Sydney Harbour Ecological Response Model

Model Set-up, Calibration and Water Quality Investigations

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Greater Sydney Local Land Services

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Executive Summary

This report describes the purpose, data, model systems and methods applied to the development of the Sydney Harbour Ecological Response Model (SHERM for Greater Sydney Local Land Services (GSLLS).

Greater Sydney Local Land Services is using an integrated hydrological and ecological modelling approach to develop the Sydney Harbour Catchment Water Quality Improvement Plan (SHCWQIP). The objectives of the project are to achieve an improvement in the water quality and ecological integrity of Sydney Harbour and its catchment; to engage key land managers and other stakeholders in the project design and process; and encourage ownership of the outcomes.

The process includes the characterisation of land and its use within the catchment draining to Sydney Harbour. Intensive water quality monitoring has been undertaken to assist the development and validation of catchment pollutant export models (CPEM) to simulate and quantify the transport of stormwater pollutants to the Parramatta River and Port Jackson. A high resolution 3-dimensional hydrodynamic model of the Harbour and its tributaries was developed and integrated with the CPEMs for the development of water quality models that simulate and predict the transport and fate of pollutants and phytoplankton under varying weather and land use management scenarios. Probabilistic higher order ecological response models were developed to predict the influence of management strategies on the ecology of the Harbour.

Integration of the above models into a Decision Support System (DSS) has been undertaken to investigate the impact of different management strategies on water quality and Harbour ecology. Output from the DSS is to be provided in terms of social, economic and ecological probability distributions for decision-making – by others.

The project has secured funding partnerships with the majority of the local governments within the Sydney Harbour Catchment, as well as Sydney Water, Roads Maritime Services, Office of Environment and Heritage (OEH), Harbour City Ferries and the Sydney Institute or Marine Sciences (SIMS).

Sydney Harbour, together with its foreshores, headlands and tributaries is the city’s largest and most accessible open space and natural area. It is Sydney’s best loved urban space; a national icon; a busy transport corridor; an economic powerhouse for industry, commerce, trade and tourism; and much more.

Sydney Harbour and its catchment have natural resource assets of national significance and as identified within the *Environment Protection and Biodiversity Conservation Act* (1999), these assets include: three threatened ecological communities; 62 threatened species; 29 migratory species; and 48 marine protected species.

Although much has been done, the sediments still carry the toxic legacy of years of industrial discharges. Testing of fish and crustaceans has revealed high levels of dioxins that resulted in a complete ban on all commercial fishing in Sydney Harbour in January 2006. Whilst recreational fishing has not been banned, fishers have been advised that no fish or crustaceans caught west of the Sydney Harbour Bridge should be eaten and for fish caught east of the bridge generally no more than 150 grams per month should be consumed (DPI 2012). Whilst changes in legislation have made it illegal to purposely dump toxic waste in Sydney Harbour, toxic pollutants still enter the estuary each year through the stormwater system and sewage overflows.

Stormwater pollution is now the major threat to the ecological integrity of Sydney Harbour.

The SHCWQIP is the first environmental management plan to encompass the whole of Sydney Harbour’s catchment as well as the waterways and will provide the first coordinated management framework for the 25 local councils, 11 state government agencies and 2 federal government agencies who have a stake in improving the future health of Sydney Harbour and its catchments.

The SHCWQIP project is by its nature highly complex and includes several detailed modelling projects. Each of these sub projects have produced detailed reports. Whilst this paper reports on some of that work, readers are directed to the detailed reports for further information.

The SHERM modelling system forms one part of the overall Sydney Harbour Catchment Water Quality Improvement Plan (SHCWQIP).

The model system has been built upon an existing hydrodynamic model of the Harbour and Parramatta River.

LLS engaged Sydney Institute of Marine Sciences to collect and analyse sets of winter and summer water quality data, including physical and bio-chemical parameters. This data has been used to calibrate and verify the water quality model system.

Technical correspondence amongst GSLLS, OEH and Cardno/Baird has been undertaken so that OEH"s estuarine water quality experience and understanding could be incorporated into the study.

The water quality model system has included a very detailed water quality model that was de-refined in the horizontal plane by three times (3x) from the detail of the hydrodynamic model, and a box model that provides less horizontal resolution, but much faster computation times.

This box model has also been used to provide input to a Decision Support System being prepared by other members of the overall SHCWQIP study.

As well as water quality, which has included three algal species, the modelling has addressed the fate of bacterial inputs from sewerage overflows from Sydney Water waste water infrastructure and catchment inflows.

Flushing characteristics were investigated for selected regions of the estuary in terms of e-folding times.

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1 Introduction

The Hawkesbury Nepean Catchment Management Authority (HNCMA) sought submissions from suitably qualified and experienced parties to provide services to develop a whole of Sydney Harbour Ecological Response Model (SHERM). The SHERM is required to investigate water quality processes and provide outputs to support the development of the Sydney Harbour Catchment Water Quality Improvement Plan (SHCWQIP).

The purpose of this project is to develop a whole of Sydney Harbour water quality and ecological response model that is capable of modelling a range of water quality processes and primary ecological responses, including phytoplankton. Amongst other aspects, the outputs from the SHERM will provide inputs to a Decision Support System (DSS) which is progressively being developed to direct and assess the outcomes of the SHCWQIP.

HNCMA appointed a study team comprising Cardno (NSW/ACT) Pty Ltd and Baird Australia Pty Ltd to undertake this work.

1.1 Background

The Greater Sydney Local Land Services Authority (GSLLS) (formerly the Hawkesbury Nepean Catchment Management Authority), is coordinating the development of the Sydney Harbour Catchment Water Quality Improvement Plan (SHCWQIP). A critical step towards the development of this Plan is the development of a numerical model that can simulate a range of water quality processes and primary ecological responses within Port Jackson and the Parramatta River – the Sydney Harbour Ecological Response Model (SHERM).

As part of the SHCWQIP, the GSLLS had already developed a range of numerical model systems that provide suitable inputs into the SHERM. Those models include the following:-

- Catchment Pollutant Export Models (CPEMs) which have been developed as a Source Catchment numerical model system by Catchment Research Pty Ltd (CR);
- A Delft3D Hydrodynamic Model, which simulates water levels, currents, temperature and salinity throughout Sydney Harbour from the ocean entrance upstream to the Parramatta Causeway. The model extent and resolution have been increased recently within the Lane Cove River and Middle Harbour to assist with this project, including grid preparation for those particular waterways;
- A pilot ERM (Delft3D-WAQ) that was developed for the region between Cockatoo Island and the upstream river to the Parramatta Causeway.

The CPEM, Delft3D hydrodynamic model and ERM systems have all been calibrated using data available for each model system. The CPEM was developed to provide catchment flows and pollutant loads for the SHERM. The Delft3D hydrodynamic model provides advective forcing conditions for the SHERM and can also provide 3D salinity and temperature inputs (if required). These models have relatively high spatial and temporal resolution requiring considerable computational resources should they be run in a single model domain.

An extensive array of water quality and biological data has been collected as part of the SHCWQIP. Data has been collected from sites along the Parramatta River and Sydney Harbour during autumn and winter conditions (April to June 2012 – upstream of Cockatoo Island) and also during summer (November 2012 to February 2013 – downstream of Cockatoo Island, Lane Cove River and Middle Harbour). The 2012 autumn and winter data has been used to develop and calibrate the initial pilot ERM (Baird 2013). The winter and summer data sets have been applied to calibration and verification of the SHERM in this study. The GSLLS has also embarked on a data collection program to collect temporally and spatially varying physical water quality data in a program being undertaken with Sydney Ferries with newly designed sensors that will be fitted to selected ferry services operating on Sydney Harbour.

1.2 This Project

Cardno and Baird have undertaken a range of model based investigations for the GSLLS (formerly the HNCMA) over the last 24-months and have worked collaboratively on those projects. This team has recently completed a range of modelling tasks in Port Jackson and the Parramatta River using the Delft3D modelling system. Those tasks included water quality modelling using the available winter period of water quality data collected by the Sydney Institute of Marine Science (SIMS) for (the then) HNCMA, together with model expansion and grid refinement in the Lane Cove River and Middle Harbour regions.

Model output needed to be prepared also for a CAPER Decision Support System developed by isNRM Pty Ltd; see **Appendix A** for an outline of that system.

2 Methodology

2.1 Scope of Work

The specified scope of work undertaken for this project is 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 and have the capacity to include customised water quality processes implemented into the modelling system. The SHERM needed to be capable of modelling a combination of 2D and 3D reaches within the Sydney Harbour system. Initially the SHERM was built upon the Parramatta River Pilot ERM and had the following water quality processes implemented:-
   a) Transport and dispersion of conservative constituents.
   b) Water temperature (set for each season) 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) Dissolved oxygen.
   g) Faecal coliforms, Enterococci and/or E-coli.
2. Calibration and verification of the model system for winter and summer conditions, respectively, with data sets collected between April 2012 and February 2013.
3. Validation of the model system with available historical data for the Sydney Harbour system.
4. Application of the calibrated SHERM to modelling of four selected 1-year duration hydrodynamic and water quality simulation scenarios, made up of wet, dry and average years as:-
   - Wet: April 2011 - March 2012
   - Average: April 2012 - March 2013
   - Dry: April 2002 - March 2003
   - Wet: April 2011 – March 2012 with 0.9m projected sea level rise

   The winter-summer order was chosen as it better identifies wet and average cases within the period of available sewer overflows. No sewer overflows were included for the dry year (2002). The fourth simulation was for the wet year, but with a sea level rise of 0.9m, which will affect saltmarsh areas.
5. Additionally a box-model system was developed to allow much faster, but less detailed water quality simulations. It would repeat the same four simulation cases as the full model in order to provide a basis for inter-model comparison, and then some other selected cases including assessment of changes to catchment nutrient loads.
6. Prepare a report on the project and prepare high quality graphical outputs from the SHERM.
7. Provide the capability for ongoing support to the GSLLS.

The methodology applied to this scope of work is outlined in the following sections.

2.2 Model Development and Input Data Sets

Since 2011, the study team has been in a model development partnership with the GSLLS to develop a Delft3D-based hydrodynamic and water quality model system of this waterway. The Delft3D model has been refined and developed since then and recently has 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 has been calibrated with available water level and current/discharge data. This model layout is shown in **Figures 2.1** and **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**.

In 2013, the then HNCMA engaged Baird Australia to develop a pilot Ecological Response Model (ERM) for the Parramatta River Estuary between the Charles Street weir and Cockatoo Island. The pilot ERM (Baird, 2013), provided a basis for the initial SHERM developed within this study; notably in terms of developing a first understanding of water quality and algal processes within the estuary.

In terms of the hydrodynamic model, with the recent upgrades to model resolution and bathymetric data, there was no requirement for major development of the hydrodynamic model as part of this study. However, significant modifications were required to optimize run times by de-refining the model grids, more so in the wider water ways of the Harbour and 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 collected water quality data, the study team was able to undertake simulations 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 the 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 utilized 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 must be 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 study team utilised Delft3D-DIDO to generate an efficient water quality model domain. Two WAQ models, one a box model of only 33 regions, the other a more detailed model, were applied in this investigation. The level of grid de-refinement of the WAQ model in the horizontal plane was a consistent factor of three (3) in each of the “X” and “Y” directions.

Particularly during water quality model calibration, it was very important to have a highly efficient (fast computational times) model that could undertake simulations relatively quickly; and the box model fulfilled that role. Some final design simulations were undertaken with the model that had much higher grid resolution. The study team developed 2D and 3D versions of the Delft3D-WAQ model, 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 box model and detailed WAQ model.

Figure 2.3 describes the box-model version of the WAQ model in terms of grid layout details.

The study team undertook extensive analyses of the water quality and catchment data. The catchment data, discharge time-series and TN and TP concentrations, as well as sewer overflow loads provided by Sydney Water for non-dry periods, was prepared by CR (2014). It was important to undertake 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 undertaken 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.

2.3 Development of Water Quality Process Description

Based on their previous investigations in the Port Jackson Parramatta River system, the study team had a good understanding of the water quality processes description that will be required in the SHERM.

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

- Physical processes
  - Temperature
  - Salinity
  - Dissolved oxygen 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 undertaken by the Office of Environment and Heritage. 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; and
- Adjustment of the sediment-water column model to initially cycle nutrients released from the sediments into the benthic algae species.

2.3.1 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.

2.3.2 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.

2.3.3 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 2.4 describes the water quality processes adopted in the SHERM.

2.4 Outline of Calibration of the SHERM Water Quality Processes

The calibration/validation period for the SHERM was between April 2012 and December 2012 when a comprehensive water quality data collection programme was undertaken by SIMS for the then HNCMA. The period of most importance was between October 2012 and February 2013 (5-months, warmer weather) when water quality data was collected at regular intervals at 22 sampling sites throughout the harbour in warmer weather when production rates are higher. Model calibration was based on the winter months with validation being based on the summer data.

The Sydney Harbour Delft3D-FLOW model was calibrated first for transport-dispersion using suitable salinity recovery data available during this period of time. Following confirmation of the dispersion coefficients in the Delft3D-FLOW model, the model was run for the period from April to June 2012 for 2D and 3D model configurations.

The transport fluxes from the Delft3D-FLOW model were processed and aggregated initially onto a coarse grid (the box model) that was used for the initial calibration of the SHERM. Calibration was initially undertaken in a sequence of steps that can be summarised as follows:-

1. Calibration of transport and dispersion characteristics.
2. Calibration of the biological contaminant process and concentrations.
3. Calibration of total nutrient balance (i.e. TN, TP, and TOC).
4. Calibration of nutrient cycle to represent dissolved inorganic nutrient concentrations accurately within the model.
5. Calibration of the primary production including algal processes and dissolved oxygen levels.

Throughout the water quality calibration process, a detailed record of model scenarios and parameter coefficients that were tested was maintained. Calibration using the box model allowed rapid turn-around of trial simulations and hence optimisation of the calibration process in terms of time; and as shown later, little loss of water quality detail.

2.5 Validation of the SHERM with Available Historical Data Sets

A validation simulation of the SHERM with a longer term data set using reasonable available data was undertaken. For this exercise, only the SHERM was run and the model used representative hydrodynamic forcing from the 2012 to 2013 period, which had been modelled with the Delft3D-FLOW model. To undertake this validation simulation, catchment flow and concentration outputs from the catchment model were required. The historical data is more limited in terms of the sampled parameters and the validation of the SHERM was concentrated on key indicators. Data that was available included TN, TP, inorganic nitrogen and phosphorus, chlorophyll-a, dissolved oxygen and enterococci (bacteria).

2.6 Application of the SHERM to Five Selected 1-year Simulation Scenarios

Following the completion of the calibration and validation tasks of the SHERM, the model system was applied to the simulation of four selected 1-year scenarios. The 1-year scenarios were agreed with the GSLLS and involved the simulation of different rainfall conditions (i.e. wet, dry and average years) as well as the wet year with a projected sea level rise of 0.9m, and the wet year with a 20% reduction in nutrient loads (TN and TP) to examine potential water quality improvement as a result of catchment water quality improvements in the future.

2.7 E-Folding Analyses

Following a project review meeting held on 17 October 2013 at GSLLS offices, the Office of Environment and Heritage (OEH) requested that three bays and two channels be investigated in terms of e-folding times – a measure of flushing times. One of these was the Lane Cove River from Fullers Bridge to the Parramatta River; others were agreed between GSLLS/OEH and Cardno/Baird upon engagement, and were Iron Cove, Hen and Chicken and Rozelle Bays, as well as the main river channel between Parramatta and Gladesville and the Duck River. In each regional case it was necessary to undertake dry weather condition simulations and "moderately high" catchment inflow simulations, each of about two weeks duration. In each of these simulations the region of particular interest was loaded with an initial conservative contaminant at concentration 100. Results were to be presented as maps of e-folding times – there will be significant difference between e-folding times at the head and entrance to each embayment. These results provide an overview basis of the relative flushing characteristics of each modelled area.

2.8 Application of Box-Model Simulation Scenarios

The investigations described in **Section 2.6** required significant computational resources and had limited benthic/pelagic coupling of the nutrients and benthic micro-organisms/chl_a relationships. OEH were able to advise the Cardno/Baird study team on the application of those processes in the simplified box-model representation of the hydrodynamics, as well as the more detailed model – essentially the same process descriptions. The box-model hydrodynamics were prepared by aggregation of the full model hydrodynamics so that, for example, inner Iron Cove became one box, Number 10 on **Figure 2.3**, and the tidal exchange and catchment flows described bulk flows – maintaining mass conservation. Other examples were the Parramatta River above Silverwater Road and Homebush Bay (including Powell's and Haslam's Creeks). The Box-Model layout was agreed with the GSLLS early in the study. The benthic water quality processes are described schematically in **Figure 2.4**.

The box model layout needed to consider the resolution required for the DSS (see **Appendix A**) and individual Council's needs and is described in **Figure 2.3**. isNRM were provided with box model output; that model layout being consistent with the DSS model, modified from the initial DSS layout presented in **Appendix A** to match the box model.

Box model simulations were very computationally quick and hence allowed many more simulations and development scenarios to be investigated.

The study team undertook five box model design scenarios for this study. The specific cases were selected by the study team in consultation with the GSLLS.

2.9 Reporting and Provision of Model Outputs

The study team was to prepare a detailed report at the completion of this project – this document. The report was to outline the following items:-

- Project scope;
- Input data;
- Model description including water quality processes;
- Description of model assumptions and uncertainty;
- Provide the model bathymetry (not model grids per se) for research-only purposes at SIMS
- Details and outcomes of model calibration and validation;
- Details of the box-model development
- Describe the benthic micro-organisms/chl_a relationships
- Statistical and graphical outputs from the e-folding and scenario (WAQ and box-model) simulations; and
- Discussion on model system, processes and areas for further development.

The report format and draft table of contents were agreed with the GSLLS early in the project. Outputs from the SHERM have been provided to the GSLLS as time-series in MS Excel format. Spatial outputs have been provided in Shapefile format. Four high-quality animations of selected parameters and scenarios have been prepared.

3 Data

A range of data items was required for this 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 QA/QC water quality data for model calibration and validation – from GSLLS and SIMS.
- Provision of QA/QC catchment flow time-series data for wet, dry and average years – from Catchment Research Pty Ltd
- Provision by GSLLS/OEH of guidance for benthic micro-organisms/chl_a relationships and benthic/pelagic coupling of the nutrient processes.
- Bayesian analysis zone definition clarification with Rebecca Kelly (isNRM Pty Ltd);
- Catchment runoff information details from Joel Stewart (Catchment Research Pty Ltd - CRPL) (clarified 25 March 2014);
- Discharge and water level data described in Lawson and Treloar (1992), with additional data for the Rodd Point area provided by Sydney University; and
- Bathymetric and topographic data required for model set up – available from AUS charts 200 to 203, GSLLS project specific surveys and Sydney region LiDAR information.

The study team were also intended to be provided with available sediment data including data available from SIMS, however none was made available.

4 Catchment Input Data

4.1 Catchment Model

A Sydney Harbour Catchment Model (SHCM) was developed for the then Hawkesbury Nepean Catchment Management Authority and is detailed in (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 requested from and provided by CR, and used as input discharges to the hydrodynamic model, as presented in **Figure 4.1**. Data was provided at 30 minute time-steps in comma separated (csv) format for each of the catchments discharging directly to the hydrodynamic model.

The catchment flow time-series, discharges and nutrient concentrations, were provided for the period from 1 January 2000 to 25 July 2013 and contained 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)

In addition, discharge and water quality data for thirty-two sewerage overflow sites (SOF), provided by Sydney Water to CR as daily flows, were provided as 30 minute time-series data for input to the hydrodynamic model. This data was available only over a shorter three years period between 2010 and 2013. It was not available, and not required, for the dry year simulation.

4.2 Data Verification

Due to the large amount of data supplied from the catchment model, quality checking procedures were important to ensure that the model was producing reliable results and that outputs were being extracted correctly. While a detailed quality assurance analysis was outside the scope of the SHERM modelling study, and could not be undertaken without access to the catchment model itself, the data provided by CR was reviewed in the following ways:-

- Cross checking of supplied sub-catchment flows with those requested,
- Comparison of reported total flow values to those supplied,
- Discharge rates from individual sub-catchments were checked,
- A comparison of water quality concentrations to documented sources, and
- A comparison of pathogen concentrations to measured pathogen data upstream of Parramatta Weir.

4.2.1 Flow Rates

Examination of the supplied data was undertaken to ensure that flows were being received and processed correctly. Following the initial identification of a small number of inconsistencies, which were subsequently resolved with assistance from CR, the catchment flow data was deemed suitable for input to the SHERM. It was confirmed that the processed flow data matched the reported values in CR (2014) - all sub-catchment flows were in relative proportion to the area of the upstream catchment and the summation of all flows equalled the outlet values extracted separately by CR.

4.2.2 Parameter Concentrations

Water Quality parameter validations were made for each sub-catchment of the catchment model. The mean and standard deviation concentration of each parameter from the catchment model were compared to the mean and standard deviation values from Australian Runoff Quality guidelines (ARQ, 2006). **Figure 4.2** shows that for TN, 188 of the 195 sub catchment discharges contain a TN concentration within the ARQ guidelines. The catchment model mean values are consistently lower than the ARQ mean, however, they are usually well within the standard deviation of the ARQ guidelines. Seven of the 195 sub catchment discharges were lower than the standard deviation bands of the ARQ guidelines. A similar result is seen for TP as shown in **Figure 4.3**. In general, the concentrations from the catchment model are consistent with ARQ data and are considered suitable for input to the ERM.

4.2.3 Catchment Bacterial Load Assessment

Measured data of Enterococci concentrations upstream of the Charles Street Weir was provided by Parramatta City Council. It covered the period from April 2011 to January 2013. Data from this site, which is effectively a source location for the Charles Street Weir inflows into the SHERM, was compared to the catchment model inflows which were being input to the SHERM.

Figure 4.4 presents a comparison of the Enterococci concentrations, from the catchment model, of all catchment sources and sewer overflows upstream of the Charles Street Weir against the measured data, collected at or near the Barry Wilde Bridge. The figure shows that the modelled pathogen load from the catchment is reasonably consistent with the measured data when sewerage overflows (SOF) are included. Sewer overflows are shown to be the source of spikes in pathogen counts, observed in both datasets. Without the sewerage overflows, the catchment inflow pathogen concentrations are relatively small.

Small delays in the peak pathogen loads are seen in the measured data due to the difference in location of the catchment inflows and the sampling site. The catchment inflows are taken as discharge locations into the river, extending some 2km upstream as far as Westmead, whilst the measurements are taken within the Parramatta River (receiving body) close to the Parramatta Weir. In addition, some dilution and decay would take place once the catchment and sewer overflows enter the receiving body.

4.3 Selection of Simulation Periods

Wet, average and dry years were required to be simulated in order to cover a broad range of conditions within the estuary and river areas. The selection of the most appropriate simulation periods was subject to restriction due to data availability. Whilst catchment data was available from 1 January 2000 to 25 July 2013, sewerage overflow data was only available from Sydney Water from 1 July 2010 to 1 July 2013.

A simulation year was defined as starting on 1 April and ending 31 March of the following year. While somewhat arbitrary, in doing so, the years aligned with traditional seasonal definitions and made better use of the limited sewerage overflow data. Simulations also began in less active periods of the year.

Figure 4.5 shows a bar graph of the total flow for each yearly period (April through to March the following year) and for the coinciding winter and summer seasons. The horizontal lines indicate the average values for each period across all years of data. The wet, average and dry years selected were as follows.

4.3.1 Wet Year – 2011 (April 2011 – March 2012)

Whilst 2007 is the wettest year, no sewerage overflow data is available and hence it was excluded because it was likely to underestimate the pathogen load in the system, given the data available. Therefore, the second wettest year, 2011, was selected as the wet year. In addition, 2011 had the wettest summer period of all years analysed.

4.3.2 Average Year – 2012 (April 2012 – March 2013)

The average rainfall year was selected to be 2012. This time period was shown to have annual, summer and winter periods with flows very close to the average, while having concurrent sewer overflow data.

4.3.3 Dry Year – 2002 (April 2002 – March 2003)

For the dry year, sewerage overflows are not expected to be of particular importance to overall water quality with major overflow events unlikely to occur. This resulted in 2002 being the selected dry year.

4.4 Data Preparation for Delft3D

4.4.1 Units and Conversions

Catchment inflow data was supplied as time-series of daily flows. The list below summarises the units supplied and the conversions used for implementation in the Delft3D model (all conversions were reviewed and approved by CR):-

- 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).
- Coliforms and e-coli: Supplied as kg/day. Divided by (1,000*ML/d) to convert to mg/L; however, treated as cfu/100mL within the water quality model.

4.4.2 Preparation of Input Data for Hydrodynamic and Water Quality Models

A Matlab routine was developed to load the catchment data from the comma separated format (csv) provided by CR into a Matlab structure file (mat). The routine converted the supplied data into standard units and file structure consistent with hydrodynamic and water quality model inputs as detailed in **Section 4.4.1**. The data was then output 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 weeks warm-up period prior to the period of interest.

4.4.3 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. Following the wet weather event in June 2012, the water quality data measured at Sample Sites LPR1 and LPR3, (see **Figure 5.8**), on 12 June 2012 was essentially catchment flow data which was characterised by very low salinity. The surface and bottom samples collected on the 12 June 2012 at these sites showed very consistent values, which indicate that there was little to no stratification present at these sites on that date.

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 dissolved oxygen and dissolved silica measured during this freshwater flow event were used to specify the concentrations for these variables from the catchment inflows. **Table 4-1** summarises coefficients applied to the catchment water quality inflow conditions.

Compared to the pilot model study (Baird, 2013), the phosphorus breakdown has been adjusted to reduce the inorganic fraction to 20% of TP, and the slow organic fraction has been increased to 50% of TP.

Table 4-1 Summary of Coefficients Applied to Catchment Water Quality Inflow Specification

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
Salinity	Sal	1	ppt
Escherichia Coli	ECOLI	1	Ecoli
Faecal Coliforms	FCOLI	1	Fcoli
Enterococci	TCOLI	1	Enter

5 Model Calibration

This section summarises the construction and development and then the recalibration of a detailed 2D/3D hydrodynamic model of Port Jackson and the Parramatta River. The purpose of this hydrodynamic model was to provide spatial and temporal descriptions of water levels, currents, discharges and salinity that were used to drive the detailed water quality and ecological response model for Port Jackson and the Parramatta River - termed the Sydney Harbour Ecological Response Model - SHERM. Water temperatures were included by adopting seasonal temperatures based on recorded water temperature data.

The model described herein is an extension of a pre-existing Port Jackson-Parramatta River hydrodynamic model that has previously been used by the then HNCMA and the study team to successfully simulate the advection and dispersion of salinity and passive tracers (Baird, 2013), including calibration and operation of a winter period water quality (WQ) model. This winter WQ data was collected by SIMS (2012) for the then HNCMA. An additional set of spring-summer WQ data was collected over the period from October to December 2012 for GSLLS.

This hydrodynamic model has now been extended by the study team to cover Port Jackson, the Lane Cove River, upstream of Parramatta, streams such as Haslam's Creek, and Middle Harbour.

The model layout was first setup and optimized to only cover the Parramatta River upstream of Cockatoo Island; albeit there was an overall calibrated model that extended to the Tasman Sea. Hence, the model became computationally slower with this increase in model extent, which maintained very detailed resolution in many of the small waterways such as Powell's Creek and the Duck River. This model grid setup was still manageable in 2D, but could not be used for the 3D runs required for the water quality modelling.

5.1 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.

5.1.1 2D Optimisation & Re-Calibration

Significant effort was put into making the pre-existing 2D hydrodynamic model more computationally efficient without sacrificing essential flow structure resolution. The challenge consisted in locally coarsening the grid resolution (mainly along the flow and transversally where flow structure was consistent in order to conserve bathymetric gradients, (horizontally and vertically) - in order to reduce the run times and also minimize the effect on the calibrated model flows.

Figure 2.1 shows the overall model extent. For computational efficiency, the overall hydrodynamic model has been constructed as a series of nine individual domains, using a procedure known as 'Domain Decomposition'; which are processed in parallel by the computational engine, thereby enhancing computational efficiency.

Table 5.1 summarizes the optimizing process by presenting the number of cells and minimum and maximum grid resolutions of the nine model domains (pre and post de-refinement stages).

Table 5-1 Model Grid Counts and Dimension Ranges

Grid (Domain Name)	Number of Cells				Resolution (m)			
	Pre		Post		Pre		Post	
	M	N	M	N	Min.	Max.	Min.	Max.
Port Jackson	300	279	100	98	11	60	32	160
Middle Harbour	629	257	246	105	6	30	5	85
Parramatta River (Lower)	265	458	98	164	9	35	20	95
Parramatta River (Upper)	837	170	314	71	2	25	5	80
Lane Cove	919	500	343	195	2	20	4	55
Hen and Chicken Bay	146	73	42	25	14	30	44	90
Haslam's Creek	168	369	67	160	3	15	3	40
Powell's Creek	194	344	80	145	2	10	5	30
Duck River	587	236	233	81	2	10	4	20

The number of cells pre and post the optimization process indicates an average de-refinement by a factor of 3 in both the M and N grid directions. However, one can notice that the minimum resolution of the finest grid cells is only slightly coarser. It enables the model to still perform accurately in the most demanding sections of the estuary. The excessive details of the pre-optimization grid setup have been removed (grid resolution under 4m).

The 2D post-optimization model is 25 times faster than the pre-optimization model due to the reduction in the number of grid cells, which also enabled an increase in the time step by a factor of 10 (from 0.01 to 0.1 of a minute), without compromising the stability and accuracy of the model.

Local weirs are modelled as sub-grid structures. This overall influence is modelled by the energy losses due to each weir. These energy losses are described as an additional quadratic friction term in the momentum equations. Weirs have been introduced in the model, with specified crest levels, at:-

- Marsden Street (4.1 m AHD)
- Charles Street (1.9 m AHD)
- Lane Cove weir (1.4 m AHD)

These structures are critical for the management of important catchment flows coming from upstream and they also control the water levels upstream of the weirs. These weirs were incorporated into the model as sub-grid scale structures (lwl in Delft3D-FLOW).

Figure 2.2 presents the overall model bathymetry overlain by the location of the nine cross-section discharge measurement locations from Lawson and Treloar (1992).

Figure 5.1 describes the water level calibration results for the tested wave model systems. Agreement is very good.

Figures 5.2a and **5.2b** show the calibration results that compare the measured flow discharges with the pre and post-optimisation model results. This figure demonstrates that the pre and post-optimisation models both perform very well when compared to measurements at all cross-sections. The very good agreement between the measurements and the models can be linked to the intensive calibration of the pre-optimisation model (eddy viscosity, roughness maps, bathymetry, and tidal ocean boundary) and the conservation of these key hydrodynamic features in the computationally optimised model layout. For the purposes of the water quality modelling undertaken in this project, there are no appreciable differences in the hydrodynamic fluxes that are provided by either the original detailed model, or the computationally optimised model layout.

5.1.2 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. 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 the conversion of a hydrodynamic 2D-FLOW model into a 3D-FLOW model, 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 the Sydney Harbour Ecological Response Model (SHERM) project. Eight vertical layers have been used in both cases.

5.1.3 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 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 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 5.2 presents the horizontal layer configuration adopted for the Z-layer model. Note that the 8th layer is the surface layer.

Table 5-2 Z-Layer Model Vertical Grid Structure

Z-model		Depth Extent Levels		Maximum Thickness (m)
		Bot (m AHD)	Top (m AHD)	
Layer Number	8	+0.5	+5.0	4.5
	7	0.0	+0.5	0.5
	6	-0.5	0.0	0.5
	5	-1.0	-0.5	0.5
	4	-2.0	-1.0	1
	3	-4.0	-2.0	2
	2	-9.0	-4.0	5
	1	-45.0	-9.0	36

The top layers were chosen to be thinner at the top (down to 0.5m) 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.

Figure 5.3a is a map of the depth averaged horizontal velocity (from the Z-model) that covers the complete extent of the model; near the time of peak ebb flow, no catchment flows. It also displays the location of a selected cross-section (transect) in Iron Cove used in **Figure 5.3b** to show the velocity magnitude (colours) and direction (white vectors) – not necessarily in the plane of the transect. It also clearly describes the distribution of the horizontal layers in the Z-model.

Figures 5.2a and **5.2b** show that output discharges from the Z-layer model are very comparable to the depth-averaged measurements and the output from the 2D model.

The 3D Z-layer model setup may be the most appropriate to describe the 3D hydrodynamic features of Sydney Harbour to be used in the water quality model. However, it requires very demanding care to achieve a stable configuration and is also very computationally demanding.

5.1.4 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. However, this is not a common feature of the water column in Sydney Harbour, as demonstrated by the salinity data collected by SIMS for the CMA and presented in **Figure 5.4.** Analyses of measured salinity gradient data, defined by the variation between concurrent near-surface and near-bed salinity samples, collected at 26 sites between October and December 2012, indicate that for nearly 80% of site samples collected over that period, the observed salinity difference is 0.25 ppt or less. A total of 10% of observed samples exhibited a salinity difference of greater than 1 ppt. Based on the typically small salinity-induced vertical density gradients, which commonly only persist for short periods of time in the upper reaches of the estuary following rainfall events, a sigma-layer model was considered to be appropriate for the 3D hydrodynamic model discretization.

The topography of Sydney Harbour has a great range of water depths, but the bathymetric gradients are not particularly steep. Hence the sigma-layer model is suitable for modelling flow in Port Jackson and the Parramatta River for both the detailed WAQ and box-model water quality simulations.

Figures 5.2a and **5.2b** show that the 3D-sigma layer model performance is nearly identical to the depth averaged results for the post-optimization 2D model; due to the similar numerical calculation methods.

Figure 5.5a is a map of the depth averaged velocity from the sigma-model that covers the complete extent of the model. **Figure 5.5b** shows the vertical cross-section (transect) of the velocity with the sigma-model that can be compared with **Figure 5.3b** (Z-model). Velocity magnitudes and directions are very comparable, despite the important changes in the bathymetry. The sigma-model has the advantage of having a better representation of the flows near the seabed because the layer thickness adapts to bathymetric changes.

Importantly, the sigma-model is also much less computationally demanding than the Z-model and also more stable.

5.1.5 Salinity & Dispersion Calibration - FLOW

Cardno/Baird have undertaken a detailed calibration of the horizontal eddy diffusivity that greatly influences dispersion processes. Salinity gradient influences the current flows in horizontal and vertical directions and hence mixing processes. It is therefore important to use an appropriate horizontal dispersion coefficient for the model. Vertical dispersion is controlled by the layer definition and the k-ϵ turbulence model.

The spatial recovery of salinity gradients following a period of fresh water inflows provides an opportunity to calibrate the dispersion coefficient. **Figure 5.6** shows calibration time-series of salinity at various locations in Sydney Harbour comparing the depth averaged salinity of the model with the weekly measurements from SIMS from October 2012 to December 2012. The measured salinity data (top and bottom values) was averaged with an 80% weight applied to the upper reading, given that fresh water inflows would affect that area of the water column most.

The model performs well throughout this period in terms of salinity recovery (post inflow dry period) and also with large inflows of fresh water from the catchment model included, as prepared by CR (March 2014).

Eddy diffusivity has been adjusted to fit the dispersion characteristics and grid resolution of all hydrodynamic sub-domains. **Figure 5.7** describes the eddy diffusivity calibration result, with values ranging from 40 to 100m2/s.

5.2 Water Quality Model

The water quality model component of the SHERM is capable of modelling the water quality processes described in Section 2.3 in 2D or 3D, at high horizontal resolution or the 33-element box model of the Sydney Harbour. The Delft3D Water Quality suite utilizes the outputs from the calibrated hydrodynamic model described in **Section 5.1** to describe transport fluxes between grid cell or box elements, 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 in both a 3D box model application and subsequently a detailed model with similar grid resolution to the hydrodynamic model summarized in **Table 5-1**.

5.2.1 Salinity & Dispersion Calibration - WAQ

The water quality model has been 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 numerical scheme;
- Suitable model time step; and
- 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 schemes were 15 (2D) and 16 (for 3D only).

Table 5-3 summarizes the dispersion coefficients and time steps selected for the box and full scale water quality models based on the salinity and dispersion calibration. Due to the large volume of each cell, and mass fluxes between cells in the box model, the horizontal dispersion coefficient only needs to be a nominally small value.

Table 5-3 Water Quality Model Time Step and Dispersion Coefficient Details

Model Parameter	Box Model	Full Scale Model
Vertical Schematization	3D (sigma layers)	2D/3D (sigma layers)
Time Step (min)	10	2
Horizontal Dispersion Coefficient (m^2/s)	0.1	75
Vertical Dispersion Coefficient (m^2/s)	$1x10^{-7}$	$1x10^{-7}$

5.2.2 Nutrient Balance and Primary Production Model Calibration – April 2012 to June 2012 Period

The initial calibration period for the water quality model was for the April 2012 to June 2012 period, which had previously been modelled in a pilot study undertaken in 2013 (Baird, 2013). The results of the pilot study model, which was only developed for the Parramatta River upstream of the Cockatoo Island, were constrained by the accuracy of the catchment load model output that was available in 2013. In order to assess the improvement of the model with the latest catchment model outputs available for this study, the 3D box model configuration of the SHERM was used to simulate the period from April 2012 to June 2012 where weekly water quality data was available at eleven sites in the Parramatta River – see **Figure 5.8**.

The initial nutrient conditions for the April 2012 to June 2012 calibration period have been developed by computing depth-averaged and average values using data from up to 11 sites sampled over the whole sampling campaign analysed in the pilot study (Baird, 2013).

Figures **5.9** to **5.19** present time series of key water quality indicators from the 3D Box-model calibration simulation for these eleven data collection locations. The time-series have been presented as depth averaged data and model results.

The parameters presented in time series are:-

- Salinity (**Figure 5.xa**);
- Dissolved oxygen (**Figure 5.xa**);
- Chlorophyll-a (**Figure 5.xa**);
- Silica (**Figure 5.xa**);
- Total nitrogen and phosphorus (**Figure 5.xb**);
- Nitrate (NOx) and ammonium (NH_4) (**Figure 5.xb**); and
- Dissolved inorganic phosphorus (DIP) (**Figure 5.xb**).

Comparing the modelled results and depth-averaged measurements across the eleven-sites indicates that the SHERM is simulating the water quality processes in the Parramatta River sections of the model reasonably well, particularly with respect to salinity, dissolved oxygen, silica and total nitrogen and phosphorus. The model is also simulating the observed variations in the inorganic nitrogen fractions to a reasonable level of skill.

Compared to the 2013 pilot study, the model calibration has improved considerably and the modelled nutrient balance in the water column is in reasonable agreement with the measurements.

5.2.3 Model Validation – October 2012 to December 2012 Period

Following the initial calibration of the upper Parramatta River section of the model with the April 2012 to June 2012 data set, a second model calibration process was undertaken for the whole of Sydney Harbour model using a data set from October 2012 to December 2012 where weekly water quality data was available at twenty four sites throughout the whole of Port Jackson and the Parramatta River - see **Figure 5.20**.

The model calibration for this period was undertaken in two stages, the first adopted the DYNAMO based primary production model applied in the Parramatta River pilot model (Baird Australia, 2013). The second model validation was undertaken using the BLOOM primary production model and included three water column algae species and a fixed benthic algae species.

The initial nutrient conditions for the October 2012 to December 2012 validation period were developed by computing depth-averaged and average values using data from up to 26 sites sampled over the whole sampling campaign SIMS (2012). Boundary conditions at the entrance to Sydney Harbour were specified as a depth-averaged time-series of concentrations based on the measurements at the entrance to Sydney Harbour (Site PJ7, see **Figure 5.20**).

5.2.3.1.1 DYNAMO Primary Production Model

Figures 5.21 to **5.44** present time-series of key water quality indicators from the 3D Box-model validation simulation for the twenty-four data collection locations. The time-series have been presented as depth averaged data and model results. The parameters presented in time-series are:-

- Salinity (**Figure 5.xa**);
- Dissolved oxygen (**Figure 5.xa**);
- Chlorophyll-a (**Figure 5.xa**);
- Silica (**Figure 5.xa**);
- Total nitrogen and phosphorus (**Figure 5.xb**);
- Nitrate (NOx) and ammonium (NH_4) (**Figure 5.xb**); and
- Dissolved inorganic phosphorus (DIP) (**Figure 5.xb**).

Compared to the initial model calibration for the April to June 2012 in the Parramatta River, the model validation compared to the measurements is variable, and reduces with distance from the entrance to Sydney Harbour. During the model validation process, the growth and mortality coefficients for the green algae group were adjusted to reduce the phytoplankton biomass in the model.

Table 5-4 presents a summary of the key SHERM model calibration coefficients for the DYNAMO model option. Compared to the initial calibration for the upper Parramatta River using the April to June 2012 data set, the maximum primary production rate for the green algae species has been reduced to 1.35 (day^{-1}).

Table 5-4 Summary of SHERM Calibration Coefficients – Delft3D-Water Quality DYNAMO Model Option

Process (General Description)	Model Variable	Parameter Value	Unit
1st Order mineralisation rate – Organic Carbon	RcDetC	0.12	day^{-1}
Sedimentation velocity – Organic Carbon	VSedDetC	0.15	m/day
1st Order mineralisation rate – Organic Carbon in Sediment	RcDetCS1	0.1	day^{-1}
1st Order mineralisation rate – Organic nitrogen	RcDetN	0.12	day^{-1}
1st Order mineralisation rate - Organic nitrogen in Sediment	RcDetNS1	0.1	day^{-1}
1st Order mineralisation rate – Organic phosphorus	RcDetP	0.1	day^{-1}
1st Order mineralisation rate - Organic phosphorus in Sediment	RcDetPS1	0.1	day^{-1}
1st Order mineralisation rate – Organic silica	RcDetSi	0.075	day^{-1}
1st Order mineralisation rate – Organic silica in sediment	RcDetSiS1	0.04	day^{-1}
Max Primary Production - Diatoms	PPMaxDiat	1.5	day^{-1}
Maintenance Resp. - Diatoms	MRespDiat	0.075	day^{-1}
Growth Resp. - Diatoms	GRespDiat	0.15	day^{-1}
Mortality - Diatoms	Mort0Diat	0.6	day^{-1}
Sedimentation vel - Diatoms	VSedDiat	0.425	m/day
Max Primary Production - Greens	PPMaxGreen	1.35	day^{-1}
Maintenance Resp. - Greens	MRespGreen	0.045	day^{-1}
Mortality - Greens	Mort0Diat	0.7	day^{-1}
Sedimentation vel - Greens	VSedDiat	0.2	m/day
First order mortality – Enterococci and Coliforms	RcMrtTColi	0.8	day^{-1}

5.2.3.1.2 BLOOM Primary Production Model

Figures 5.45 to **5.68** present time-series of key water quality indicators from the 3D Box-model validation simulation for the twenty-four data collection locations. The time-series have been presented as depth averaged data and model results. The parameters presented in time-series are:-

- Salinity (**Figure 5.xa**);
- Dissolved oxygen (**Figure 5.xa**);
- Chlorophyll-a (**Figure 5.xa**);
- Silica (**Figure 5.xa**);
- Total nitrogen and phosphorus (**Figure 5.xb**);
- Nitrate (NOx) and ammonium (NH_4) (**Figure 5.xb**); and
- Dissolved inorganic phosphorus (DIP) (**Figure 5.xb**).

Overall, compared to the DYNAMO primary production model results presented in **Section 5.2.3.1.1**, the BLOOM primary production model presents a generally better trend to the measurements, including for chlorophyll-a and dissolved oxygen. However, model performance is again related to the relative distance from the ocean boundary conditions, which indicates that the sediment and/or catchment load dynamics in the upper sections of the Sydney Harbour are not well described in the model.

Table 5-5 presents a summary of the key SHERM model calibration coefficients for the BLOOM model option.

Table 5-5 Summary of SHERM Calibration Coefficients – Delft3D-Water Quality BLOOM Model Option

Process (General Description)	Model Variable	Parameter Value	Unit
1st Order mineralisation rate – Organic Carbon @ 20ºC	POC1	0.08 – 0.12	day^{-1}
1st Order mineralisation rate – Slow Organic Carbon @ 20ºC	POC3	0.005 – 0.01	day^{-1}
Sedimentation velocity – Organic Carbon	VSedPOC1	0.1	$m\ day^{-1}$
1st Order mineralisation rate – Organic Carbon in Sediment	RcDetC	0.03	day^{-1}
1st Order mineralisation rate – Organic nitrogen @ 20ºC	PON1	0.08 – 0.12	day^{-1}
1st Order mineralisation rate – Slow Organic Nitrogen @ 20ºC	PON3	0.005 – 0.01	day^{-1}
1st Order mineralisation rate - Organic nitrogen in Sediment	RcDetN	0.03	day^{-1}
1st Order mineralisation rate – Organic phosphorus @ 20ºC	POP1	0.08 – 0.12	day^{-1}
1st Order mineralisation rate – Slow Organic phosphorus @ 20ºC	POP3	0.01 – 0.005	day^{-1}
1st Order mineralisation rate - Organic phosphorus in Sediment	RcDetP	0.03	day^{-1}
1st Order mineralisation rate – Organic silica@ 20ºC	POS1	0.08 – 0.12	day^{-1}
1st Order mineralisation rate – Slow Organic silica@ 20ºC	POS3	0.01 – 0.005	day^{-1}
1st Order mineralisation rate – Organic silica in sediment	RcDetSi	0.015	day^{-1}
Algae Species	-	Freshwater diatoms, marine diatoms, marine green and Ulva rooted to seabed	-
Algae – fraction autolysis		0.35	day^{-1}
Algae – fraction detritus		0.55	day^{-1}
Zero order sediment oxygen demand	fSOD	0.5	$g\ O^2\ m^{-2}\ day^{-1}$
First order mortality – Enterococci and Coliforms		0.8	day^{-1}

5.2.3.1.3 Bacterial Pollutants Model

The SHERM includes bacterial pollutants represented by e-coli, enterococci and faecal coliforms. For the validation of the bacterial component of the SHERM, measured enterococci were available for surface and bottom samples at up to twenty-four sites for the October to December 2012 period. The bacterial water quality process was integrated into the BLOOM primary production process description to provide the most realistic vertical light profile which can affect the bacterial mortality.

Figures 5.69 to **5.92** present time-series of modelled and measured enterococci concentrations from the surface and bottom locations in the water column. The performance of the model is variable, although there is typically a model response following a catchment inflow period. At some locations the magnitude of the modelled and measured enterococci agree well, whilst at other locations the measured enterococci concentrations are up to several orders of magnitude larger. This result indicates that the catchment inflows may not be representing all major sources of bacterial pollutants into the harbour.

5.2.4 Sensitivity Simulations

Sensitivity simulations are being completed and will be reported in the final report. Sensitivity simulations covering a 1-year period have been undertaken on nutrient and primary production process coefficients and also boundary condition specifications.

6 E-Folding Time Investigations

Section 2.7 describes the background to this investigation. In order to assess the 'tidal' flushing performance of the nominated estuarine reaches, hydrodynamic simulations over periods of spring and neap tides were undertaken using the calibrated model in 2D mode. This analysis was undertaken using an inert tracer having no density – simulating a dissolved contaminant. Initially each entire, selected reach was filled with this conservative tracer at a concentration of 100.

Conservative tracer testing provides a measure of the flushing rate of a particular reach of an estuary. A useful measure for quantification of the flushing time is to determine the e-folding time, which is the time taken for the tracer to reduce from the initial concentration to Co/e ≈ 0.37 x Co; in this case reduction from 100 to 37.

Flushing times depend on the shape of the test area and its connectivity to uncontaminated water, tidal range and whether or not the area is affected by diurnal or semi-diurnal tides. Catchment runoff is also important. Preliminary analyses showed that all of the nominated areas flushed relatively quickly and so each simulation can be described as spring or neap flushing in dry or wet conditions. Each simulation was undertaken using 48 hours of hydrodynamic 'warm-up' after which the actual "flushing" simulation began. The wet and dry years were April 2011 to April 2012 and April 2002 to April 2003, respectively. **Figure 6.1a** describes the full wet year tides and total catchment flows. **Figures 6.1b** and **6.1c** present the e-folding simulation period for the selected wet-neap and wet-spring cases. The warm-up and start times for each simulation are shown. **Figures 6.2** describe similar time-series for the dry year.

