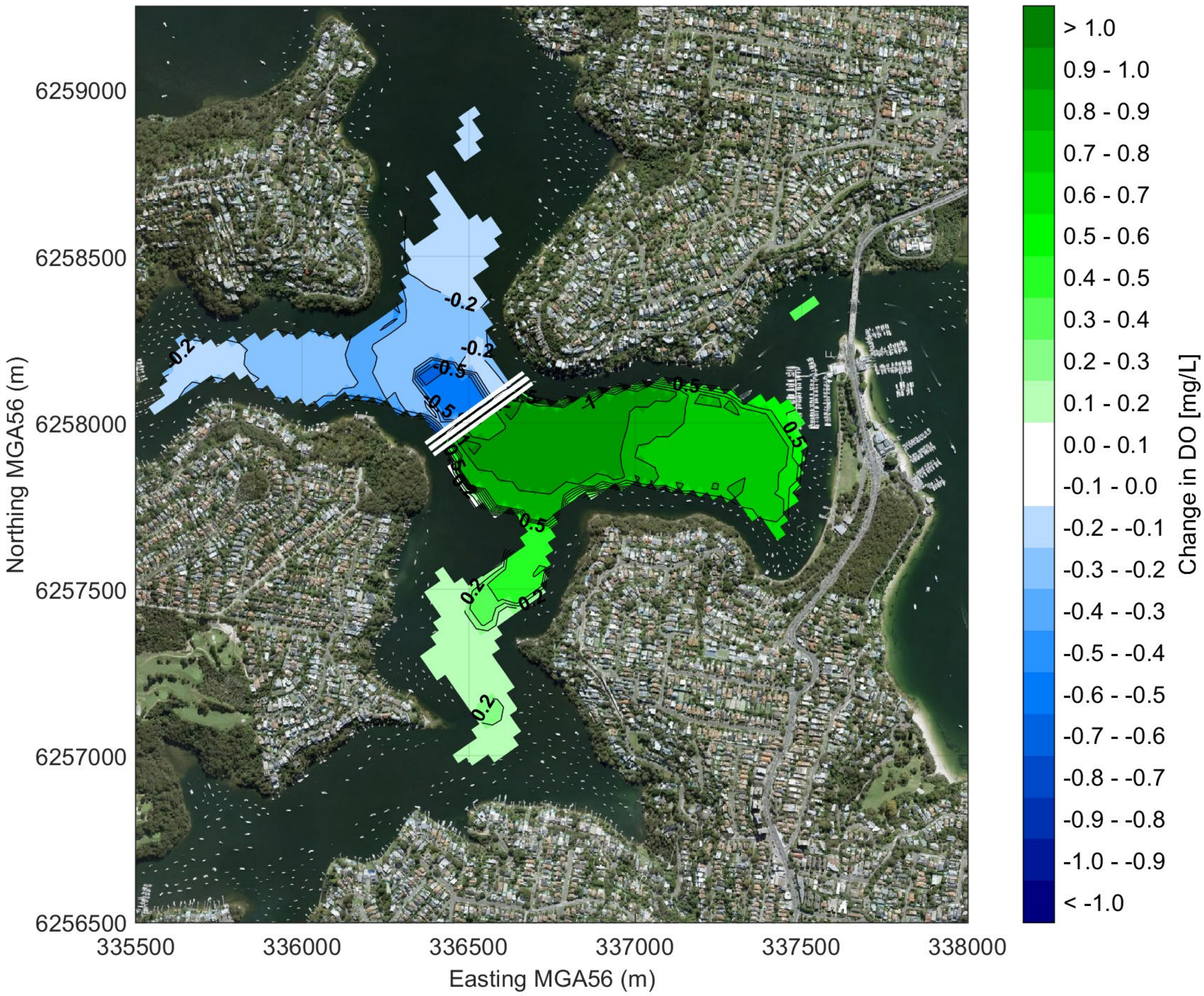


Figure 8-12 Modelled change in near bed DO concentration with the Immersed Tube Tunnel Sill – 30 January 2017, increased SOD (1 g/m^2/day) sensitivity runs

8.3.2 SOD Sensitivity Test 2

As mentioned in **Section 6.2.2**, the DO at the bed of the harbour was measured to be 4 mg/L at the end of January 2018. Although the model is able to replicate the time series measurements of near bed DO collected in May 2020, the model does not predict a near bed DO concentration less than 5 mg/L. The sensitivity test including a higher SOD also predicts a near bed DO concentration of 5 mg/L.

Therefore, to try and match the 4 mg/L measurement, the SOD was increased further to 1.5 g/m^2/day. Based on Thomson and Mueller (1987), a value of 1.5 g/m^2/day represents aged municipal sewage sludge. Similar to the SOD sensitivity test 1, this value was applied to be constant and independent of water temperature and organic matter in the model. This is likely to be a conservative assumption given the low rate of deposition noted in Middle Harbour and the generally lower water temperatures at the bed of the harbour.

The effect of the increased SOD is shown below in **Figure 8-13**, **Figure 8-14, Figure 8-15** and **Figure 8-16**. With a higher SOD rate, the near bed DO levels tend to reduce further and reduces to 4 mg/L after most rainfall events. With a higher SOD, the model is predicting that the near bed DO upstream of the tunnel sill would be up to 1.2 mg/L lower once the immersed tube tunnel is constructed, however recovery of DO is still predicted to occur rapidly and within 12 hours of the case without the immersed tube tunnel sill included. The area with lower DO is generally similar to the simulations presented in **Section 7.1**, with the largest reduction predicted to occur within 200 metres upstream of the tunnel sill, and smaller reductions further afield.

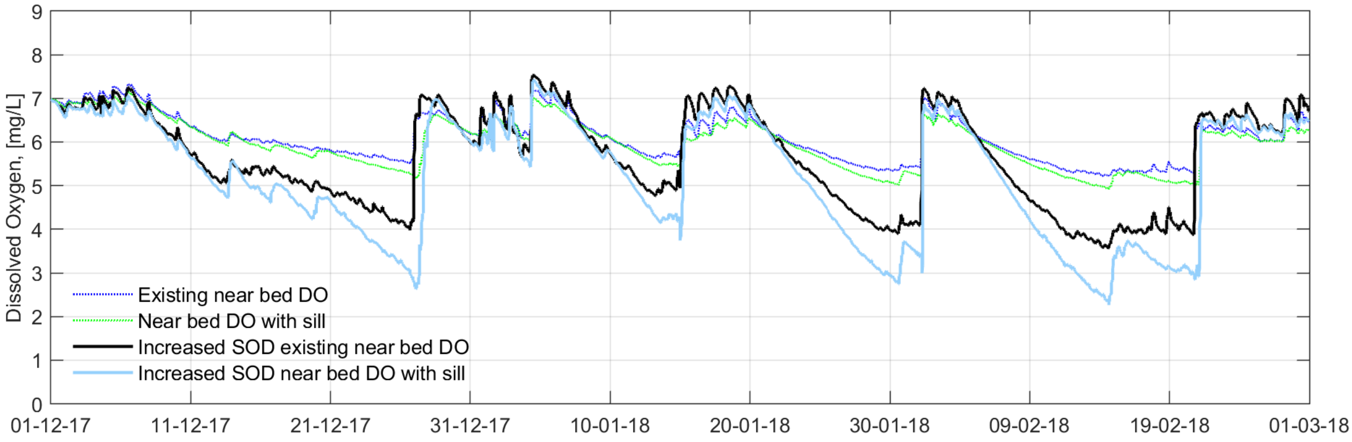


Figure 8-13 Time series plot showing the predicted near bed DO during simulation period 1 and the increased SOD (1.5 g/m^2/day) sensitivity runs