Figures 6.3 provide modelled tracer time-series with jointly occurring water level and total catchment inflow for the dry and wet periods (neap and spring). A typical point within each of the six nominated estuarine reaches was selected. Each area has a different flushing capability, Hen and Chicken Bay generally flushing more quickly than other areas and the Parramatta River and Lane Cove River most slowly. This outcome arises mainly from the different flow connectivity for each part of the estuary. The difference between neap and spring tide cases does not appear to be significant.

Figures 6.4 provide plan views of e-folding times as spatial maps. As expected, upstream reaches flush more slowly than those connected to the Parramatta River downstream of the weirs. For example, upstream reaches of the Duck River near Parramatta Road have e-folding times of about 30 days, whereas at the junction with the Parramatta River times are near zero – as expected. On the other hand, flushing times for Rozelle Bay are uniformly less than 6 days.

7 Conservative Tracer Assessment for DSS Model Input

The 3D box model version of the SHERM has been applied to undertake a conservative tracer assessment of the contribution of the discharges within each of the 33 cells in the 3D box model to the overall catchment nutrient load into the harbour. The box model layout is shown in Figure 2.3.

isNRM Pty Ltd are developing a Decision Support System (DSS) model in conjunction with the development of the SHERM and the DSS requires tracer simulations to define the contribution of each catchment zone in the harbour, to the total harbour wide load. To ensure consistency between the SHERM and the DSS, the catchment inflows into the harbour have been characterised by the cell of the box model they discharge into.

Conservative tracer simulations were undertaken for the three different simulation periods to represent a range of catchment inflow scenarios, these were:

- Average Year: April 2012 - March 2013;
- Dry Year: April 2002 – March 2003;
- Wet Year: April 2011 – March 2012.

For each simulation period a range of cases were modelled. **Table 7-1**Table 7-1 summarises these cases.

Table 7-1: Summary of Conservative Tracer Box Model Simulations

Case Description	Discharge Concentration (g/m³)	Initial / Ocean Boundary Conc. (g/m³)	Number of Tracer Maps
Discharge from all 33 boxes	100	18	1
Discharge from all 33 boxes with tracer concentration reduced by 20%	80	18	1
Discharge from all 33 boxes with tracer concentration increased by 20%	120	18	1
Individual tracer for each of the 33 boxes	100	18	33
		Total	36

Initial tracer and boundary concentrations for the simulations were specified following analysis of the TN and TP data sampled at the entrance to the Harbour between October 2012 and December 2012 (SIMS 2012), and comparing those concentrations with the annual whole of catchment TN and TP from the catchment model for the year rainfall scenario. Based on that analysis, the ratio of boundary to catchment TN and TP concentrations were both consistent, and indicated that the TN and TP concentrations at the entrance to the harbour were on average 18% of the average catchment inflow concentration. A ratio of 18% against existing catchment conditions was specified for the initial condition and harbour boundary concentrations on all simulations.

Outputs from the conservative tracer simulations were provided to isNRM as a map of the mean tracer concentration in each of the model boxes; calculated from the yearlong time-series output. Presenting the mean value, rather than the median value, ensured that a realistic tracer concentration response was observed above the background concentration, even for boxes with relatively small catchment inflow volumes.

8 Current Vectors

A set of typical spring peak flood and ebb depth averaged current vector maps was prepared for key modelled areas such as:-

- Harbour Entrance – **Figures 8.1a** and **8.1b**
- Port Jackson – **Figures 8.2a** and **8.2b**
- Middle Harbour – **Figures 8.3a** and **8.3b**
- Parramatta River – **Figures 8.4a** and **8.4b**

The colour scheme enables the reader to develop an overview-estimate of the depth averaged velocity magnitude and directly identify the areas prone to stronger currents. Stronger currents are to be found at steep bathymetric changes such as those in Middle Harbour, but most often in abruptly narrowed sections of the estuary.

No catchment loads have been included in these results.

9 Annual Water Quality Model Simulations

9.1 Box Model

The following sections present the summary statistics for four key water quality indicators based on 1-year simulations of the SHERM model with the BLOOM primary production option. The four key indicators presented are:-

- Chlorophyll-a concentrations – Surface Layer;
- Total nitrogen and phosphorus concentrations – Surface Layer; and
- Enterococci – Surface Layer.

All simulations adopted the following boundary conditions:-

- Water temperature based on a combined 1-year of measurements from the Parramatta River and Sydney Harbour (April 2012 to March 2013).
- Daily solar radiation from the BoM global solar exposure data set.
- Daily daylight hours from Geoscience Australia's day length data set.
- Time-series of physical and nutrient concentrations at the entrance to Sydney Harbour compiled from the Sydney Harbour water quality data collection program (April 2012 to June 2013).
- Time-series of measured wind speed from Fort Denison.
- Time-series of catchment flows and loads for each simulation period as discussed in **Section 4.4**.
- Fluxes from the 3D hydrodynamic model as presented in **Section 5.1**.

9.1.1 Average Year (2012-2013)

Spatial statistics are presented for the following water quality indicators for the April 2012 to March 2013 simulation period:-

- **Figure 9.1a to Figure 9.1c**: 50, 90 and 99th percentile chlorophyll-a
- **Figure 9.2a** to **Figure 9.2c**: 50, 90 and 99th percentile TN
- **Figure 9.3a** to **Figure 9.3c**: 50, 90 and 99th percentile TP
- **Figure 9.4a** to **Figure 9.4c**: 50, 90 and 99th percentile Enterococci

For all parameters, the upper distribution 90th and 99th percentile concentrations are largest in the upper reaches of the model, for example the upper Parramatta River and upstream of the weir on Lane Cove River.

9.1.2 Wet Year (2011-2012)

Spatial statistics are presented for the following water quality indicators for the April 2011 to March 2012 simulation period:-

- **Figure 9.5a** to **Figure 9.5c**: 50, 90 and 99th percentile chlorophyll-a
- **Figure 9.6a** to **Figure 9.6c**: 50, 90 and 99th percentile TN
- **Figure 9.7a** to **Figure 9.7c**: 50, 90 and 99th percentile TP
- **Figure 9.8a to Figure 9.8c**: 50, 90 and 99th percentile Enterococci

Compared to the average rainfall scenario results that are presented in equivalent concentration scales in **Figures 9.1** to **9.4**, the concentrations of all four water quality indicators are significantly higher for the average year condition. The catchment effects propagate further downstream in the Parramatta and Lane Cove Rivers.

9.1.3 Dry Year (2002-2003)

Spatial statistics are presented for the following water quality indicators for the April 2002 to March 2003 simulation period:-

- **Figure 9.9a to Figure 9.9c**: 50, 90 and 99th percentile chlorophyll-a
- **Figure 9.10a** to **Figure 9.10c**: 50, 90 and 99th percentile TN
- **Figure 9.11a** to **Figure 9.11c**: 50, 90 and 99th percentile TP
- **Figure 9.12a** to **Figure 9.12c**: 50, 90 and 99th percentile Enterococci

Compared to the average and wet annual rainfall scenario results presented in **Figures 9.1** to **9.8**, the 90th and 99th percentile concentrations of the selected water quality indicators are still highest in the catchment dominated segments of the model. However, the peak concentrations are reduced, and the downstream influences of the catchment loads from the upper Parramatta River and Lane Cover River are reduced

9.2 Detailed Model

The study team worked on the development of a detailed water quality model with a computational mesh similar to the hydrodynamic model. The detailed model was extremely computationally intensive, and had significantly reduced stability compared to the Box Model for the detailed water quality processes description presented in **Section 2.3**. The detailed model can be potentially be applied in three applications in future studies. They are:-

- Short duration simulations (≈ 1 month) using initial concentration conditions from the Box Model results run over the equivalent period.
- Modelling a section of the Sydney Harbour domain (i.e. one of the model sub-domains) with initial conditions and boundary conditions derived from the Box Model.
- Modelling only the biological contaminant processes (i.e. Enterococci) for medium duration simulations.

The Box Model is a more practical tool that does not significantly compromise the outcomes of investigations. It could be refined further for specific investigations.

9.3 Sensitivity Simulations

The SHERM water quality model has been applied to a series of sensitivity simulations, including:-

- Catchment load simulations with a 20% reduction in catchment nitrogen and phosphorus loads for the wet year simulation period – **Sections 9.3.1**.
- Wet year simulation with a 0.9 m sea level rise (SLR) boundary condition – **Section 9.3.2**;

9.3.1 Wet Year (2011-2012) with 20% Reduction in Catchment TN/TP Loads

Spatial statistics are presented for the following water quality indicators for the April 2011 to March 2012 simulation period with 20% reduced TN/TP loads from catchment sources:-

- **Figure 9.13a** to **Figure 9.13c**: 50, 90 and 99th percentile chlorophyll-a
- **Figure 9.14a** to **Figure 9.14c**: 50, 90 and 99th percentile TN
- **Figure 9.15a** to **Figure 9.15c**: 50, 90 and 99th percentile TP
- **Figure 9.16a to Figure 9.16c**: 50, 90 and 99th percentile Enterococci

Compared to the wet year rainfall scenario results with the modelled catchment TN/TP loads that are presented in equivalent concentration scales in **Figures 9.5** to **9.8**, a noticeable reduction in the concentrations of chlorophyll-a, TN and TP are observed upstream of the Sydney Harbour bridge in the main branches and embayment's of the Parramatta and Lane Cove Rivers for the 90th and 99th percentile concentrations. The variations in median (50% percentile) concentrations are smaller as this range is dominated by drier periods in the simulation when catchment loads have a smaller effect on primary production and nutrient concentrations compared to the ocean boundary and the sediment/water column nutrient exchange.

Figure 9.17 presents the relative change in 90th percentile chlorophyll-a concentration compared to the base wet year case. The results indicate that the reduction in chlorophyll-a concentration due to reduced catchment nutrient loads gradually increases upstream from the entrance and is up to 15% compared to the base case in the upper reaches.

There is no variation in Enterococci concentration compared to the results in **Figures 9.8** because the catchment loads in the model were unchanged between the two wet year scenarios.

9.3.2 Wet Year – 0.9m SLR

Spatial statistics are presented for the following water quality indicators for the April 2011 to March 2012 simulation period with a 0.9m Sea Level Rise (SLR) that is reflective of a 2100 scenario based on current guidelines. The results are presented in the following set of figures:-

- **Figure 9.18a** to **Figure 9.18c**: 50, 90 and 99th percentile chlorophyll-a
- **Figure 9.19a** to **Figure 9.19c**: 50, 90 and 99th percentile TN
- **Figure 9.20a** to **Figure 9.20c**: 50, 90 and 99th percentile TP
- **Figure 9.21a to Figure 9.21c**: 50, 90 and 99th percentile Enterococci

Compared to the wet year rainfall scenario results with the modelled catchment TN/TP loads that are presented in equivalent concentration scales in **Figures 9.5** to **9.8**, only small reductions in nutrient and chlorophyll-a concentrations are observed in the upper reaches of the model. Although the volume of water within the harbour is increased, the overall tidal prism is similar for both wet year scenarios and the reduction in nutrient and chlorophyll-a concentrations is smaller.

The modelled Enterococci concentrations presented in **Figures 9.21** indicate a noticeable reduction compared to the wet year scenario modelled at the present sea level (**Figures 9.8**). The model adopts a zero concentration condition for Enterococci from the open ocean boundary and with the sea level rise, the unchanged catchment loads are being diluted in a larger receiving water volume. **Figure 9.22** presents the relative change in 90th percentile Enterococci concentration compared to the base case. The results indicate the reduction in drains and creeks that feed into the Parramatta River from the south.

9.4 Spatial Variation in Algal Concentrations

Figures 9.23 to **9.26** describe the breakdown in algal species modelled and the spatial variation over the period of 2011. Four locations between Parramatta and Sydney Heads are presented. Three water column species (freshwater diatoms, green algae and marine diatoms), as well as Ulva representing benthic macro-algae are included in the model. In the Upper Parramatta River (Box 19), diatom species are generally dominant with chlorophyll-a spikes highly correlated to rainfall events. In the shallower Hen and Chicken Bay (Box 30), dominant species following catchment inflows vary between the green and diatom species. During the summer period the benthic algae (Ulva) is the dominant algae species in terms of biomass per area.

Downstream towards the lower Parramatta River in the deeper main channel, and then the near the entrance to the Harbour, green algae species dominate, with some periods of elevated marine diatoms. The significant spatial and temporal variation reflects the variation in nutrient load conditions from the upper sections to the entrance, and also the variation in light climate between shallow embayment's where benthic algae dominates during the summer months, and the deeper main channel sections where insufficient light reaches the seabed to sustain benthic algae.

9.5 Comparison between the Detailed and Box Models

The detailed water quality model, which has 4,600 horizontal grid cells, has been compared to the 33 horizontal grid cell Box Model for modelled bacterial contamination of Sydney Harbour. **Figures 9.27 and 9.28** present comparisons of surface layer Enterococci for a significant wet weather event in July 2011. For the upper Parramatta River, Lane Cove River, Middle Harbour and the major bays along the Parramatta River, the agreement between the detailed and Box Models is generally quite good. However, between Ryde Bridge and downstream to the Sydney Harbour bridge the agreement is not as good because of increased dispersion downstream of about Ryde Bridge. The Box Model has higher Enterococci concentrations in this region, which indicates that for this section of the harbour the Box Model has an inherent numerical dispersion as a result of the large computational cells increasing the net transport of catchment sourced contaminants through the middle section of the model. **Figures 9.29** to **9.32** present time-series comparisons of Enterococci at four locations between Parramatta and Sydney Heads. Agreement at the Upper Parramatta River sites, and near the entrance is good, whilst the Box Model Enterococci concentrations near Cockatoo Island are significantly higher than the detailed model. In this section of the harbour, the Box Model is conservative through the middle sections of the harbour in – terms of the net transport of catchment sourced contaminants.

9.6 Discussion of Water Quality Model Application

The SHERM water quality model has been developed to a stage that can be used to assess the relative strengths and limitations of the model in its present form. Firstly, the coarse scale 3D Box Model has proven to be a useful tool for assessing water quality processes on a harbour wide scale in an extremely computationally efficient manner. The Box Model allows users to examine the outcomes of changes to loads and boundary conditions, or water quality processes in a short time frame with a relatively minor reduction in the spatial characterisation of the model outputs compared to the detailed model.

The performance of the water quality model appears to be highest in two general regions of the harbour. The boundary conditions applied at the entrance to Sydney Harbour appear to be representative of the tidal inflows. This influence is demonstrated in the model validation by the relatively good model validation for sites closest to the ocean entrance, where water quality is dominated by coastal waters that flow into the harbour. Similarly, the catchment inflows to the SHERM model provided by the modelling presented in Catchment Research Pty Ltd (2014) appear to provide spatially and temporally realistic descriptions of catchment inflows into the estuary. The SHERM model demonstrates a strong water quality response in the upper reaches of the model due to catchment loads.

Bacterial contamination, represented by Enterococci is dominated by modelled sewer overflow loads that are provided as inputs into the model in conjunction with catchment inflows. Compared to available data sets, the modelled Enterococci concentrations appear to respond to loads in a reasonable manner. However, the spatial variation in modelled Enterococci, or specific event peak Enterococci concentrations, do not consistently agree with the measured Enterococci concentrations. This may suggest that there are bacterial contamination sources in the harbour that are not represented in the model, but which can be the dominant load source for particular locations in the estuary.

At present, the SHERM is limited in its description of sediment related processes in the harbour that can influence water quality, including dissolved oxygen concentrations and available nutrients. No specific data on spatial variation in organic sediment characteristics was available for the development of the SHERM and this could be an area of future model development.

Currently the SHERM water quality model is most useful for examining the relative water quality trends on a harbour wide scale from changes to rainfall, catchment loads and/or sea level rise. Due to the complexity of the complete water quality process description and the large size of the overall model system, the detailed water quality model at the same horizontal and vertical scale as the hydrodynamic model has only limited application in a manner described in **Section 9.2**.

10 References

ARQ (2006): Australian Runoff Quality: A guide to Water Sensitive Urban Design. Engineers Australia, National Committee for Water Engineering.

Baird Australia (2013): Pilot Ecological Response Model for the Parramatta River Estuary. Report No.: 12087.101.R1.Rev1 prepared for Hawkesbury-Nepean catchment management Authority.

Catchment Research Pty Ltd (2014): Development of the Sydney Harbour Catchment Model. Report Prepared for Hawkesbury-Nepean Catchment Management Authority.

DECCW & ABER (2009): Environmental Trust, Research Project RD2006/0010, Final Report.

Deltares, 2011. Delft3D-WAQ User Manual, 4.03 ed. 14509.

Delft Hydraulics (1985). A mathematical model to compute phytoplankton blooms. WL | Delft Hydraulics, Delft, The Netherlands, 2 ed. (F.J. Los). pp 102, 117.

Developing Ecological Function Indicators for Riverine Estuaries (DEFIRE).

Lawson and Treloar (1992): Port Jackson Hydraulic Data Collection, March 1992. Report 1405 prepared for Sydney Water.

Mancini, J. L., 1978. "Numerical estimates of coliform mortality rates under various conditions." Journal Water Pollution Control Federation -: 2477–2484. 364, 365

SIMS (2012): Water Quality Sampling of Parramatta River – Methods & Sampling Protocol. Data collected by the Sydney Institute of Marine Science for the Hawkesbury Nepean Catchment Management Authority.

Sydney Harbour Ecological Response Model

APPENDIX A

OUTLINE OF CAPER DSS (isIRM)

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Shaping the Future

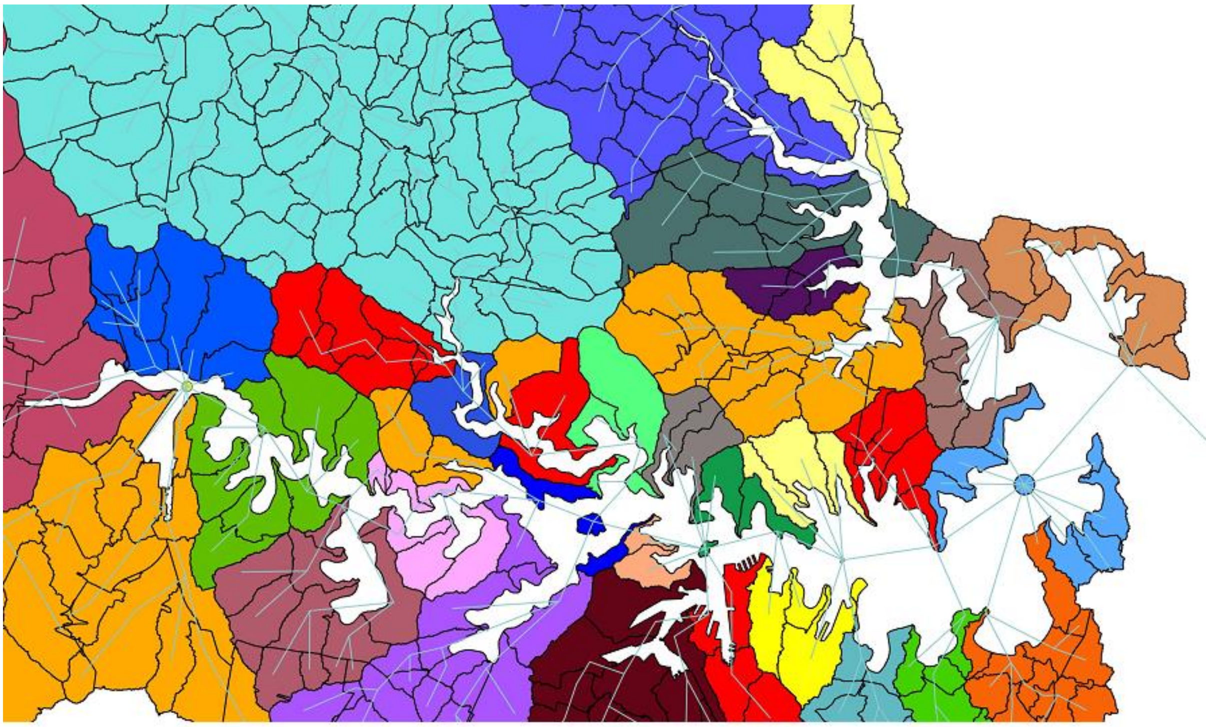
RWQM FOR THE SYDNEY HARBOUR CAPER DSS

INTRODUCTION

In order to implement the CAPER DSS for Sydney Harbour, a metamodel of the RWQM needs to be developed. This metamodel is a substantial simplification of the original model but aims to capture sufficient detail to produce useful outputs for estimating the impacts of management actions. This document describes runs required from the RWQM to set up and test the metamodel as well as the basic metamodelling approach to using these runs in the DSS.

INPUTS

One of the simplifications necessary to create a metamodel of the detailed RWQM for the DSS is to have a small number of input locations across which inputs are assumed to occur. A map of these input locations is shown below. Input locations have been named using a simple numbering system (zones 1-34). The estuary numbers for the zones linking to the Source Catchments boundaries is given in the EstuaryZone column in the RWQMInputZones shapefile.



Estuary input zones for runs of the RWM for producing the Sydney Harbour CAPER DSS

MODEL RUNS

Two sets of runs are required: a set of 'tracer' runs, where inputs are 'switched off' for all but a single input zone including the ocean (if relevant); and a set of scenario runs to test the accuracy and estimate the errors in the final metamodel where inputs come from all zones and the ocean. In all 38 runs of the RWQM are requested.

Tracer runs	Scenario runs
Tracer 1 – zone 1 inputs ‘on’ Tracer 2 – zone 2 inputs ‘on’ Tracer 3 – zone 3 inputs ‘on’ Tracer 4 – zone 4 inputs ‘on’ Tracer 5 – zone 5 inputs ‘on’ Tracer 6 – zone 6 inputs ‘on’ Tracer 7 – zone 7 inputs ‘on’ Tracer 8 – zone 8 inputs ‘on’ Tracer 9 – zone 9 inputs ‘on’ Tracer 10 – zone 10 inputs ‘on’ … All input zones to Tracer 34 – zone 34 inputs ‘on’ Tracer ocean – ocean inputs only ‘on’	Base case Scenario 1. 50% increase in pollutant loads from all zones Scenario 2. 20% Decrease in pollutant loads from all zones

Outputs

RWQM outputs will be reported in the DSS using simple percentiles of TN, TP, TSS and ChlA. Outputs requested from the model for all runs outlined above are:

- Median, 75th and 90th percentile TN – grid based across estuary for the simulation period.
- Median, 75th and 90th percentile TP – grid based across estuary for the simulation period.
- Median, 75th and 90th percentile TSS – grid based across estuary for time the simulation period.

It is requested that the full simulated output from all runs is also stored in case it needs to be further interrogated in developing the DSS.

Empirical relationships will be developed between TSS, TN, TP and ChlA and light attenuation. These will be applied to the relevant RWQM metamodel outputs inside the DSS.

Using the model runs in the DSS

Information from each of the ‘tracer’ runs will be used in a ‘weighted average’ model within the DSS to estimate the effects of changes in pollutant loads. The error induced using this approach will be estimated using outputs from the base case and three additional scenario runs which have been requested above.

Let $T_{n,j}$ be the tracer map defined as the output from the tracer model run for input *j* and pollutant *n*. If $k_{n,j}$ is the average concentration of pollutant *n* for input zone *j* for the base case run, that is,

$$k_{n,j} = \frac{L_{n,j}}{F_j}$$

where $L_{n,j}$ is the annual load of pollutant *n* from input zone *j* for the base case run and F_j is the annual flow from input zone *j*. P_n, the grid based map of pollutant *n* is then given by

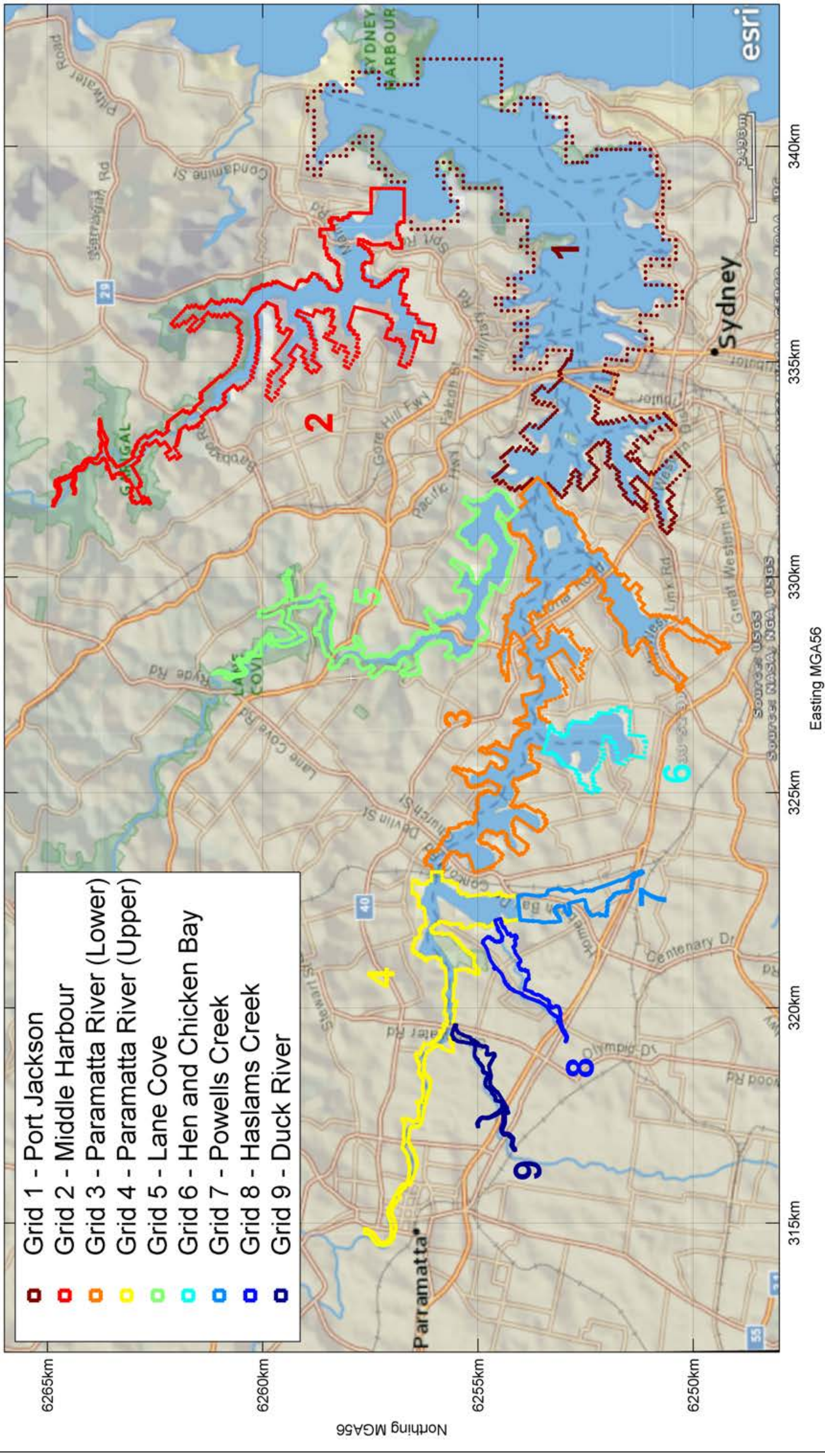
$$P_n = \sum_j \frac{c_{n,j}}{k_{n,j}} \times T_{n,j}$$

Where $c_{n,j}$ is the average concentration for the scenario run, calculated in the same manner as $k_{n,j}$.

Empirical relations for ChlA and light penetration are then applied to this map based output.

Sydney Harbour Ecological Response Model

FIGURES



Sydney Harbour Ecological Response Model

Model Extent and Domain Decomposition Definition

Figure 2.1

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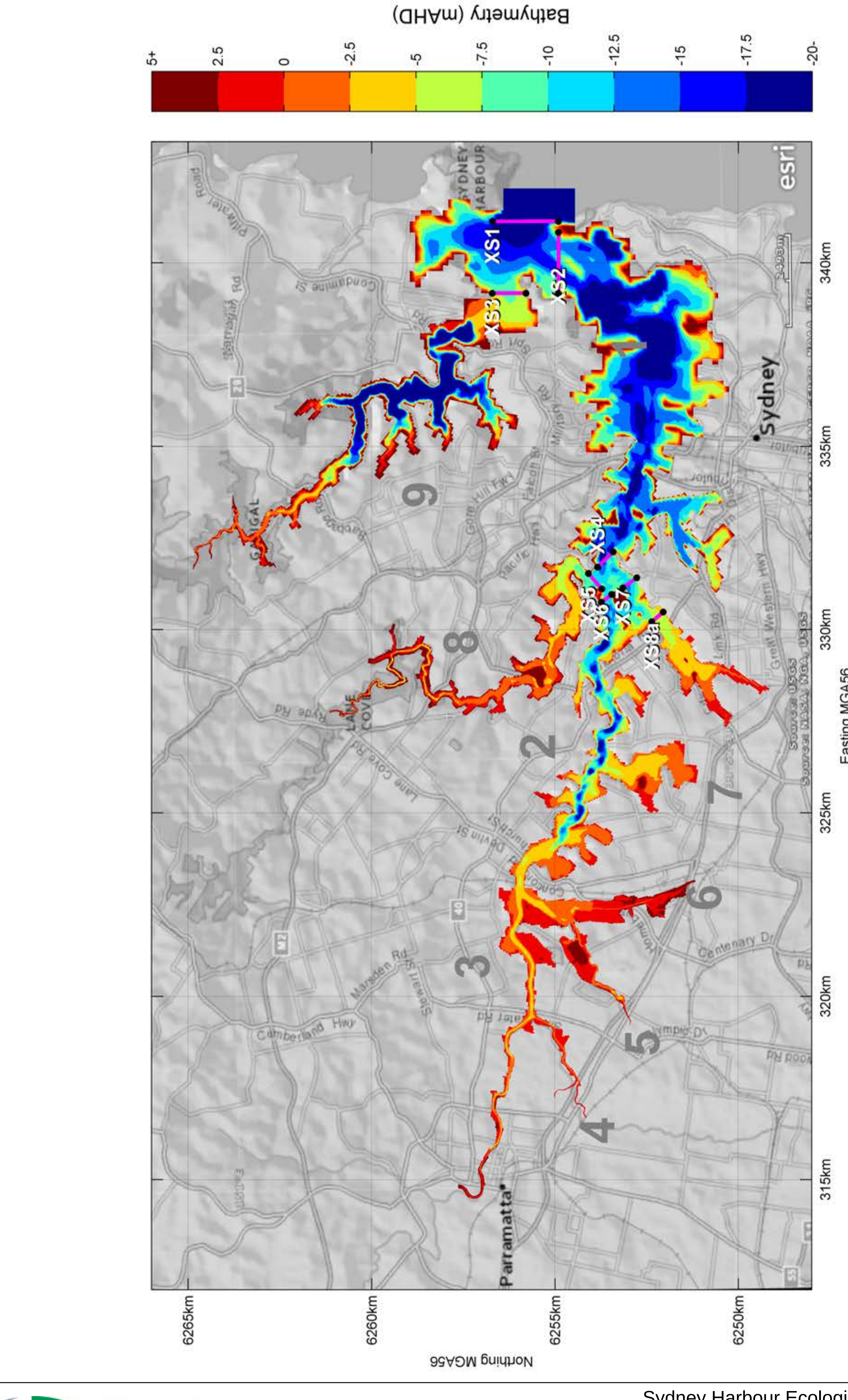


Sydney Harbour Ecological Response Model

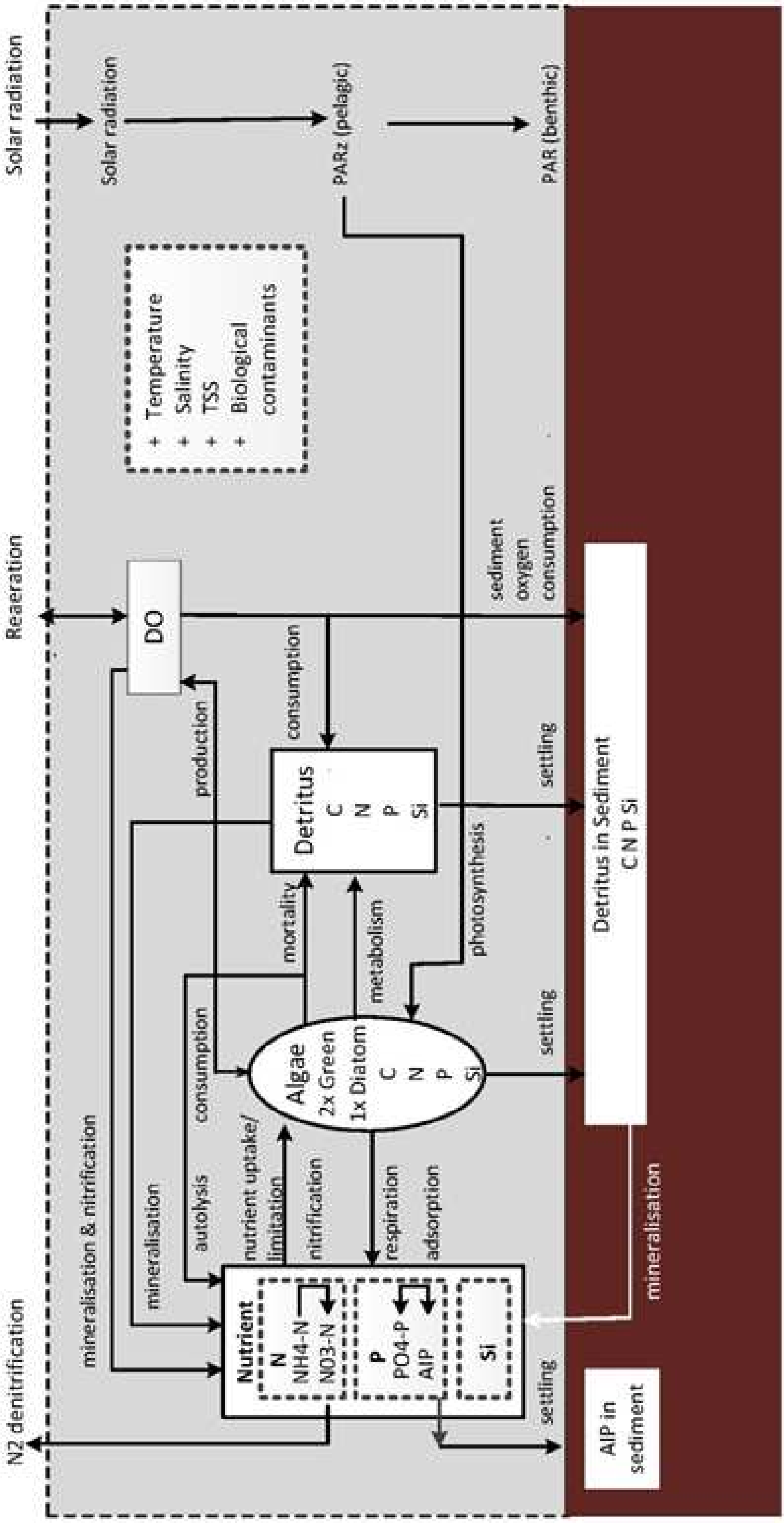
Model Bathymetry and
Discharge Calibration Cross−Section Locations

Figure 2.2

Sydney Harbour Ecological Response Model

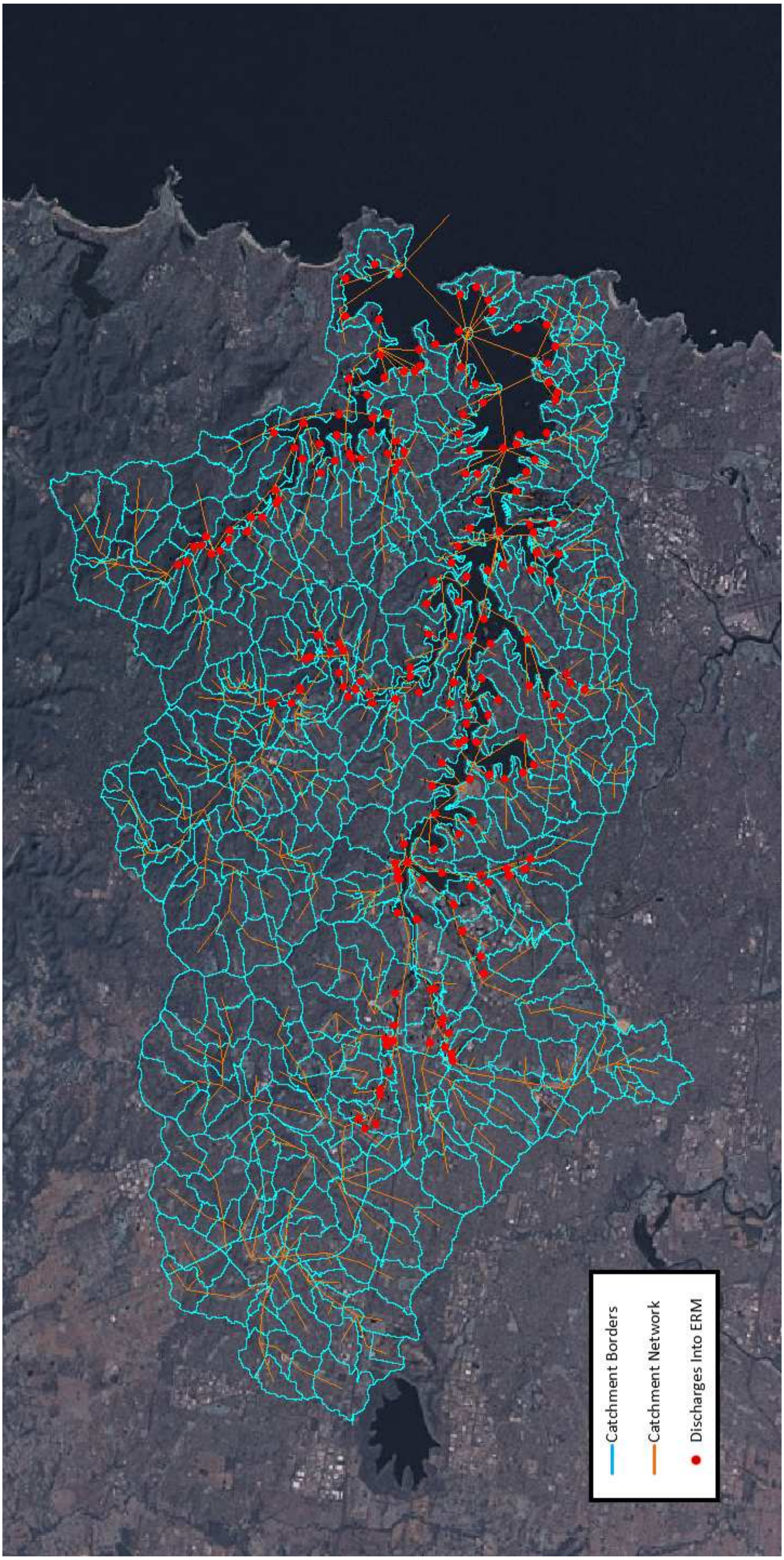
Map of WAQ−BOX Grid Setup
33 Boxes

Figure 2.3



Water Quality Processes Included
WAQ Module of SHERM

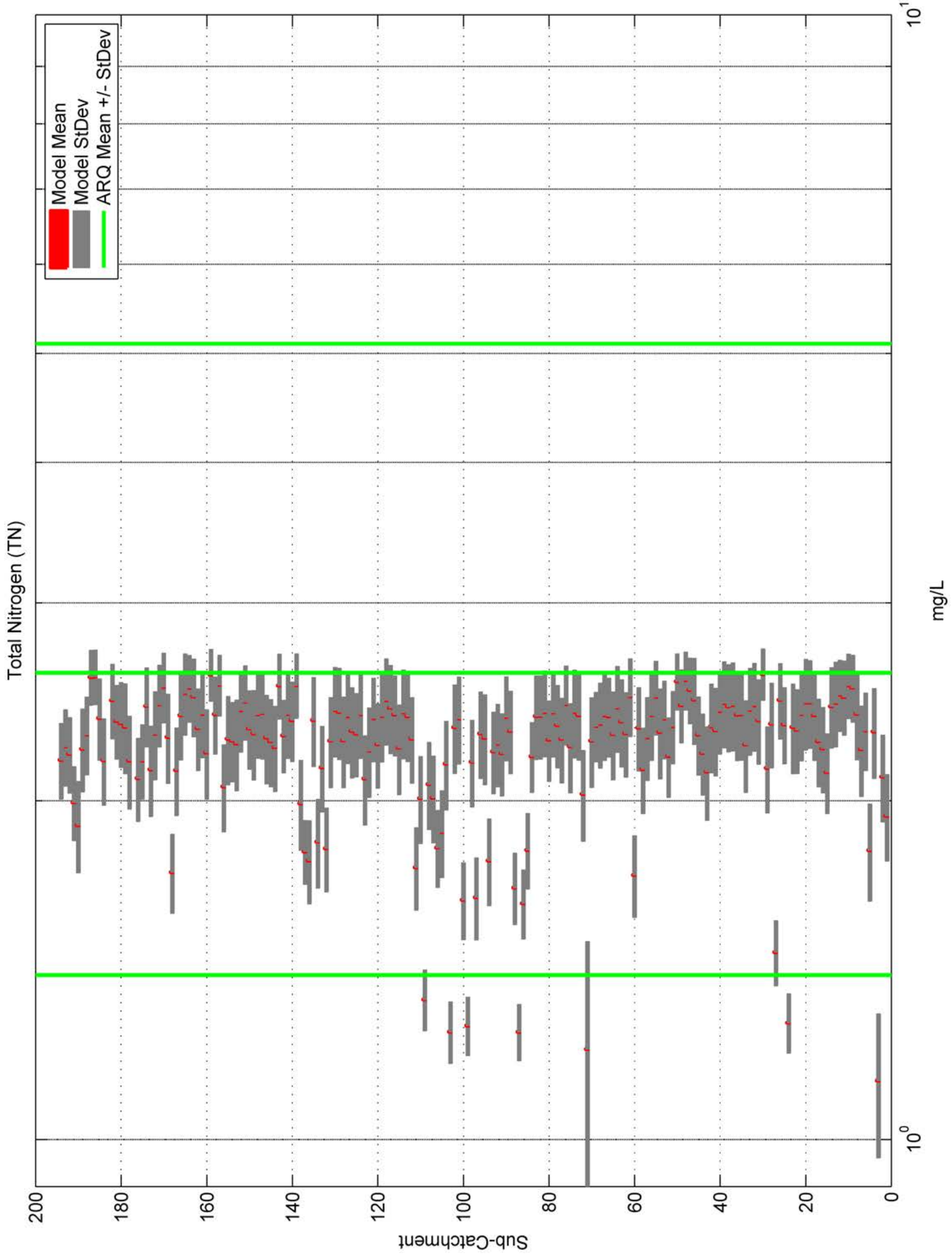
Figure 2.4

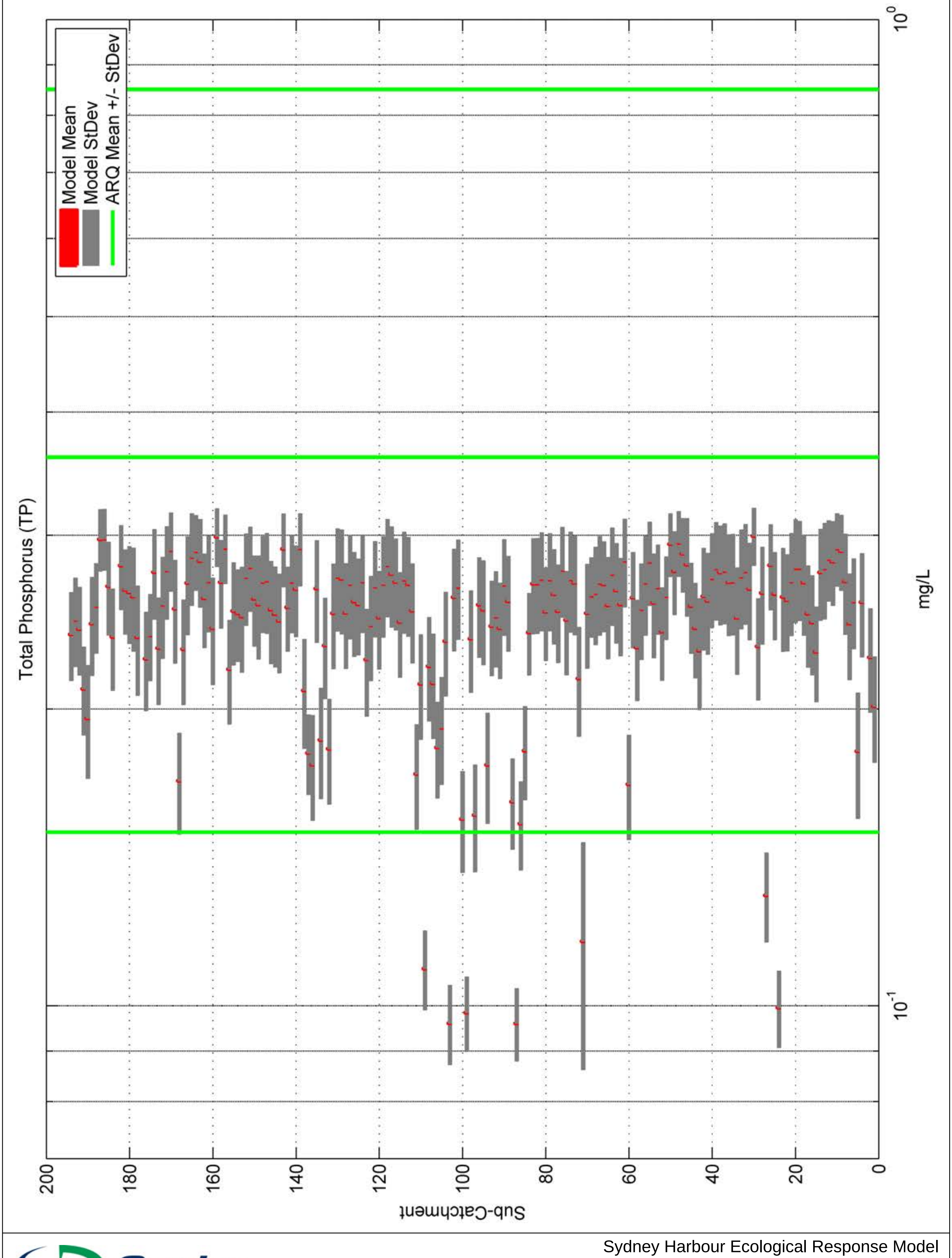


Sydney Harbour Ecological Response Model

Map of Catchment Model and Inflows Discharged into ERM
195 Sub−Catchments

Figure 4.1

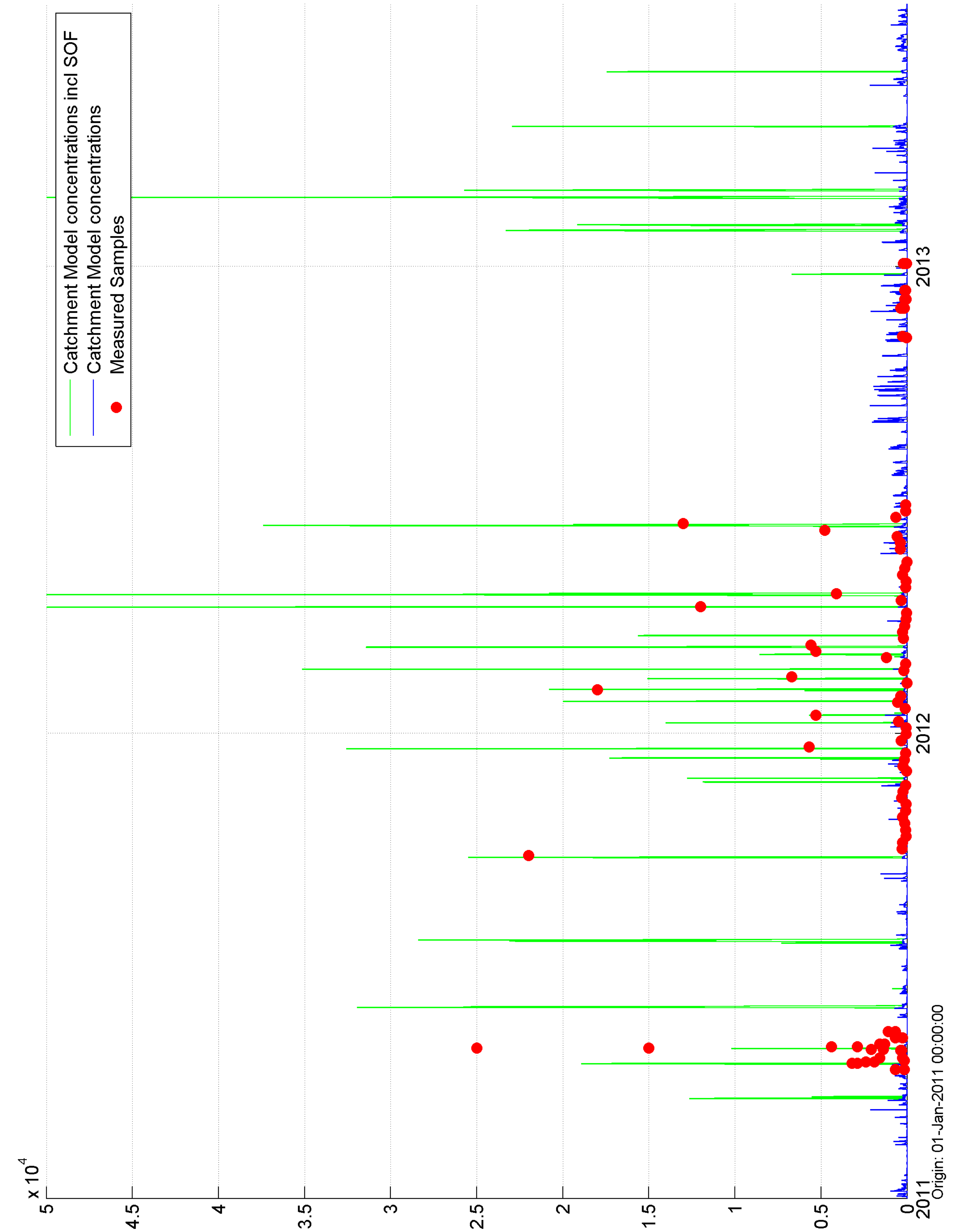

Total Nitrogen (TN)
Model Mean
Model StDev
ARQ Mean +/- StDev
mg/L
10^0
10^1
Sub-Catchment
200
180
160
140
120
100
80
60
40
20
0



Sydney Harbour Ecological Response Model

Comparison of Catchment Inflows with ARQ Guidelines
195 Sub−Catchments − Total Phosphorus

Figure 4.3



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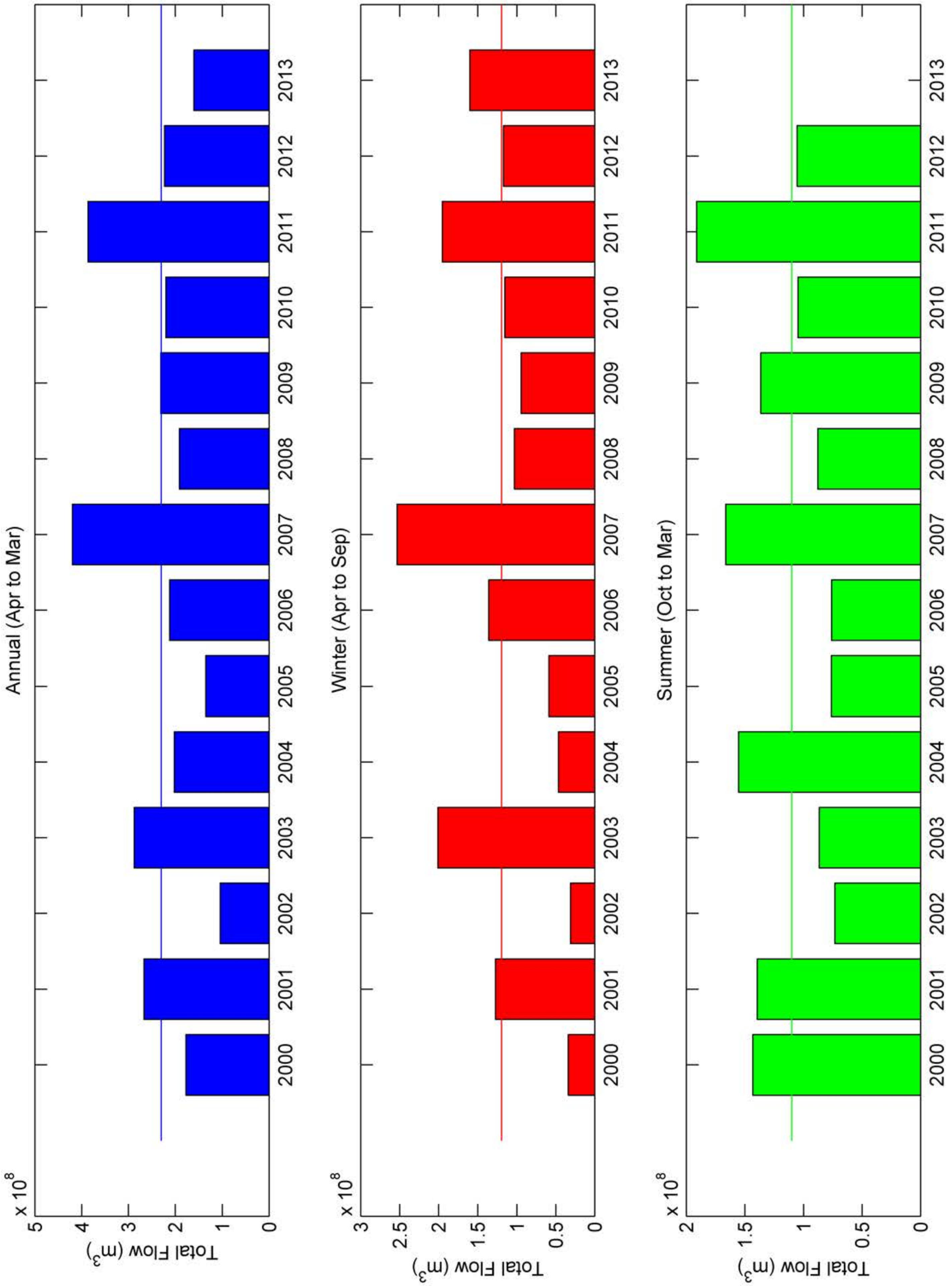
Sydney Harbour Ecological Response Model

Time−Series of Enterococci Concentration in Catchment Inflows
2011 to June 2013 − Calibration with Measured Data

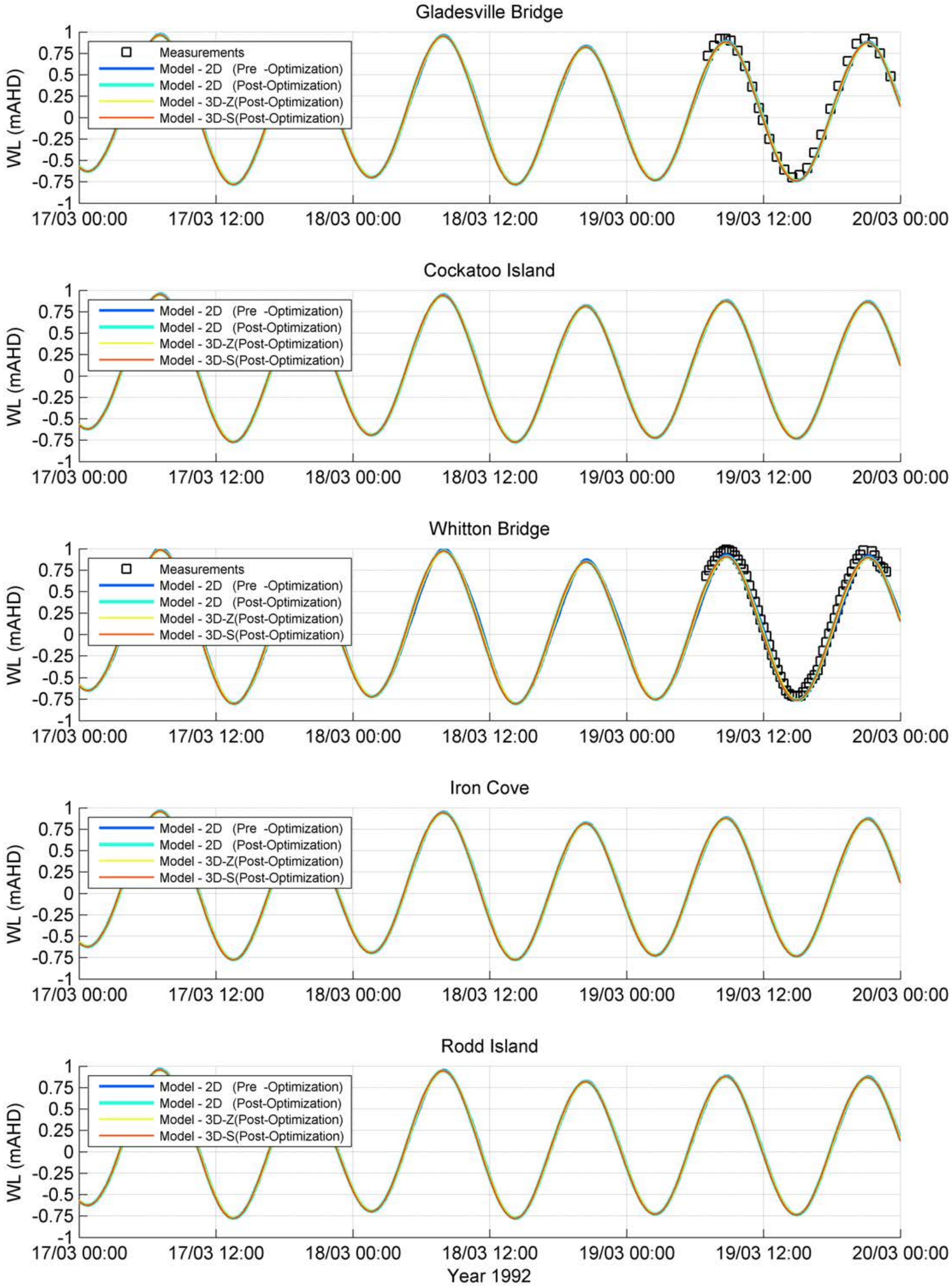
Figure 4.4



Sydney Harbour Ecological Response Model

Histogram of Annual and Seasonal Total Catchment Inflows

Figure 4.5



Sydney Harbour Ecological Response Model

Water Level Calibration Time−Series
Measured & Modelled

Figure 5.1

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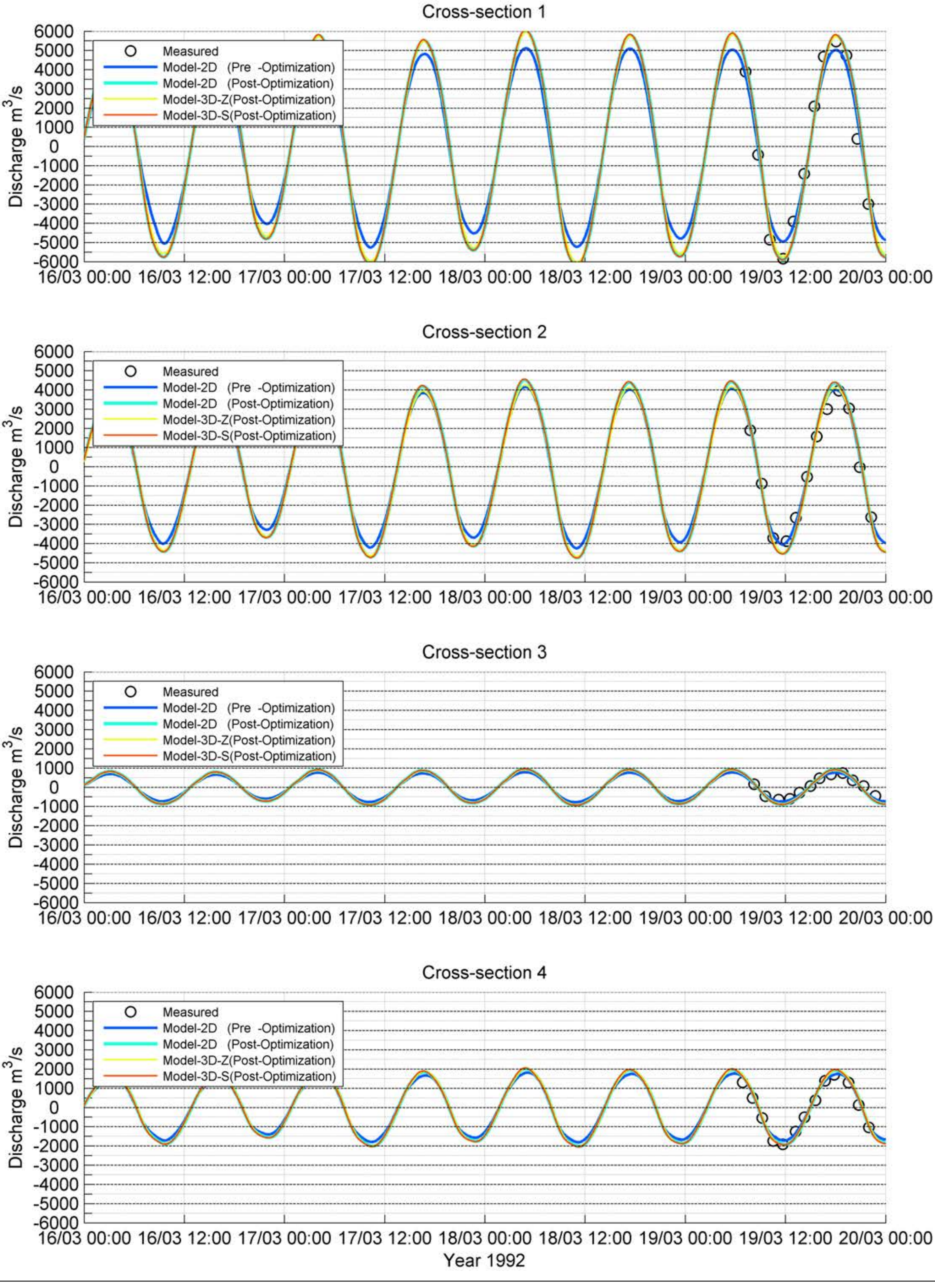
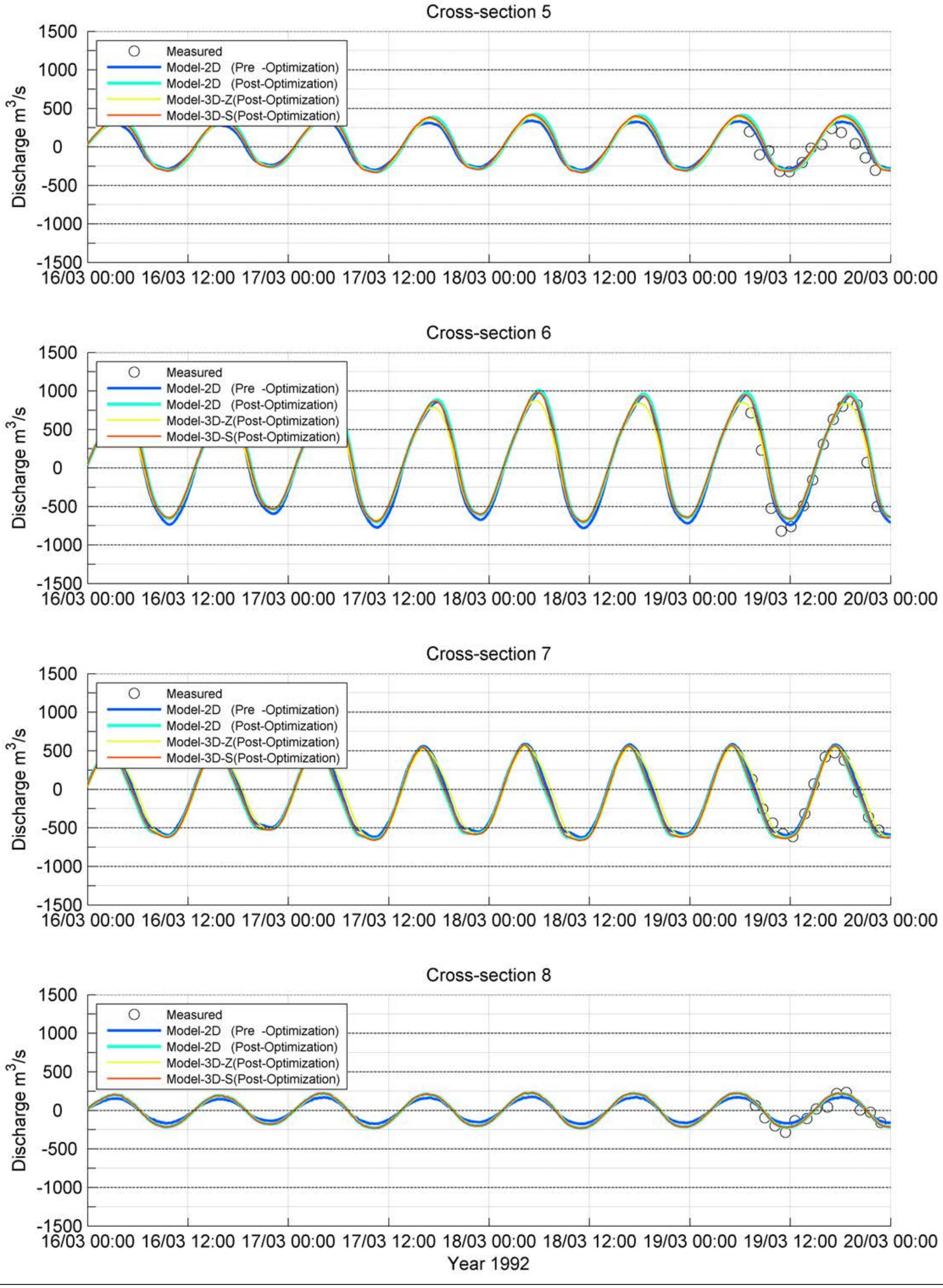


Sydney Harbour Ecological Response Model

Discharge Calibration Time−Series
Cross−section 1 to 4

Figure 5.2a



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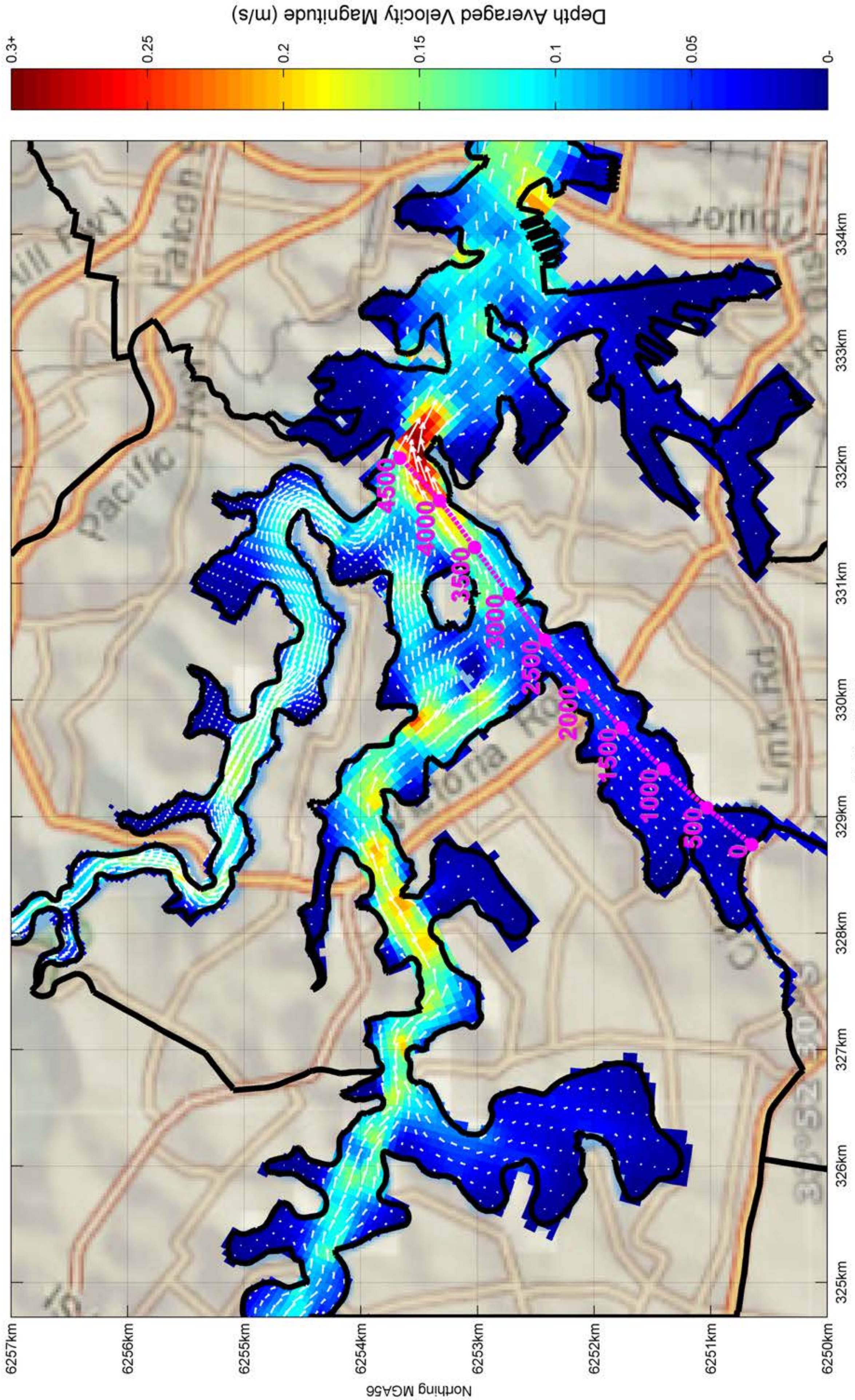
Sydney Harbour Ecological Response Model

Discharge Calibration Time−Series
Cross−section 5 to 8

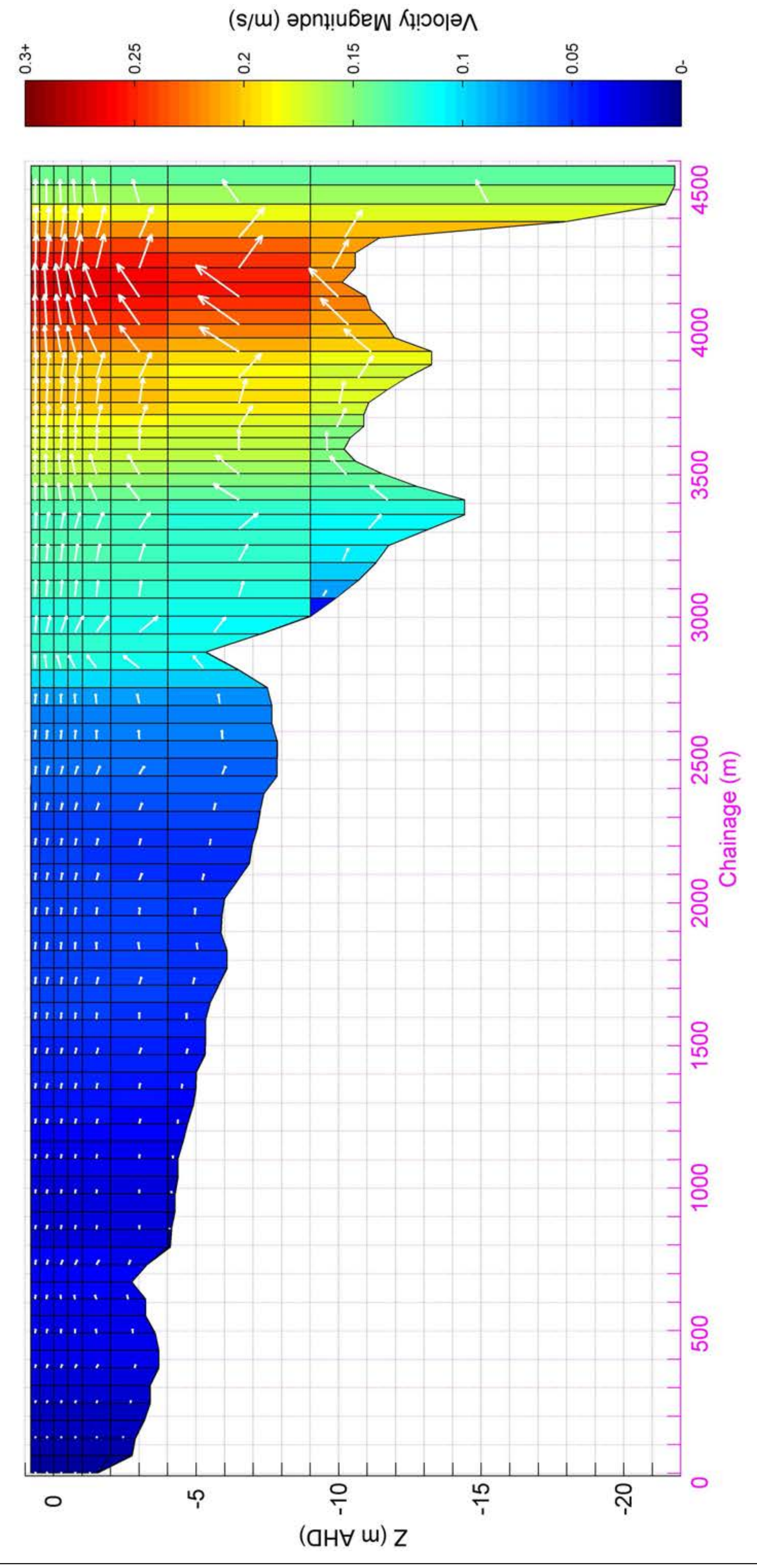
Figure 5.2b



Sydney Harbour Ecological Response Model

Depth Averaged Velocity Map and Transect Location
Z−model (3D)

Figure 5.3a



Sydney Harbour Ecological Response Model

Velocity Magnitude and Direction Transect
Z−model (3D)

Figure 5.3b

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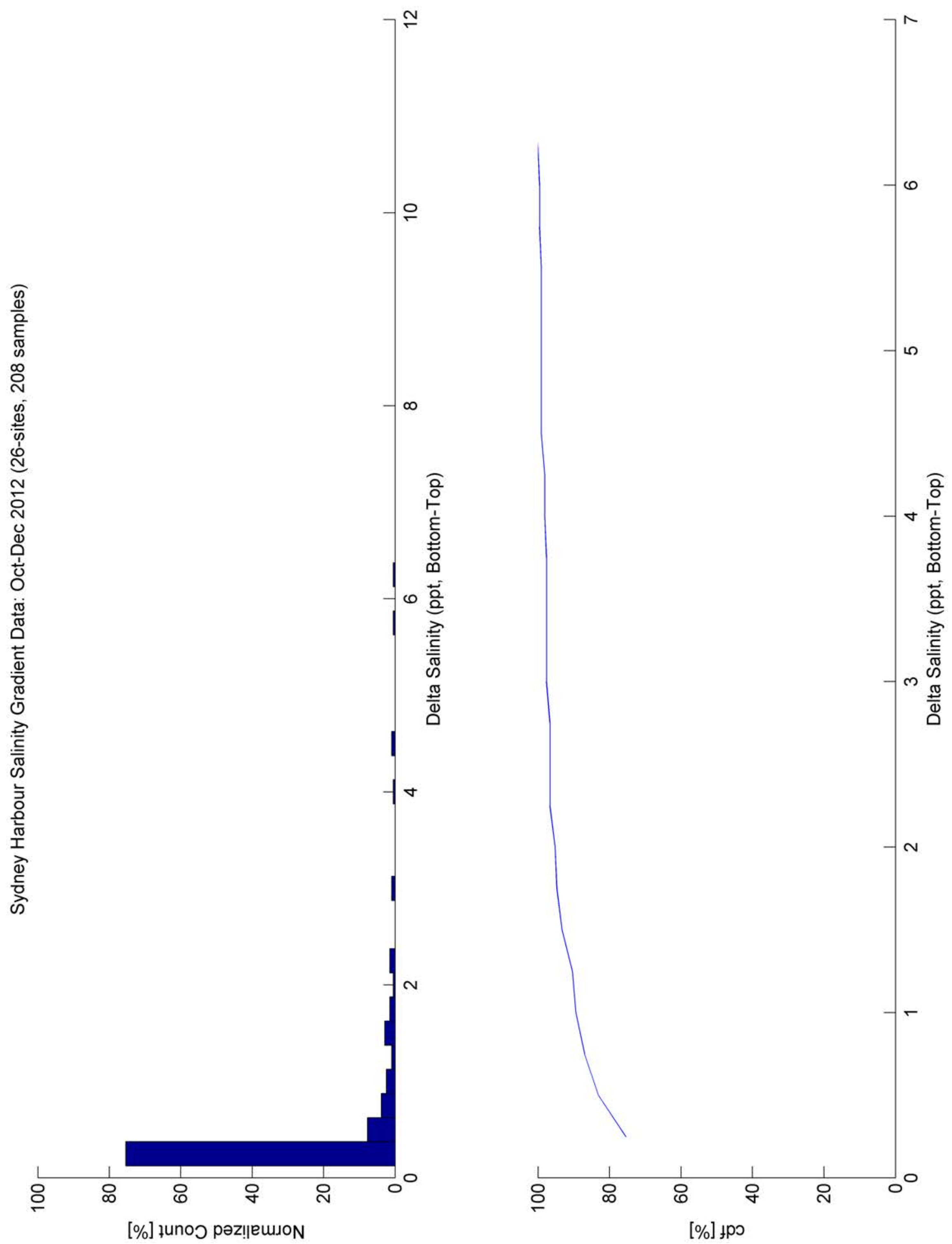
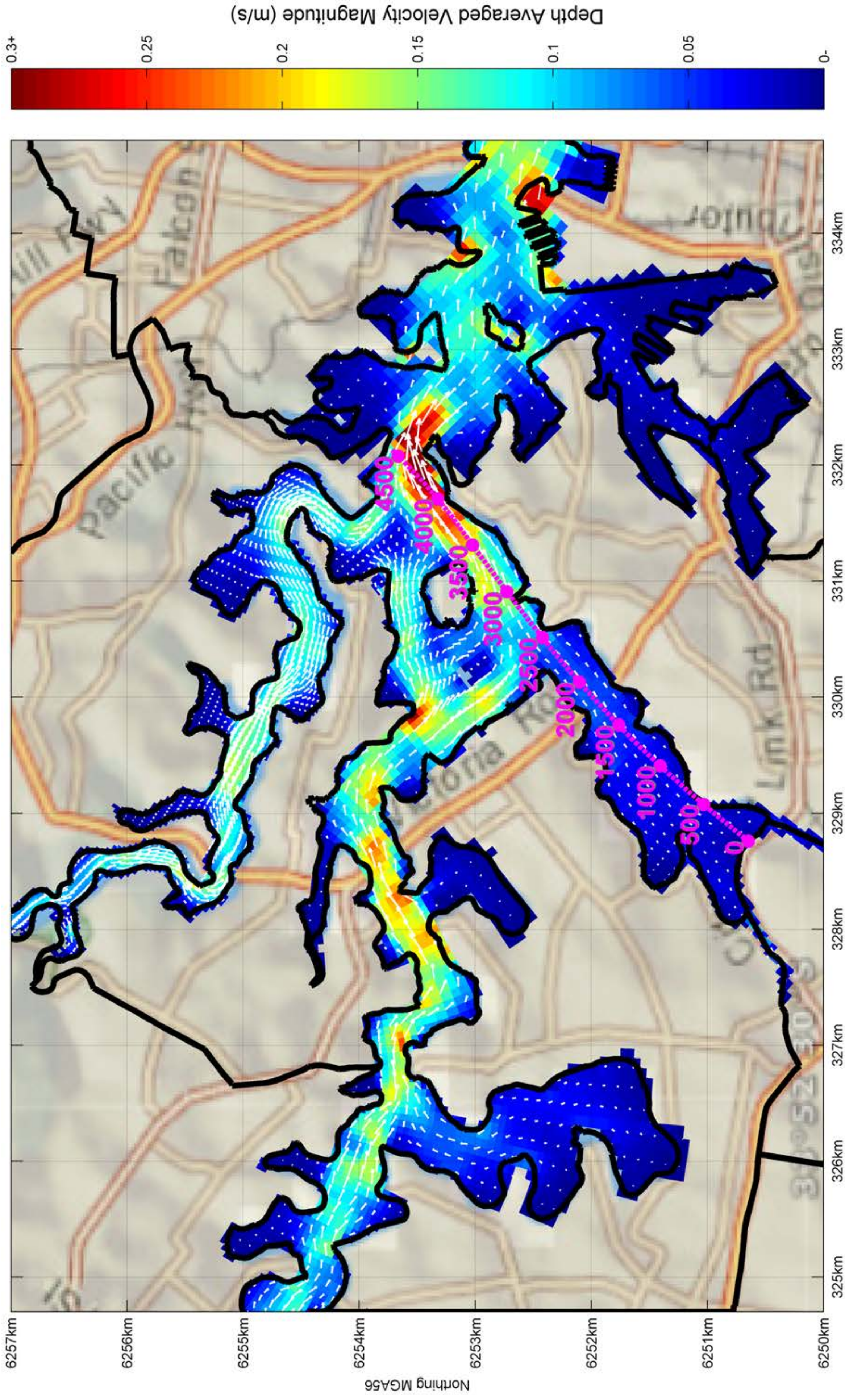


Sydney Harbour Ecological Response Model

Salinity Gradient Distributions at Measurement Sites

Figure 5.4



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Sydney Harbour Ecological Response Model

Depth Averaged Velocity Map and Transect Location
Sigma−model (3D)

Figure 5.5a

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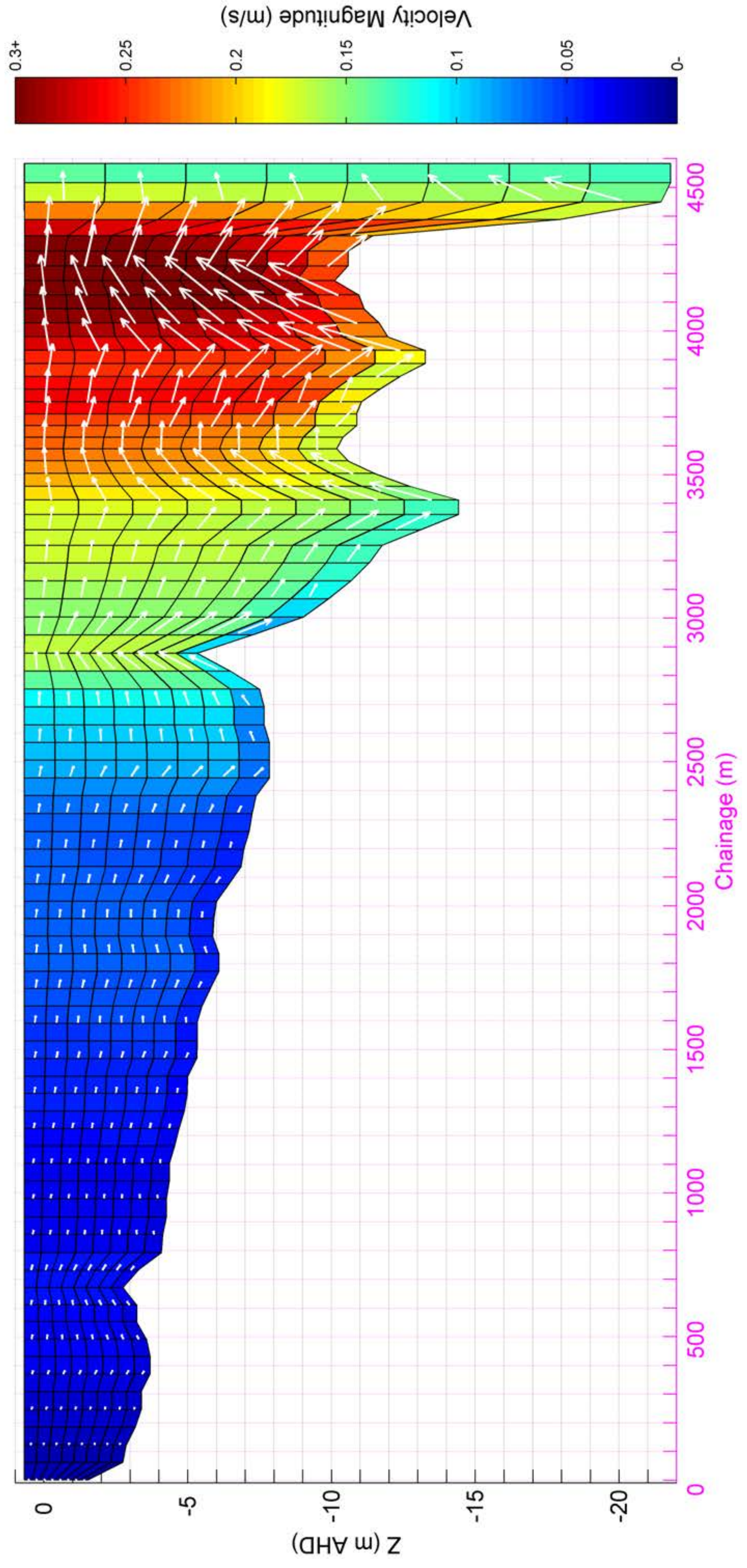
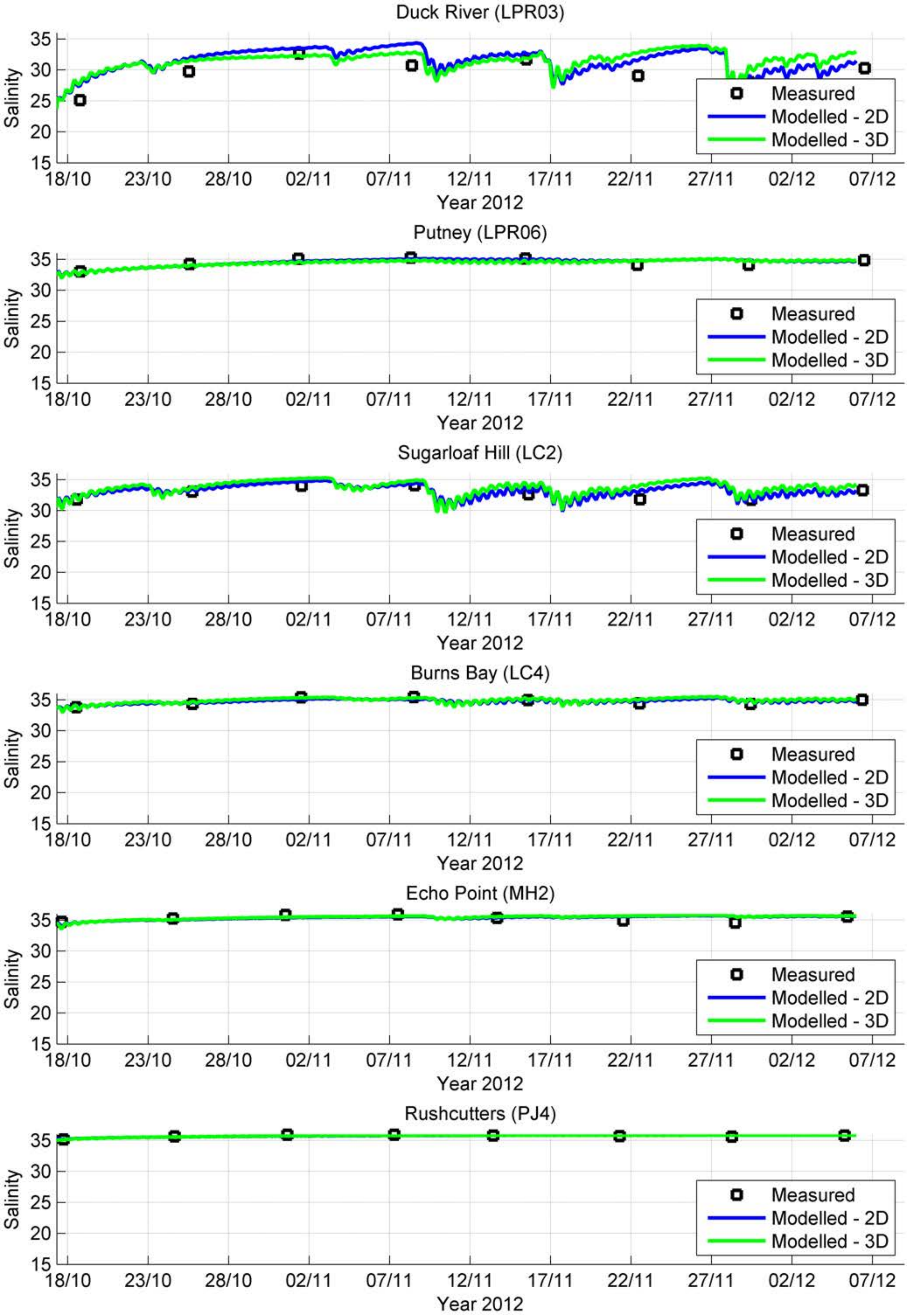


Sydney Harbour Ecological Response Model

Velocity Magnitude and Direction Transect
Sigma−model (3D)

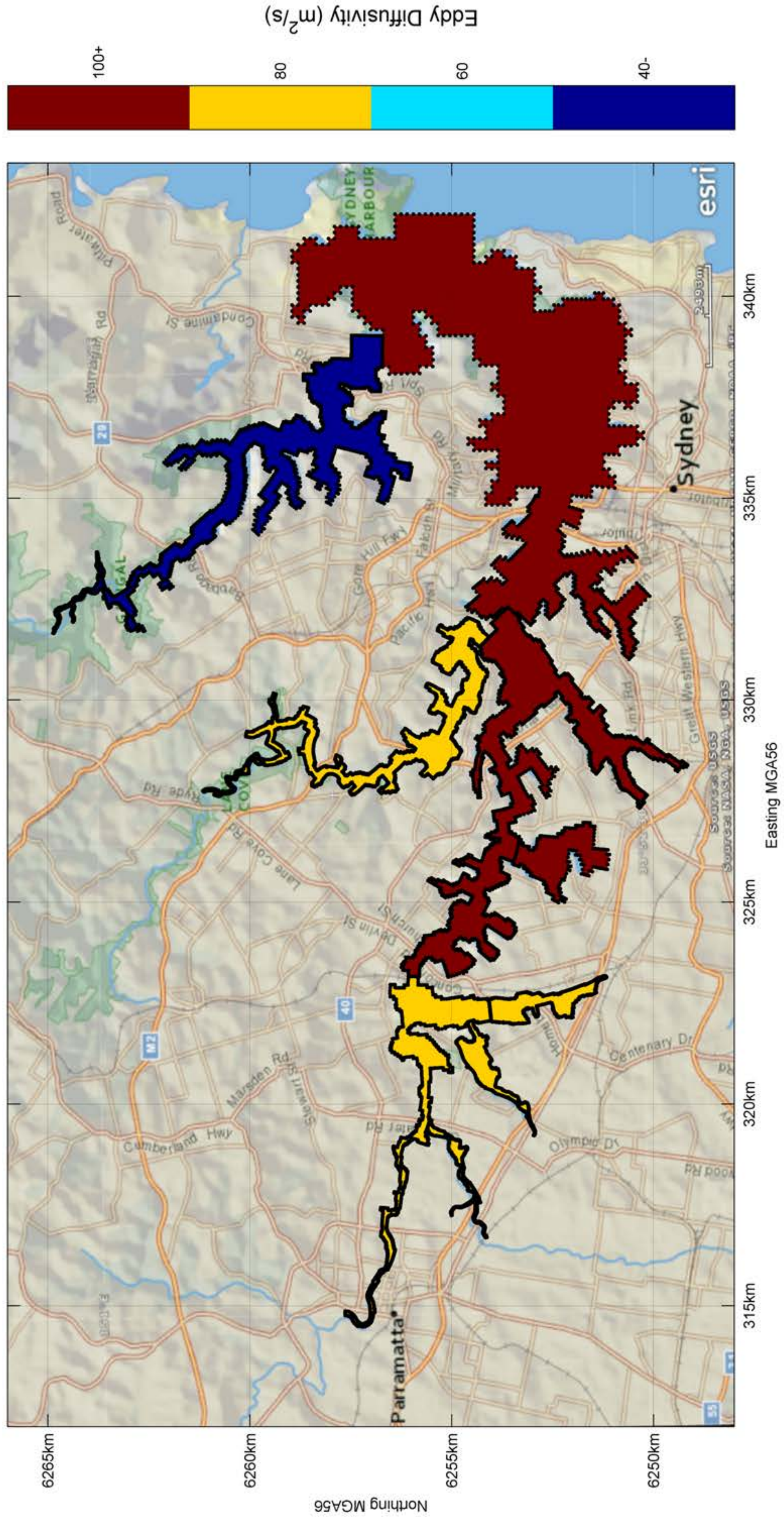
Figure 5.5b



Sydney Harbour Ecological Response Model

Salinity Calibration Time−Series
Oct−Dec 2012

Figure 5.6



Sydney Harbour Ecological Response Model

Map of Eddy Diffusivity in Delft3D−FLOW

Figure 5.7

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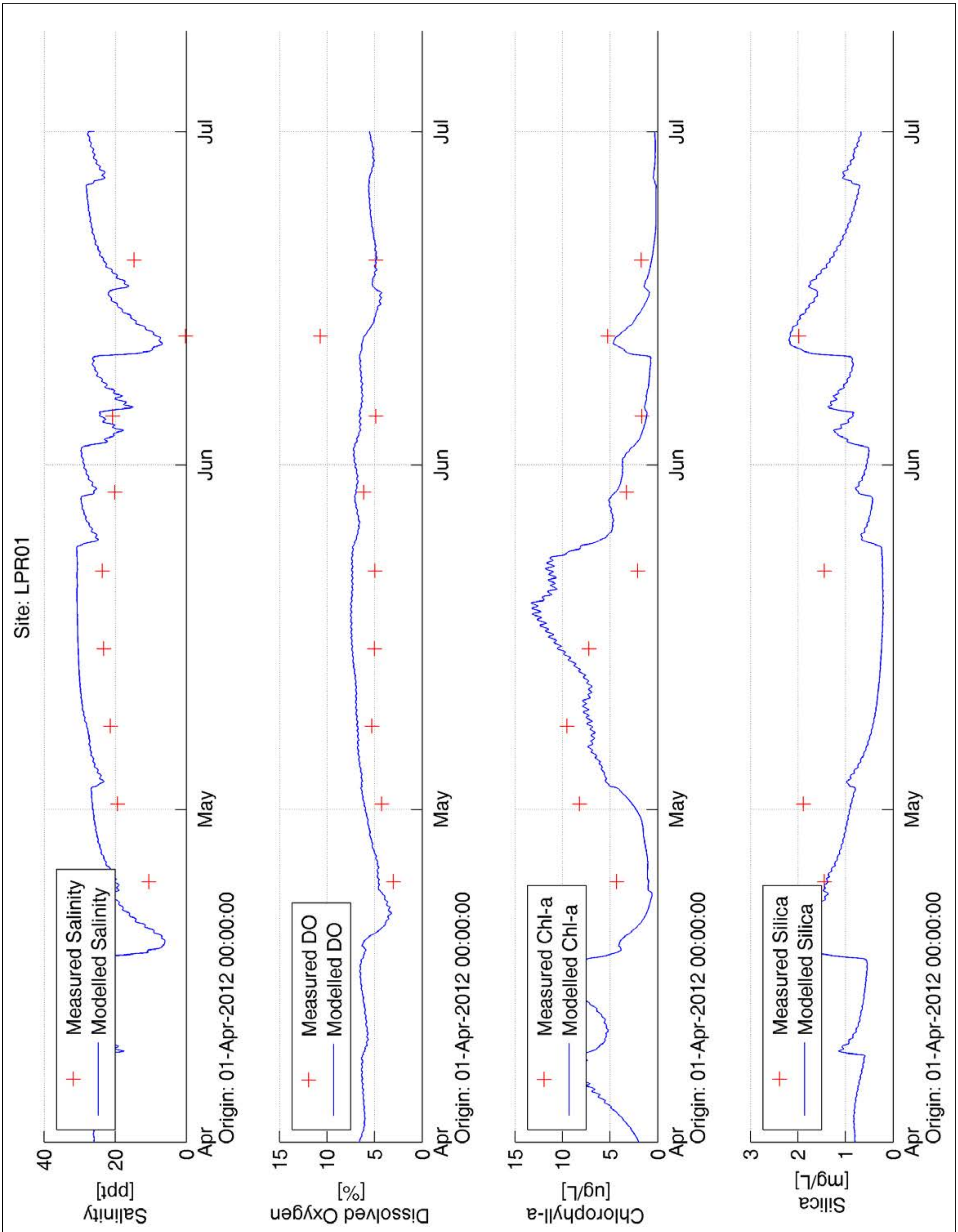
Sydney Harbour Ecological Response Model