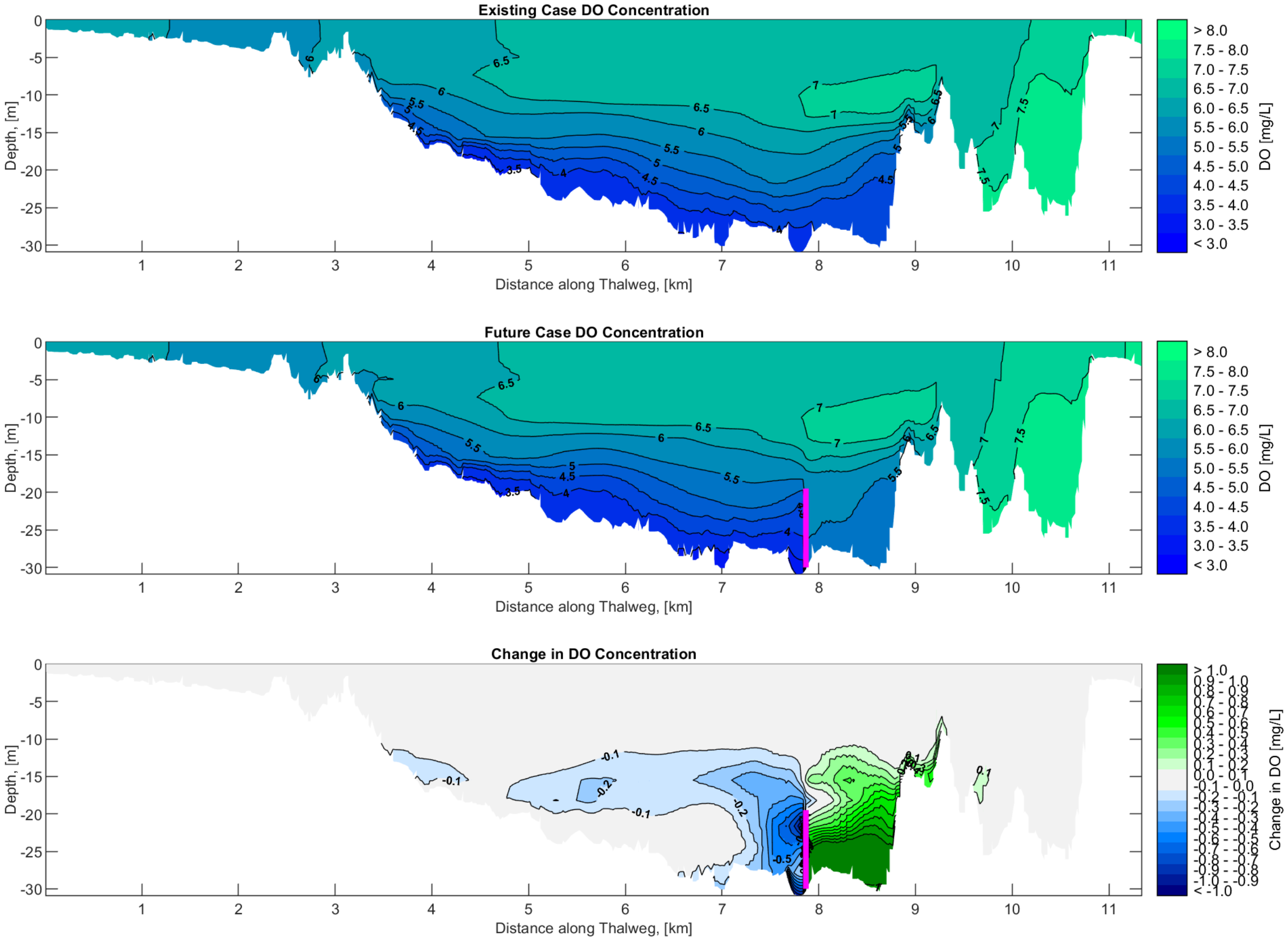


Figure 8-14 Predicted DO concentration for the existing case (top), with the Immersed Tube Tunnel sill included (middle) and the predicted change in DO (bottom) – 30 January 2017 – increased SOD (1.5 g/m^2/day) sensitivity runs

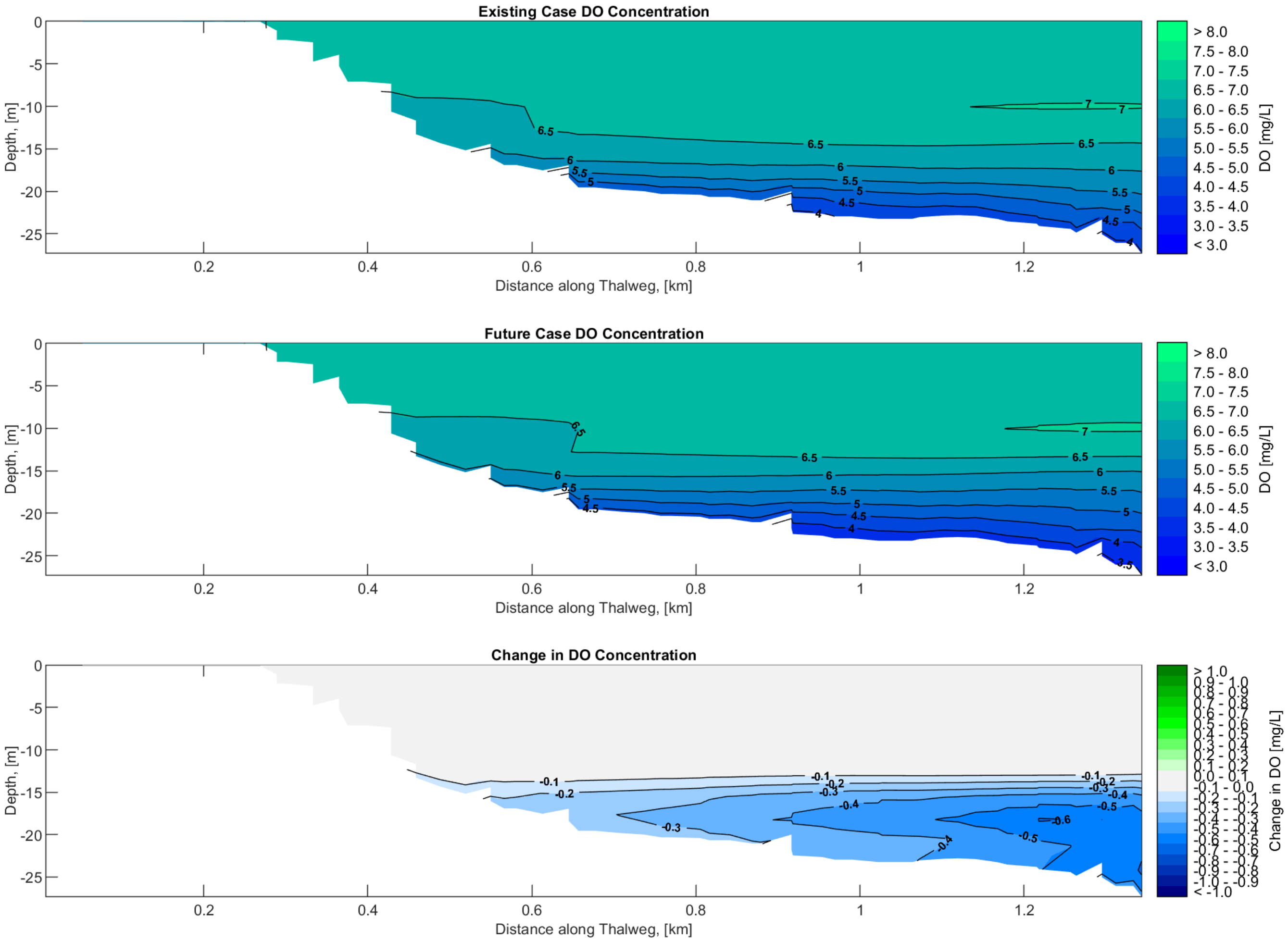


Figure 8-15 Predicted DO concentration in Sailors Bay for the existing case (top), with the Immersed Tube Tunnel sill included (middle) and the predicted change in DO (bottom) – 30 January 2017 – increased SOD (1.5 g/m^2/day) sensitivity runs