Parramatta River Weekly Sampling Sites
Apr−Jun 2012

Figure 5.8



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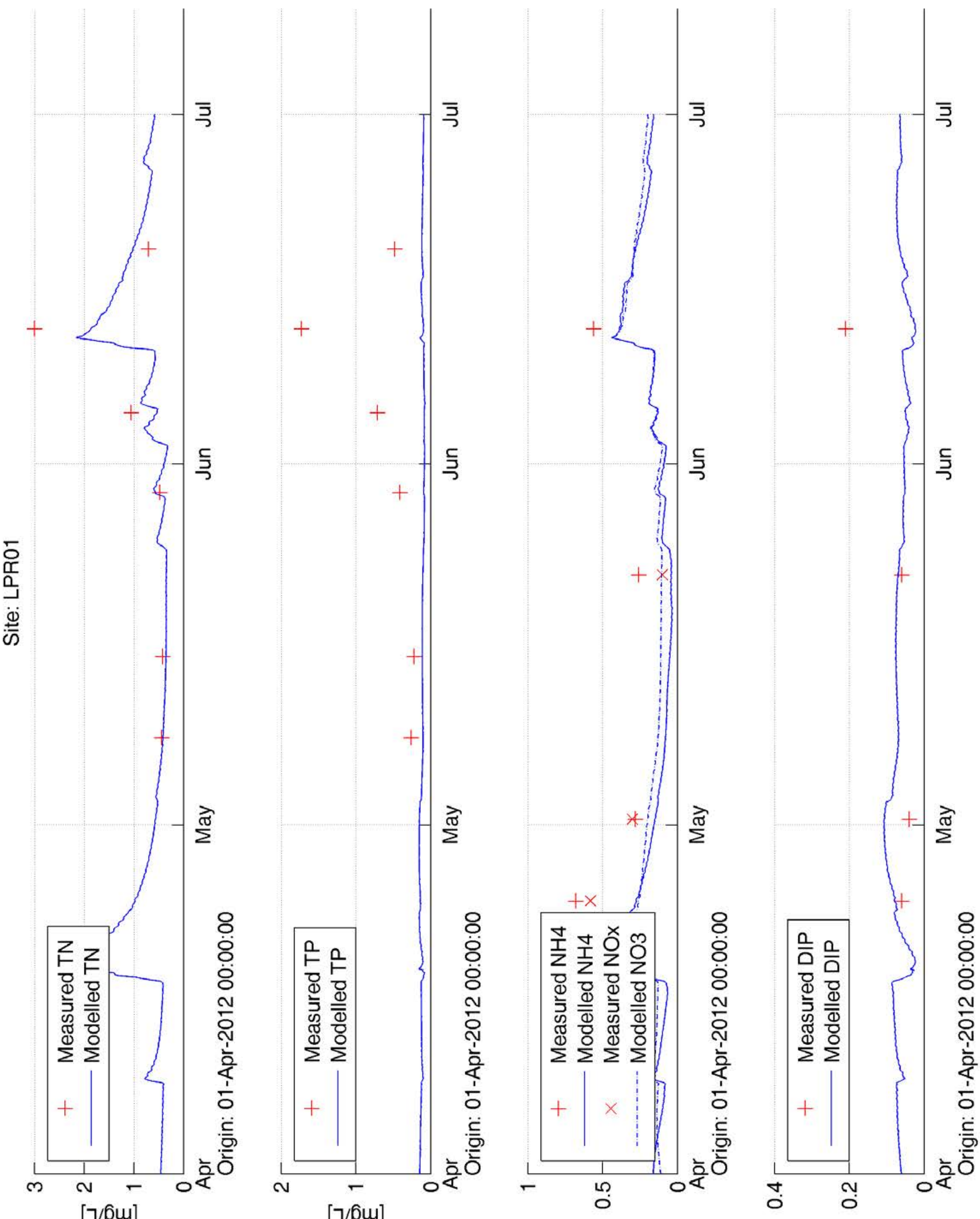
Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Apr−Jun 2012

Site: LPR01

Figure 5.9a

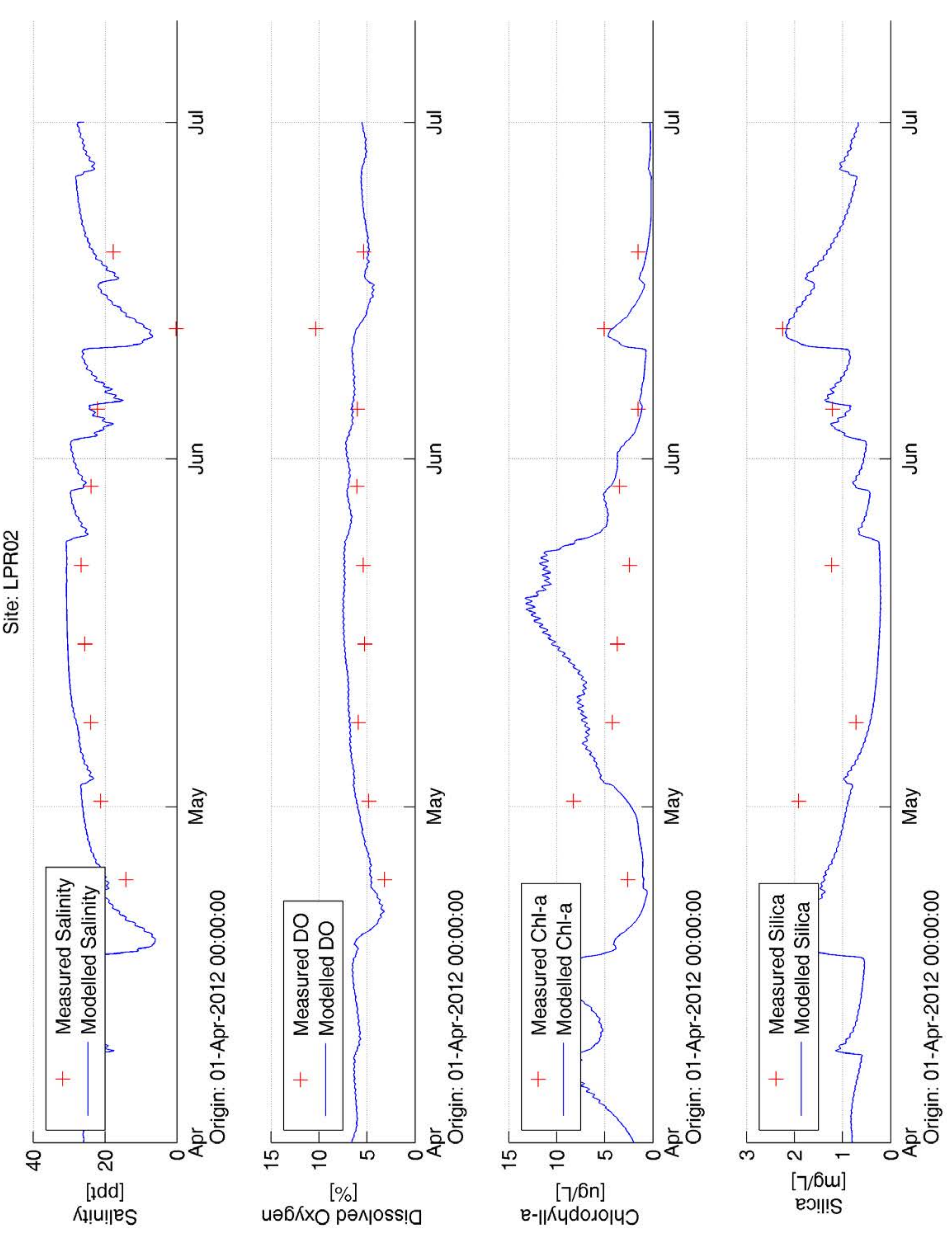


Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Apr−Jun 2012

Site: LPR01

Figure 5.9b



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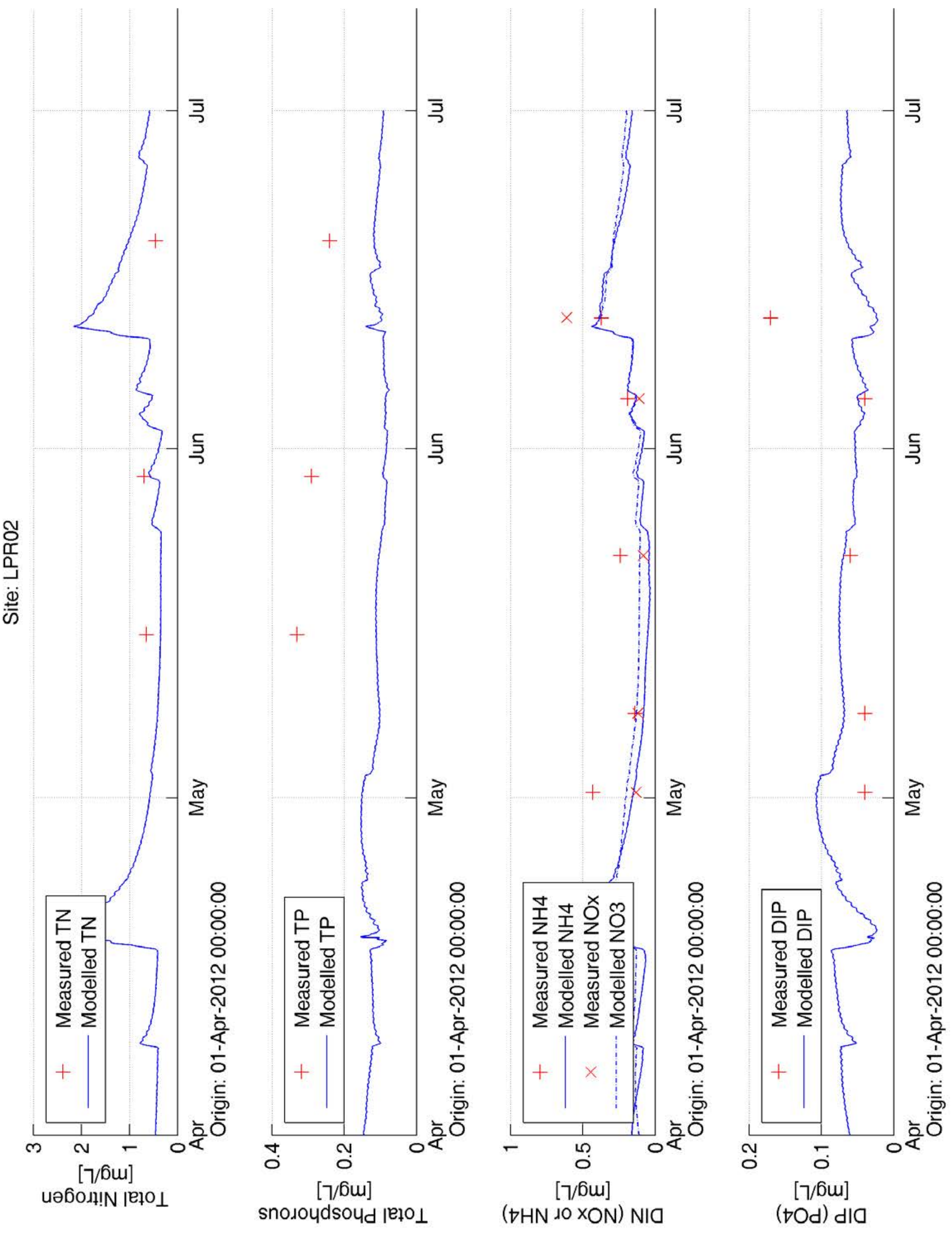
Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Apr−Jun 2012
Site: LPR02

Figure 5.10a

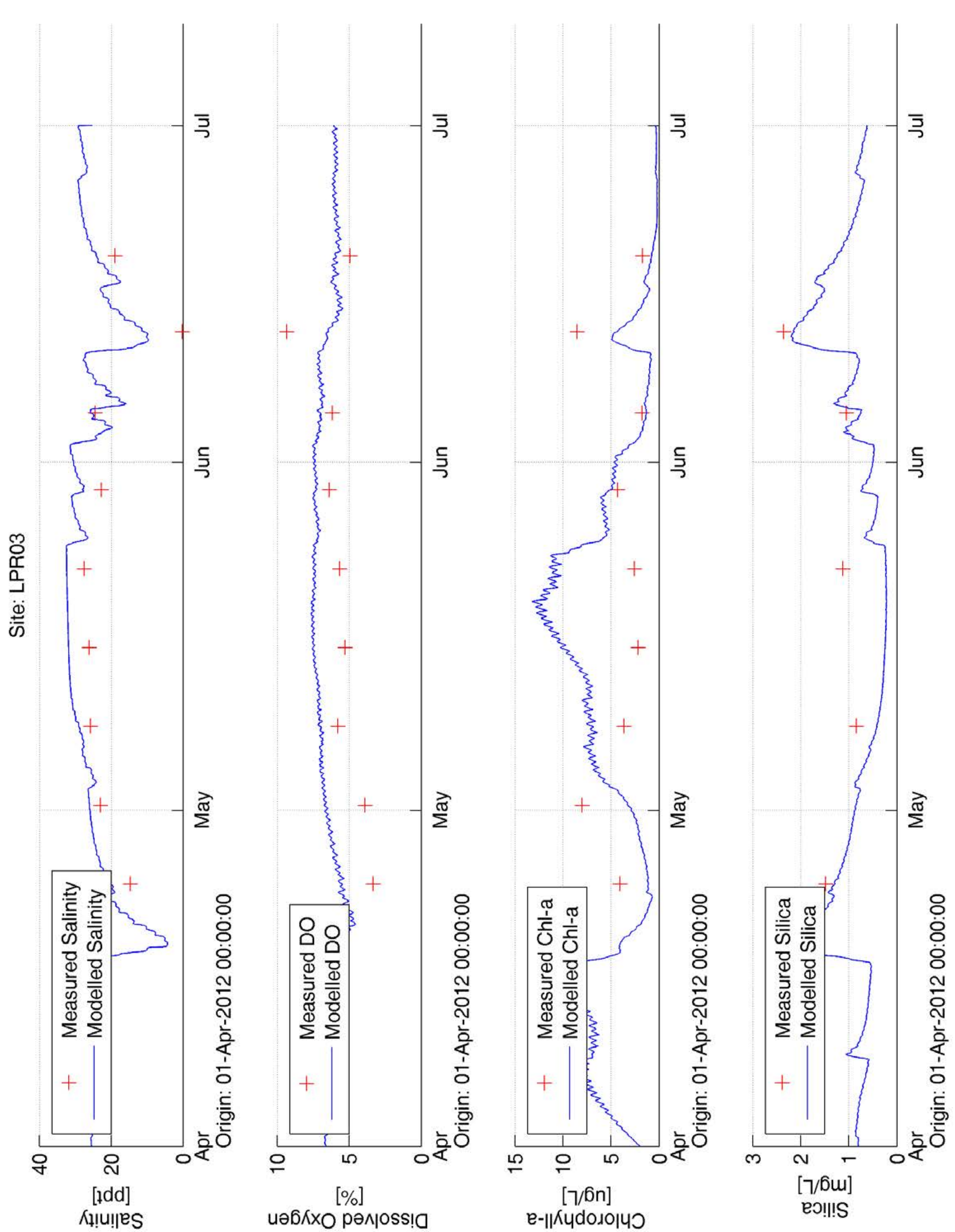


Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Apr−Jun 2012

Site: LPR02

Figure 5.10b



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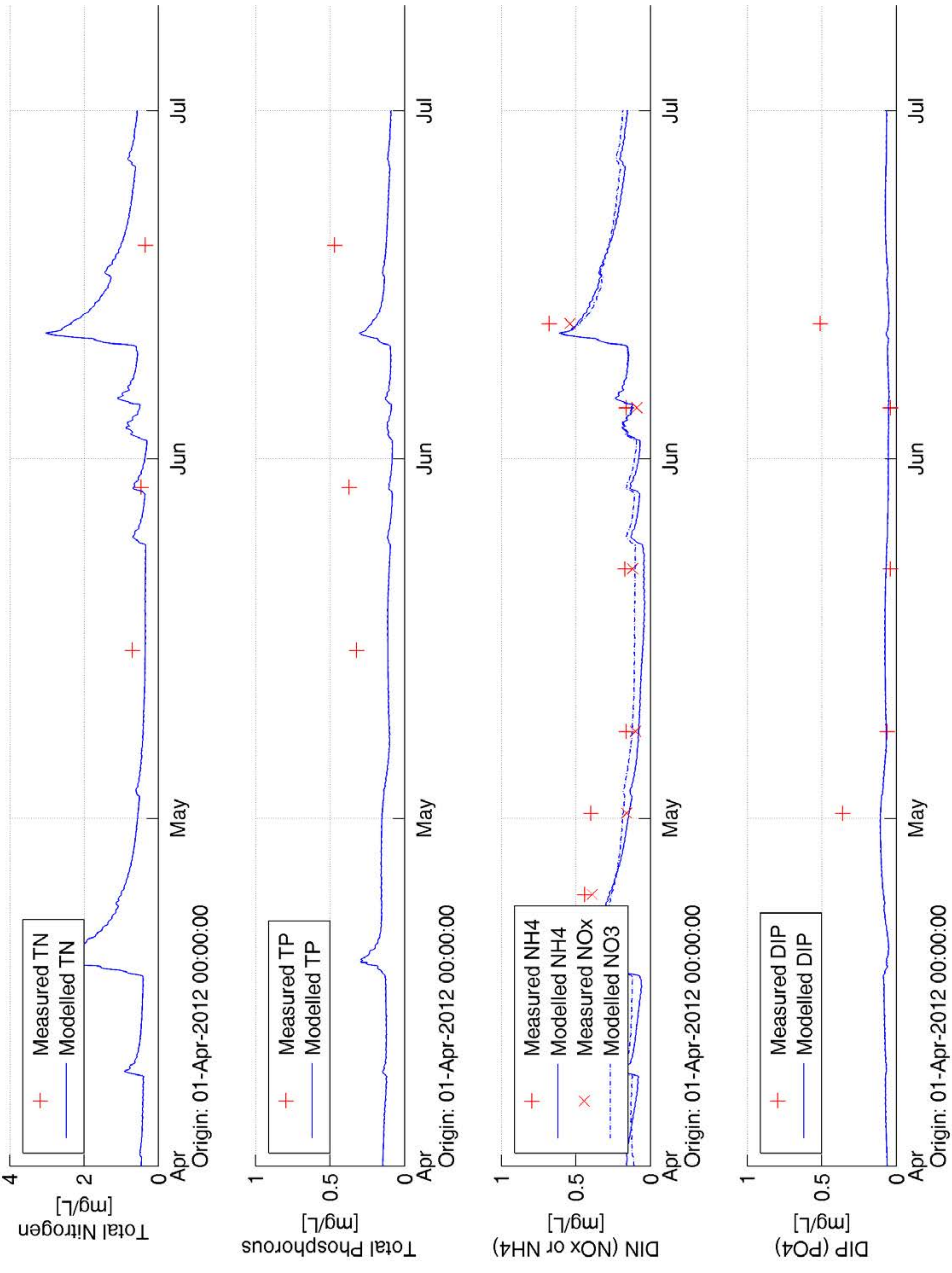
Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Apr−Jun 2012

Site: LPR03

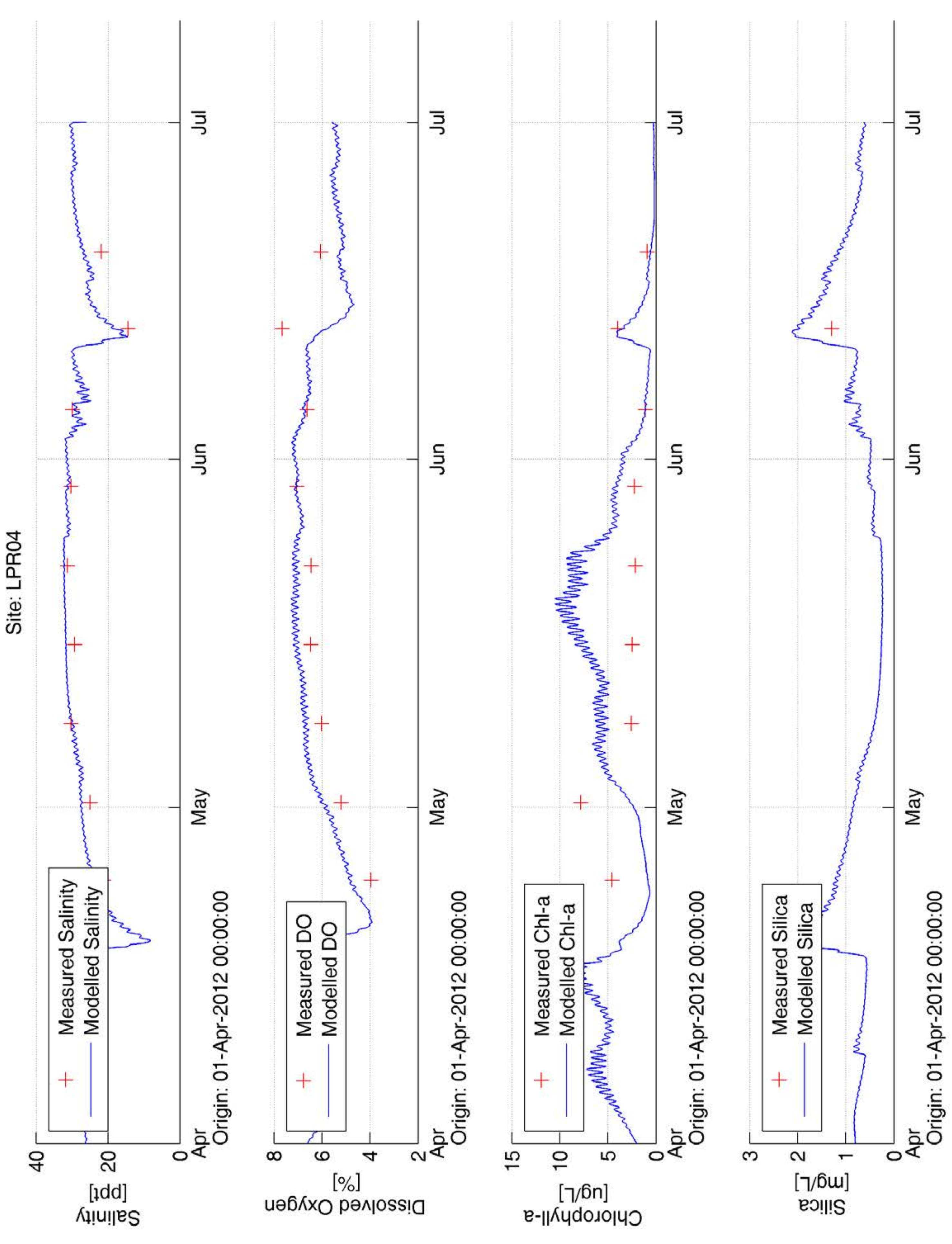
Figure 5.11a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Apr−Jun 2012
Site: LPR03

Figure 5.11b

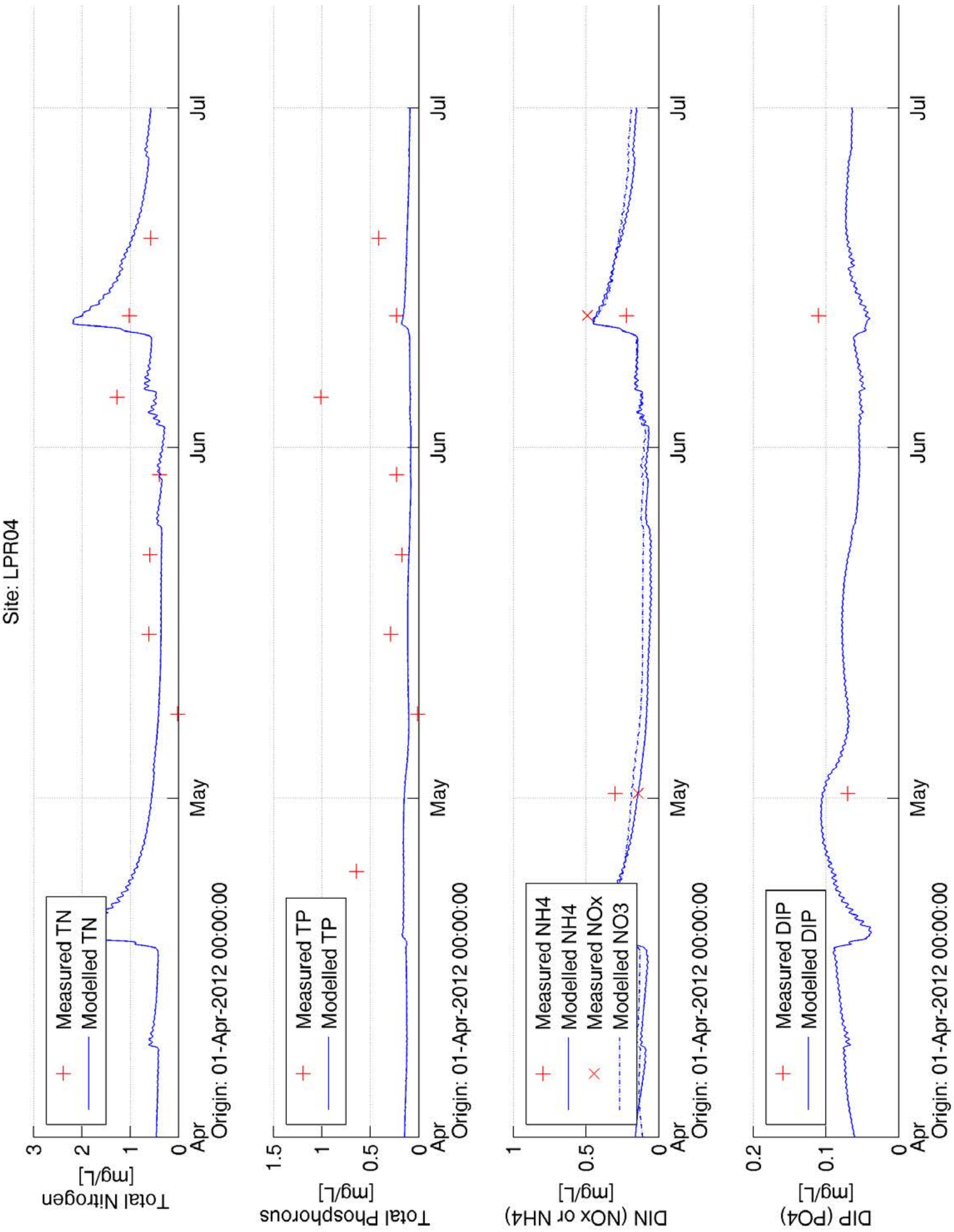


Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Apr−Jun 2012

Site: LPR04

Figure 5.12a



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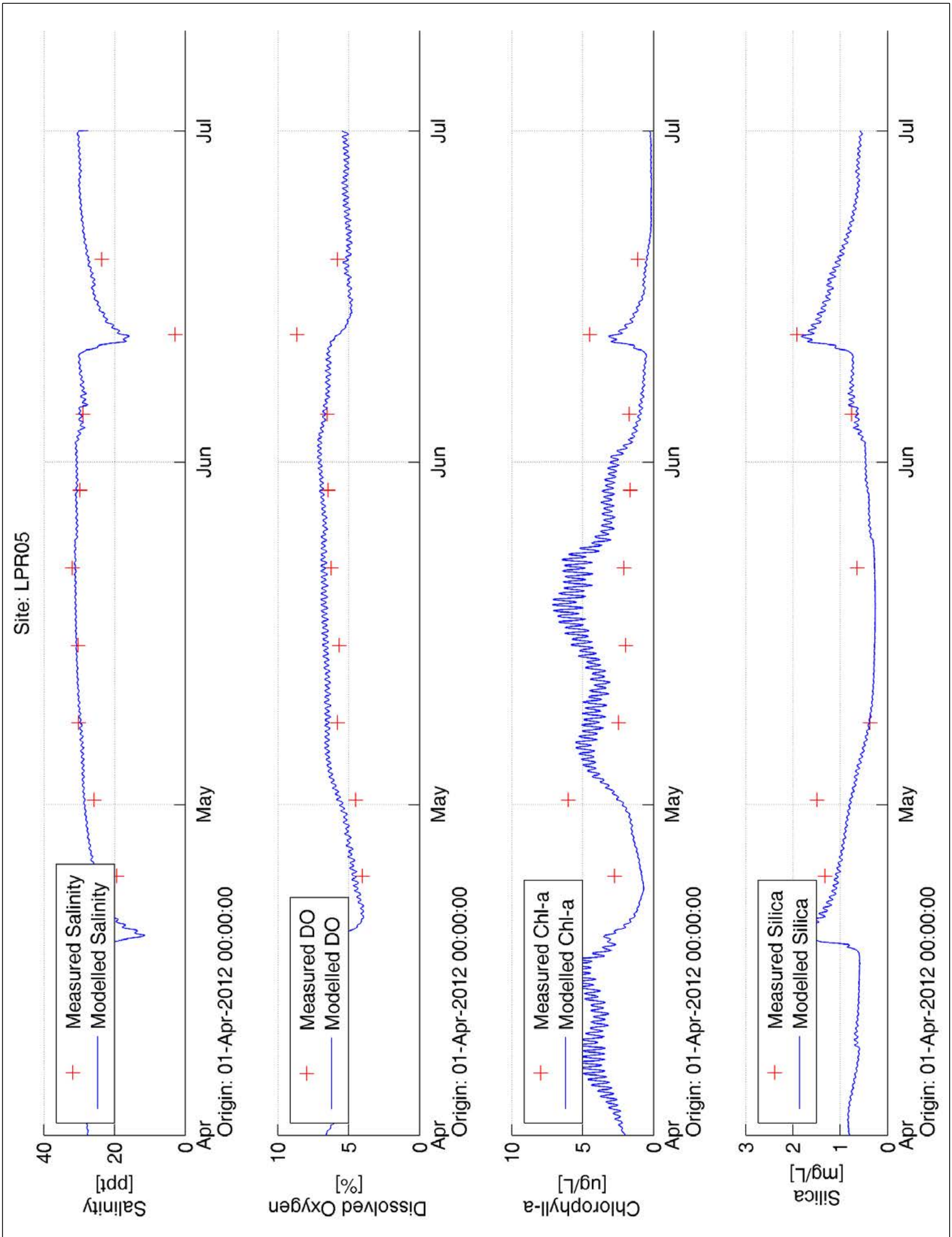
Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Apr−Jun 2012

Site: LPR04

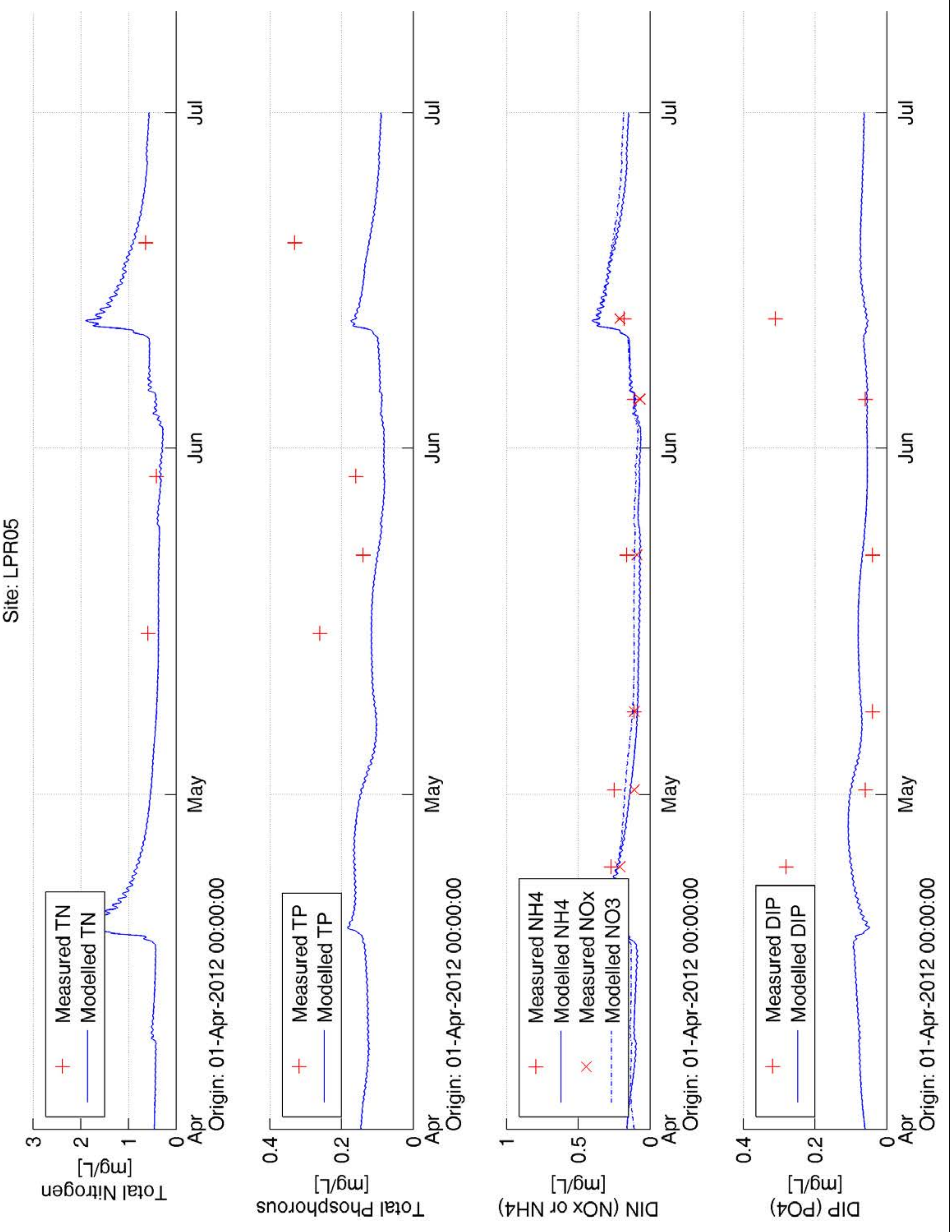
Figure 5.12b



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Apr−Jun 2012
Site: LPR05

Figure 5.13a

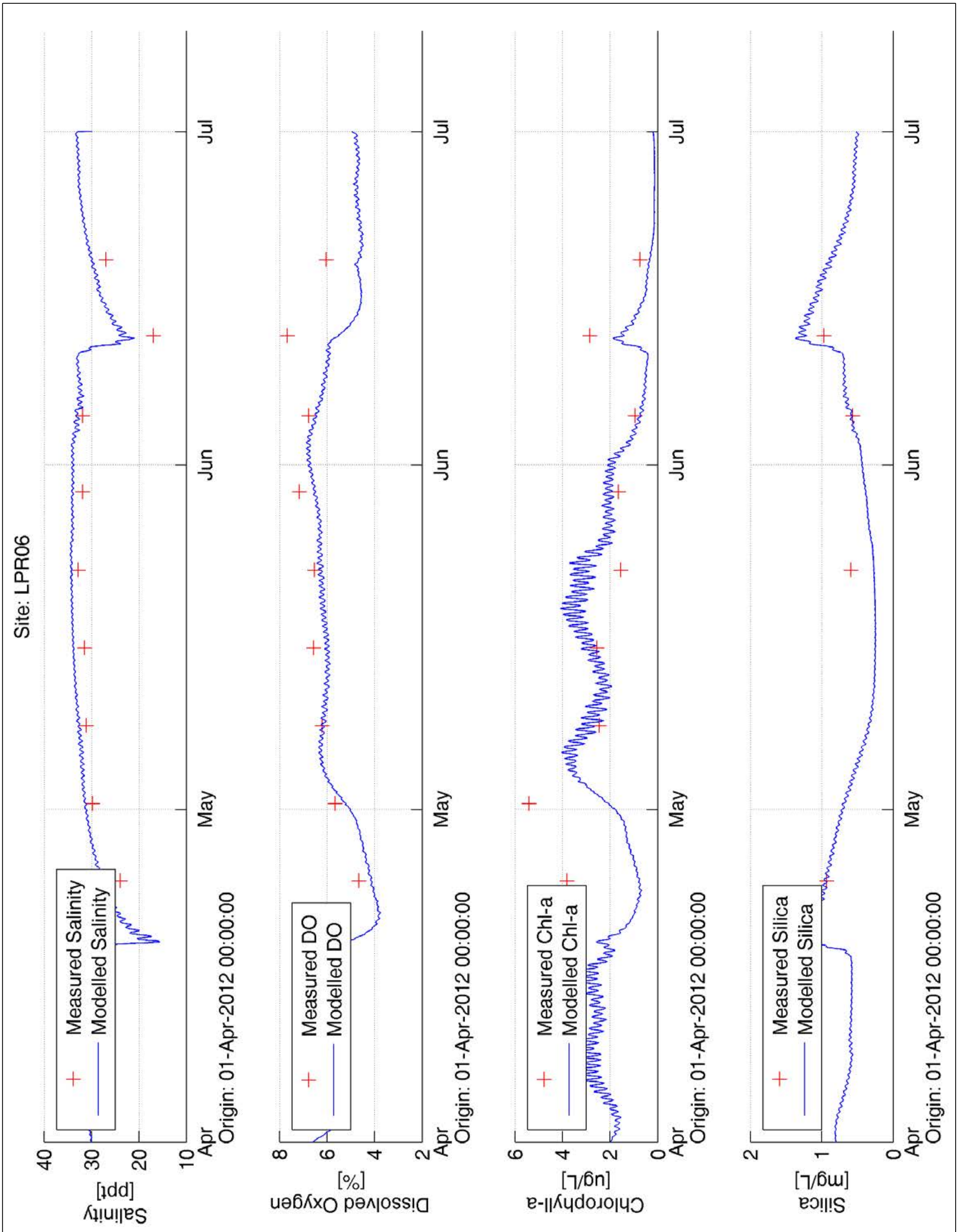


Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Apr−Jun 2012

Site: LPR05

Figure 5.13b



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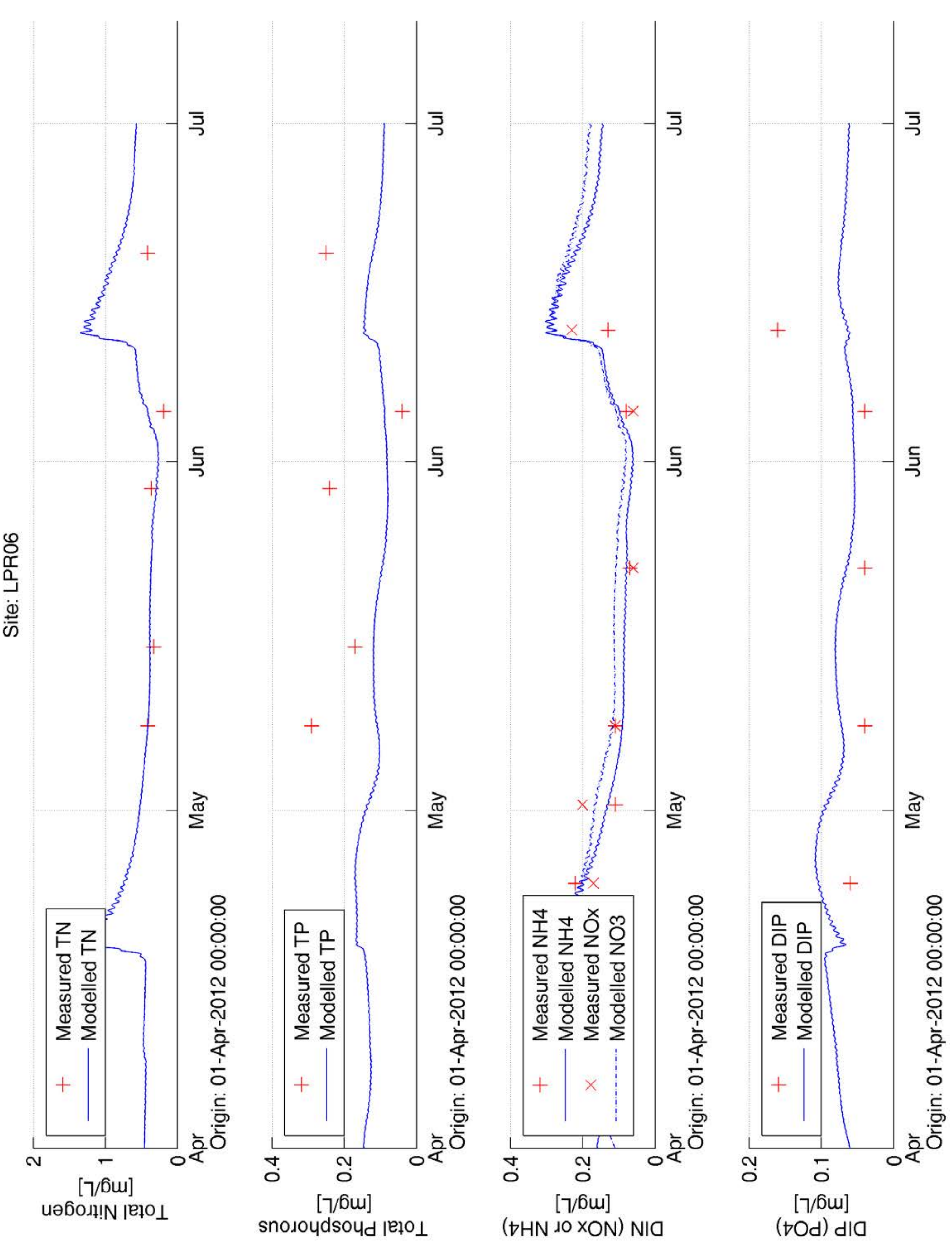
Sydney Harbour Ecological Response Model

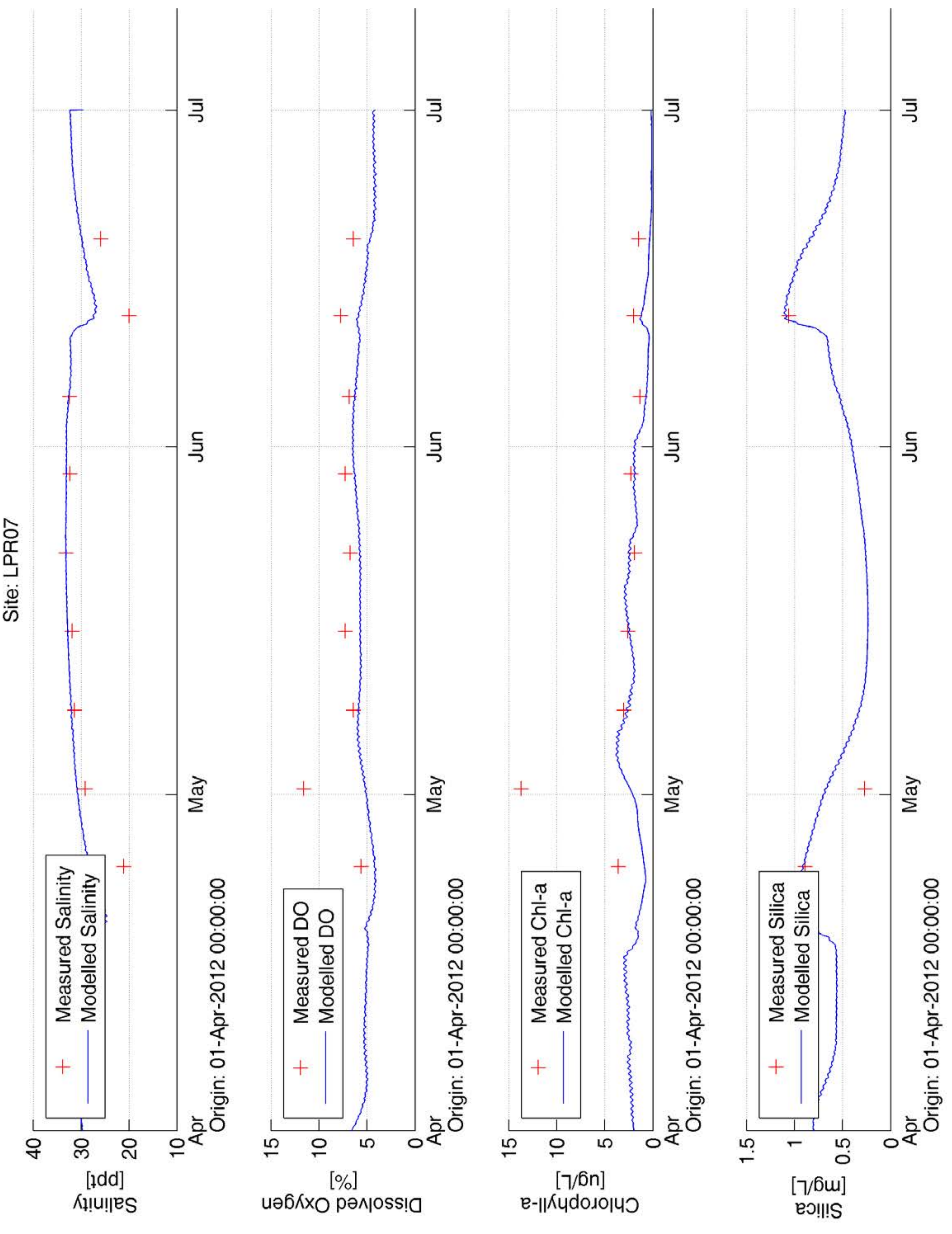
Water Quality Parameter Time−Series 3D Box Model: Apr−Jun 2012

Site: LPR06

Figure 5.14a



Sydney Harbour Ecological Response Model
Water Quality Parameter Time−Series 3D Box Model: Apr−Jun 2012
Site: LPR06
Figure 5.14b



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Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Apr−Jun 2012