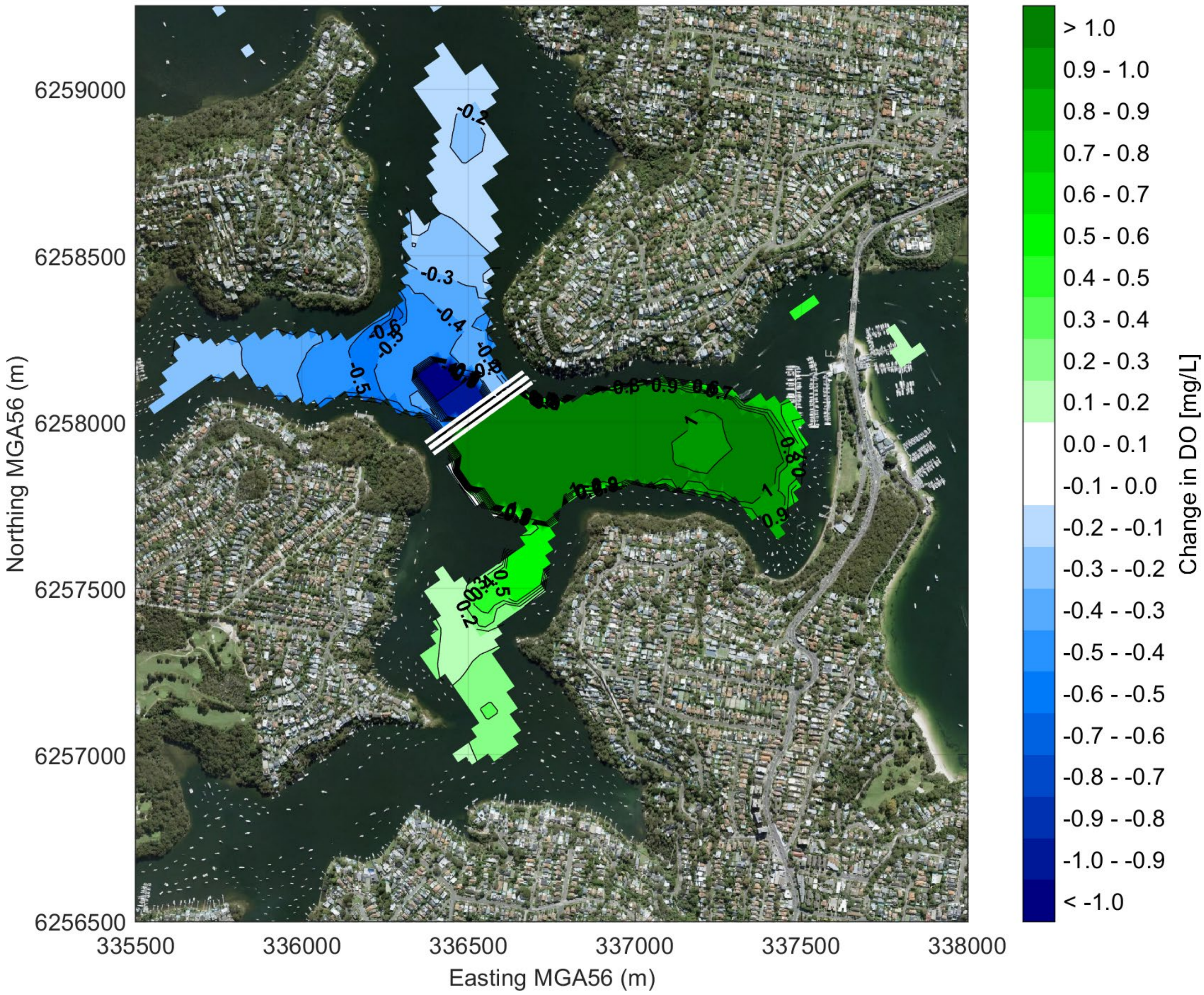


Figure 8-16 Modelled change in near bed DO concentration with the Immersed Tube Tunnel Sill - 30 January 2017, increased SOD (1.5 $g/m^2/day$) sensitivity runs

9 Impact Assessment

9.1 Effects of the Immersed Tube Tunnel Sill on Dissolved Oxygen

For this assessment, Cardno adopted the Middle Harbour grid system and re-aligned/refined that grid to align with the immersed tube tunnel to provide better horizontal resolution near the crossing; and then recalibrated the SHERM system using physical and DO data recorded in Middle Harbour in 2017/2018 and 2020.

The re-calibrated Middle Harbour model – part of the SHERM, was driven by tidal levels at its downstream end together with realistic catchment inflows, and then used to test the effect of the tunnel sill on near bed of the harbour DO concentrations and changes in the spatial extent and durations of low DO conditions – that is, the effects of the tunnel sill on DO conditions. Physically realistic values were adopted for parameters such as SOD and re-aeration rates, and the model’s sensitivity to these parameters was also assessed. As noted below, the model is predicting very minor changes to the near bed salinity and temperature and as such are not included in the ecological assessment presented in Section 9.2.

The modelling also included a range of sensitivity tests, namely in terms of summer-winter meteorological influences, the effects of vertical mixing in the model and also the sensitivity of the model to SOD.

The model system was used to model three selected 3-month duration hydrodynamic and water quality simulation scenarios, made up of:

- December 2017 to February 2018 (Sampling period 1 from Appendix Q (Technical working paper: Marine water quality))
- April to June 2020 (Sampling period 2 from Appendix Q (Technical working paper: Marine water quality))
- January to March 2012 (wet period).

The outcomes of these simulation scenarios were as follows:

- For all of the modelled scenarios, the modelling system predicted that the immersed tube tunnel sill would reduce the near bed DO concentration by up to 0.4 mg/L for short periods after heavy rainfall
- The area affected by the lower DO would be limited to the deeper parts (depths greater than 10 metres) of the waterway, below the depth of any identified sensitive marine habitats (refer to **Figure 9-1**)
- The largest decreases in near bed DO were predicted to occur immediately upstream of the immersed tube tunnel sill, in the Middle Harbour deep basin (greater than 27 metres deep)
- The model has predicted that the deeper areas downstream of the immersed tube tunnel sill will exhibit an increase in DO levels. Increases of up to 1.0 mg/L were predicted in the deep areas between the Spit Bridge and the project, which could be considered an environmental benefit.
- Each period had a range of inflow events included in the simulations. The time-series results indicate that the DO response is similar for various rainfall rates and volumes, with the exception of a high intensity rainfall event (greater than 100 millimetres in a day) in March 2012. This event appears to have flushed the system and resulted in an increase in DO at the bed of the harbour
- The sill also has the potential to slightly change near bed salinity and temperature due to reduced mixing and flushing. However, based on the modelling results, changes to these parameters are expected to be small, and less than 0.1 degrees and 0.1 ppt upstream and downstream of the sill.

Sensitivity testing was carried out to assess the influence of seasonality (i.e. summer versus winter), vertical mixing and the SOD. The sensitivity testing has indicated that:

- Near bed DO depletion is a seasonal phenomenon, with very little depletion predicted to occur during the winter months as opposed to late summer
- Vertical mixing does play a role in the predicted near bed DO concentration. The modelling carried out for this assessment has conservatively assumed very low vertical mixing and diffusion for both the hydrodynamic and the water quality models. With the inclusion of an average (higher) vertical diffusion coefficient, the model predicts significantly more vertical mixing, resulting in less DO depletion near the bed of the harbour

- The model, and hence DO in upper Middle Harbour itself, is sensitive to SOD. Two higher values have been tested and indicate that a larger SOD results in lower dissolved oxygen levels near the bed of the harbour. Recommendations regarding pre-construction monitoring of SOD are provided in Section 10.2 below.

The modelling indicates that at the peak of the low dissolved oxygen events the area upstream of the immersed tube tunnel where DO is predicted to change is less than 1% of the tidal area, or 1.8% of the area where the bed level is below -10m AHD. As a worst case scenario based on the sensitivity testing the affected area is only slightly larger, being 1.8% of the tidal area and 3.6% of the deep water area. The affected areas upstream of the sill are presented in **Table 9-1**.

Table 9-1 Modelled area (in %) upstream of the immersed tube tunnel where near bed dissolved oxygen is predicted to reduce at the peak of the low DO events

Model run	% area of DO change upstream of sill	% area change DO upstream of sill Bed level below -10m AHD
Simulation Period 1	0.48%	0.95%
Simulation Period 2	0.05%	0.10%
Simulation Period 3	0.91%	1.79%
Winter Sensitivity Run	0.23%	0.46%
Vertical Mixing Sensitivity Run	0.00%	0.01%
SOD Sensitivity Run 1	1.37%	2.70%
SOD Sensitivity Run 2	1.84%	3.63%

9.2 Ecological Impact Assessment

9.2.1 Environmental impact assessment findings

As indicated in Appendix Q (Technical working paper: Marine water quality), DO in Middle Harbour can reduce after heavy rainfall. After heavy rain, it is likely that nutrient enrichment from freshwater inflows stimulates phytoplankton production which in turn results in a mass influx of particulate organic matter to the sediments (eutrophication). The decomposition of this organic matter by aerobic microorganisms leads to a rapid acceleration of oxygen consumption, and potential depletion of oxygen in bottom waters. Further, in a stratified water column, as could be seen in summer in a tidal estuary such as Middle Harbour, bottom waters may become isolated from oxygen enriching processes and can give rise to anoxic and hypoxic events.

If near bottom water in an estuary approaches near zero DO concentrations it is considered to be 'anoxic', and if DO levels are less than 2.0 mg/L, conditions are generally considered to be 'hypoxic'. Hypoxia can cause major mortality to marine flora and fauna and can affect surviving organisms through sublethal stresses. The ecological implications of the sill formed by the immersed tube tunnel on DO should be considered in terms of whether they would exacerbate changes occurring to the intensity, duration and extent of DO levels that occur naturally following heavy rainfall.

The findings from Appendix T (Technical working paper: Marine ecology), though not quantitative, indicated a potential for the immersed tube tunnel sill to lead to a small increase in disturbances to deepwater soft sediment benthic infauna or epibiota. However, this was not considered to be of concern given these assemblages are already exposed to similar disturbances naturally and would be expected to be resilient, through rapid recolonisation, to slight increases in disturbances.

9.2.2 Intensity of low DO events and DO thresholds

A DO level of 2.0 mg/L has been widely considered as the threshold at which hypoxic conditions would be expected to cause mortality to marine organisms. However, taxonomic variability in behavioural and physiological adaptions to hypoxia lead to broad differences in vulnerability to oxygen depletion among taxa. The most sensitive group is fish and then benthic crustaceans, followed by worms and echinoderms (eg sea urchins), whereas at the other end of the scale cnidarians (eg jellyfish) and molluscs are the most tolerant.

In a comprehensive review of the thresholds of benthic taxa, Vaquer-Sunyer and Duarte (2008) considered 4.6 mg/L was a precautionary limit for 'generally' avoiding catastrophic mortality events, and hence conserving biodiversity.

This concentration of DO is the 90th percentile of the distribution of mean lethal concentrations - that is the lowest concentration that would not affect populations of most species, apart from the 10% most sensitive.

Monitoring and modelling of DO in the deep basin upstream of the location of the immersed tube tunnel sill observed near bed concentrations of DO to be generally far above 4.6 mg/L in dry periods over summer, ranging roughly between 6 and 7.5 mg/L. After heavy rainfall, it has been determined that DO may naturally decrease to levels down to roughly 4 – 5.5 mg/L. Modelling has indicated that the amount of rainfall over 50 millimetres had little effect on the minimum concentration of DO reached.

The immersed tunnel sill would reduce tidal flushing of the deep basin upstream of the project (refer Appendix P (Technical working paper: Hydrodynamic and dredge plume modelling)). Modelling carried out for this assessment has indicated that this is likely to reduce concentrations of DO at the bed of the harbour (after heavy rainfall) to levels below those that would occur without its presence. The modelled effect of the immersed tunnel sill however, for most scenarios, was not substantial, with differences in concentrations of DO (between scenarios with or without the sill) increasing gradually from the onset of declining DO after the heavy rainfall to a maximum difference of roughly 0.5 mg/L at the peak of decline. Hence, at the peak of decline after heavy rainfall, in most instances, the effect of the immersed tube tunnel sill would reduce the concentration of DO to levels of about 4.7 mg/L. These levels are close to, but still above the threshold level of 4.6 mg/L which, as stated above, is considered to be a precautionary limit for avoiding catastrophic mortality events to marine organisms. An instance of low near bed DO (4.0 mg/L at the immersed tube tunnel site, and slightly lower further upstream) was observed in January 2018, which is below the threshold of 4.6 mg/L. Noting that this low DO event was not able to be replicated in the model, based on the model results it is reasonable to expect that under these conditions the DO concentration at the bed would reduce further, and drop to about 3 to 3.5 mg/L at the peak of the decline.

Sensitivity testing indicated that a high SOD could possibly explain the naturally low DO concentration observed in January 2018 and in this situation modelling indicated that the additional effect from the immersed tube tunnel sill could potentially reduce the concentration of DO a further 1.0 mg/L (ie down to about 3 mg/L). However, given the composition of the bed of the harbour, a scenario of high SOD is considered to be unlikely. The seabed sediment sampling from DPGA (2018), found the average total organic carbon content in the surface sediment to be around 3.6%. which is low and is indicative that high SOD would not be expected. To confirm this, further pre-construction monitoring of SOD is recommended, as further detailed in Section 10.2 below.

9.2.3 Duration of low DO events

The longevity of low DO events can be important. Although mobile biota such as fish can move away from hypoxic waters, most benthic fauna cannot do so. Notwithstanding this, other studies have indicated that some benthic species within Middle Harbour (eg some of the worms, bivalves and echinoderms) would potentially have metabolic adaptations that will allow them to survive periods of low DO for hours or even days (Vaquer-Sunyer and Duarte, 2008). These adaptations may include depressing activity, metabolic rate, heart rate and feeding, which all reduce oxygen demand, or even a shift to anaerobic metabolism. Importantly, the monitoring and modelling carried out has indicated that the concentration of DO reduced gradually after rain (with or without the project) and it only generally reduced to levels close to 4.6 mg/L (ie where benthic fauna would be affected) for a very short time (one or two days) prior to rapid recovery. Importantly, given the immersed tube tunnel sill did not appear to extend the longevity of low DO events generally by more than half a day, regardless of the level of peak decline, low DO events would not be an issue to benthic ecology.

9.2.4 Extent of low DO events

Under most scenarios, DO is reduced after heavy rainfall (with or without the project) only in the deeper part of the water column where water depth is greater than 10 metres and is generally confined to small areas immediately upstream of the tunnel sill in the middle of the channel. Effects generally decline and become negligible within a few hundred metres upstream of the tunnel sill and do not extend to the sides of the Middle Harbour channel (as can been seen the contour plots in Sections 7 and 8) where sensitive marine habitats are located (refer to **Figure 9-1**).

9.2.5 Conclusion

To summarise, the benthic infauna and epifauna in deeper areas of Middle Harbour within the vicinity of the immersed tube tunnel sill are already subject to occasionally low concentrations of DO, in summer, after heavy rainfall, that reach, or become slightly less than, the threshold of 4.6 mg/L that may cause mortality to part of the population.

Modelling in this assessment has shown that, under most scenarios, the immersed tube tunnel sill would only slightly decrease concentrations of DO near the bed of the harbour after heavy rain from what would be expected under natural conditions, and not substantially increase the duration of occasionally naturally low DO concentrations. The small effects would be confined to an area of deeper water in the deep basin immediately upstream of the project. The magnitude, duration and spatial scale of the effect of the immersed tube tunnel sill to benthic infauna and epifauna in these areas would not be measurable beyond natural impacts from the occasionally low DO events. Given sensitive Type 1 or Type 2 Key Fish Habitat in the vicinity of the project, such as seagrass or rocky reef, are located in shallow water (less than seven metres deep) close to the shoreline of Middle Harbour, these habitats would be unaffected.

These findings support conclusions made in Appendix T (Technical working paper: Marine ecology) of the environmental impact statement in regard to addressing Biodiversity SEAR 6, Part 10 (refer to Section 1.1). Hence, there would be no requirement for additional management measures or offset requirements under the *Policy and guidelines for fish habitat conservation and management* (NSW DPI, 2013).