Site: LPR07

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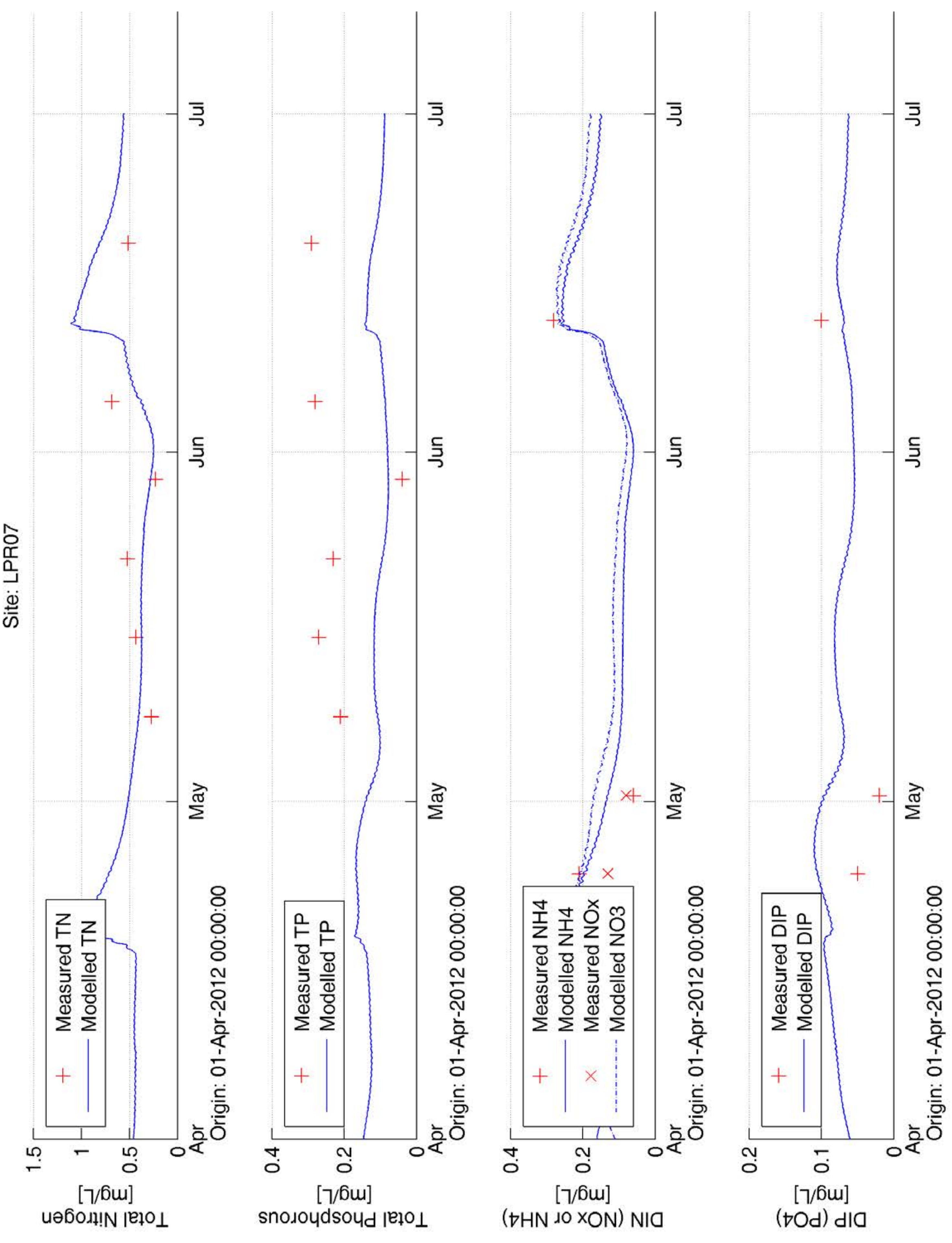
Figure 5.15a

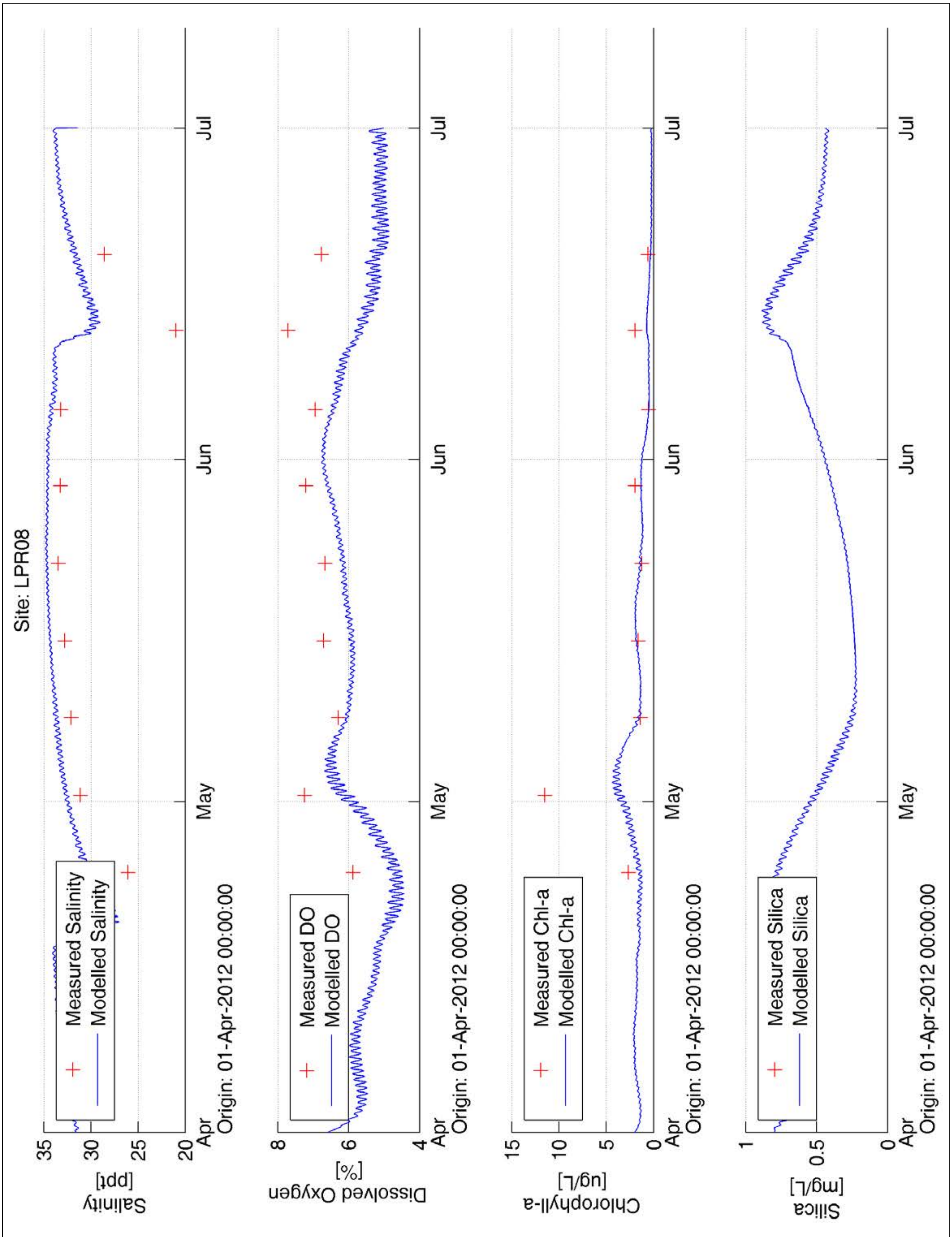


Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Apr−Jun 2012

Site: LPR07

Figure 5.15b

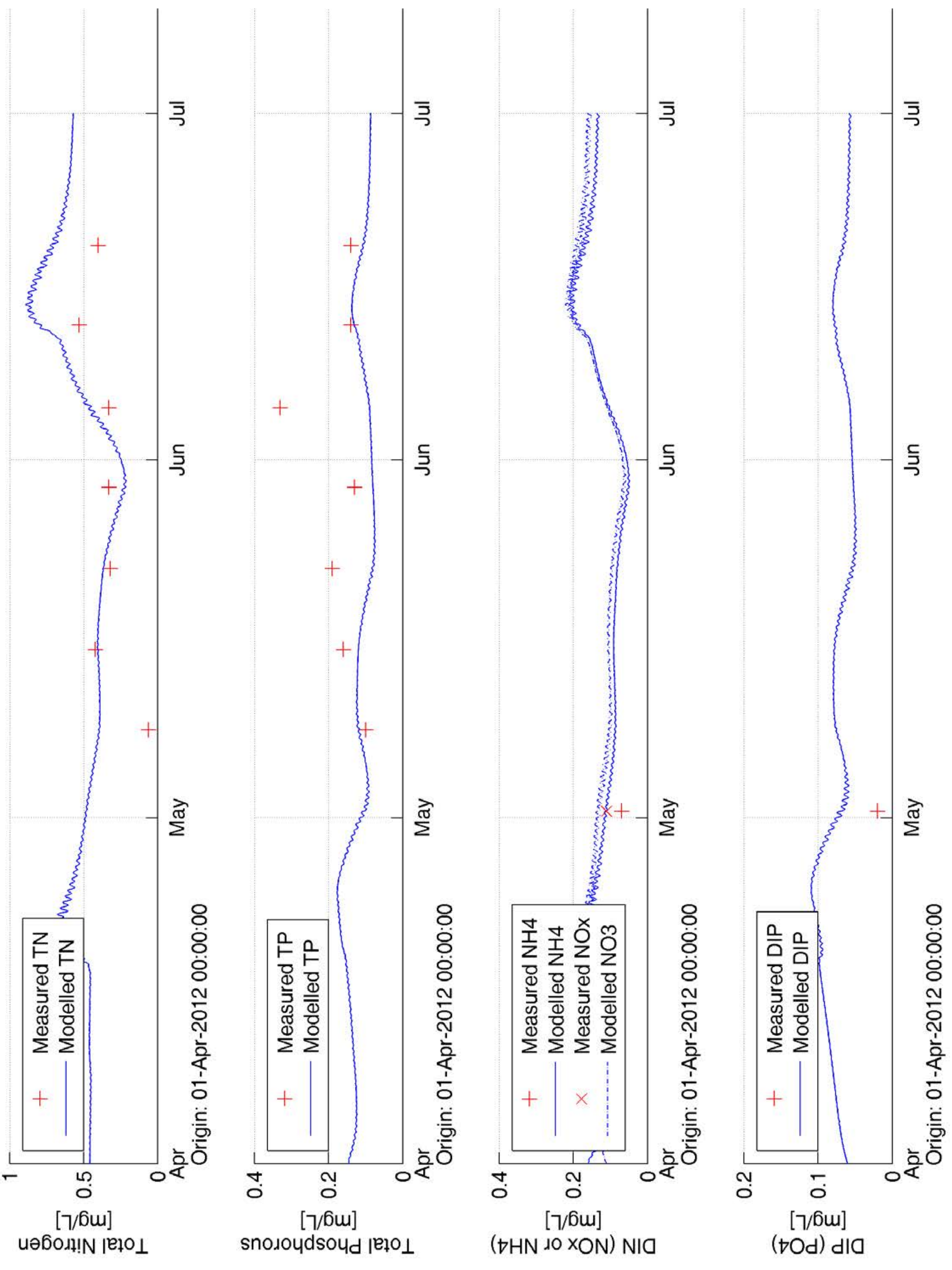


Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Apr−Jun 2012

Site: LPR08

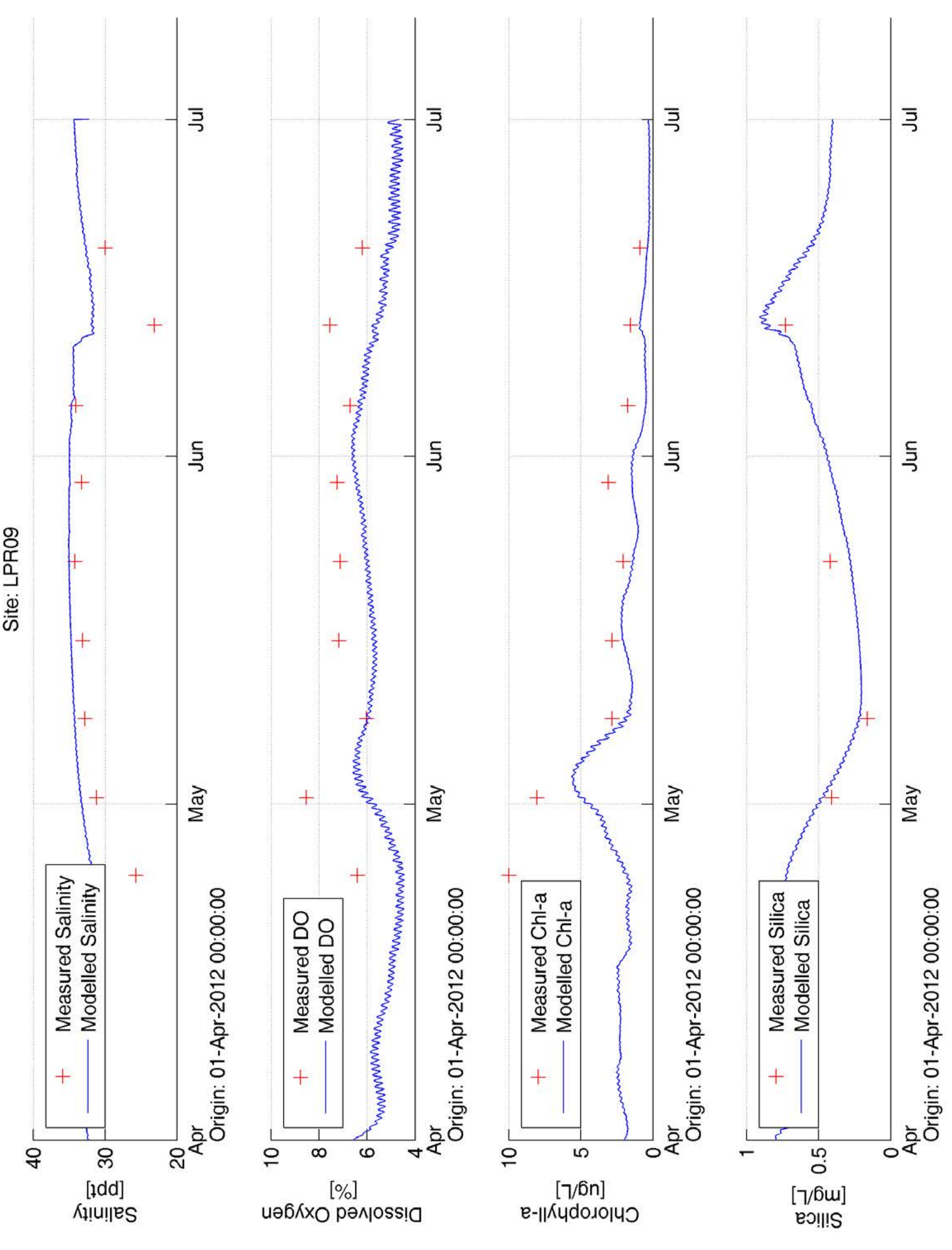
Figure 5.16a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Apr−Jun 2012
Site: LPR08

Figure 5.16b

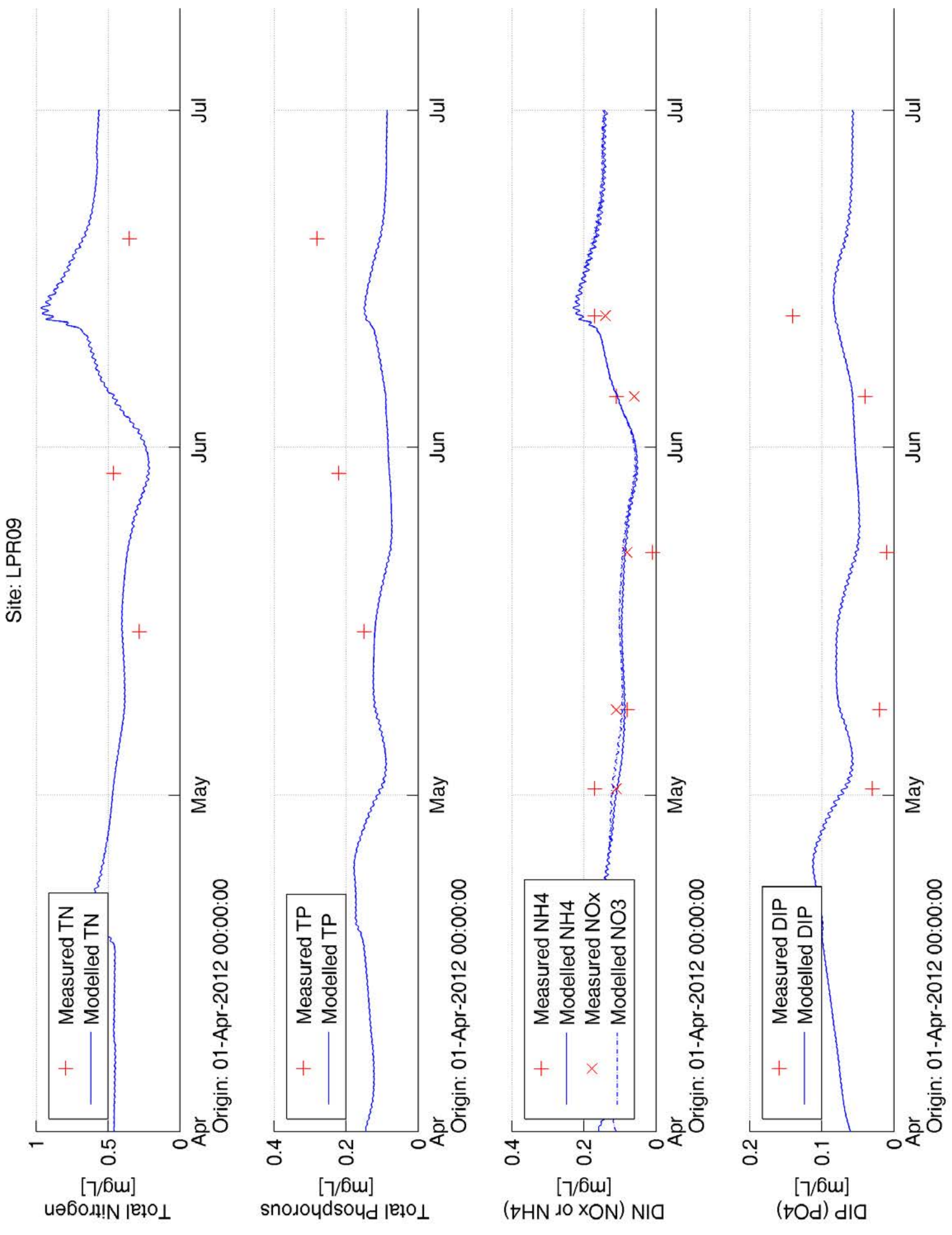


Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Apr−Jun 2012

Site: LPR09

Figure 5.17a

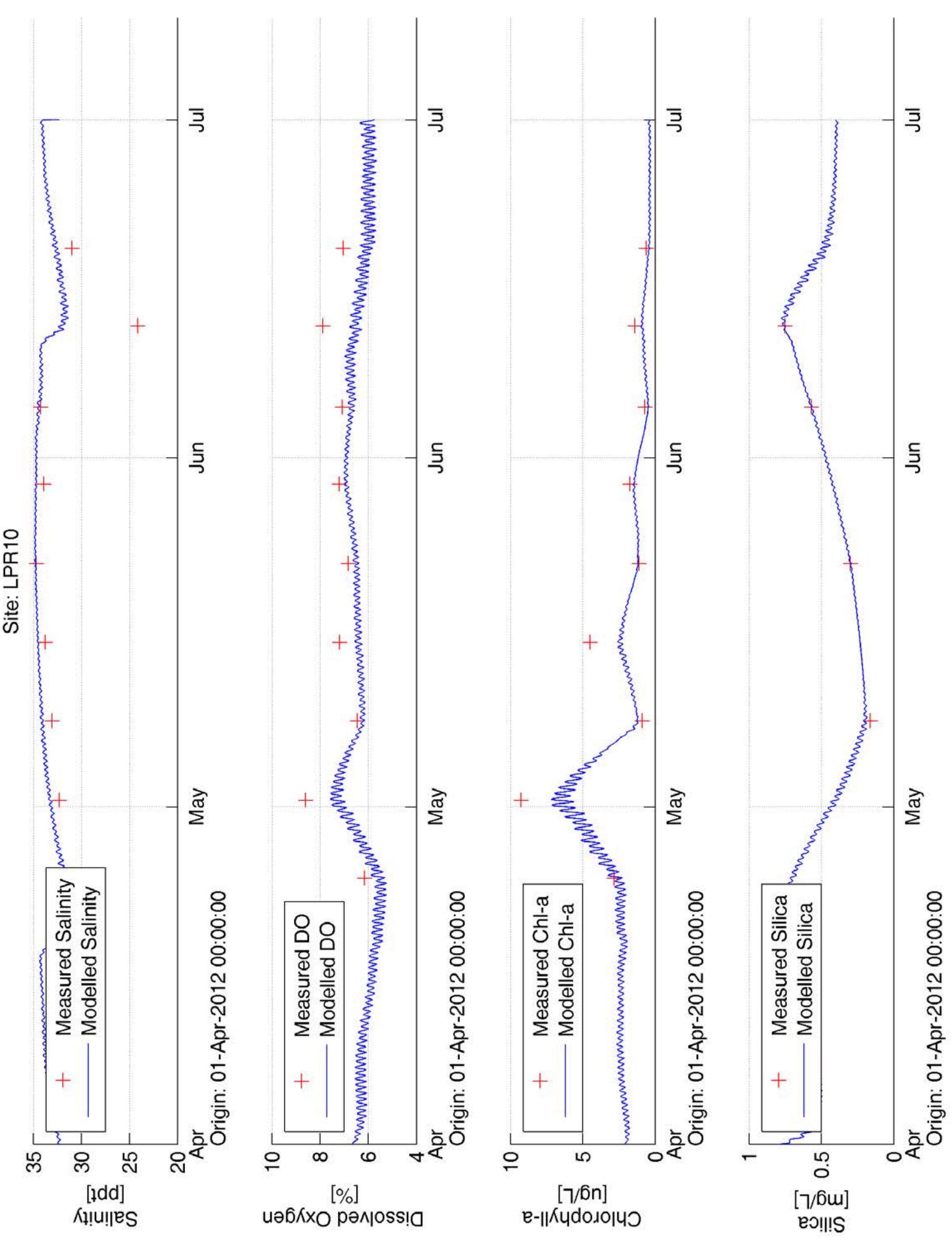


Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Apr−Jun 2012

Site: LPR09

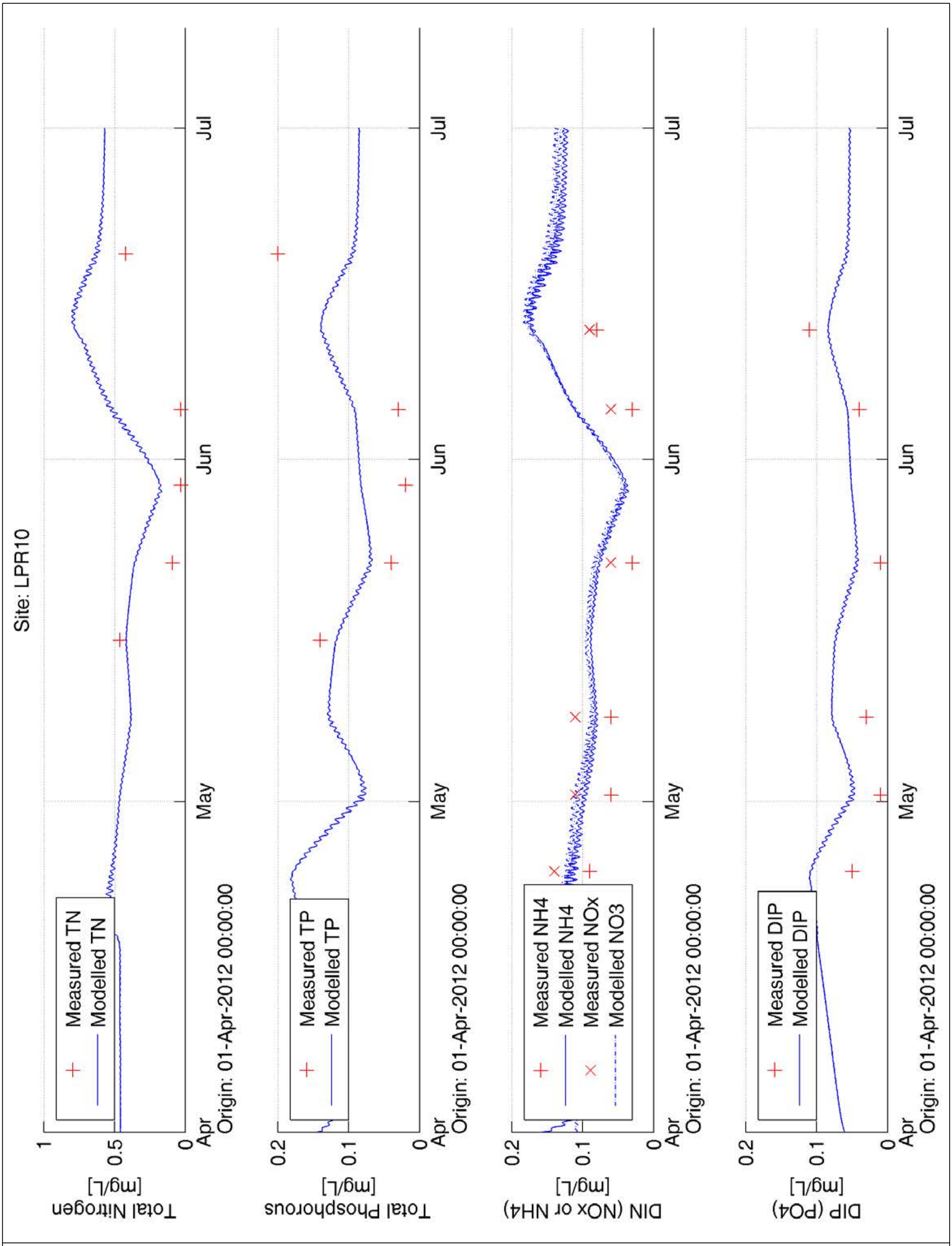
Figure 5.17b



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Apr−Jun 2012
Site: LPR10

Figure 5.18a

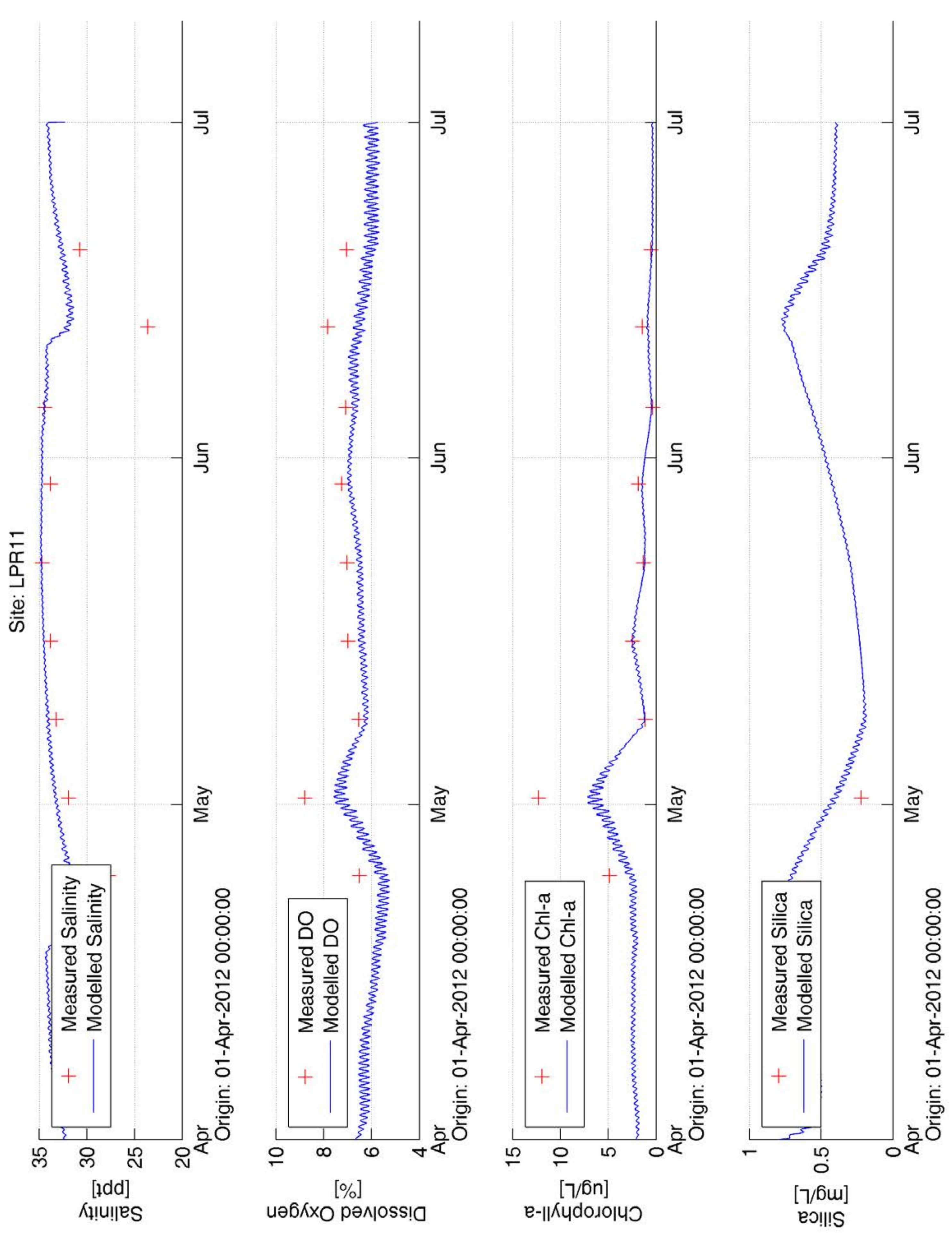


Sydney Harbour Ecological Response Model

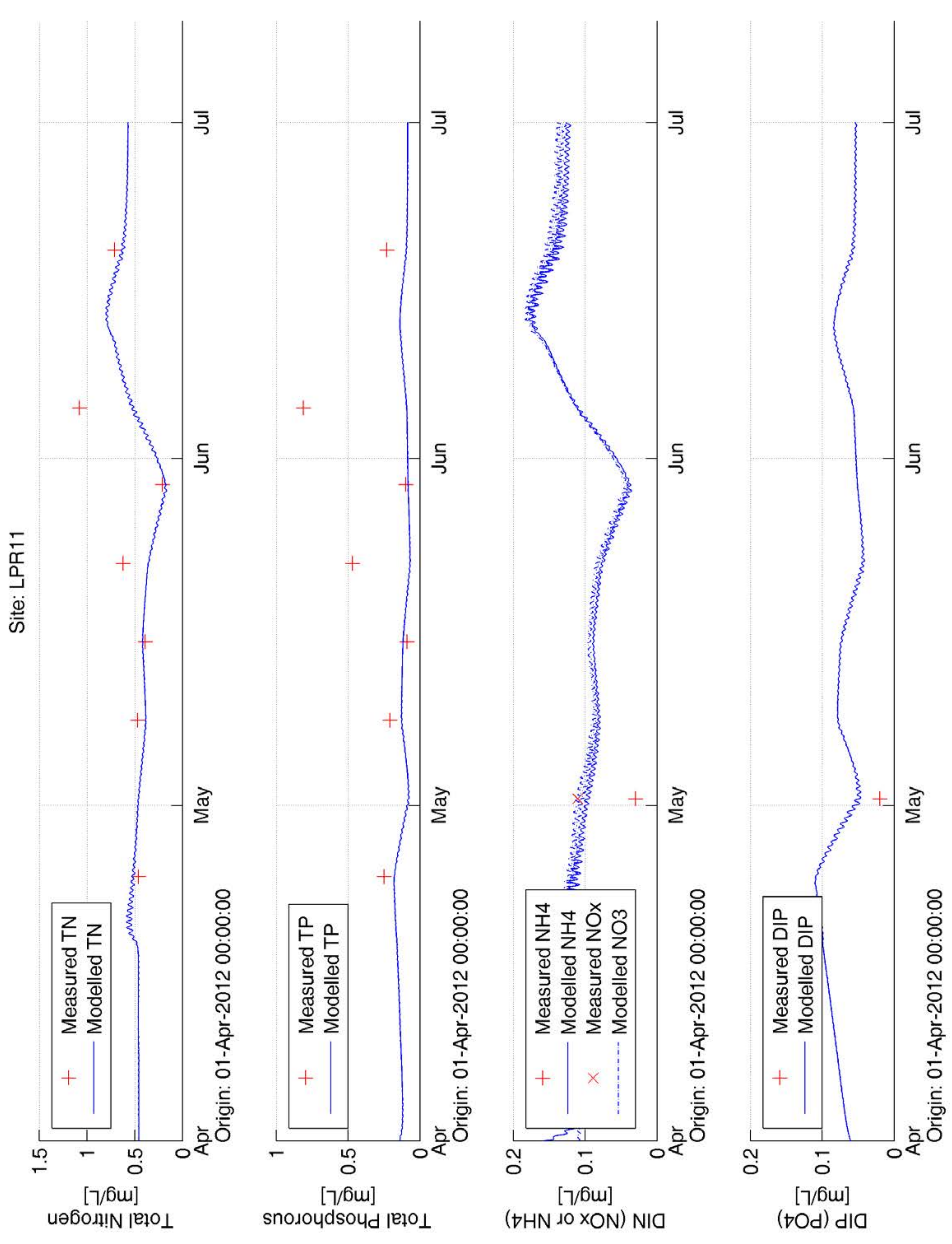
Water Quality Parameter Time−Series 3D Box Model: Apr−Jun 2012

Site: LPR10

Figure 5.18b



Sydney Harbour Ecological Response Model
Water Quality Parameter Time−Series 3D Box Model: Apr−Jun 2012
Site: LPR11
Figure 5.19a



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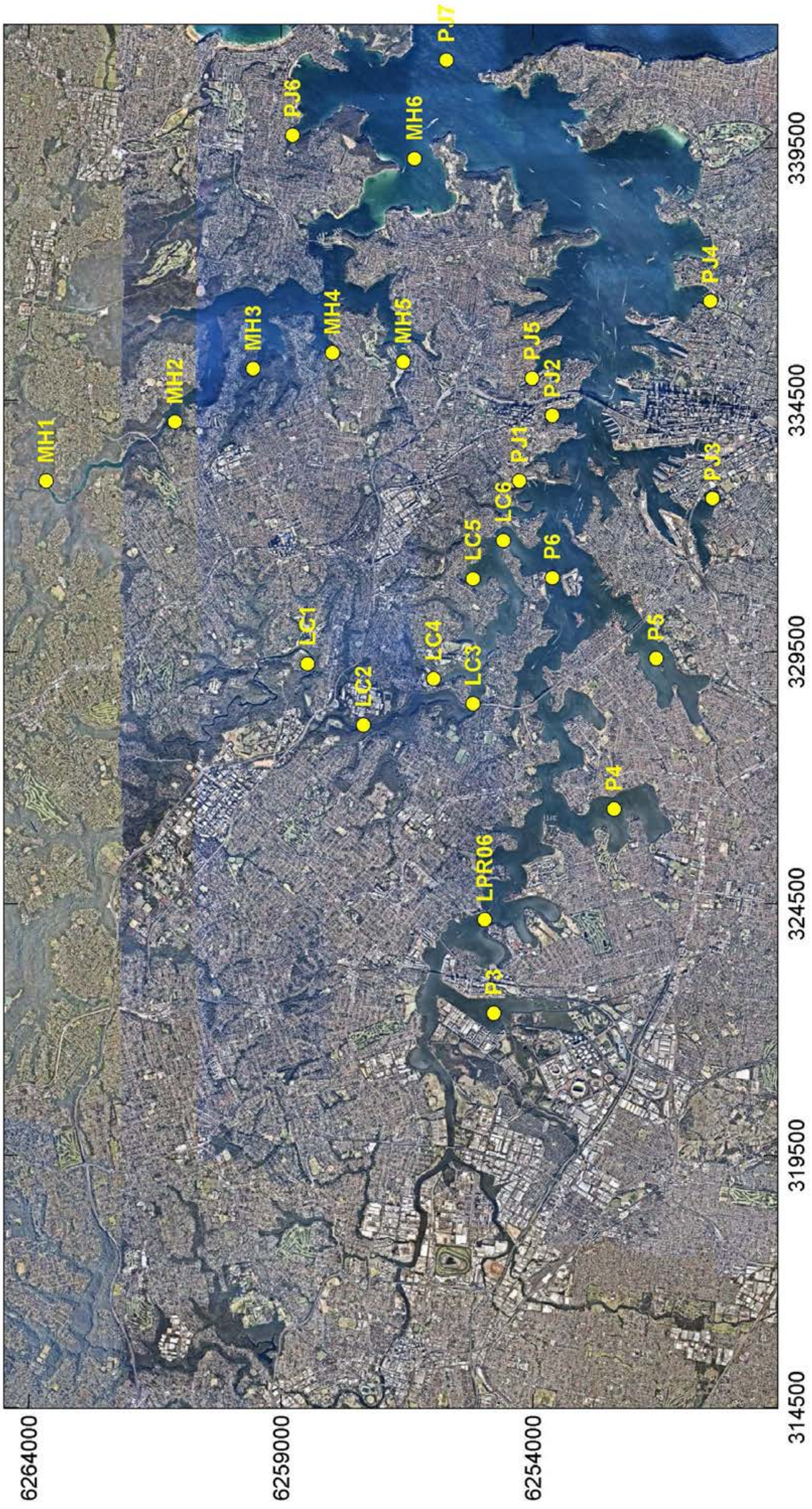
Sydney Harbour Ecological Response Model
Water Quality Parameter Time−Series 3D Box Model: Apr−Jun 2012
Site: LPR11

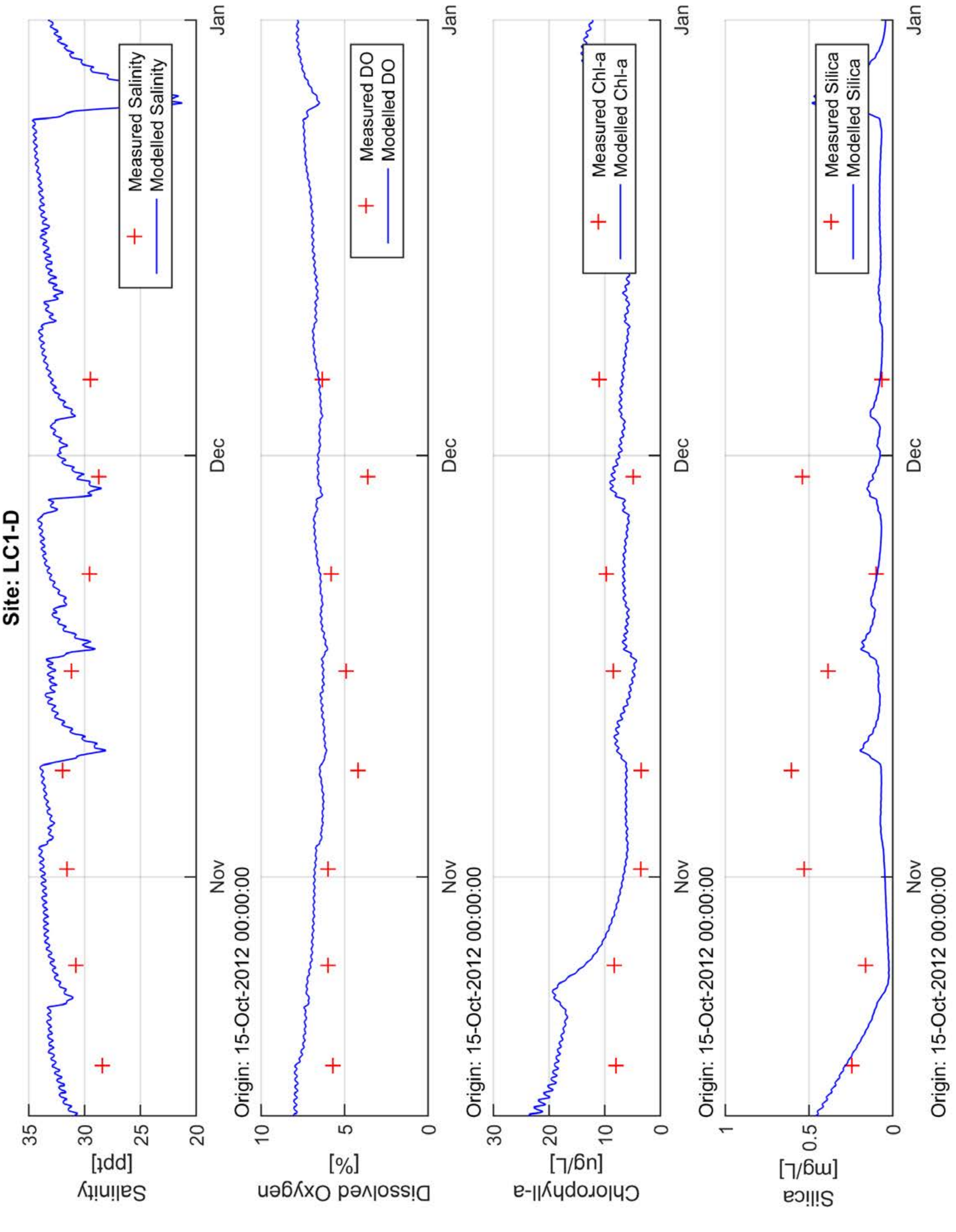
Figure 5.19b



Sydney Harbour Ecological Response Model

Sydney Harbour Weekly Sampling Sites
Oct−Dec 2012

Figure 5.20



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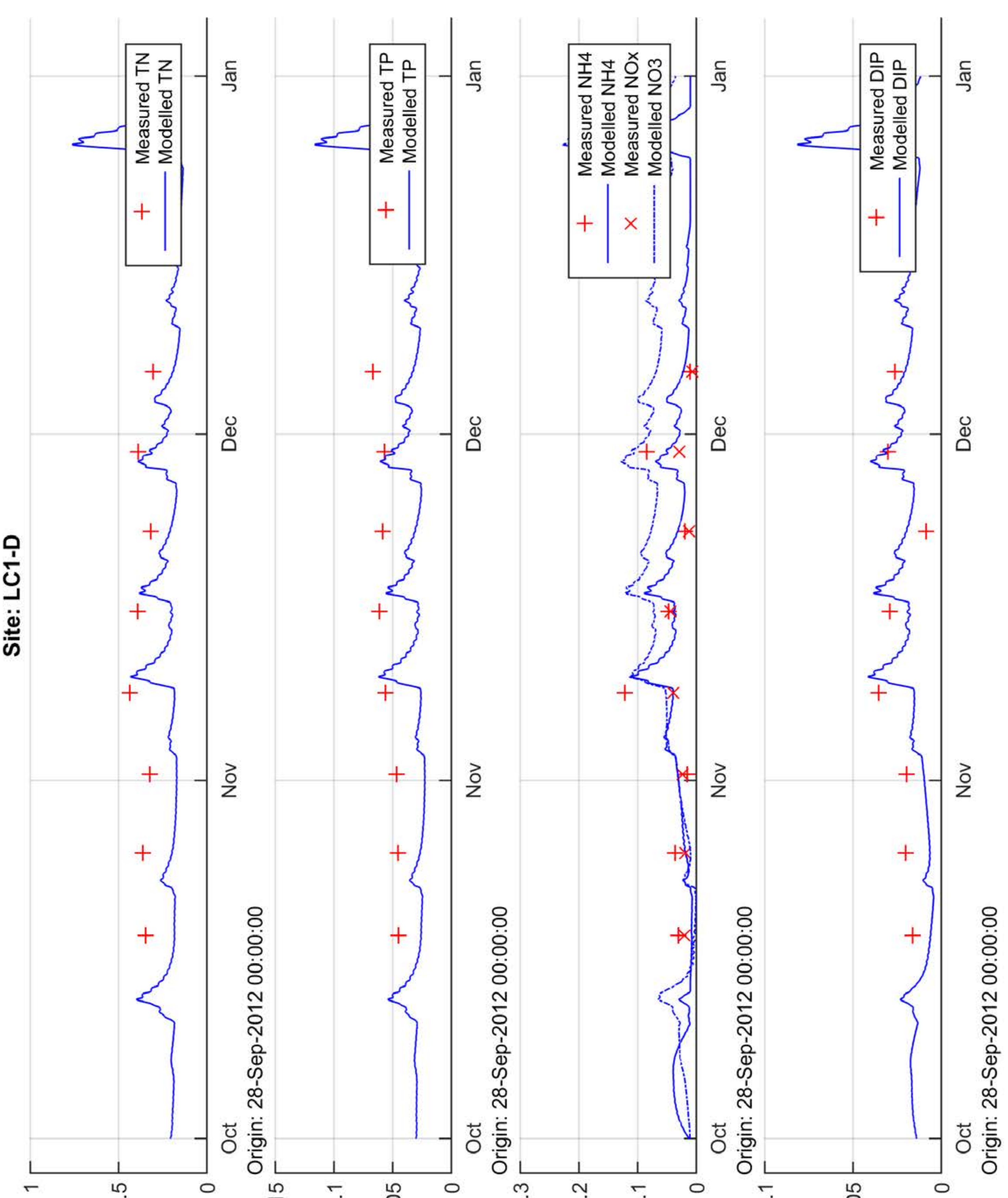
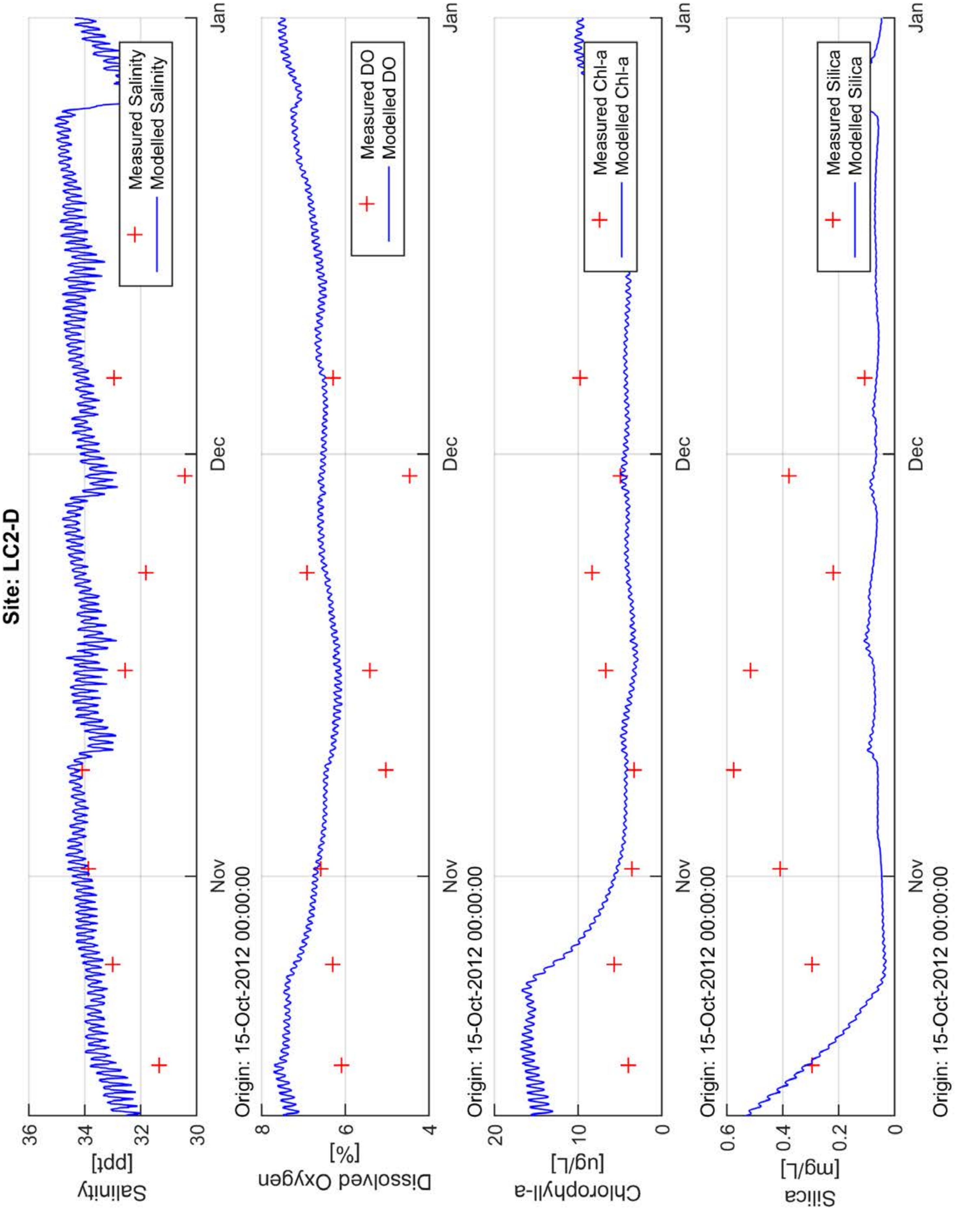
Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: LC1

Figure 5.21a



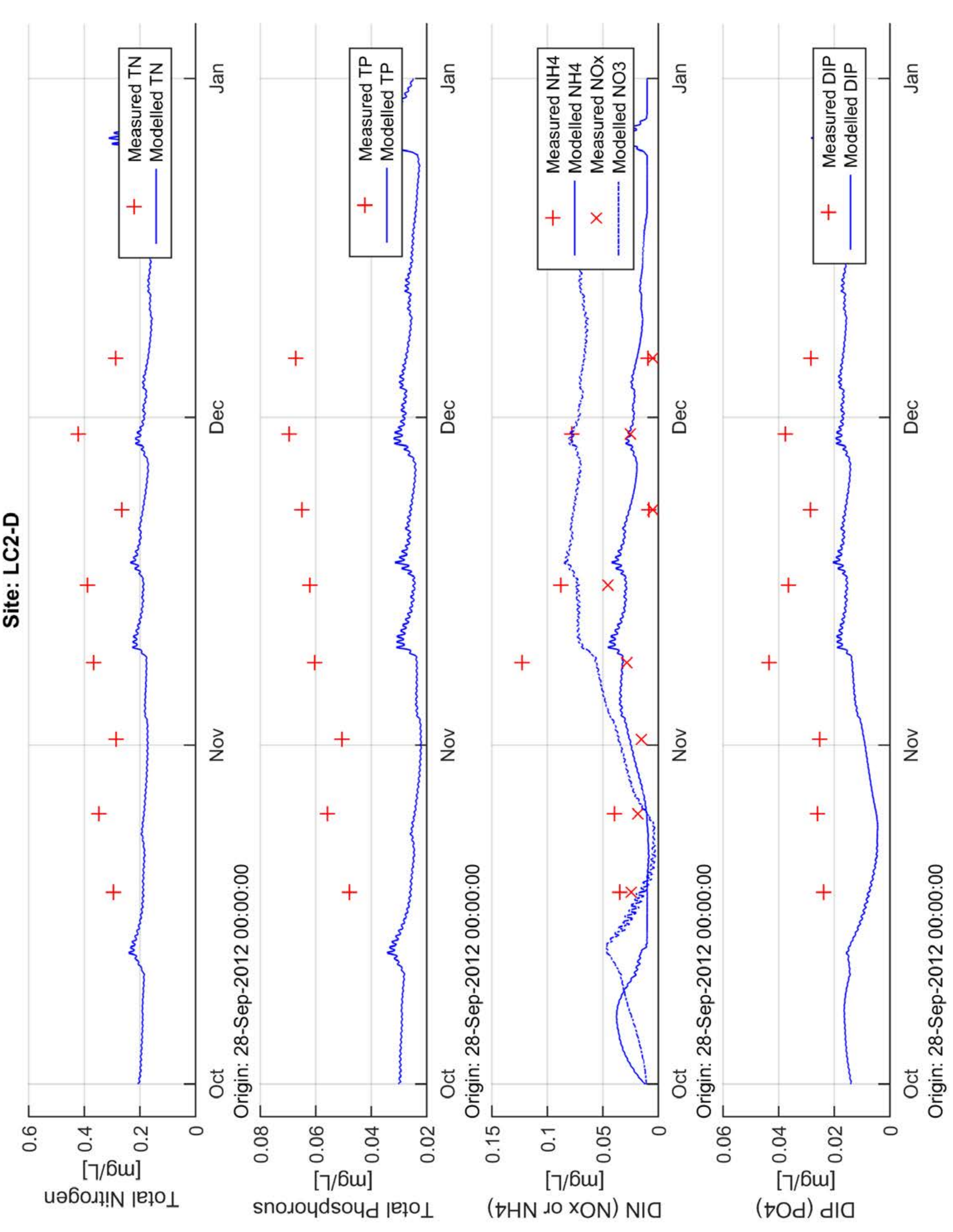
Sydney Harbour Ecological Response Model
Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: LC1
Figure 5.21b



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: LC2

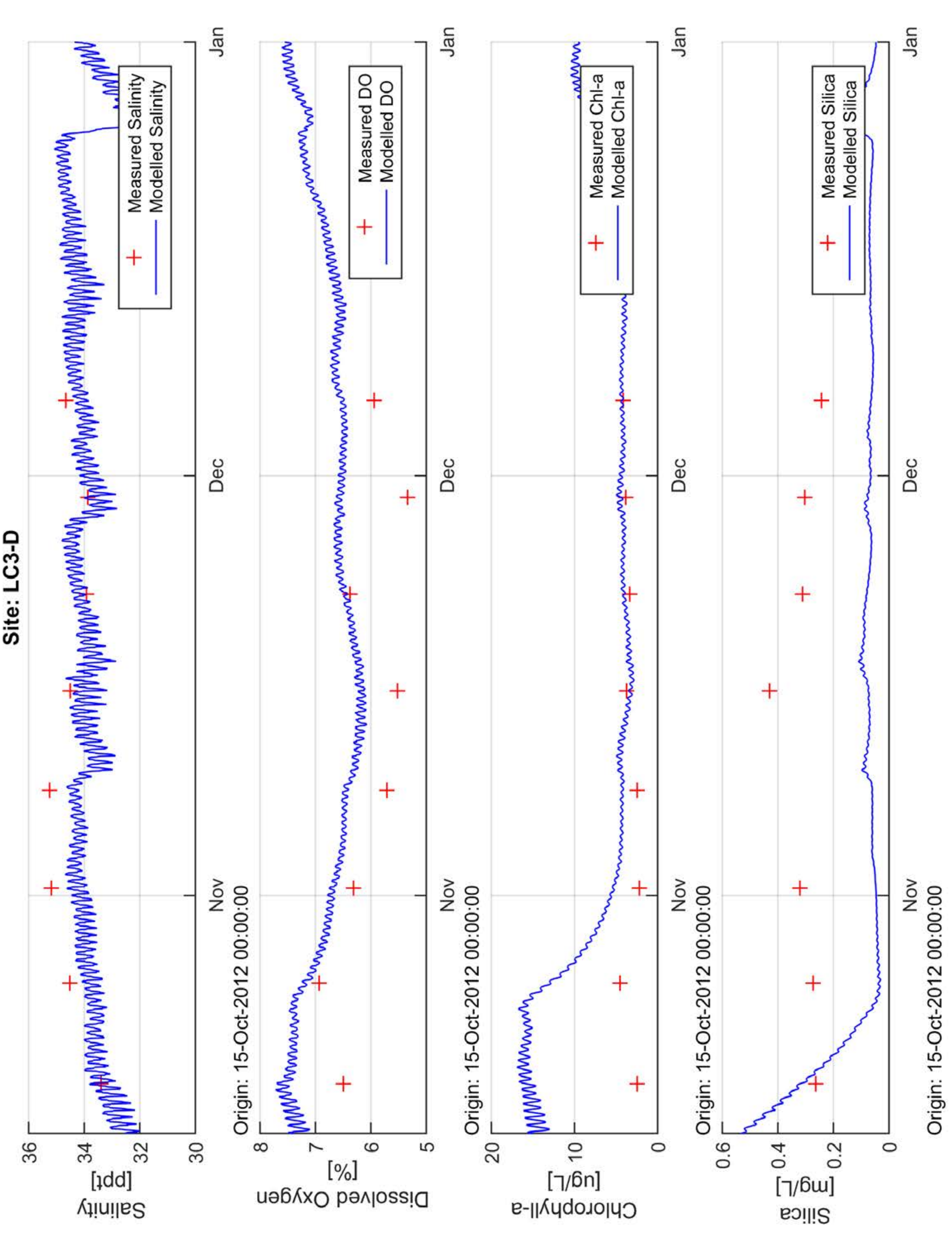
Figure 5.22a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: LC2

Figure 5.22b

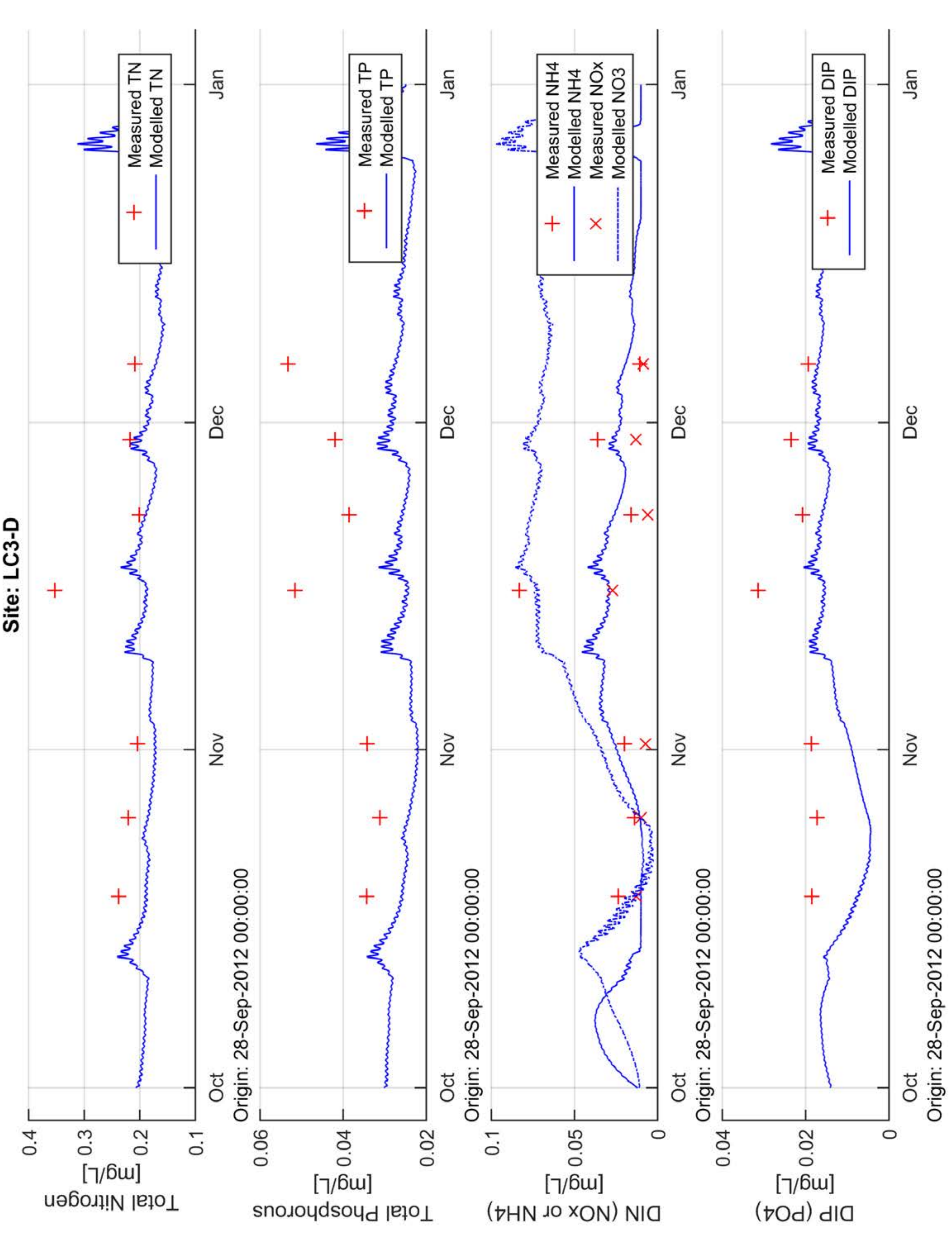


Cardno

Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: LC3

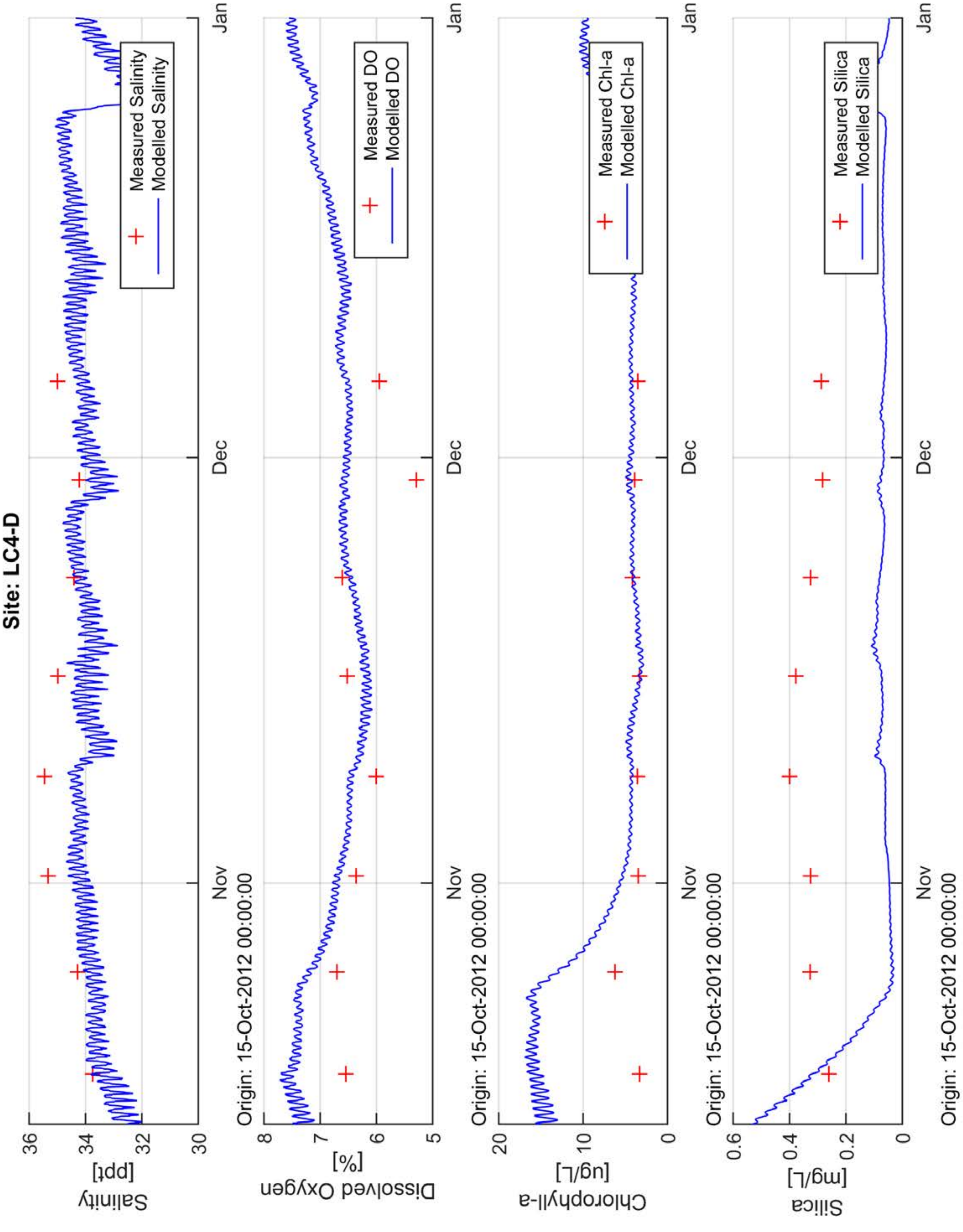
Figure 5.23a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: LC3

Figure 5.23b



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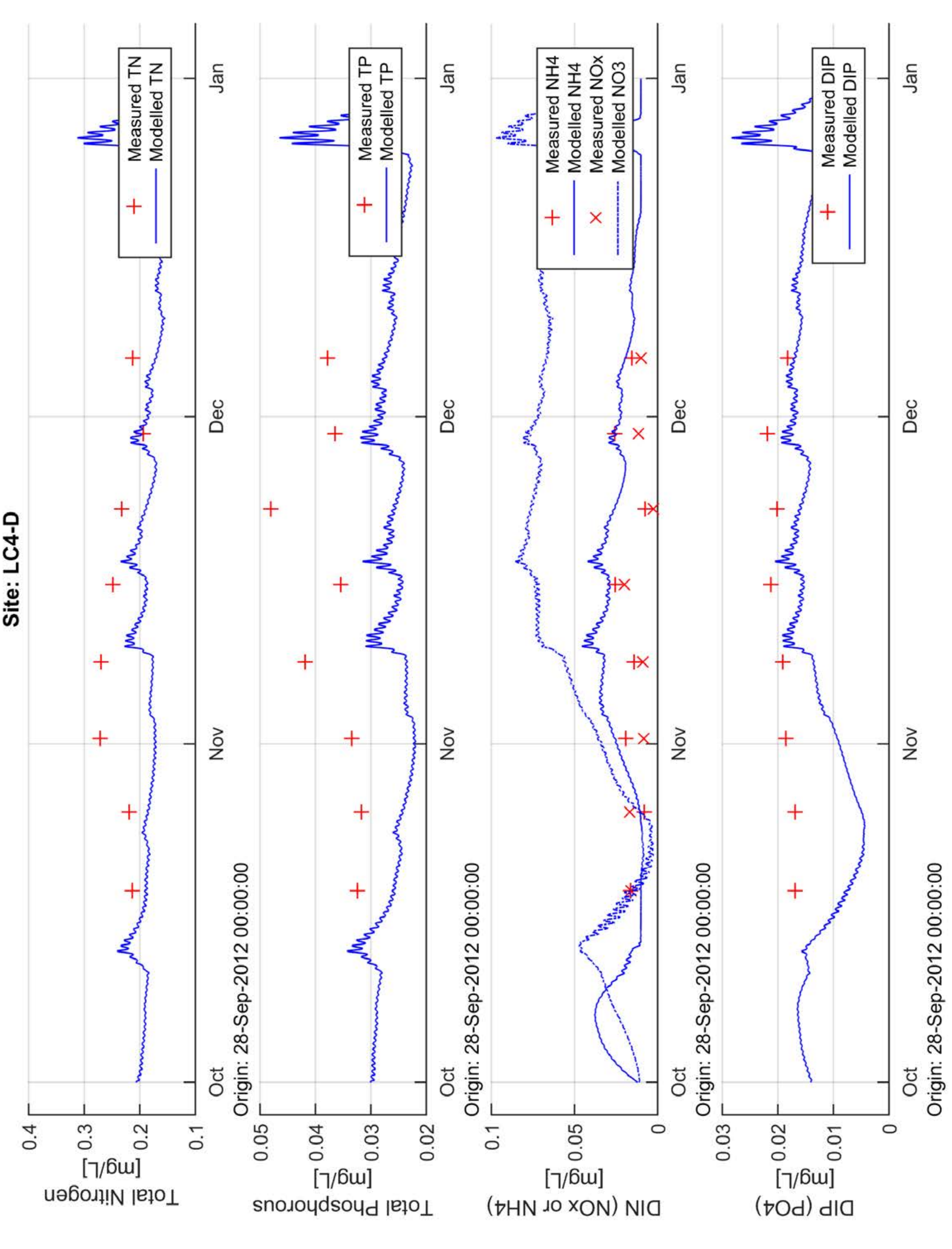
Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: LC4

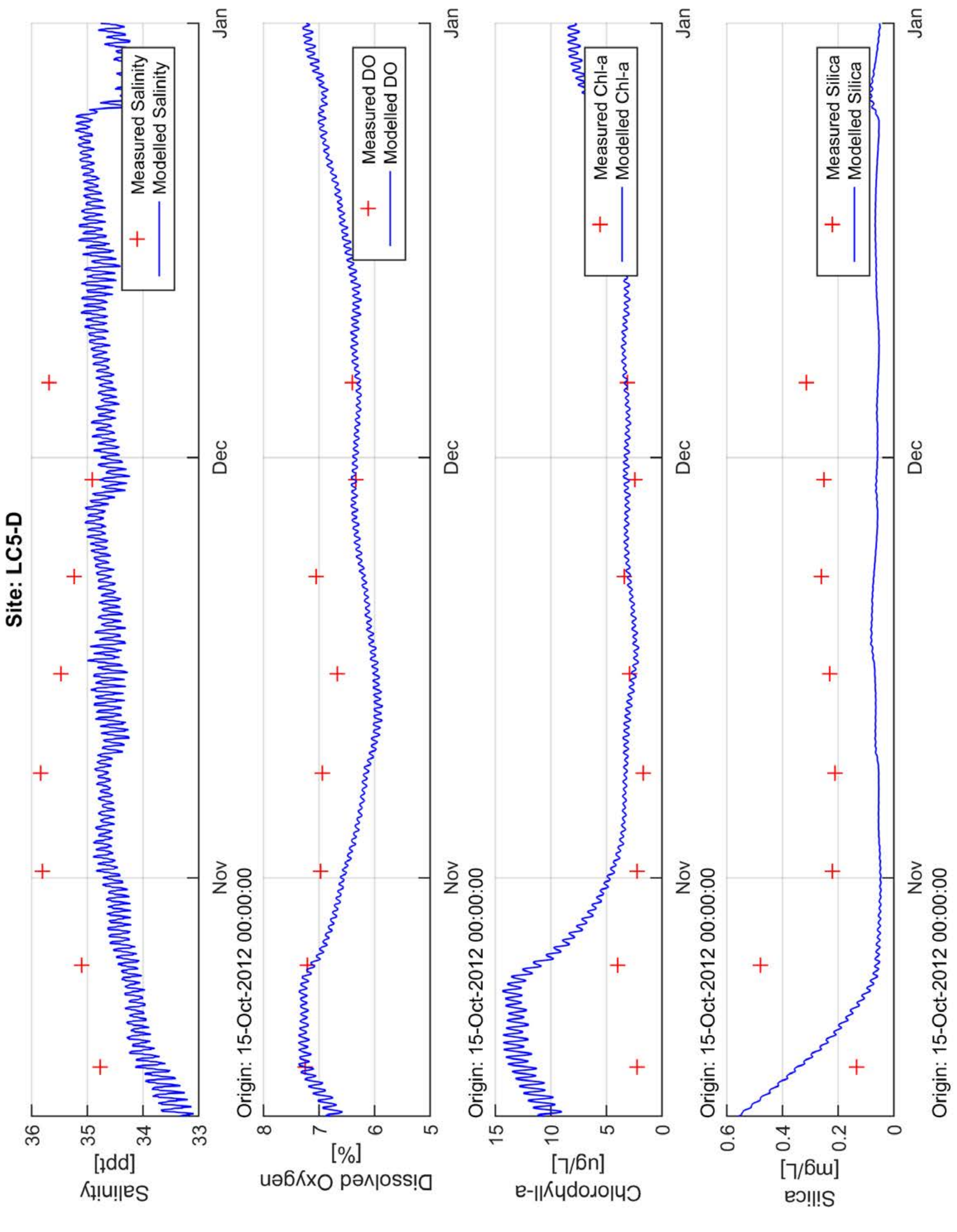
Figure 5.24a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: LC4

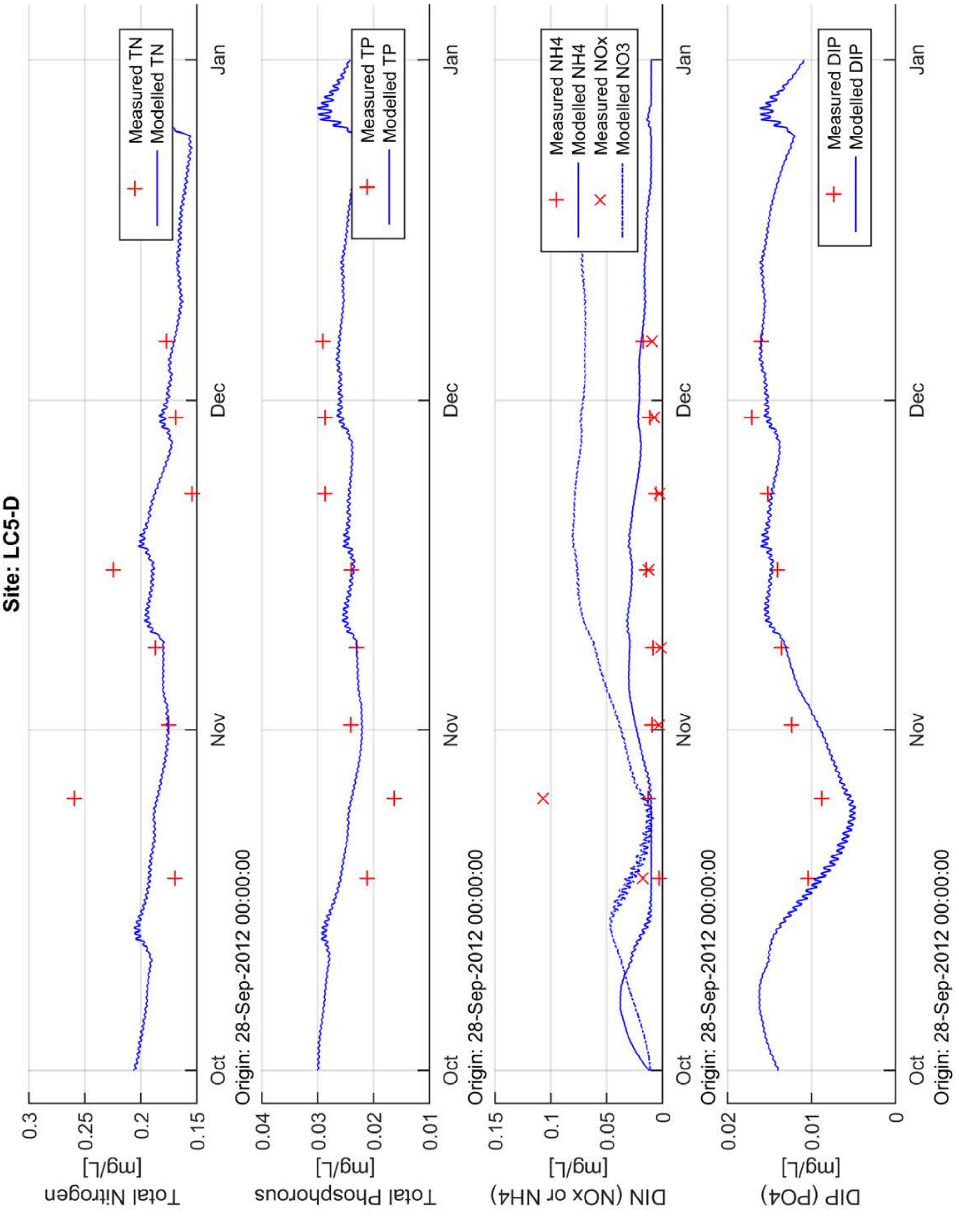
Figure 5.24b



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: LC5

Figure 5.25a



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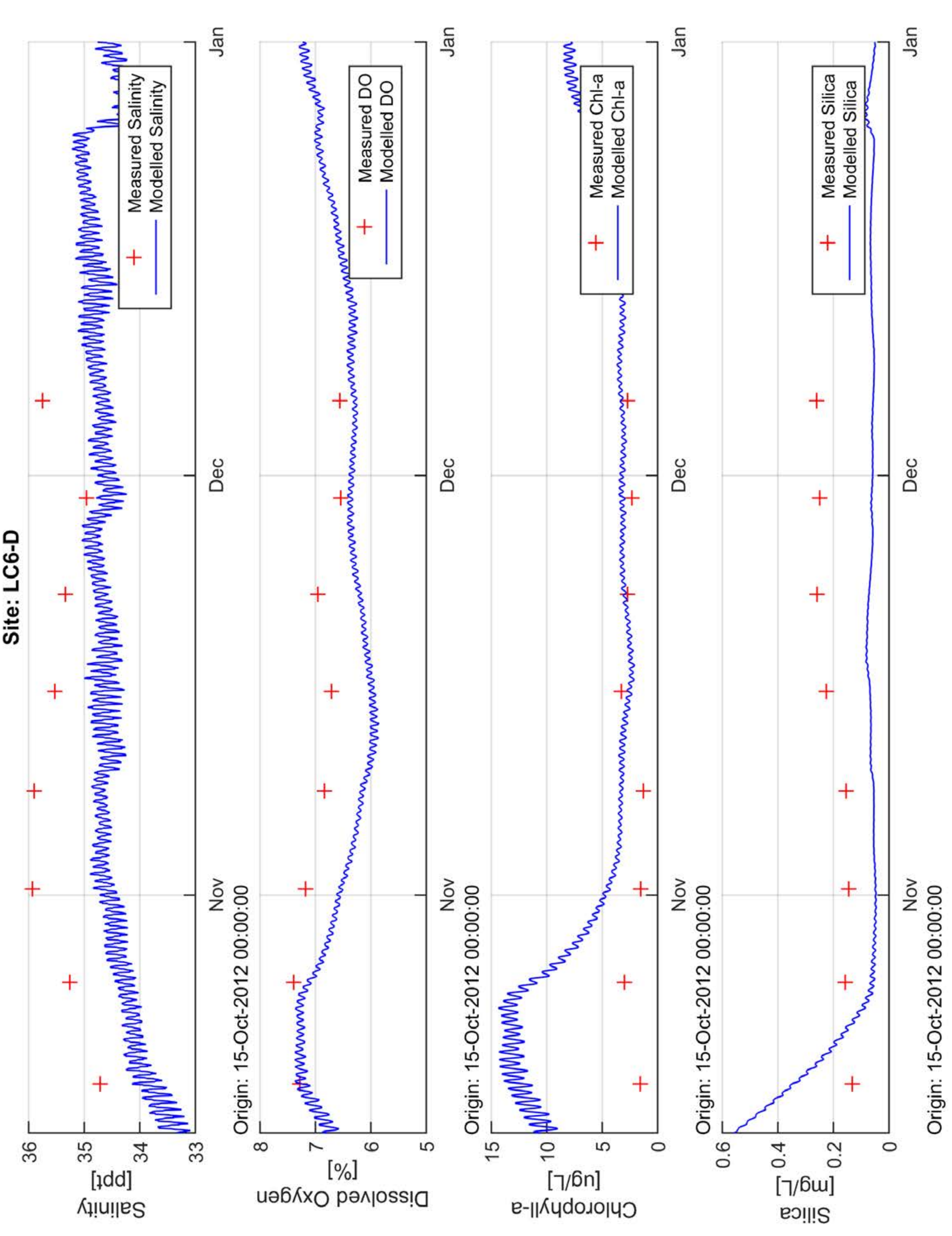
Sydney Harbour Ecological Response Model
Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: LC5

Figure 5.25b



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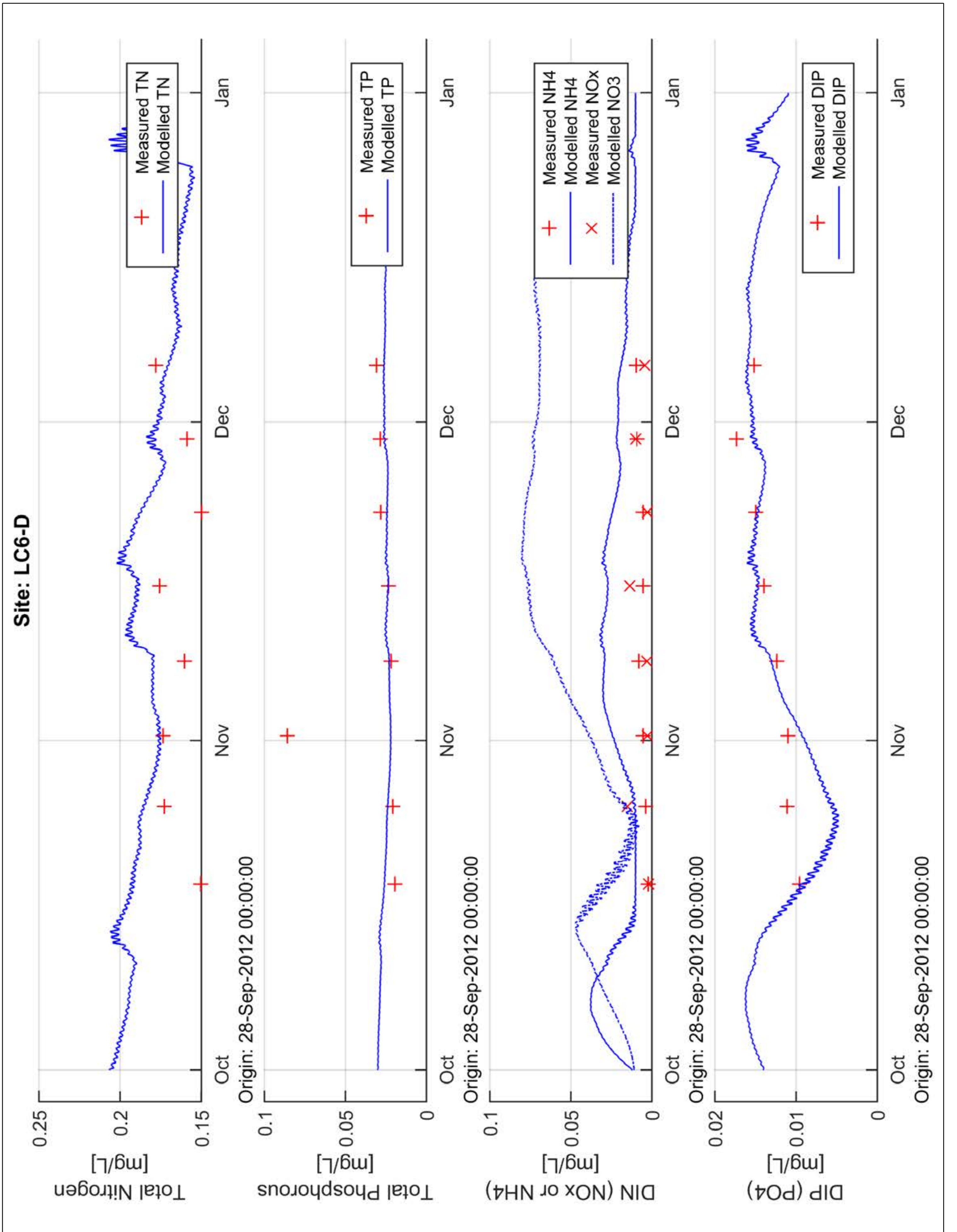
Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: LC6

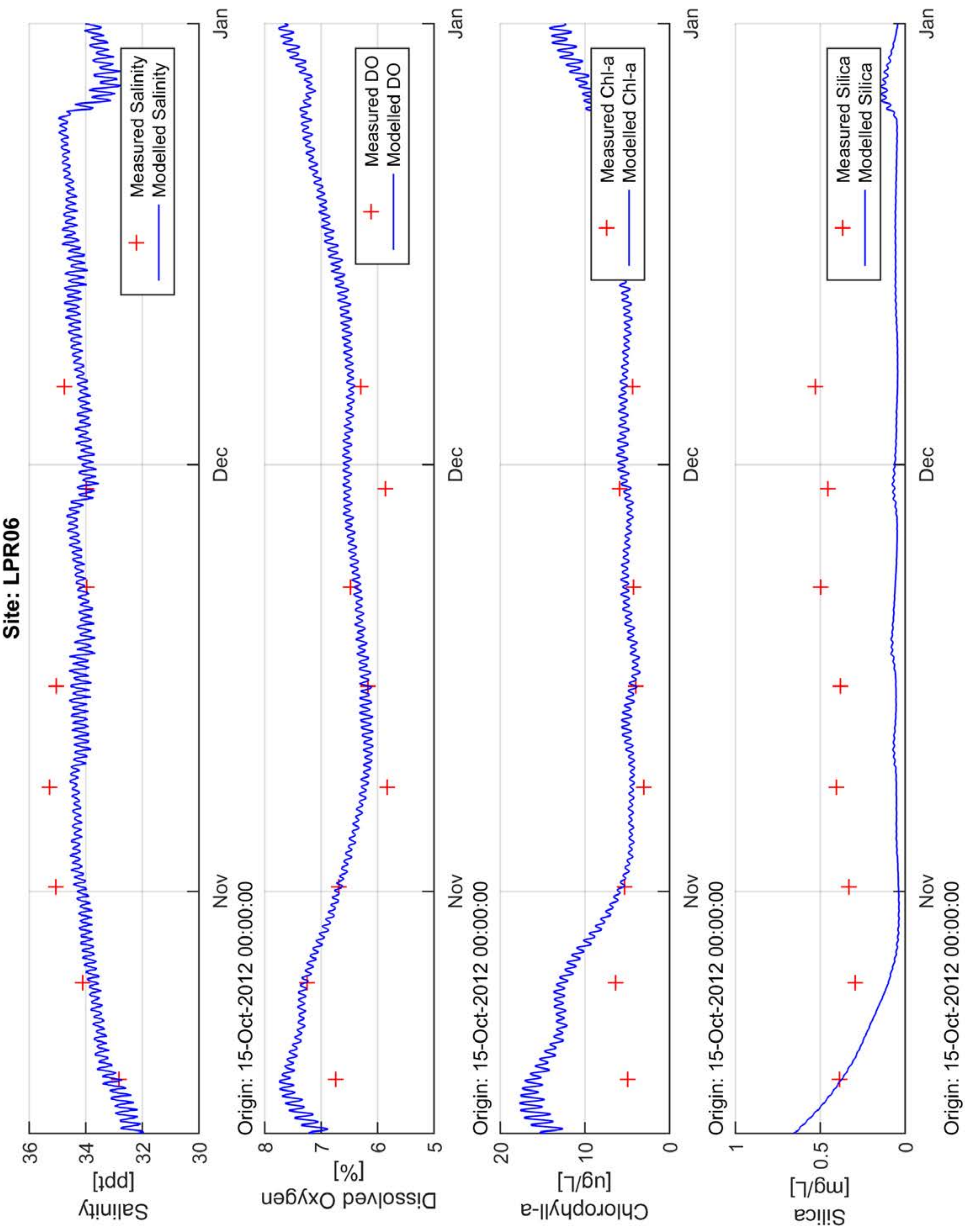
Figure 5.26a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: LC6

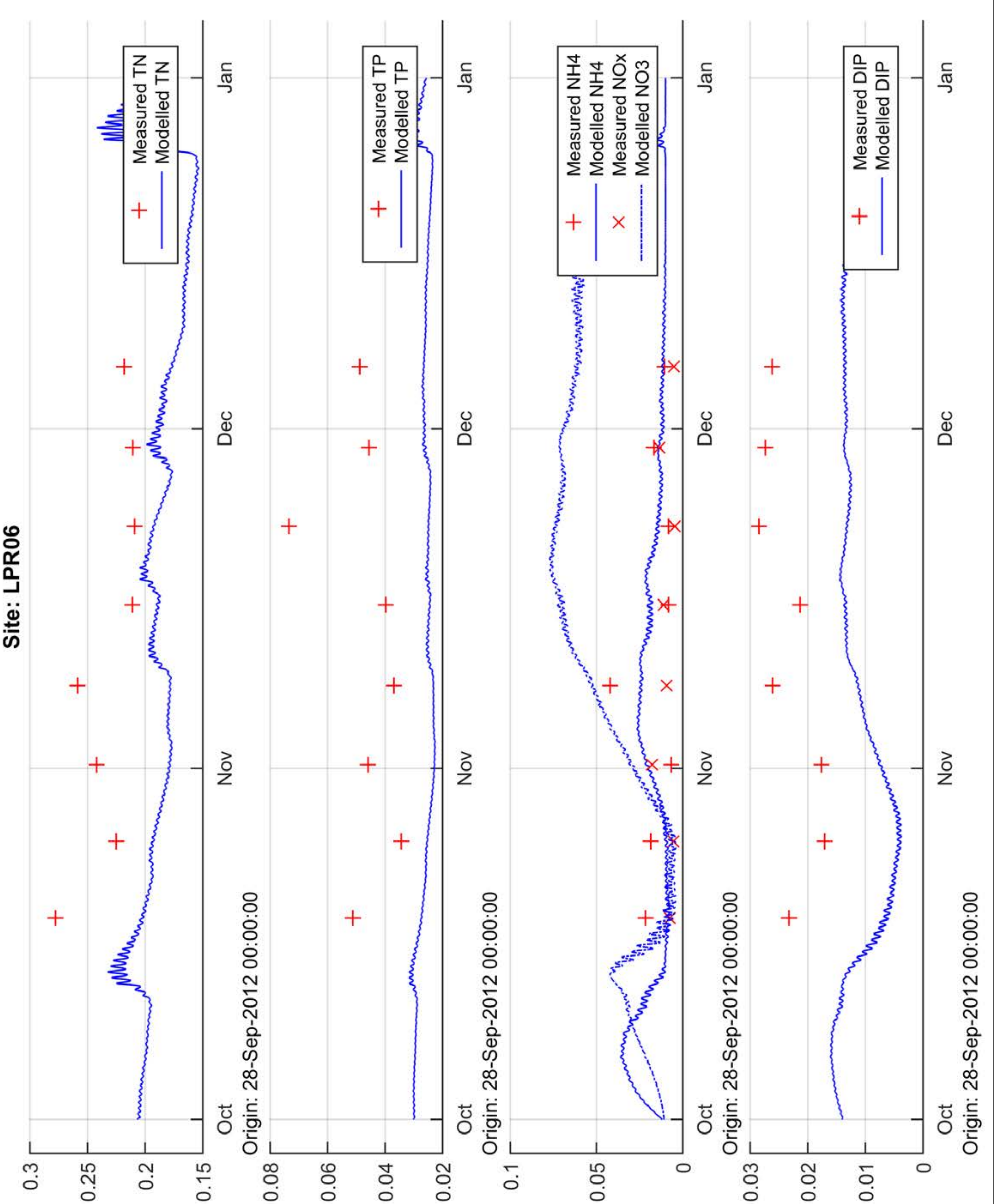
Figure 5.26b



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: LPR06

Figure 5.27a



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Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012

DYNAMO Model − Site: LPR06

Figure 5.27b

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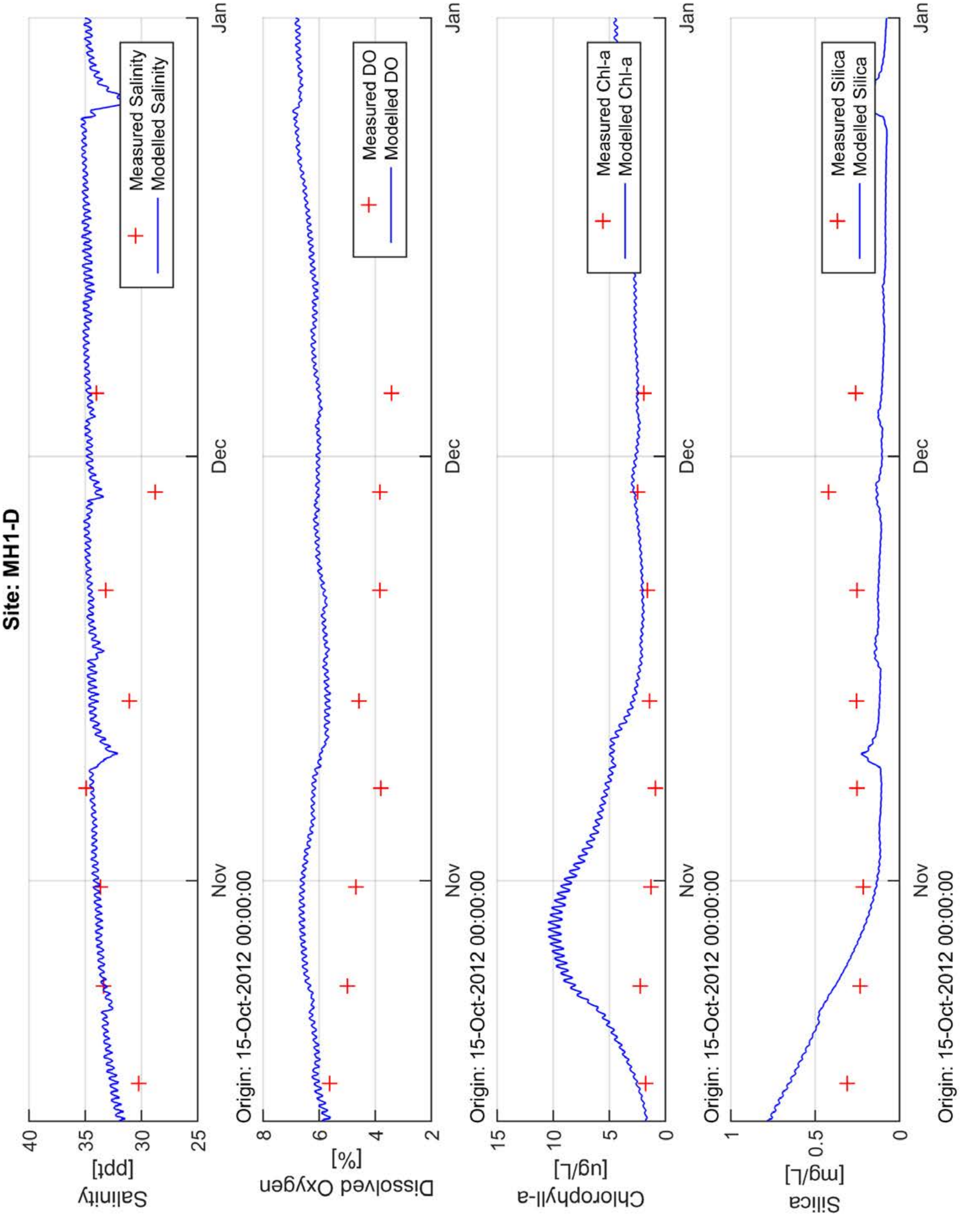
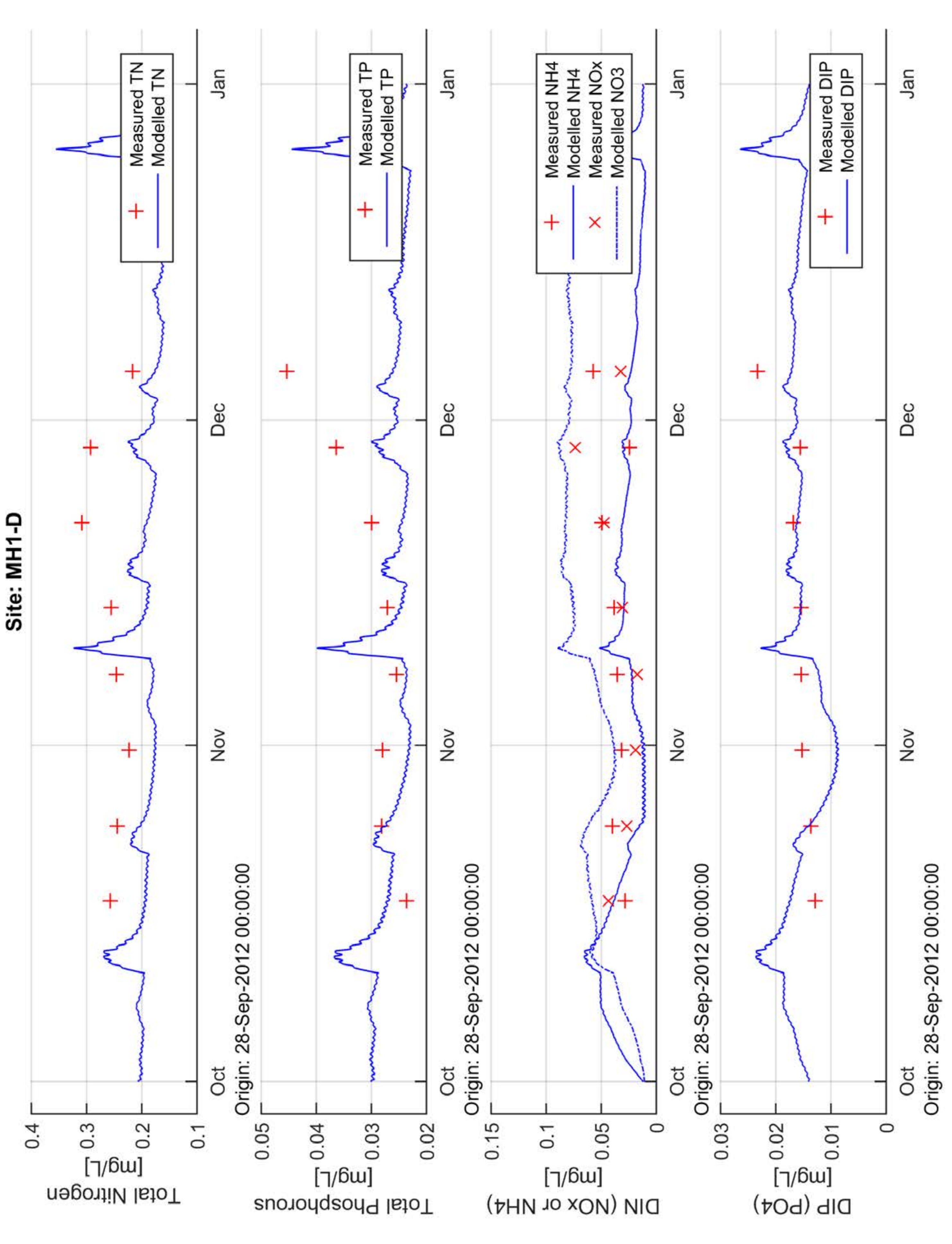


Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: MH1

Figure 5.28a

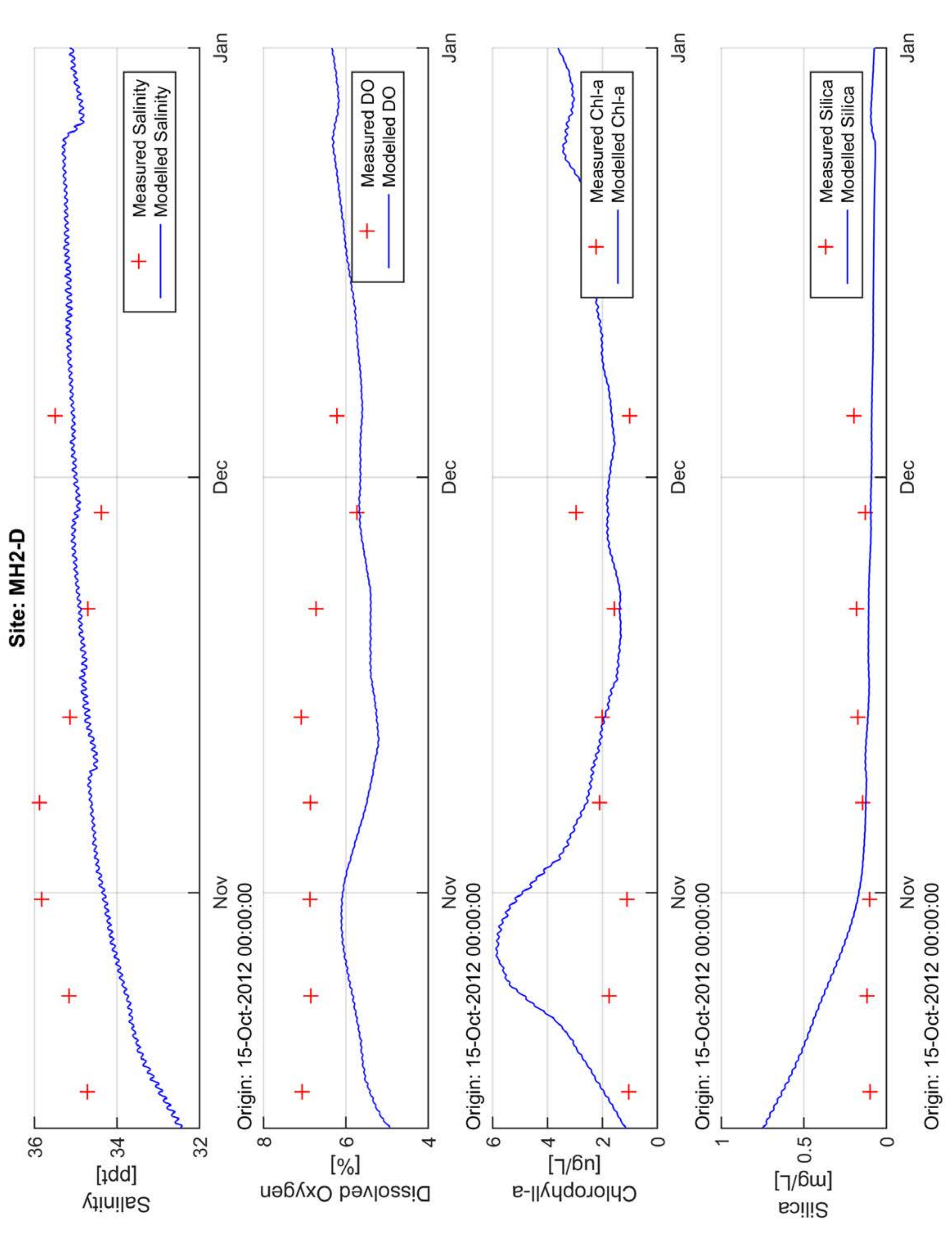


Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012

DYNAMO Model − Site: MH1

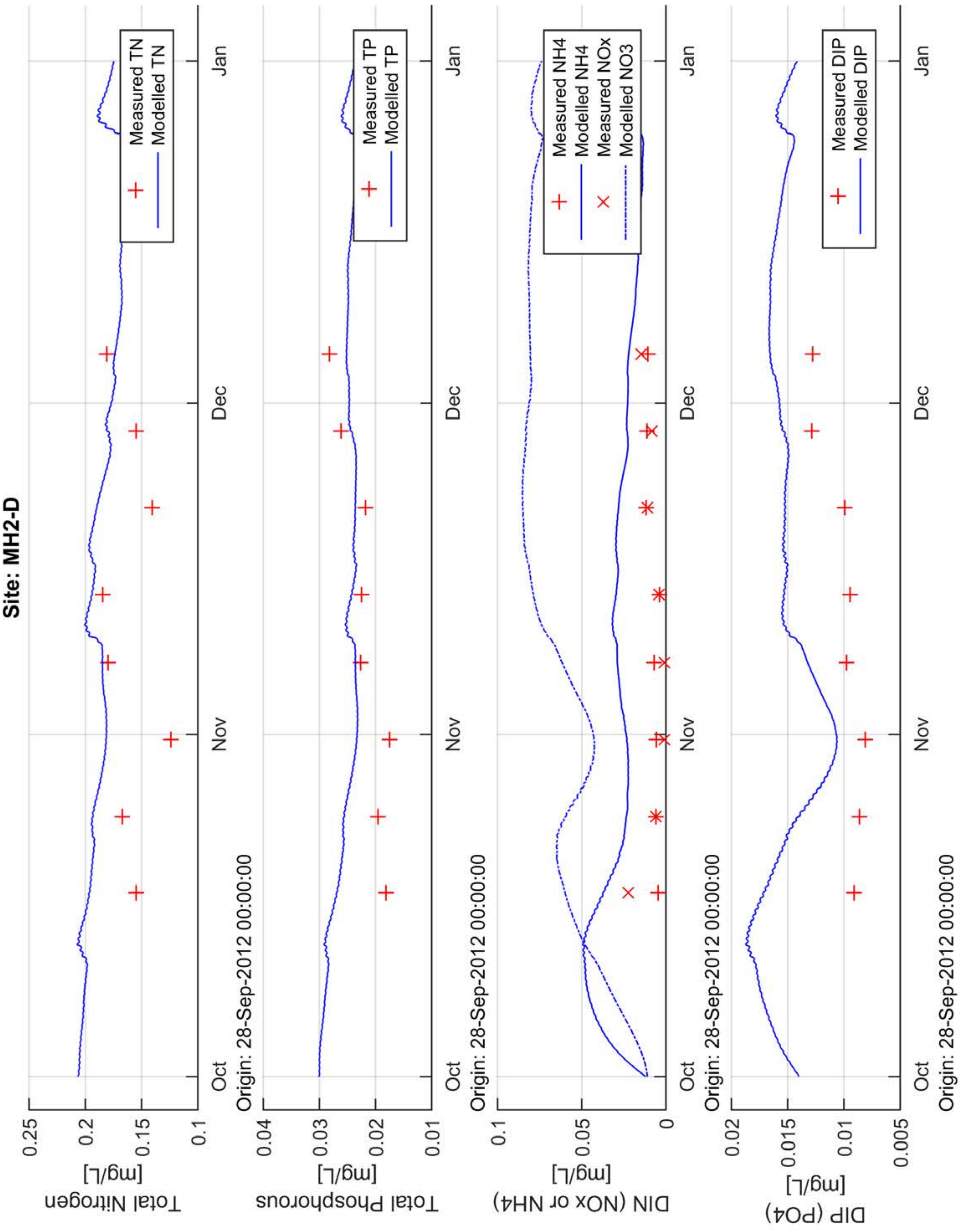
Figure 5.28b



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: MH2

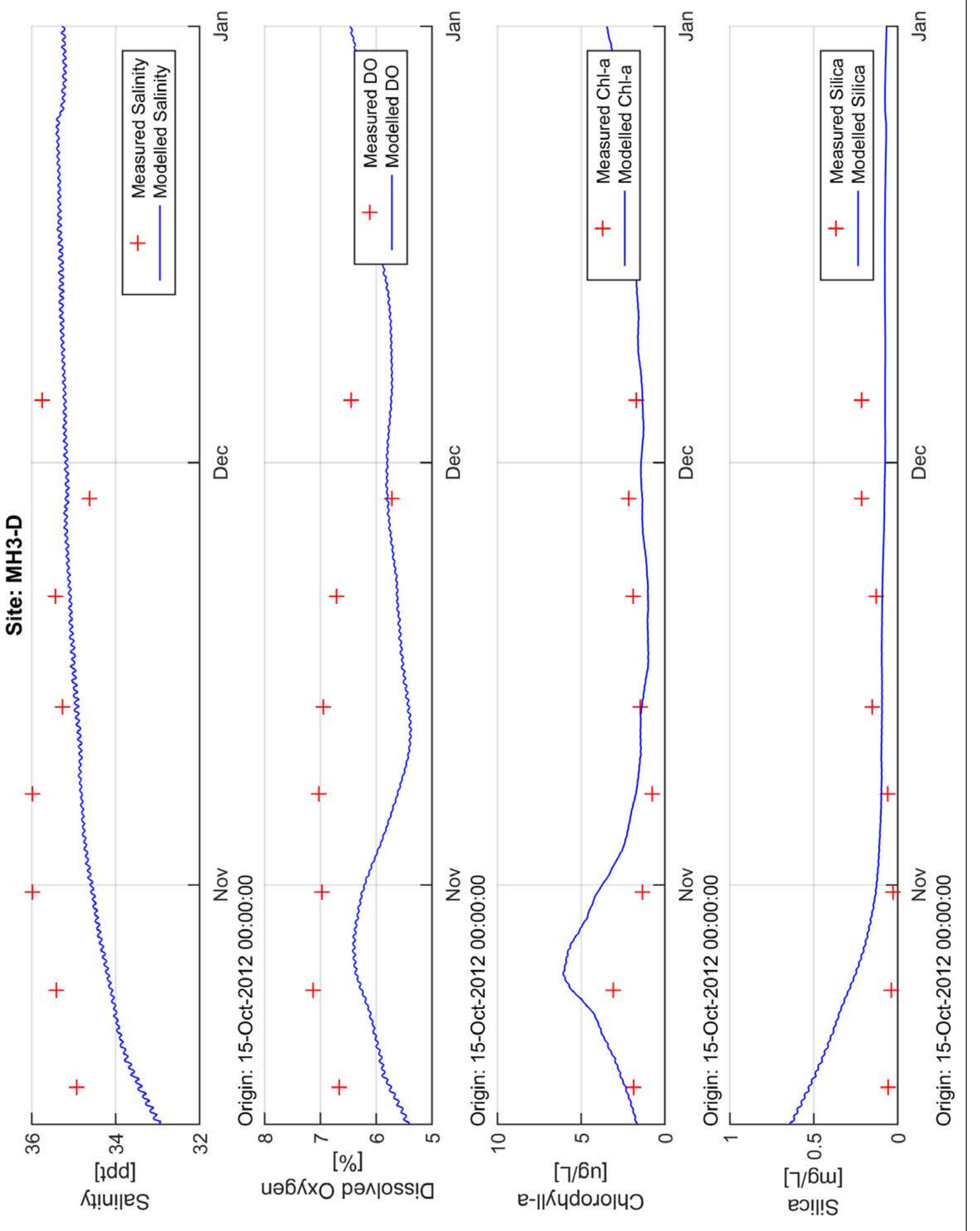
Figure 5.29a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: MH2

Figure 5.29b



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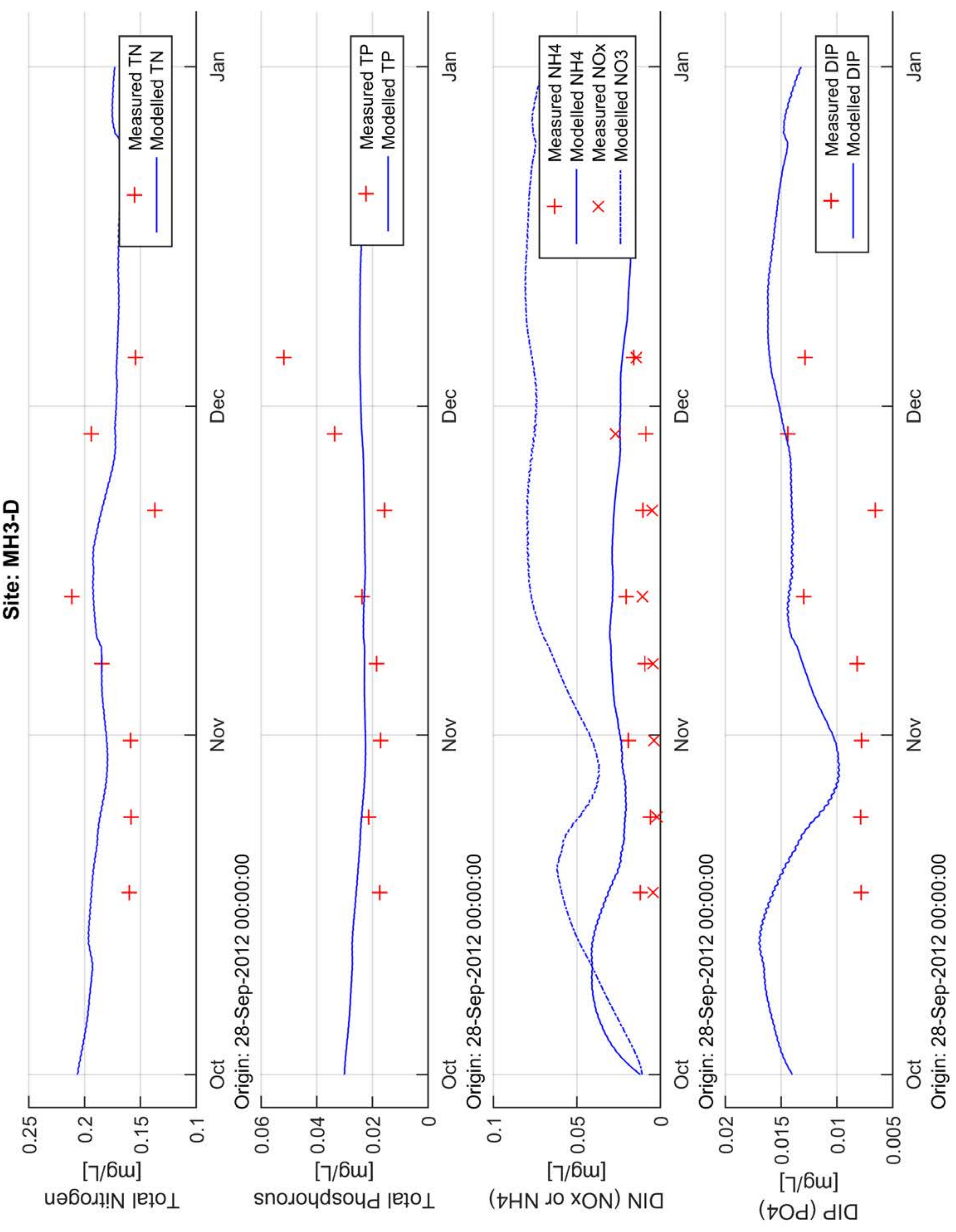
Sydney Harbour Ecological Response Model

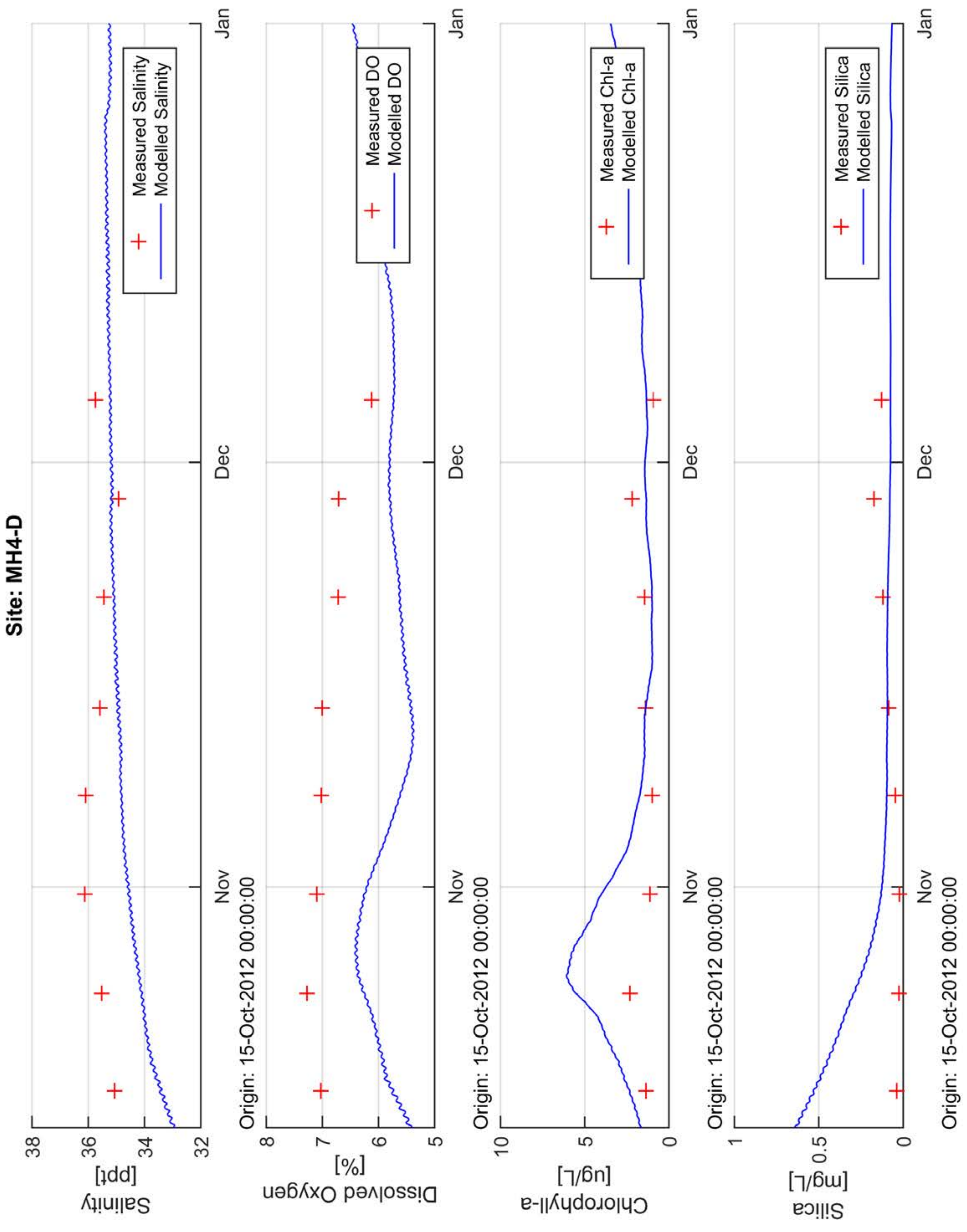
Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: MH3

Figure 5.30a



Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: MH3

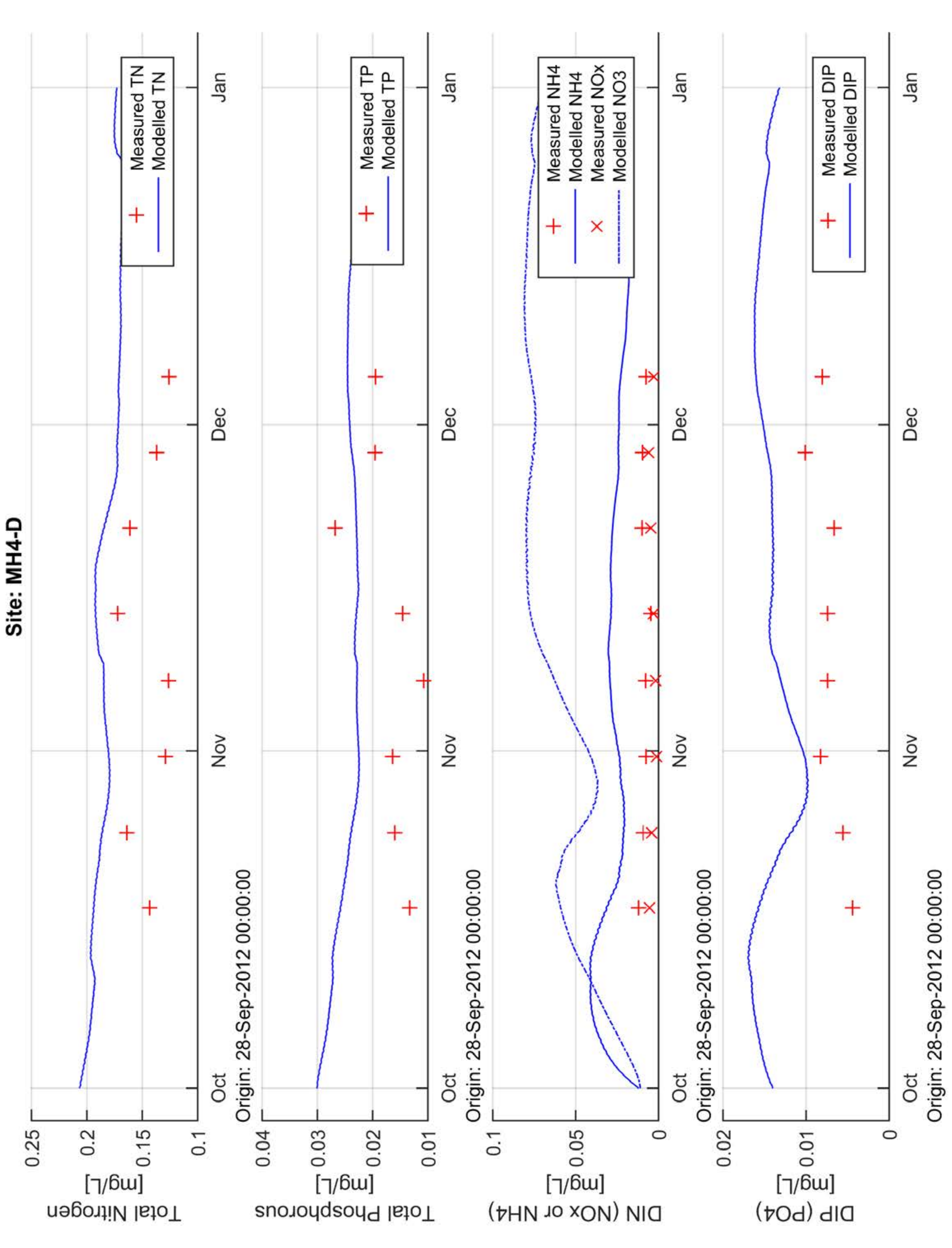
Figure 5.30b



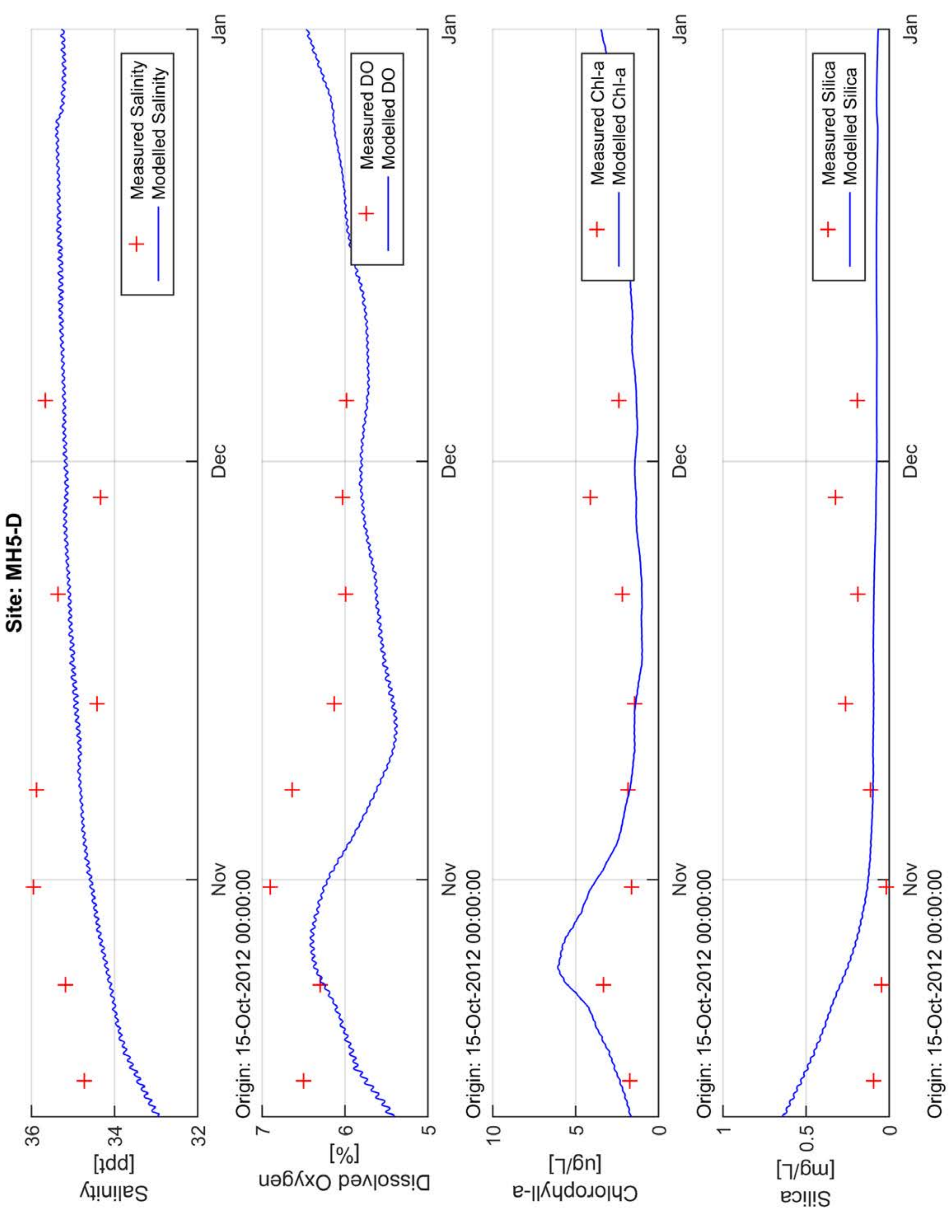
Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: MH4

Figure 5.31a



Site: MH4-D
Total Nitrogen [mg/L]
Measured TN
Modelled TN
Total Phosphorous [mg/L]
Measured TP
Modelled TP
DIN (NOx or NH4) [mg/L]
Measured NH4
Modelled NH4
Measured NOx
Modelled NO3
DIP (PO4) [mg/L]
Measured DIP
Modelled DIP
Oct
Nov
Dec
Jan
Origin: 28-Sep-2012 00:00:00



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: MH5

Figure 5.32a

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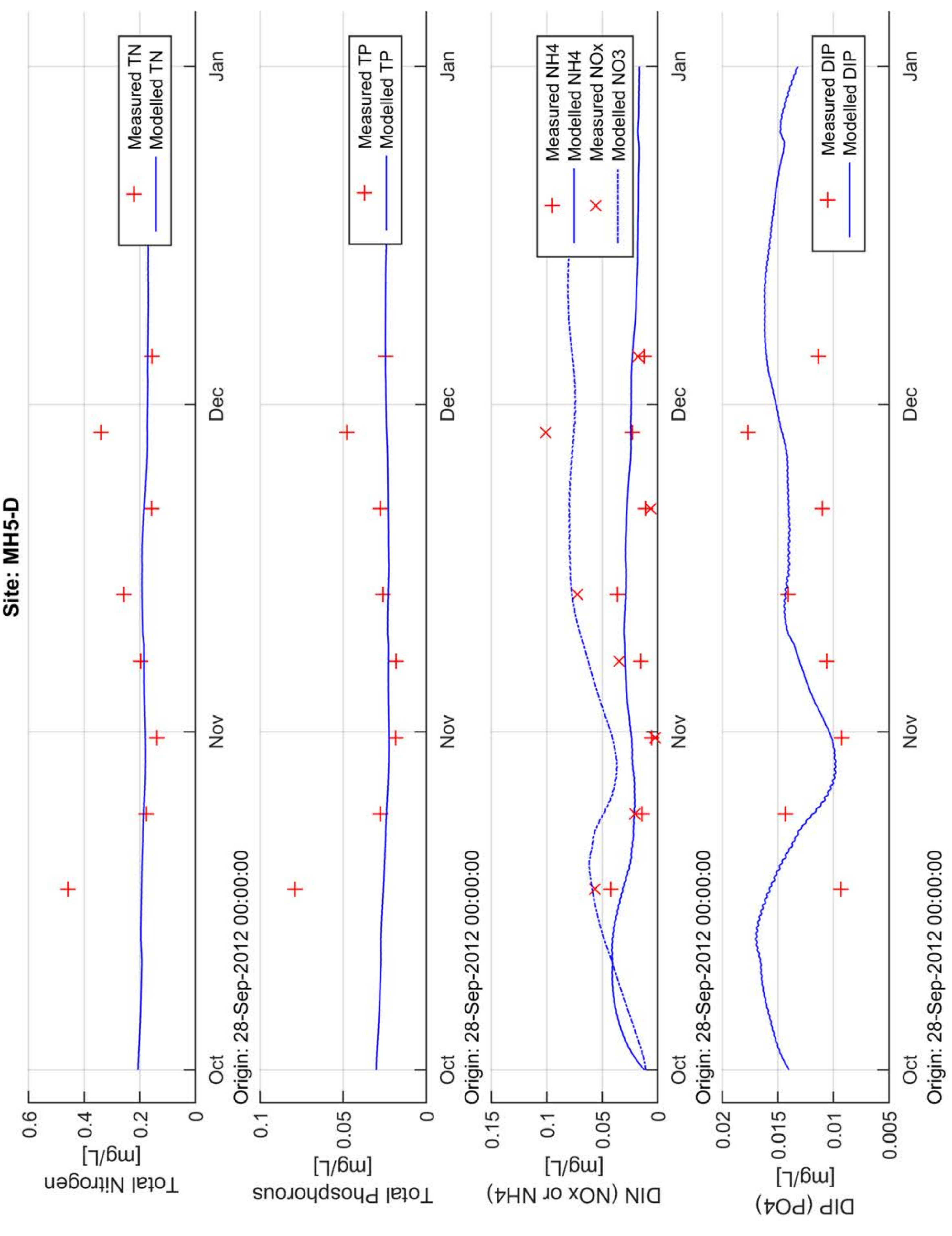
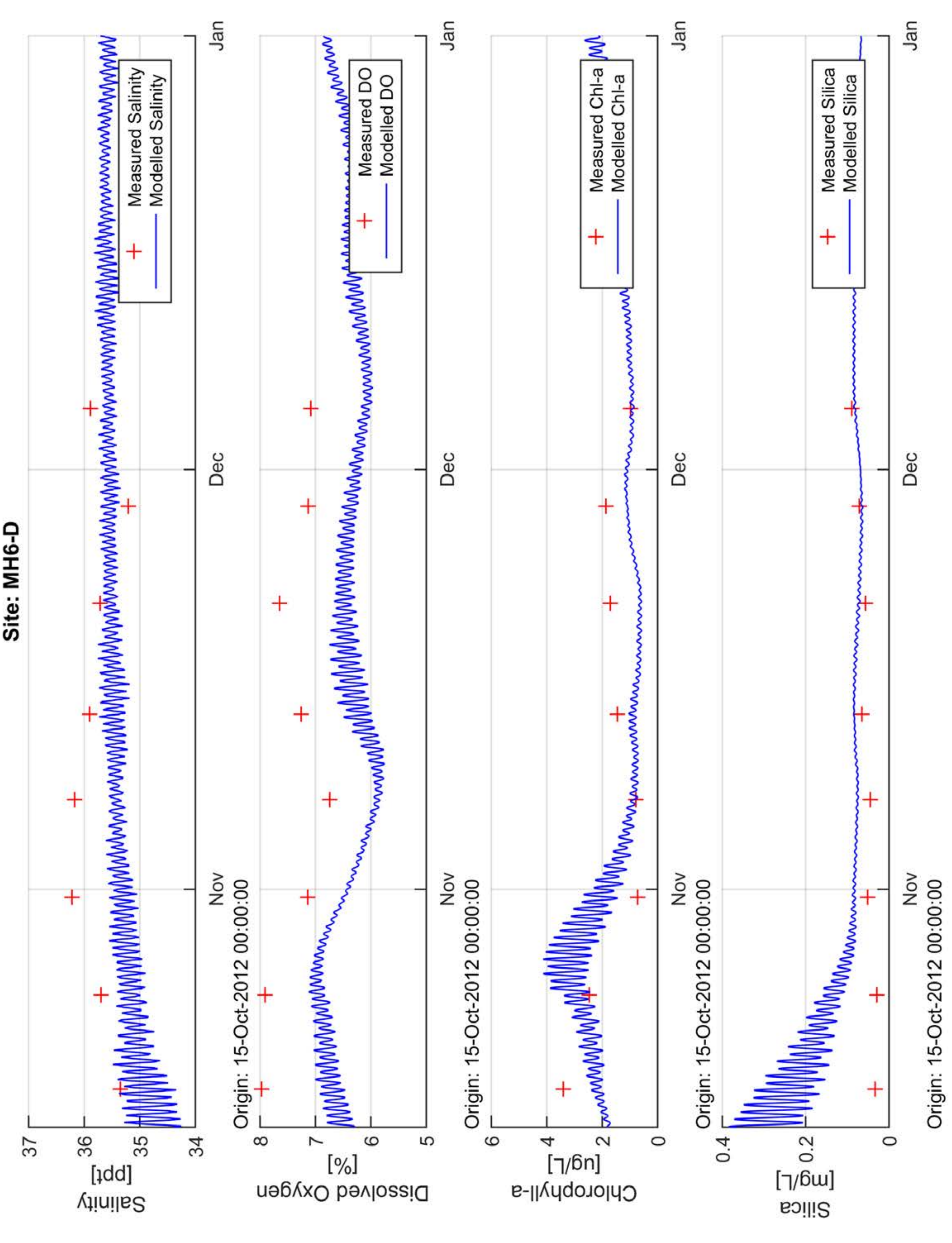


Sydney Harbour Ecological Response Model
Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: MH5

Figure 5.32b



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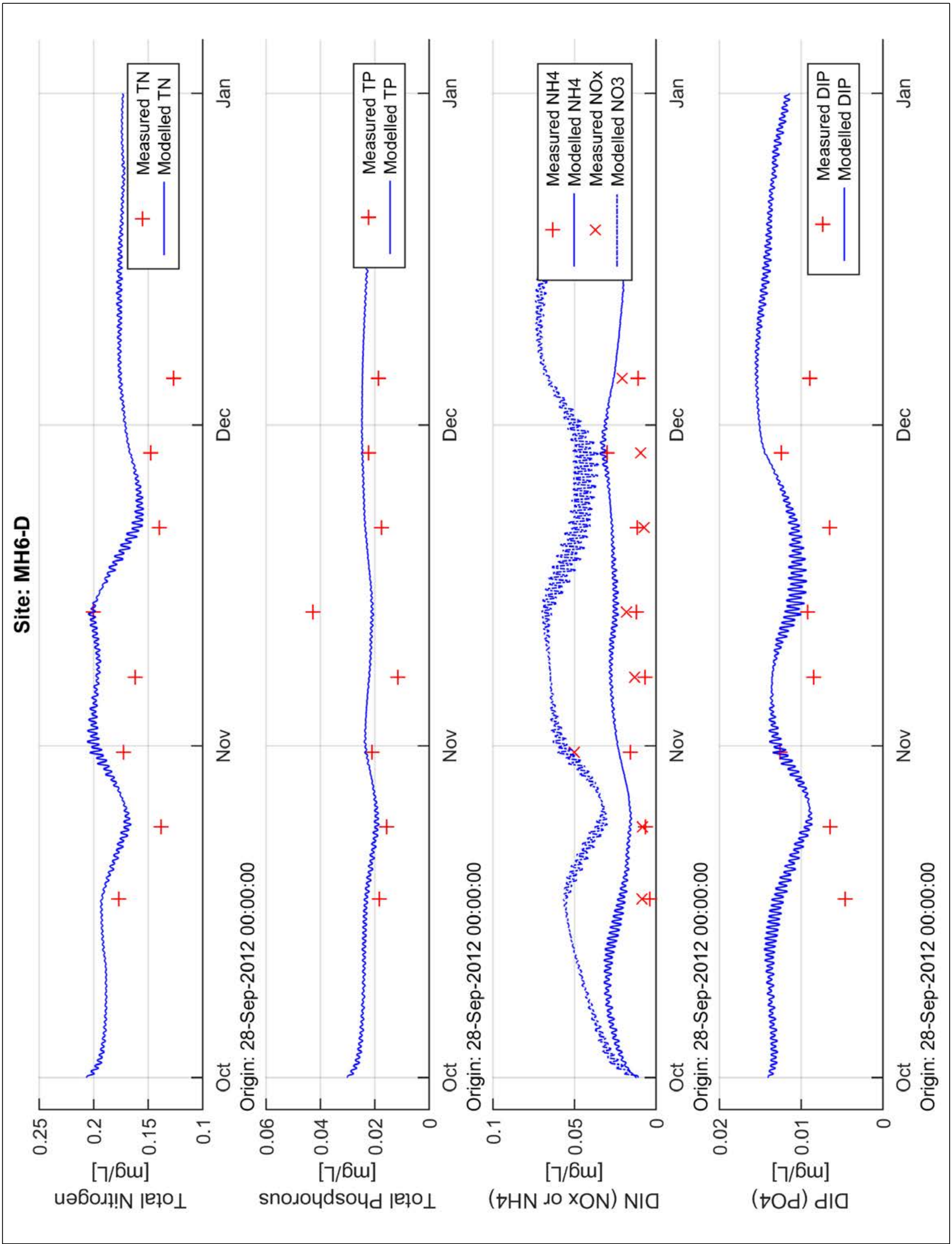
Sydney Harbour Ecological Response Model
Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: MH6

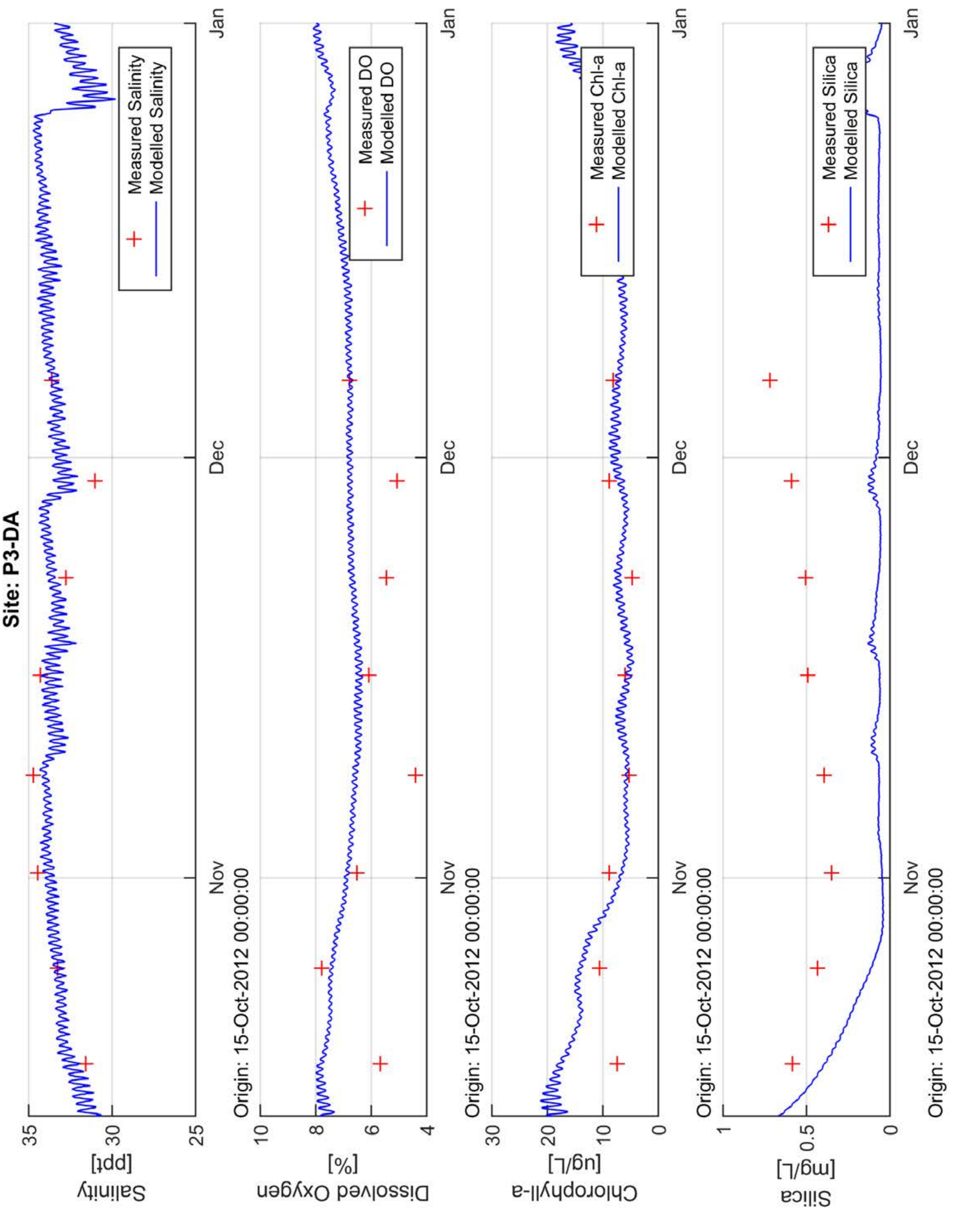
Figure 5.33a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: MH6

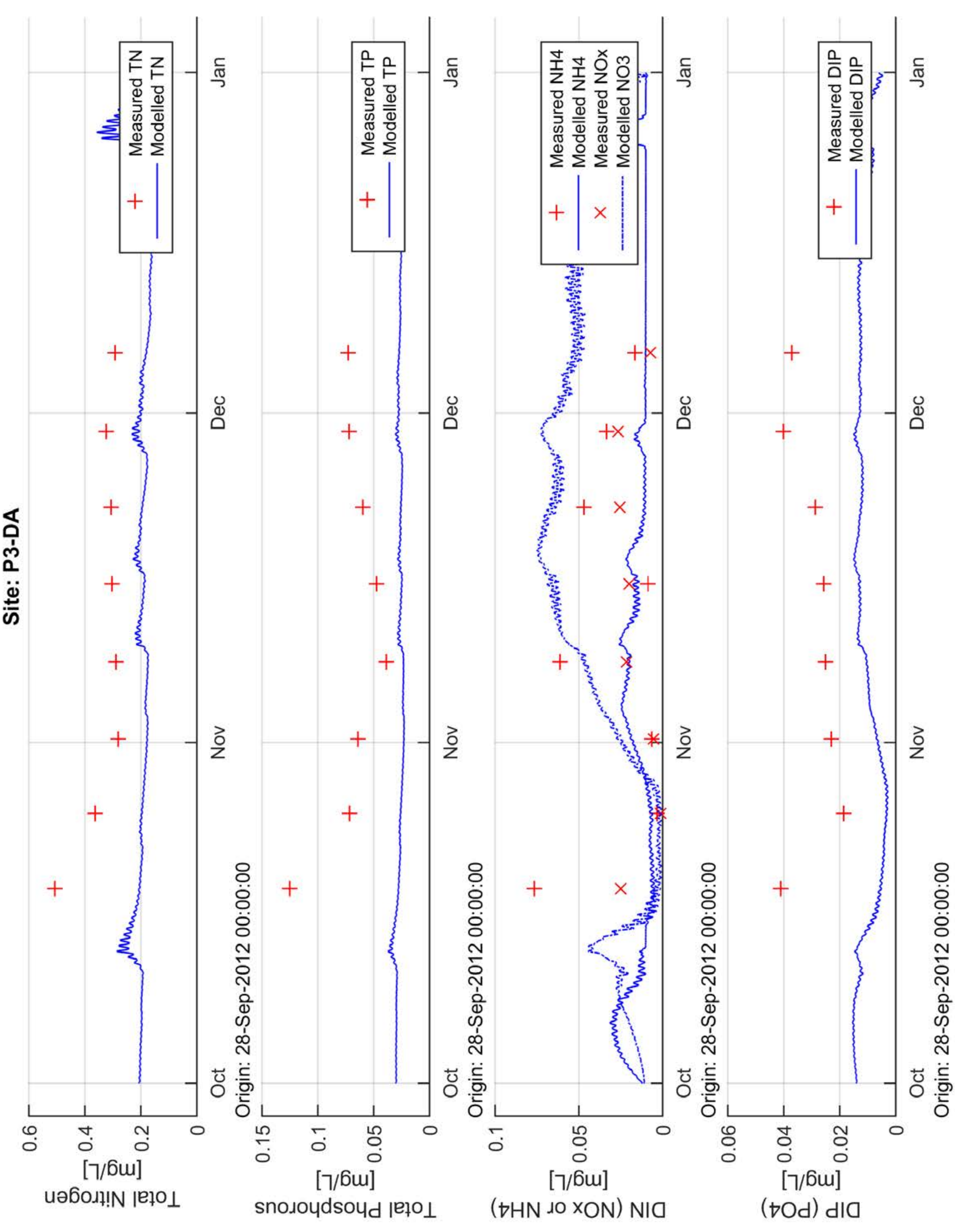
Figure 5.33b



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: P3

Figure 5.34a



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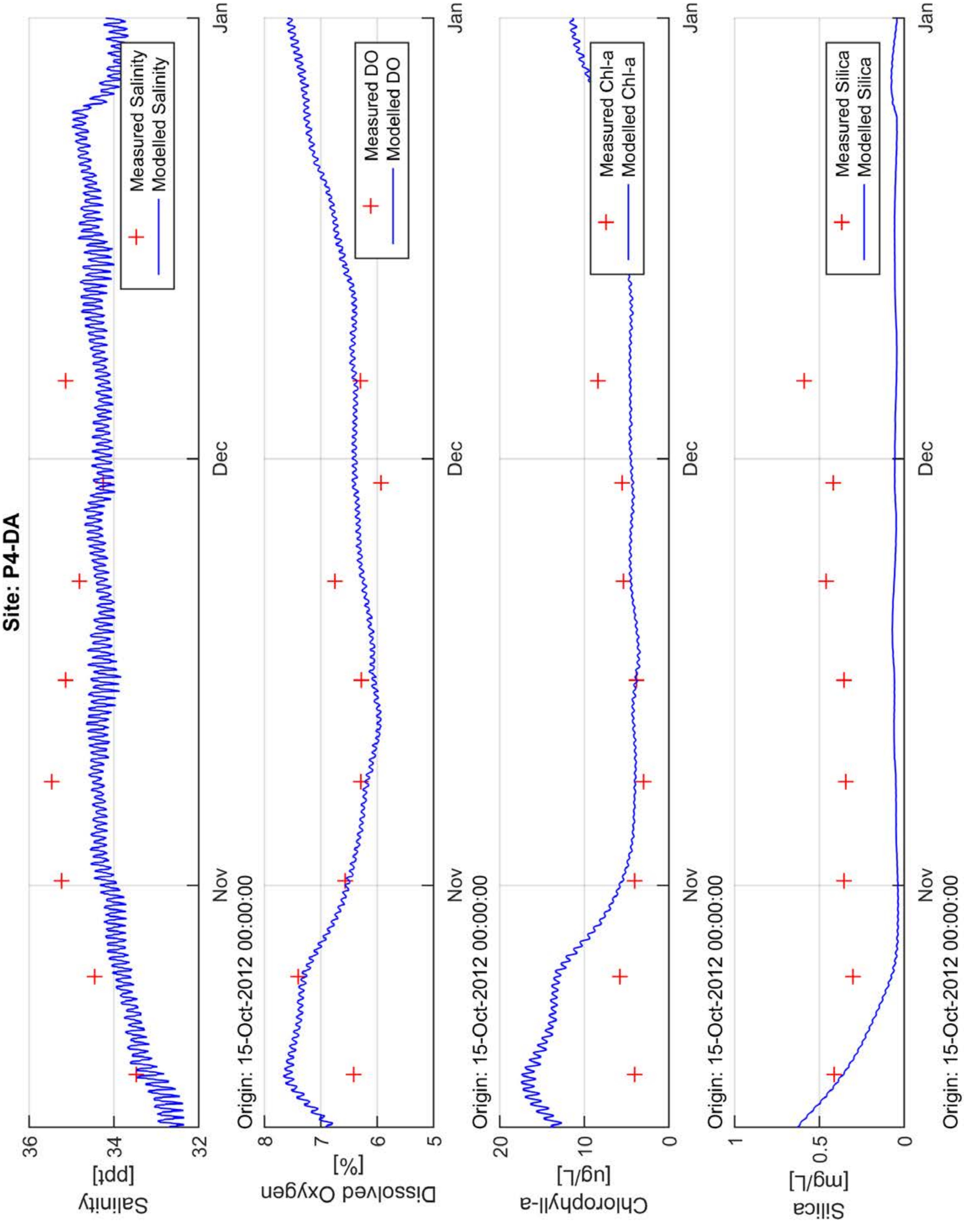
Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: P3