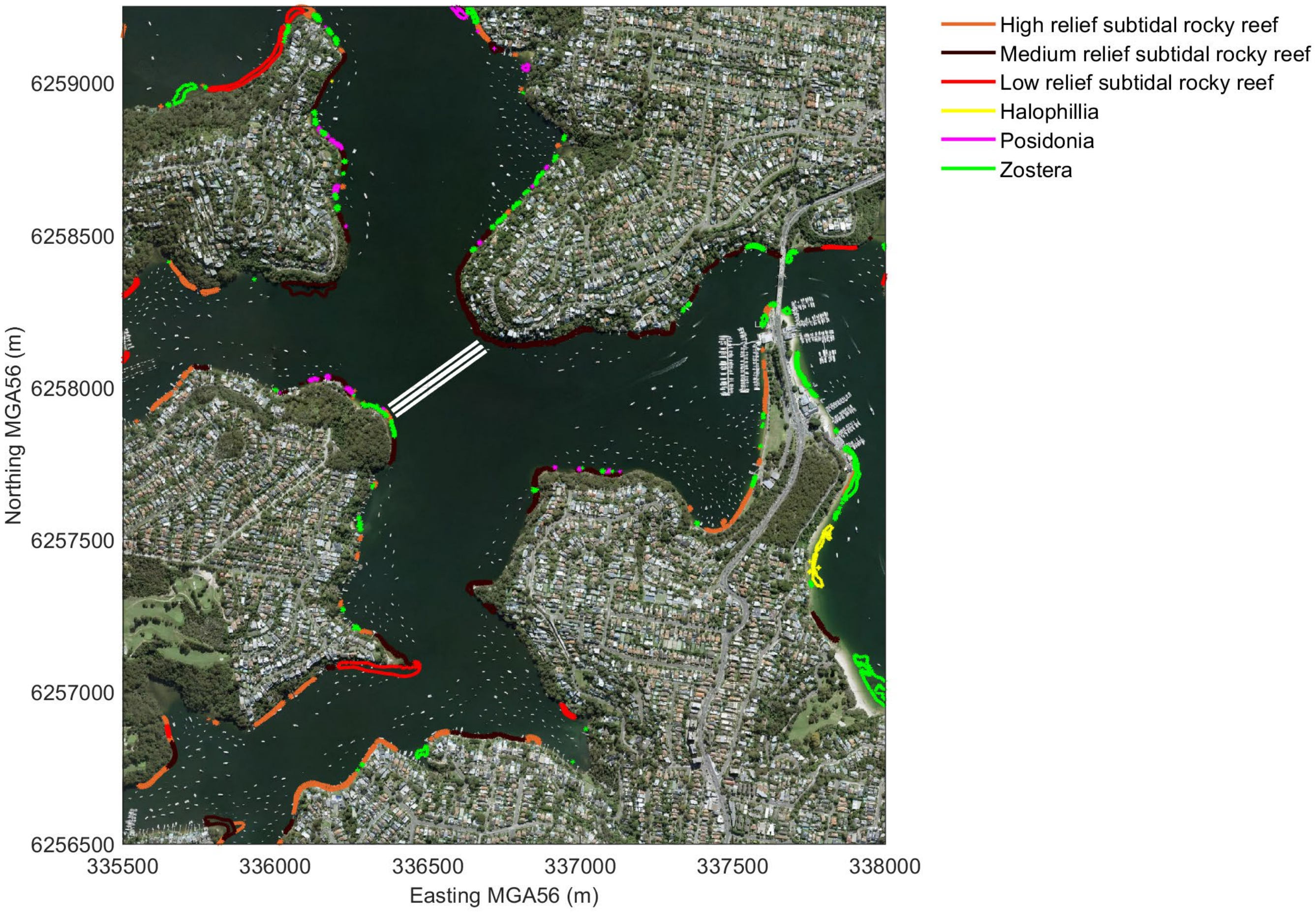


Figure 9-1 Sensitive nearshore habitats (seagrass and subtidal rocky reef) close to the crossing of Middle Harbour

10 Recommendations

10.1 Management measures

As stated above in Section 9.2.5, the assessment findings support conclusions made in Appendix T (Technical working paper: Marine ecology) of the environmental impact statement.

Hence, there would be no requirement for additional management measures or offset requirements under the *Policy and guidelines for fish habitat conservation and management* (NSW DPI, 2013).

10.2 Recommended Monitoring Program

As the modelling indicates that the near bed DO levels are sensitive to the assumed SOD, it is recommended that pre-construction monitoring be carried out for DO and SOD. This should include:

- Twelve months of continuous monitoring of DO, salinity (through conductivity measurements) and temperature through the water column at one location immediately upstream of the immersed tube tunnel sill. Continuous monitoring of turbidity would also be done at this location near the surface. The loggers should be located in the deep basin where the near bed of the harbour changes to DO are predicted to occur; and
- Monthly profiling of DO, salinity (conductivity), turbidity and temperature upstream and downstream of the sill at up to six locations within the estuary.

Noting that SOD is likely to vary over time due to organic loads (from catchment runoff), and water temperature, monthly sampling of SOD should also be carried out at the continuous monitoring station, and seasonally at each upstream vertical profile site.

The need for further modelling or post-construction monitoring of potential DO changes should be determined following the completion of the recommended pre-construction monitoring.

11 References

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ANNEXURE

A

SHERM DEVELOPMENT HISTORY

Existing SHERM System

Development History

In partnership with the Greater Sydney Local Land Services (GSLLS) and commencing in 2012, Cardno has developed a Delft3D-based hydrodynamic and water quality model system of Port Jackson and the Parramatta River, including system-wide estuarine creeks. The Delft3D model has been refined and developed since then and has recently been extended to include high resolution spatial definition of the waterway from upstream of Parramatta to the Port Jackson entrance, including the whole of the Lane Cove River and Middle Harbour estuaries. The Delft3D hydrodynamic model developed by the study team was calibrated with available water level and current/discharge data. This model layout is shown in **Figure A1** and **Figure A2**. Model development has made use of domain decomposition to allow dynamic parallel computation of the hydrodynamic processes. These domains are shown on **Figure A1**.

A pilot Ecological Response Model (ERM) for the Parramatta River Estuary between the Charles Street weir and Cockatoo Island was tested in 2013. That model system provided a basis for the initial SHERM developed within that study; notably in terms of developing a first understanding of water quality and algal processes within the estuary.

In terms of the system-wide hydrodynamic model, with upgrades to model resolution and bathymetric data, some modifications were required to optimise run times by de-refining the model grids, more so in the wider waterways of Sydney Harbour and Parramatta River, and converting the 2D model to a 3D model with 8 vertical layers. Flow structure in upstream narrow creek areas required careful ‘gridding’ to maintain correct volume and connectivity characteristics.

With the expansion of this model, and also the availability of more recently (2015) collected water quality data, simulations were carried out to verify the transport-dispersion characteristics of the model for the whole of Sydney Harbour. A suitable period of time from the water quality data collection period was identified, during which salinity levels within Sydney Harbour or upper estuarine reaches were reduced due to catchment inflows and then subsequently increased as the boundary salinity load from the harbour entrance propagated into the system under tidal flow forcing and dispersion. When, for the period following a significant rainfall event, there is little to no rainfall, the salinity recovery data can be utilised to validate dispersion coefficients adopted in the Delft3D hydrodynamic model; with some spatial variation. Even when further catchment inflows occur, the salinity data can be used by including those flows and renewed lower salinity. Care was taken in model schematization in upstream areas of the Lane Cove River, Middle Harbour and Parramatta River, for example, where catchment inflow volumes can form a significant part of waterway volume at any one time, and hence have a large influence on salinity variations.

The water quality model, Delft3D-WAQ, utilizes result files from the hydrodynamic model to represent volume fluxes within the model domain. Due to the fact that Delft3D-WAQ does not solve the equations of motion, there is considerably more flexibility with the development of the computational grid for that system. Delft3D-WAQ can accommodate a relatively unstructured grid which can be developed with a tool called Delft3-DIDO. DIDO allows the aggregation of Delft3D-FLOW hydrodynamic grids in a very flexible manner. Hence the previous study team utilised Delft3D-DIDO to generate an efficient water quality model domain. However, no grid de-refinement was carried out for the reduced area model of Middle Harbour applied in this study.

Particularly during water quality model calibration, it was very important to have a highly efficient (fast computational times), model that could carry out simulations relatively quickly. 2D and 3D versions of the Delft3D-WAQ model were developed, which formed the basis of the SHERM. The transport-dispersion processes of the Delft3D-WAQ module were calibrated to the Delft3D-FLOW model results through comparison of salinity distribution between the two models for the detailed WAQ model.

The previous study team undertook extensive analyses of the then available water quality and catchment data. The catchment data, discharge time-series and Total Nitrogen (TN) and Total Phosphorus (TP) concentrations, as well as sewer overflow loads provided by Sydney Water for non-dry periods, were available to that study. It was important to carry out mass balance tests to ensure that catchment loads were consistent with TN and TP concentrations observed in the waterways. These analyses also focused on the temporal and spatial distribution of organic and inorganic nutrient concentrations, for example, examining the ratio of Dissolved Inorganic Nitrogen (DIN) to Total Nitrogen (TN). Analyses were also carried out of the available water quality data from the Harbour and Parramatta

River, the latter being dominated by catchment flows, to understand the nutrient breakdown of the catchment loads and seasonal water temperature variation.

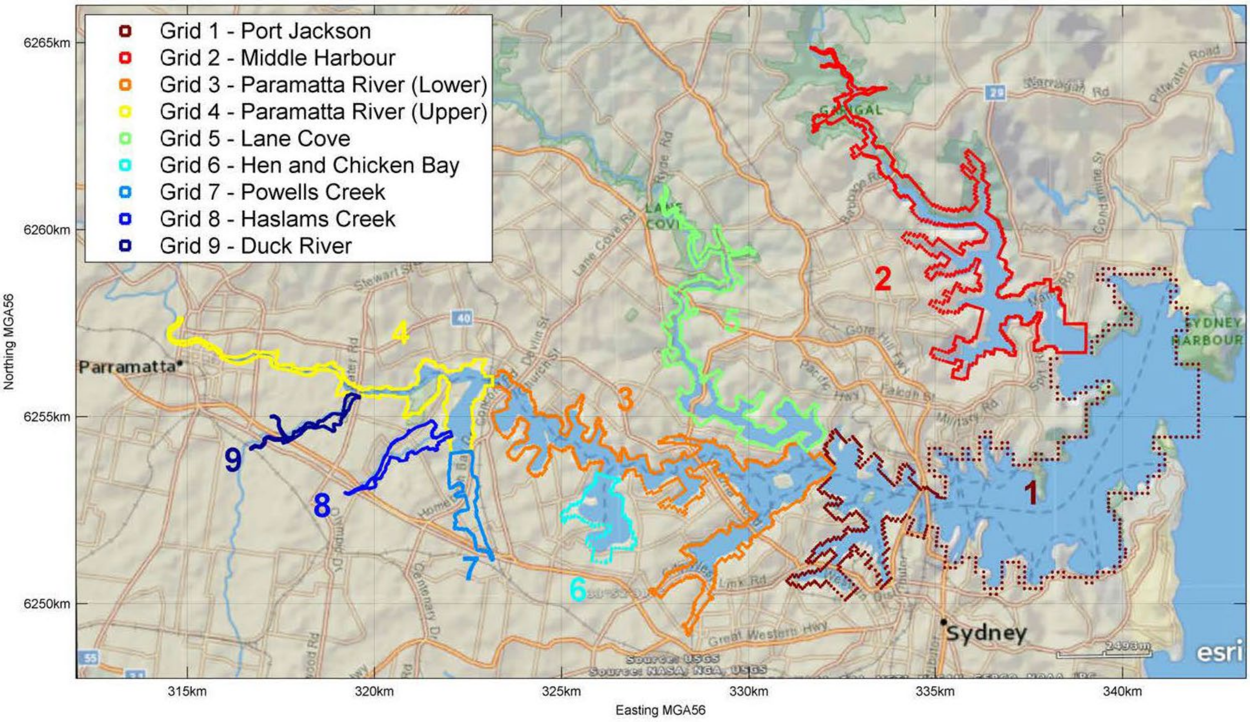

Figure A1 – SHERM - Model Extent and Domain Decomposition Definition

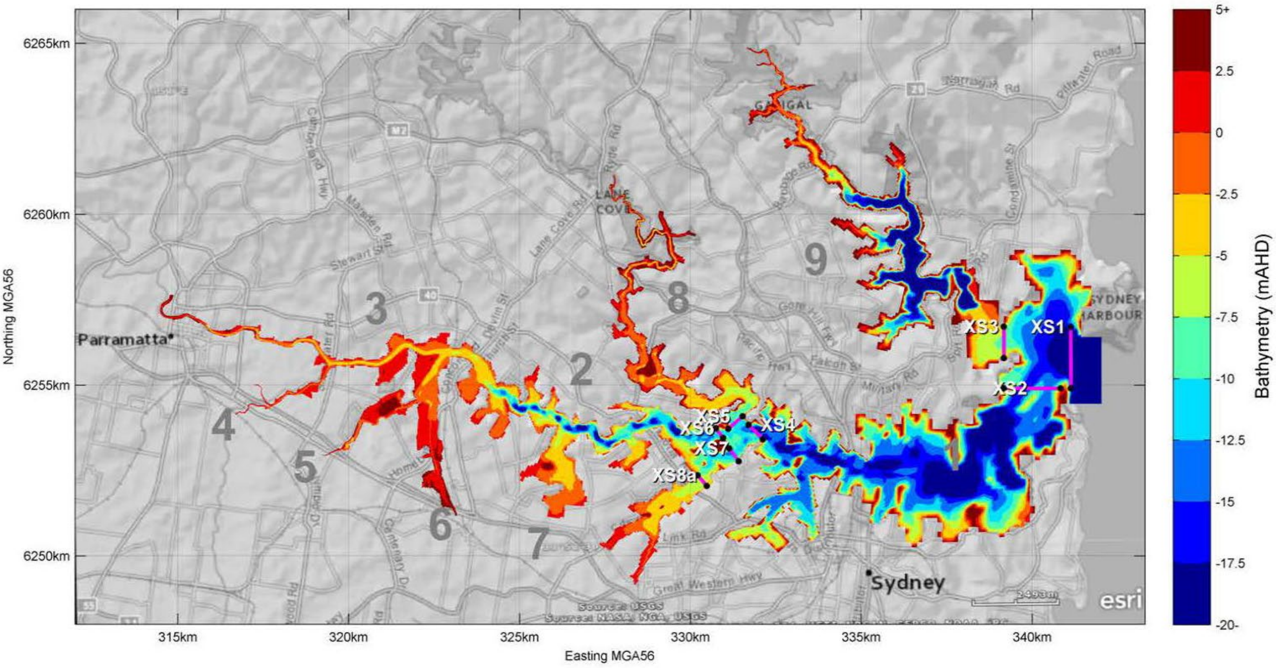

Figure A2 - SHERM - Model Bathymetry and Discharge Calibration Cross−Section Locations

Development of Water Quality Process Description

The SHERM was designed to simulate a range of water quality and biological processes. The water quality processes represented in the SHERM are as follows:

- Physical processes
  - Temperature
  - Salinity
  - DO and re-aeration
  - Solar radiation
  - Suspended sediments and light extinction.
- Nutrients
  - Nitrogen
    - NH_4, NO_x and two organic fractions (fast and slow decay fractions)
    - Nitrification and de-nitrification
    - Decomposition of organic nitrogen into soluble fractions
    - Sediment and water column exchange
    - Zero-and-first order nitrogen flux (release) from sediments
  - Phosphorus
    - PO_4 (absorbed and soluble) and two organic fractions (fast and slow decay fractions)
    - Decomposition of organic phosphorus into soluble fractions
    - Sediment and water column exchange
    - Zero-and-first order phosphorus flux (release) from sediments.
  - Carbon
    - Two organic fractions (fast and slow decay fractions).
- Algal processes
  - Primary production
  - Respiration
  - Mortality including grazing
  - DYNAMO option: Separation into green and diatom species
  - BLOOM option: Separation into three water column algae species (green, marine diatom, freshwater diatom) and a benthic algae species (represented by the Ulva process in Delft3D).
- Biological Contaminants
  - E-coli
  - Enterococci
  - Faecal coliforms.

In terms of running the model, it was possible to simulate the biological contaminants (faecal coliforms) and nutrient/primary production sections of the model separately because these two components of the SHERM are not dependant. Additionally, the SHERM could also be expanded to consider heavy metal processes.

Some process understanding and formulation was gleaned by the study team from the work carried out by the then NSW Office of Environment and Heritage (OEH). That advice was based on their research and experience in Botany Bay and Port Hacking (DECCW and ABER, 2009). In July 2014, OEH also provided some additional guidance on incorporation of benthic microalgae (BMA) into the water quality process description. As part of the model validation process, the complexity of the primary production processes in the water quality process description has been enhanced to account for the following:

- Inclusion of a benthic algae species including re-suspension
- Adjustment of the sediment-water column model to initially cycle nutrients released from the sediments into the benthic algae species.

Primary Production Model - DYNAMO option

The DELWAQ DYNAMO model was applied for the initial model configuration and calibration to examine the nutrient balance in the SHERM. The DYNAMO module applies Monod kinetics for the growth of algae biomass and competition between two algae species; green algae and diatoms.

Primary Production Model - BLOOM option

The BLOOM module in Delft3D is a more advanced primary production model that considers different groups of algae species based on the mathematical model presented in Delft Hydraulics (1985). BLOOM considers nitrogen, phosphorus, silicon and light availability in the calculation of the biomass stoichiometry. BLOOM adopts a linear programming algorithm to calculate the optimum distribution of biomass over all algae types in the model with the objective of maximising net algae growth for each time-step and grid cell. This is the primary production model that was adopted for this study.

Biological Contaminants Model

The biological contaminants component of the SHERM adopts the formulations of Mancini (1978) to compute the mortality of coliform and other bacterial indicators based on temperature, salinity and solar radiation.

Figure A3 describes the water quality processes adopted in the SHERM.

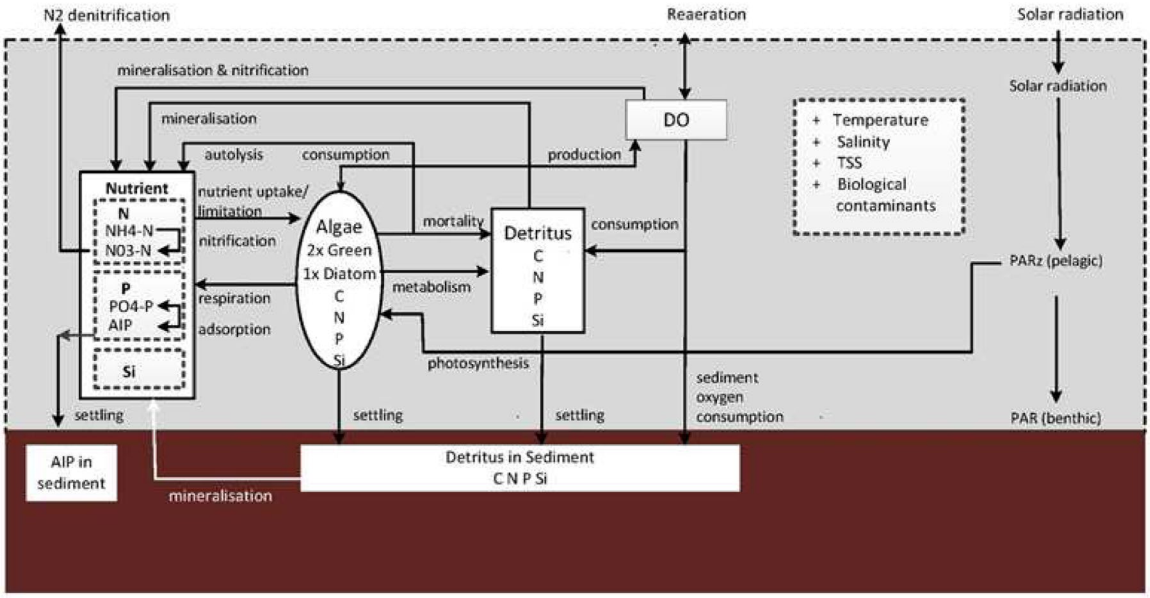

Figure A3 - Water Quality Processes Included in the WAQ Module of SHERM

ANNEXURE

B

TEMPERATURE AND SALINITY PLOTS

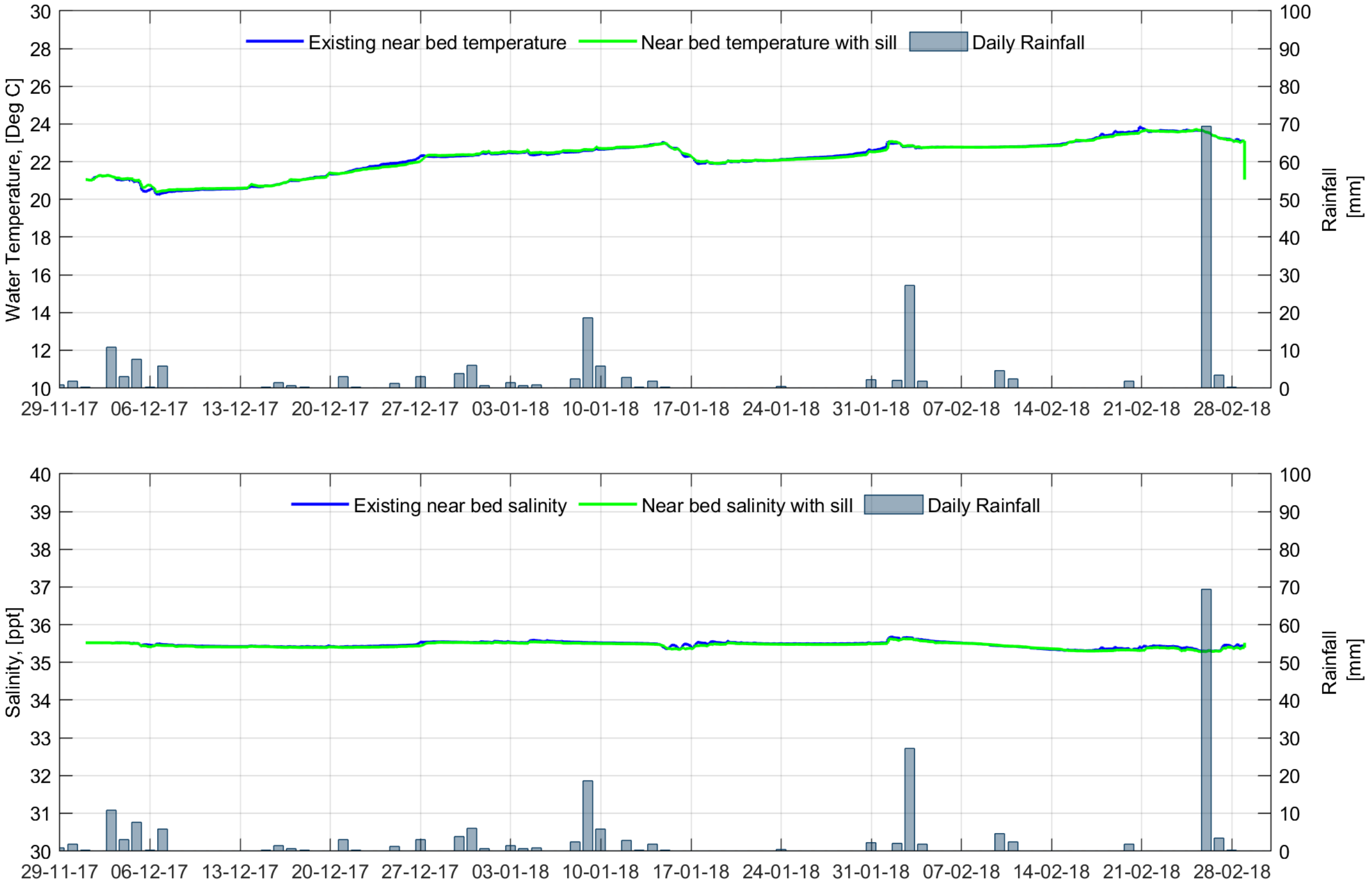

Figure B1 - Time Series Plot showing the Predicted near Bed temperature (top) and salinity (bottom) during Simulation Period 1

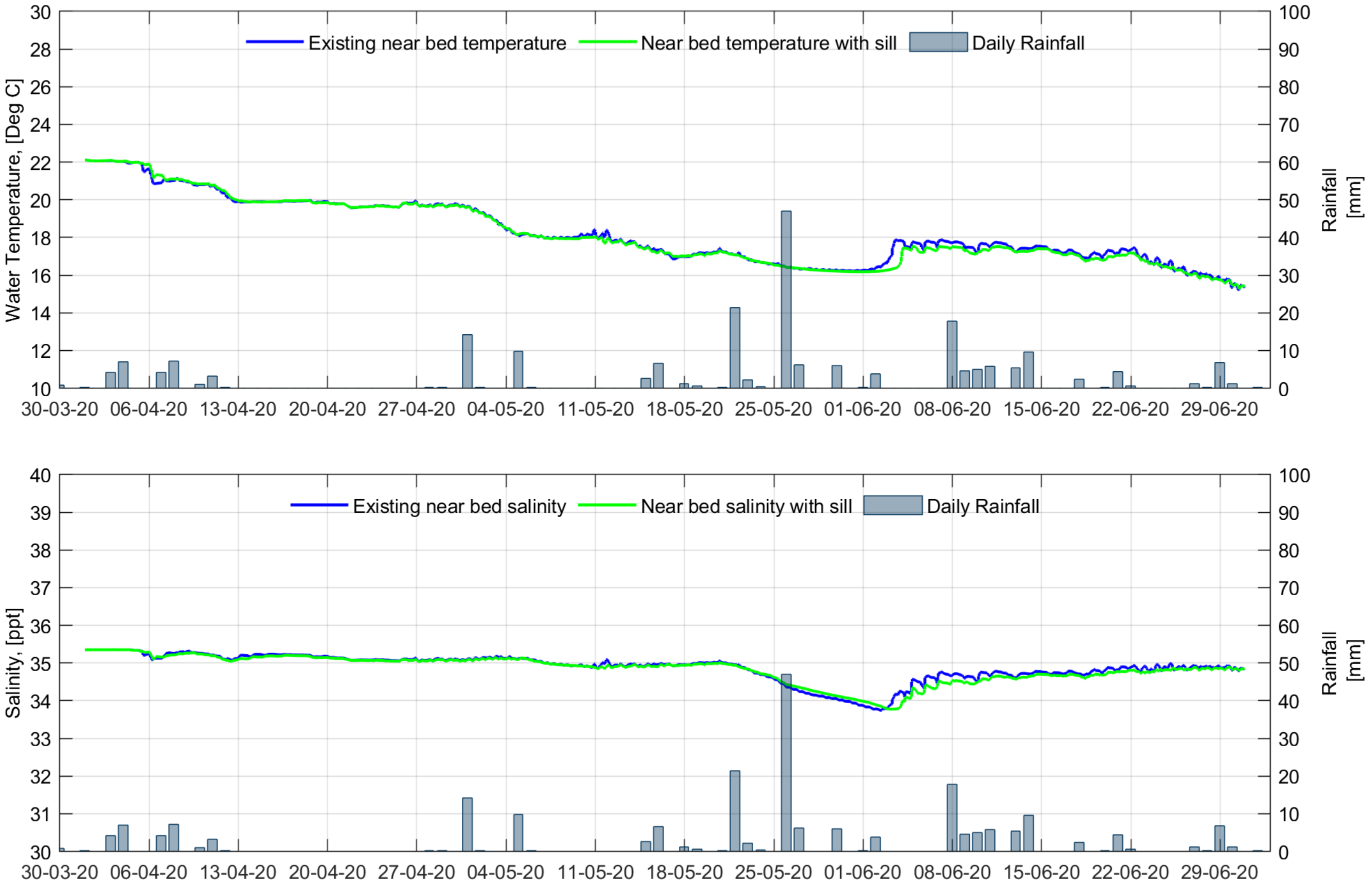

Figure B2 - Time Series Plot showing the Predicted near Bed temperature (top) and salinity (bottom) during Simulation Period 2

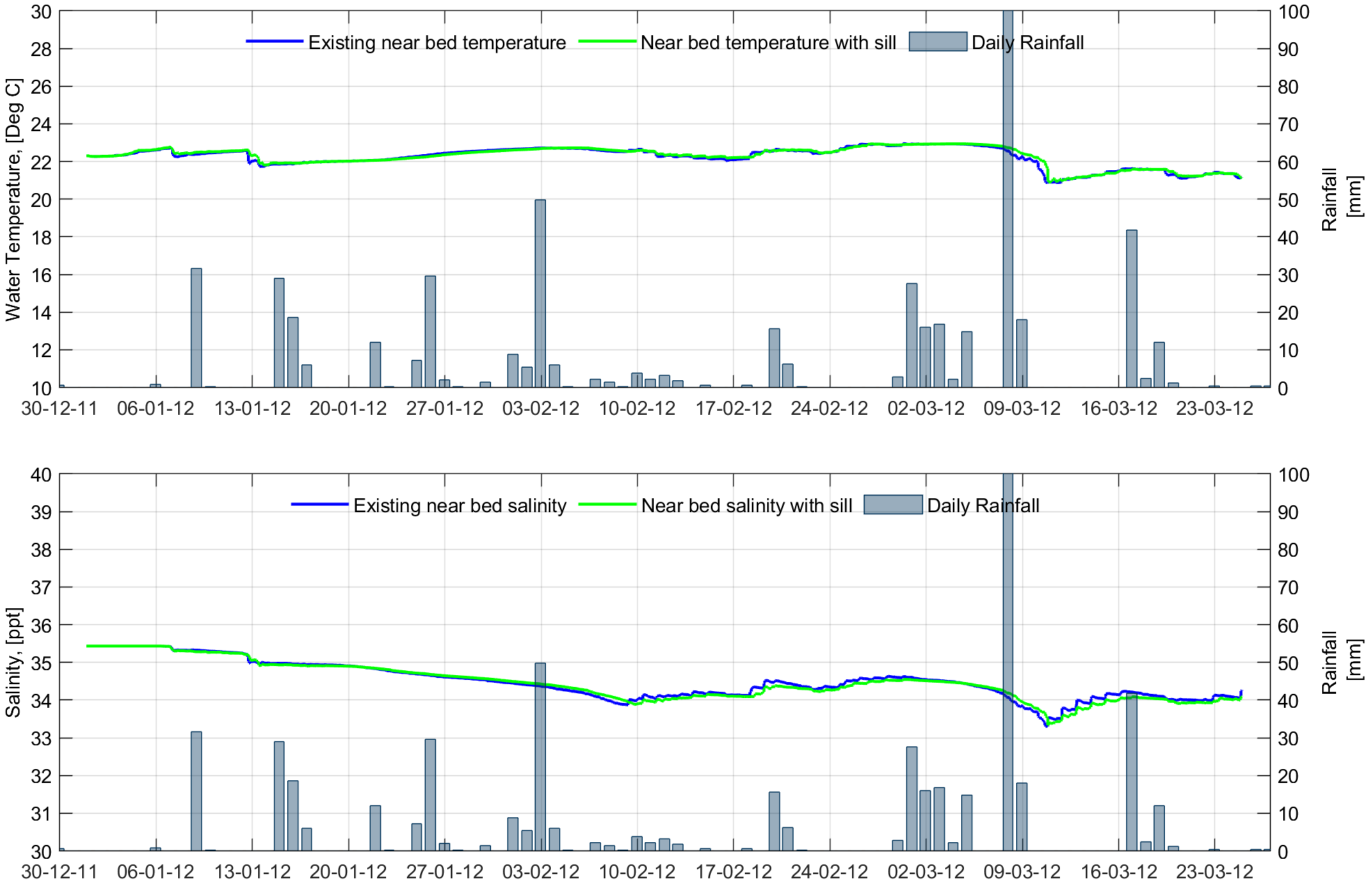

Figure B3 - Time Series Plot showing the Predicted near Bed temperature (top) and salinity (bottom) during Simulation Period 3