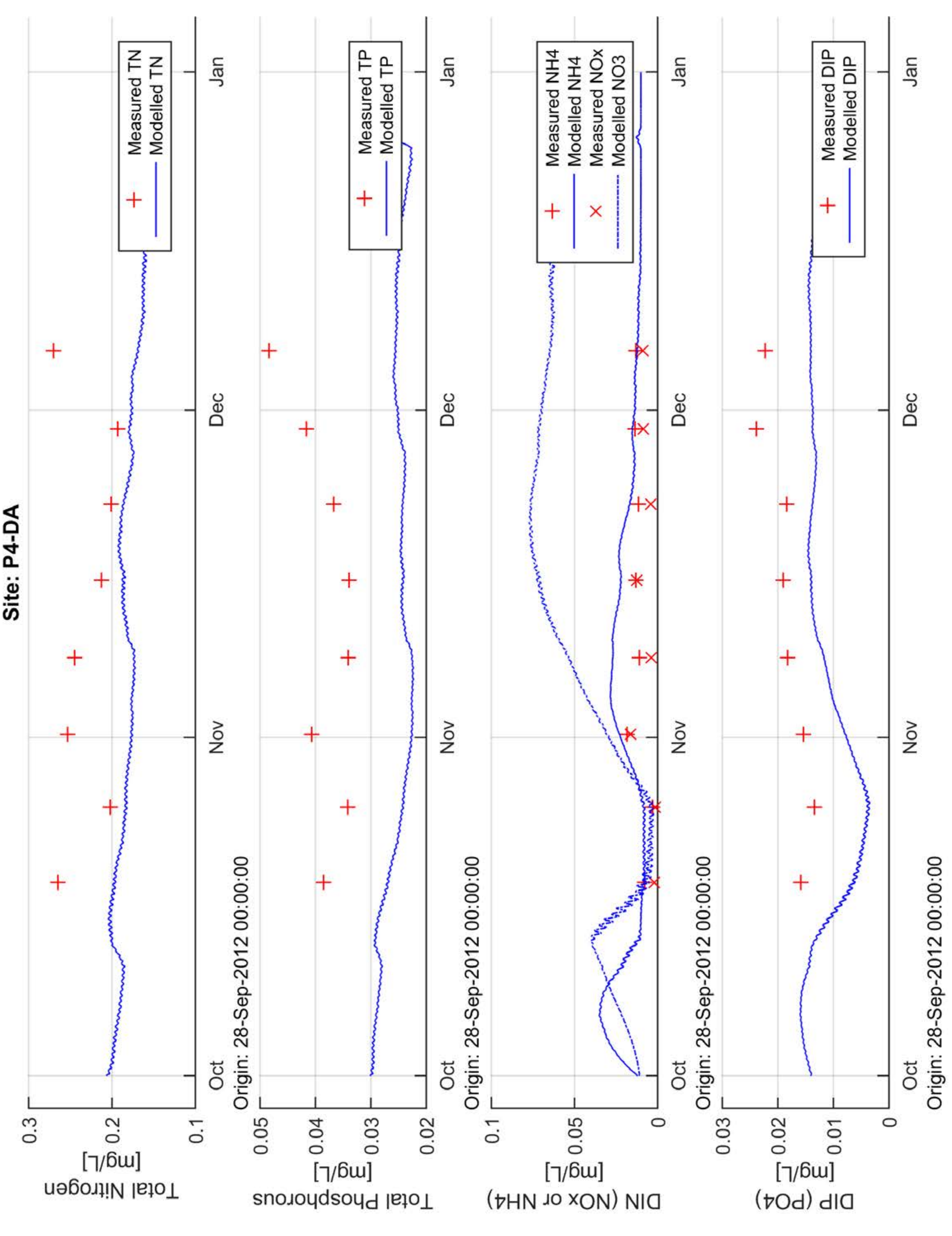
Figure 5.34b



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: P4

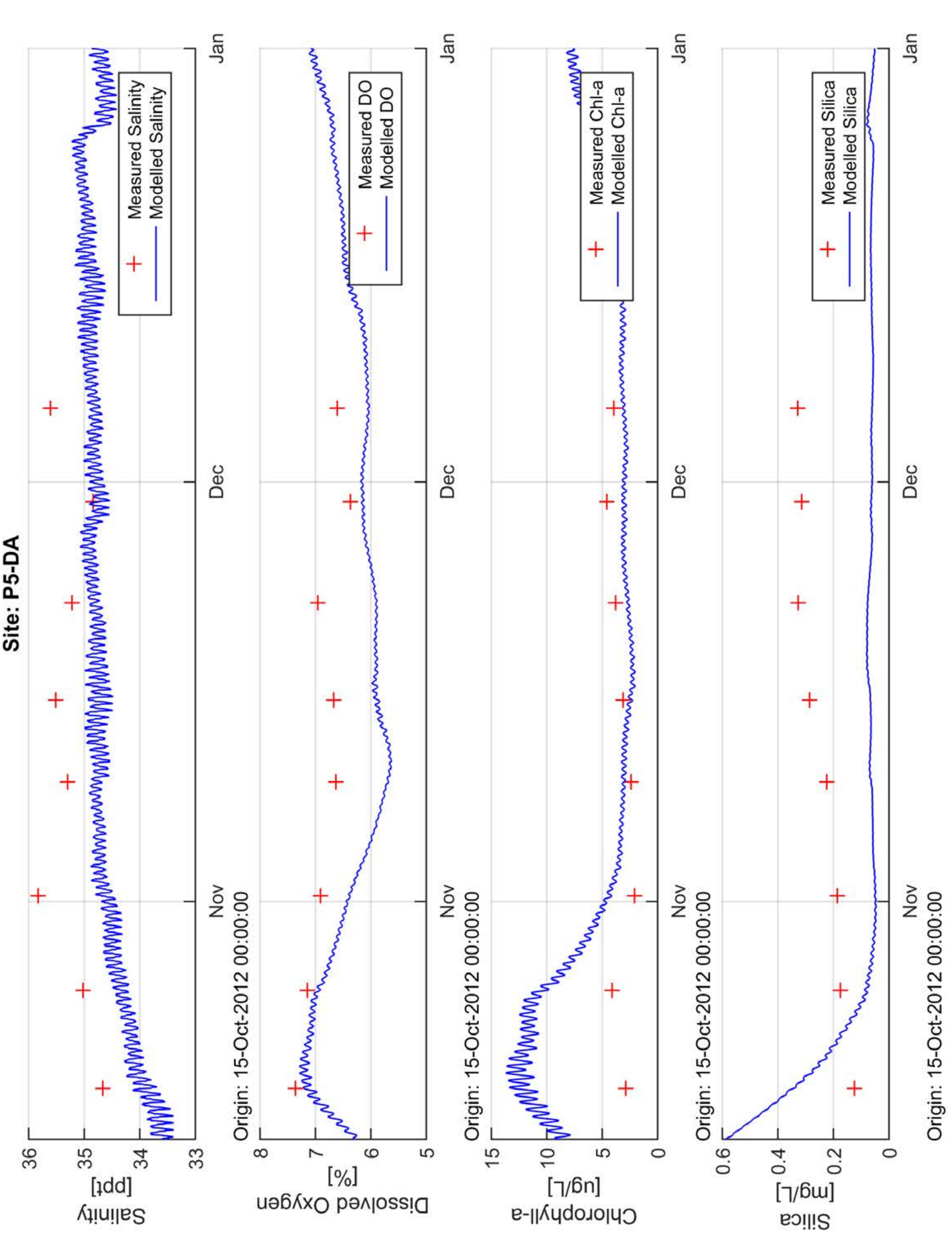
Figure 5.35a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: P4

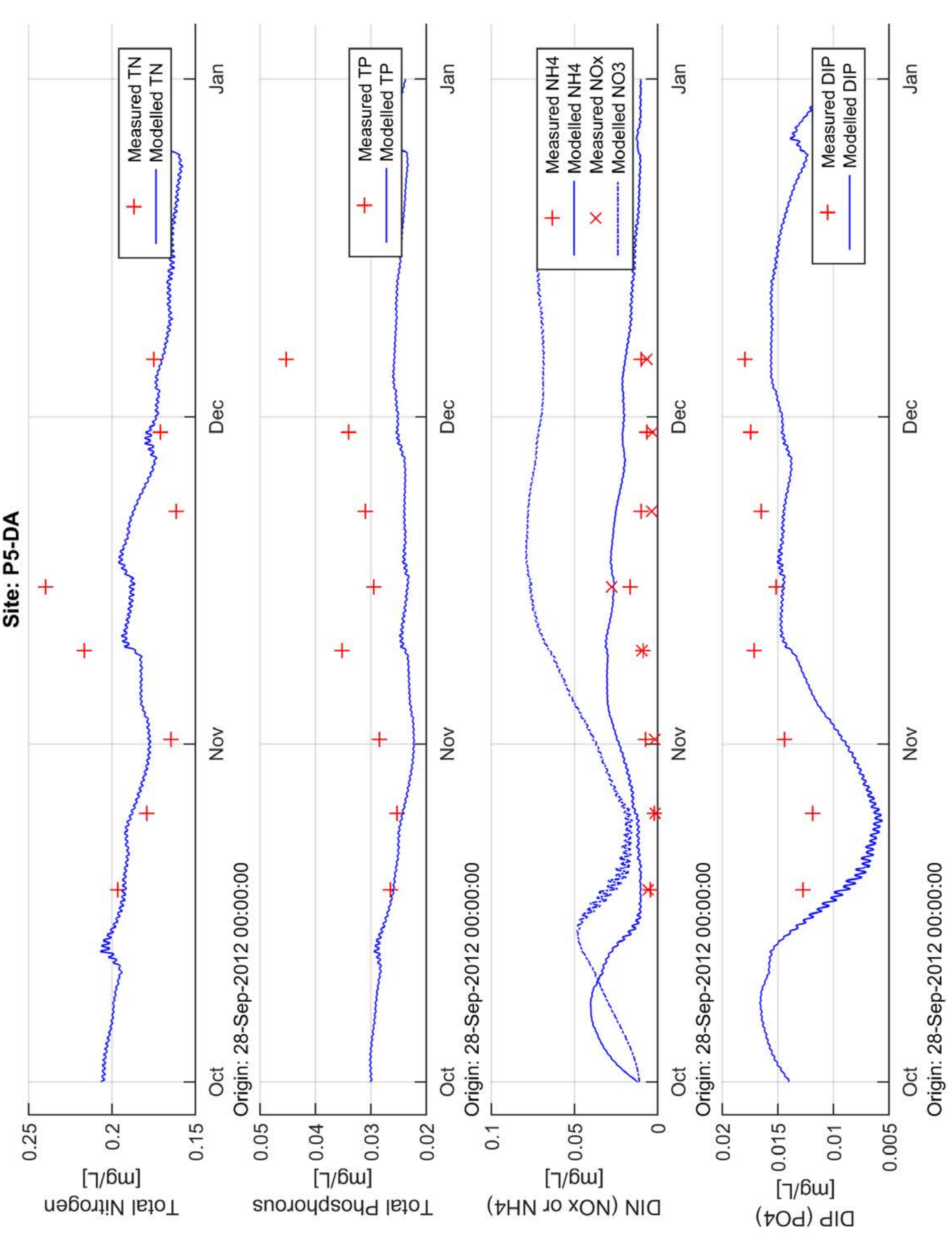
Figure 5.35b



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: P5

Figure 5.36a



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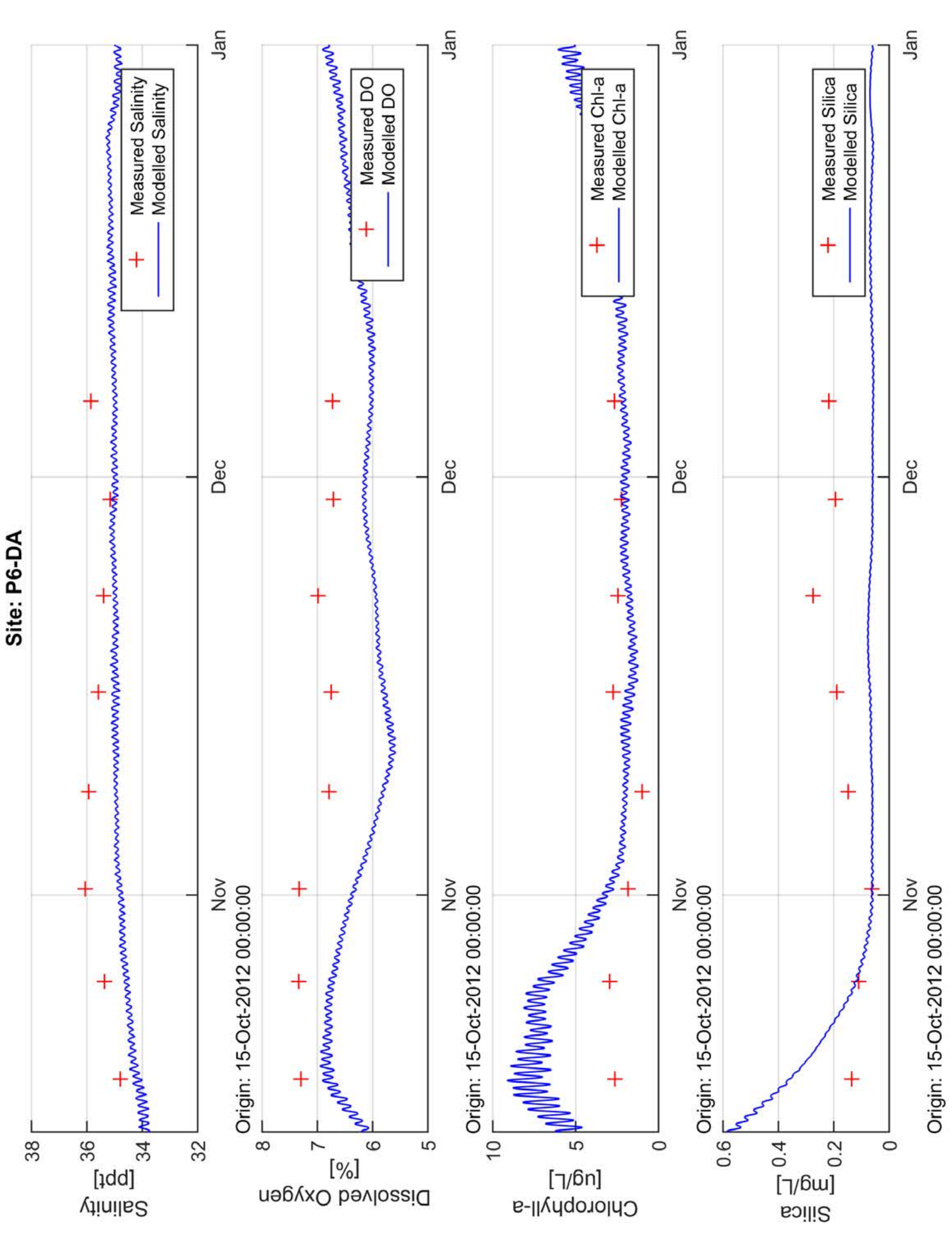
Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012

DYNAMO Model − Site: P5

Figure 5.36b

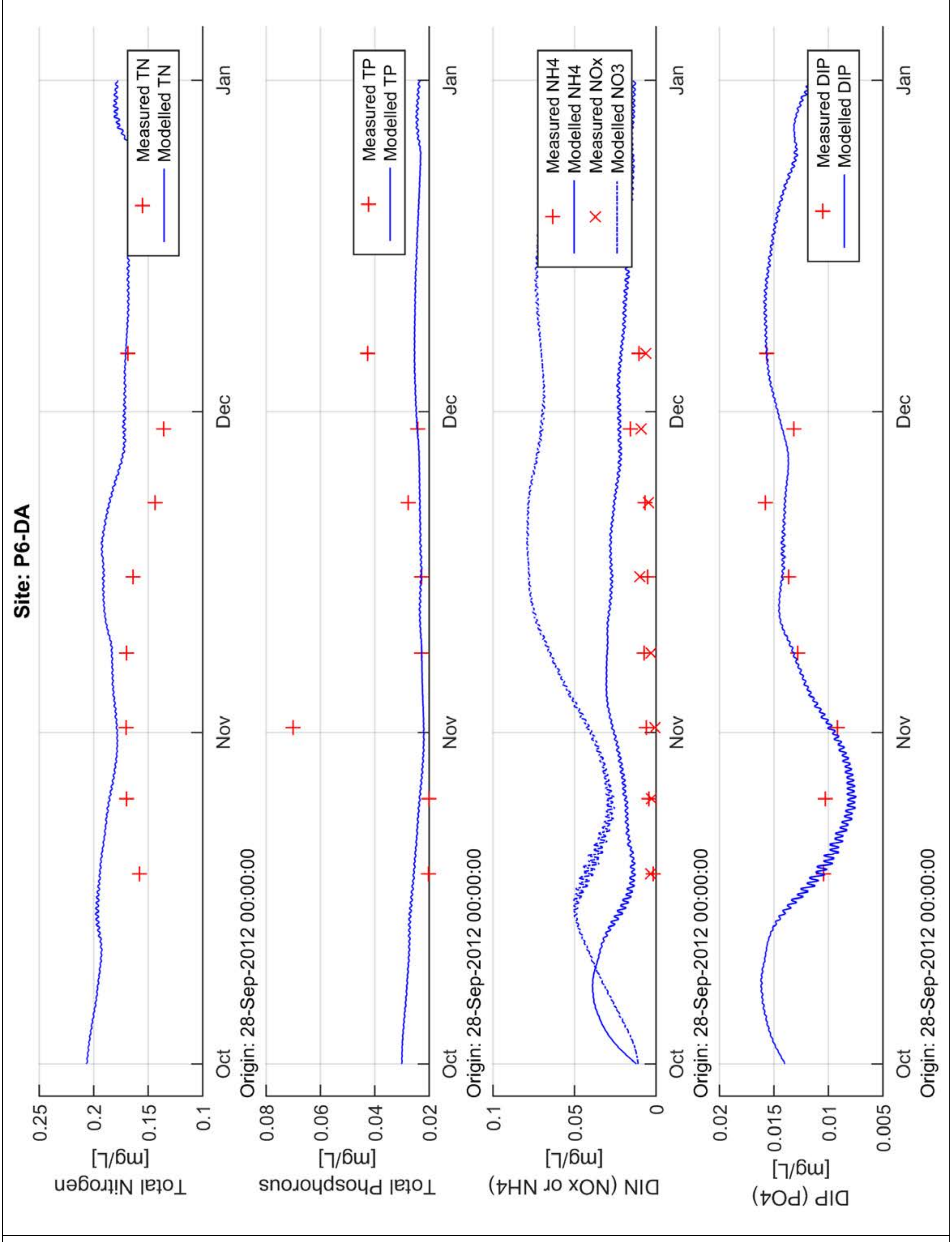


Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012

DYNAMO Model − Site: P6

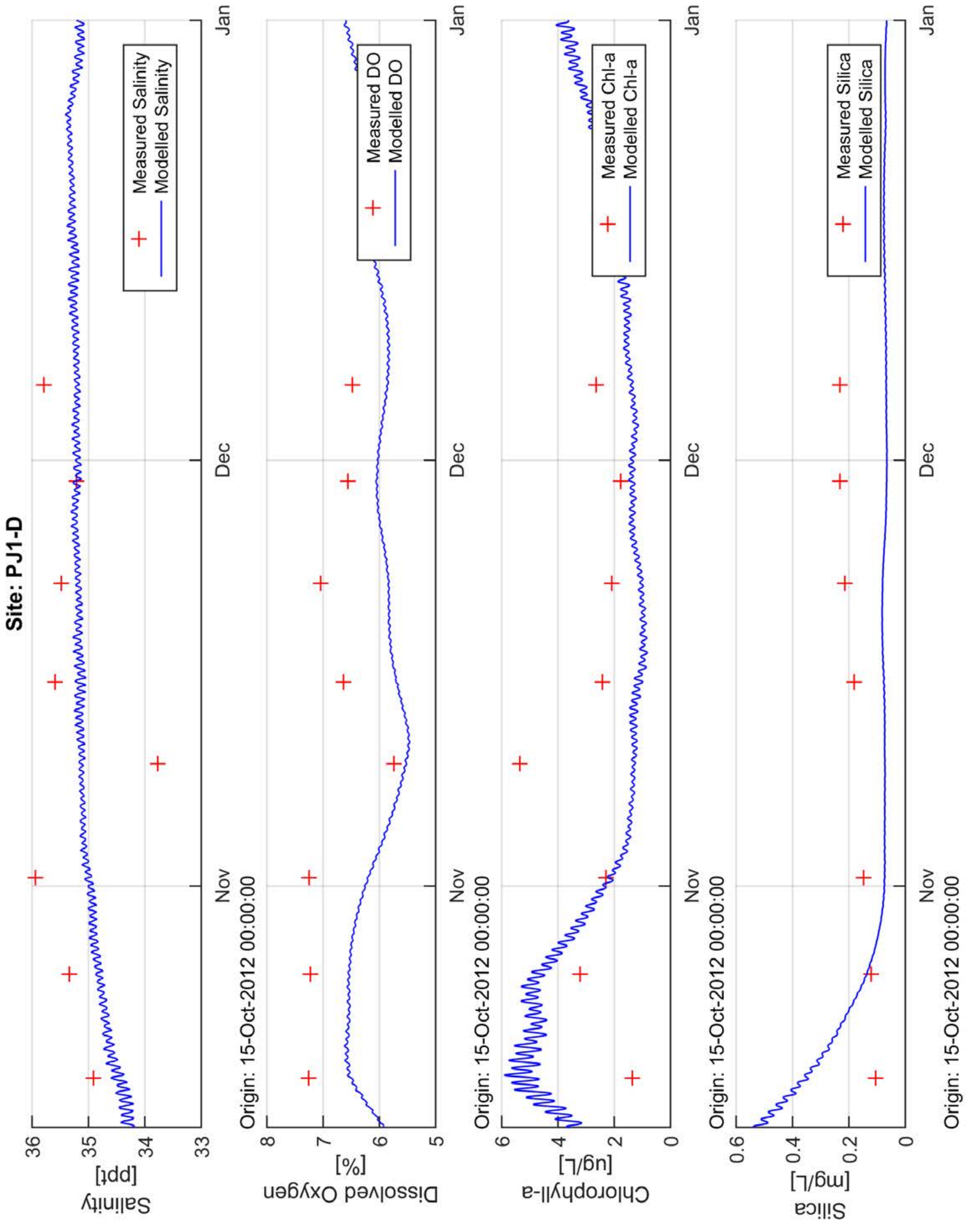
Figure 5.37a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: P6

Figure 5.37b

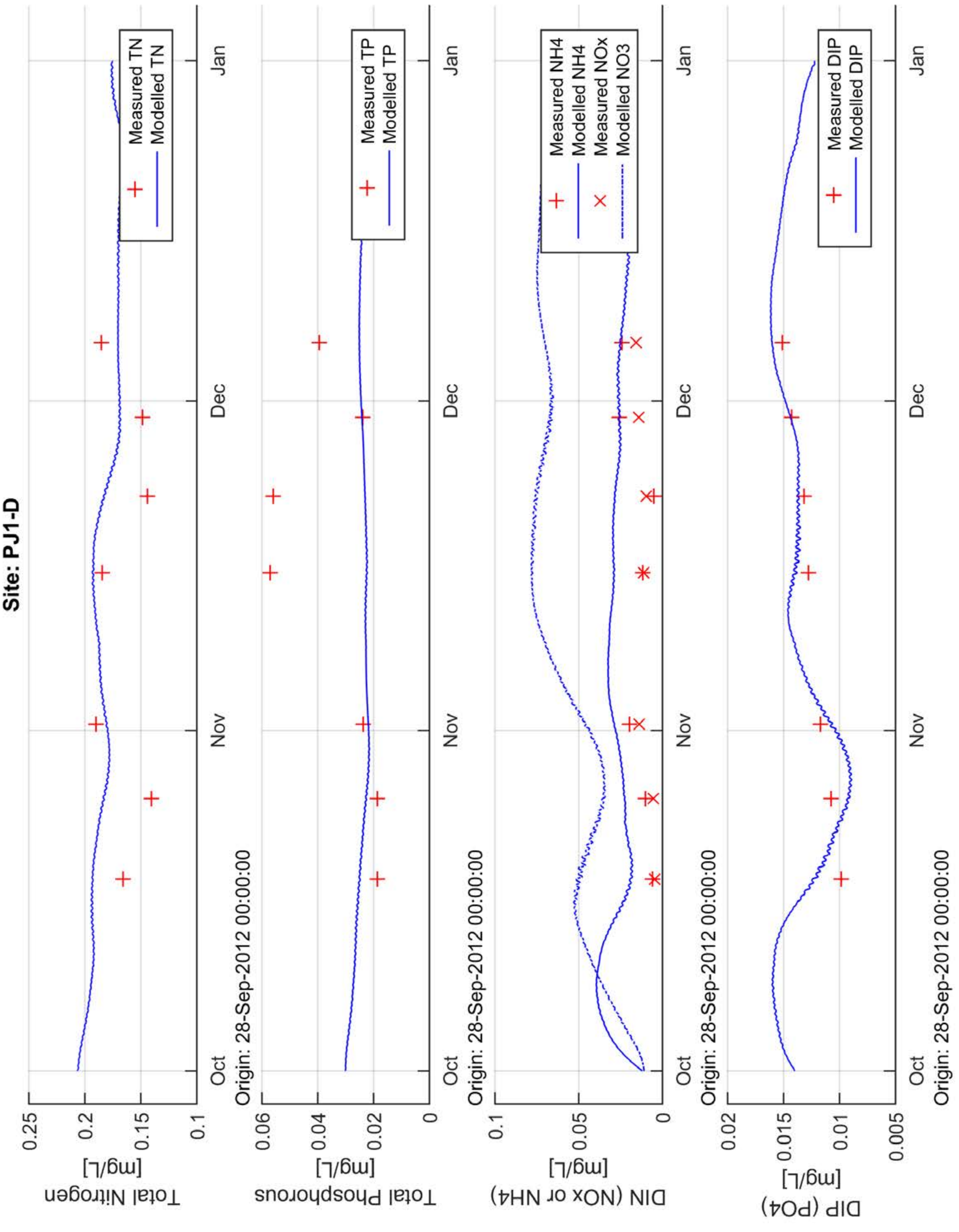


Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012

DYNAMO Model − Site: PJ1

Figure 5.38a



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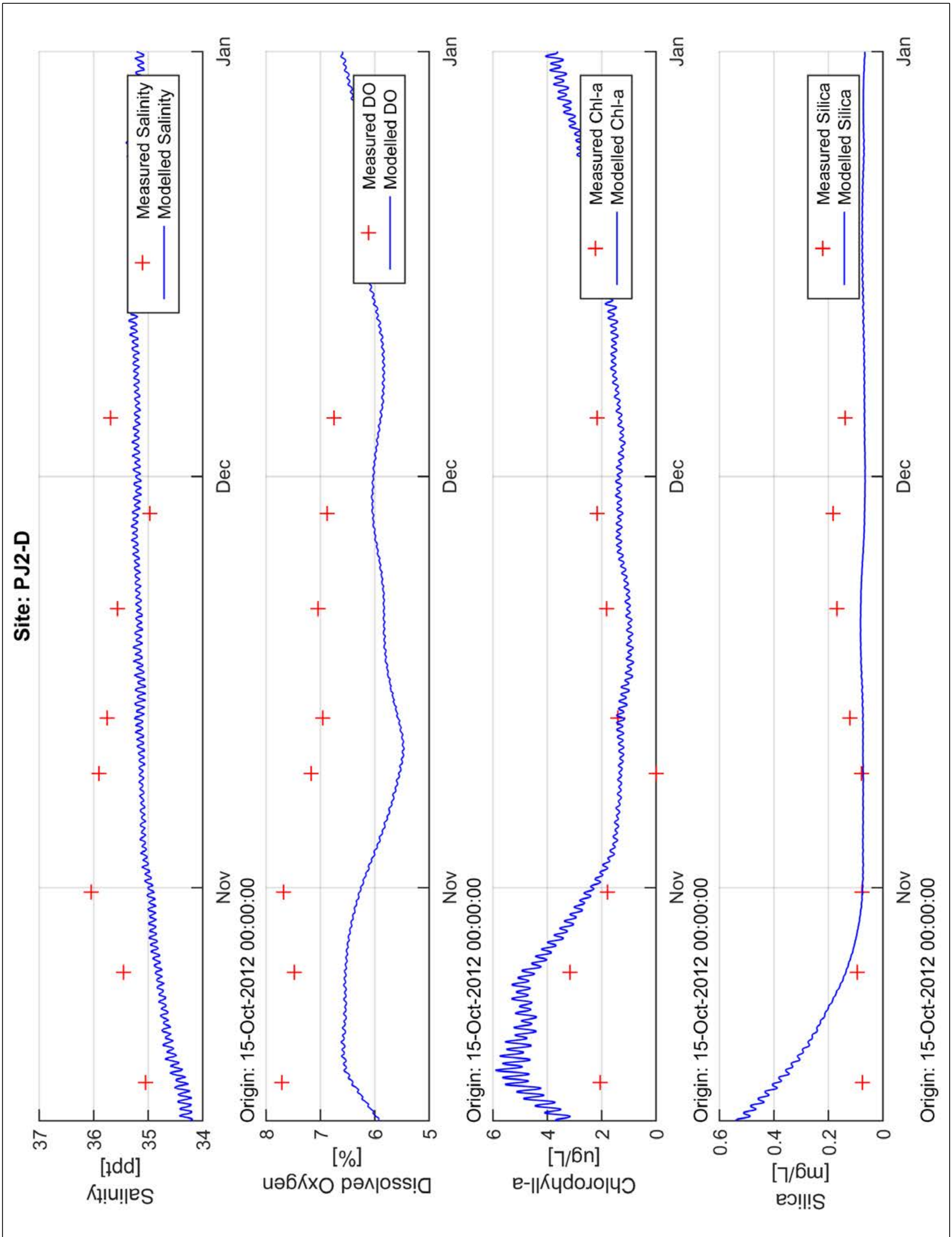
Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: PJ1

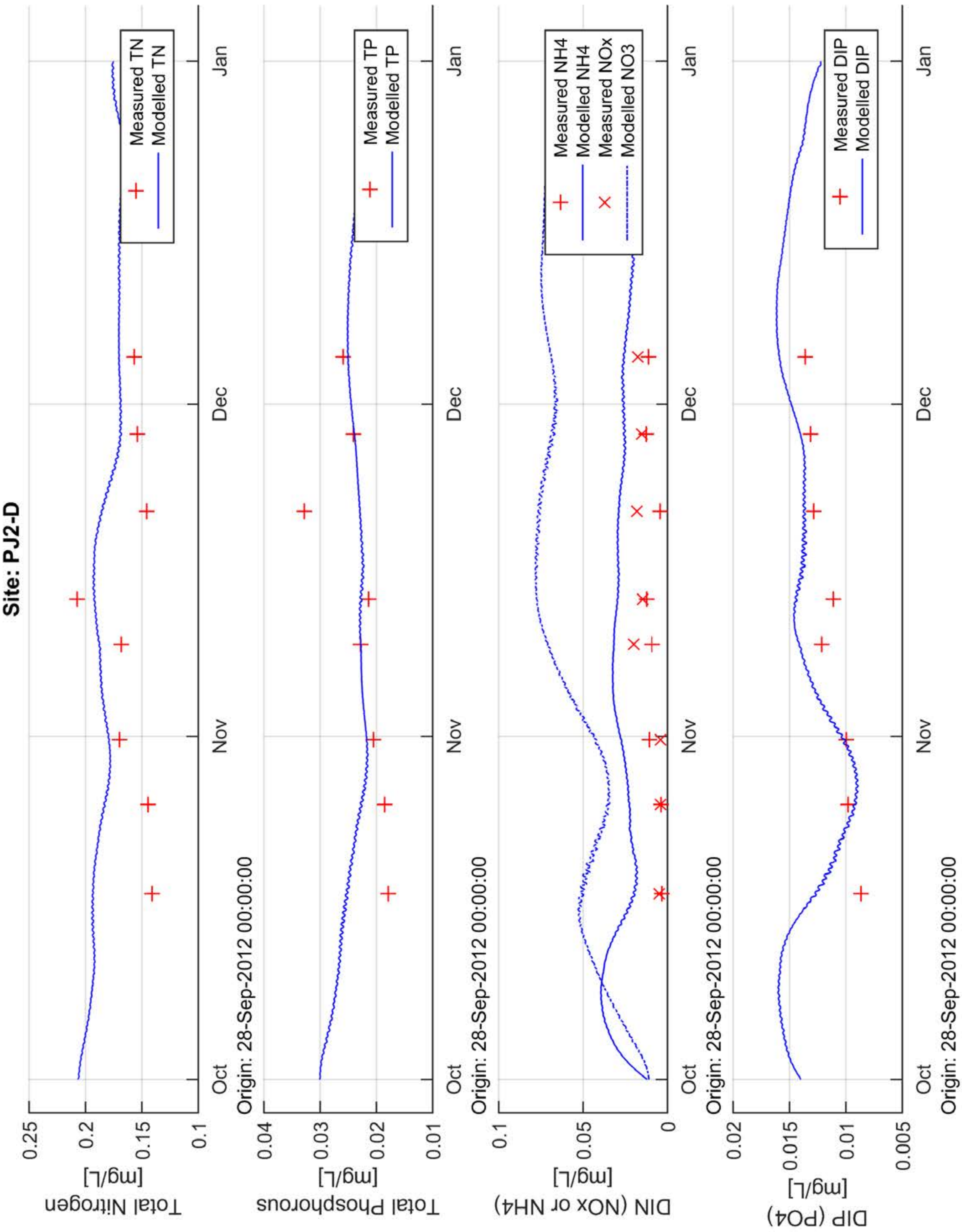
Figure 5.38b



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: PJ2

Figure 5.39a

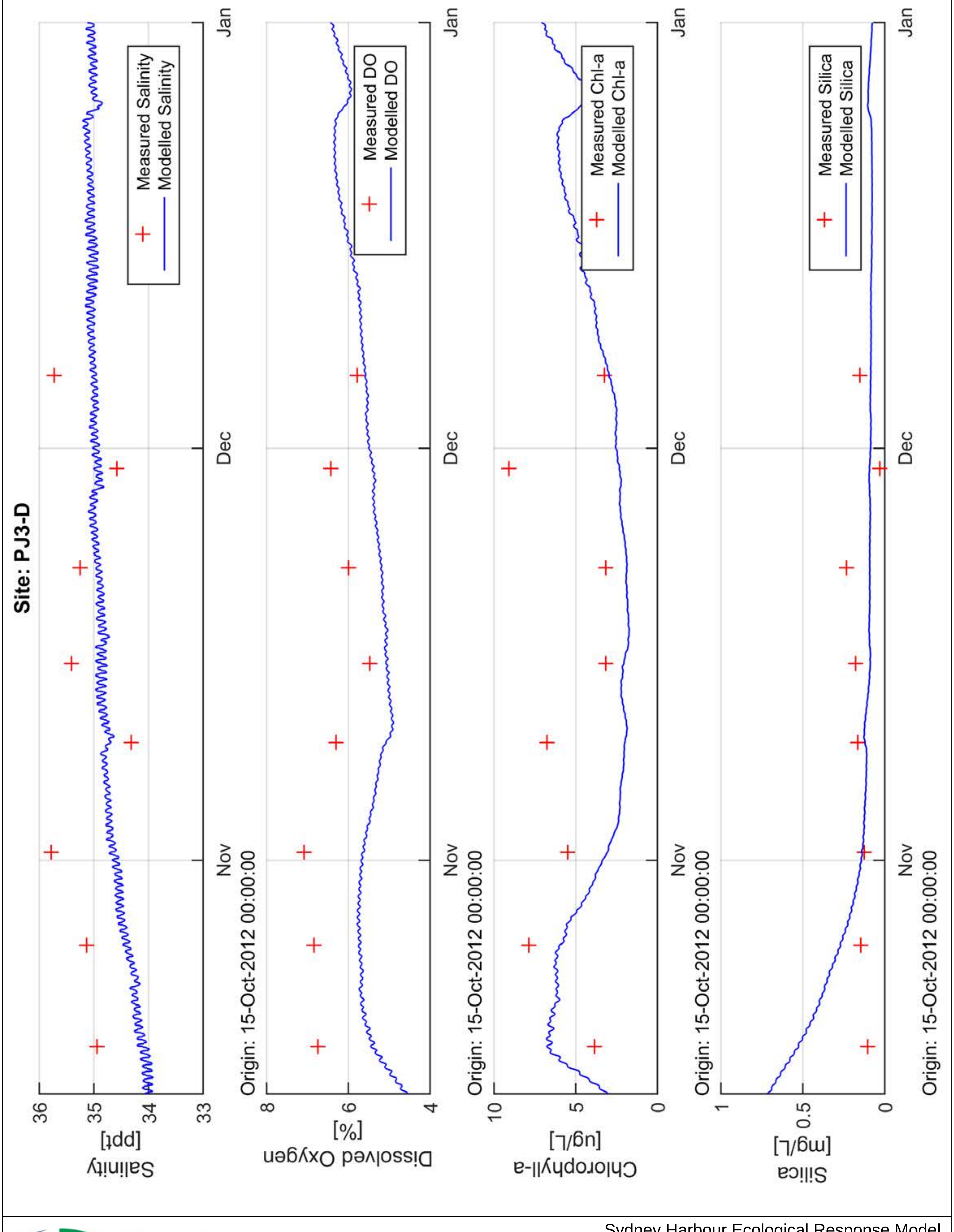


Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012

DYNAMO Model − Site: PJ2

Figure 5.39b

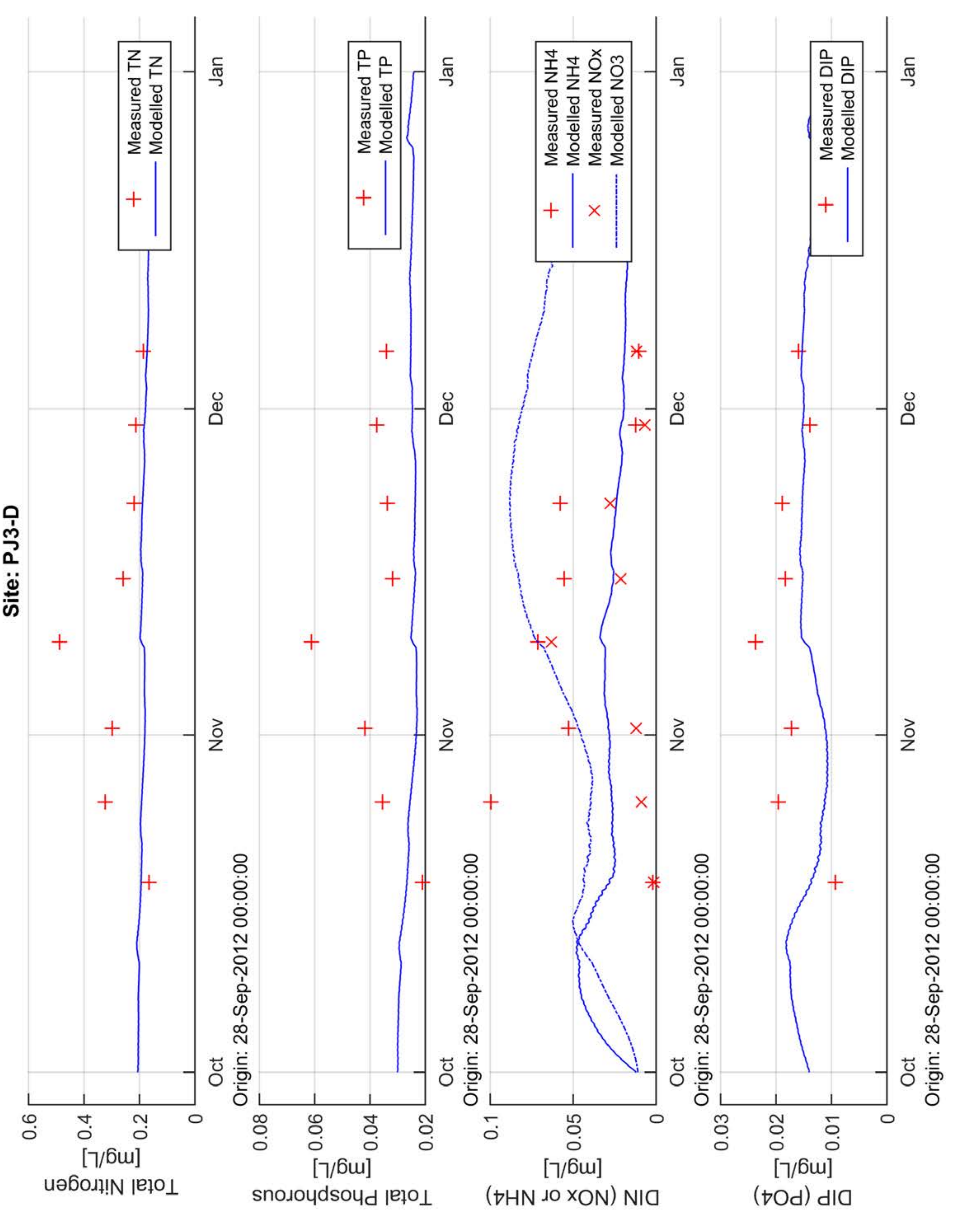


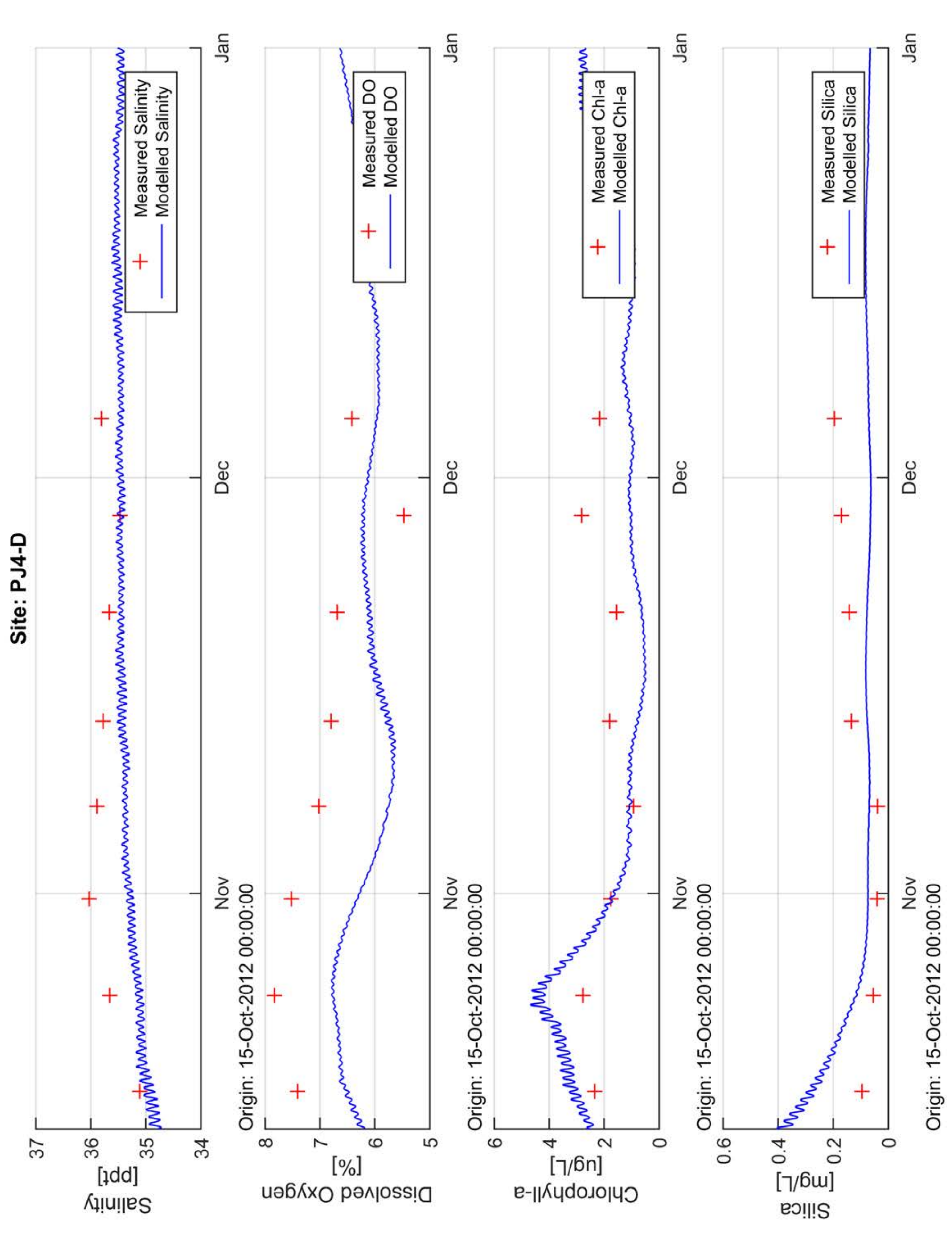
Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012

DYNAMO Model − Site: PJ3

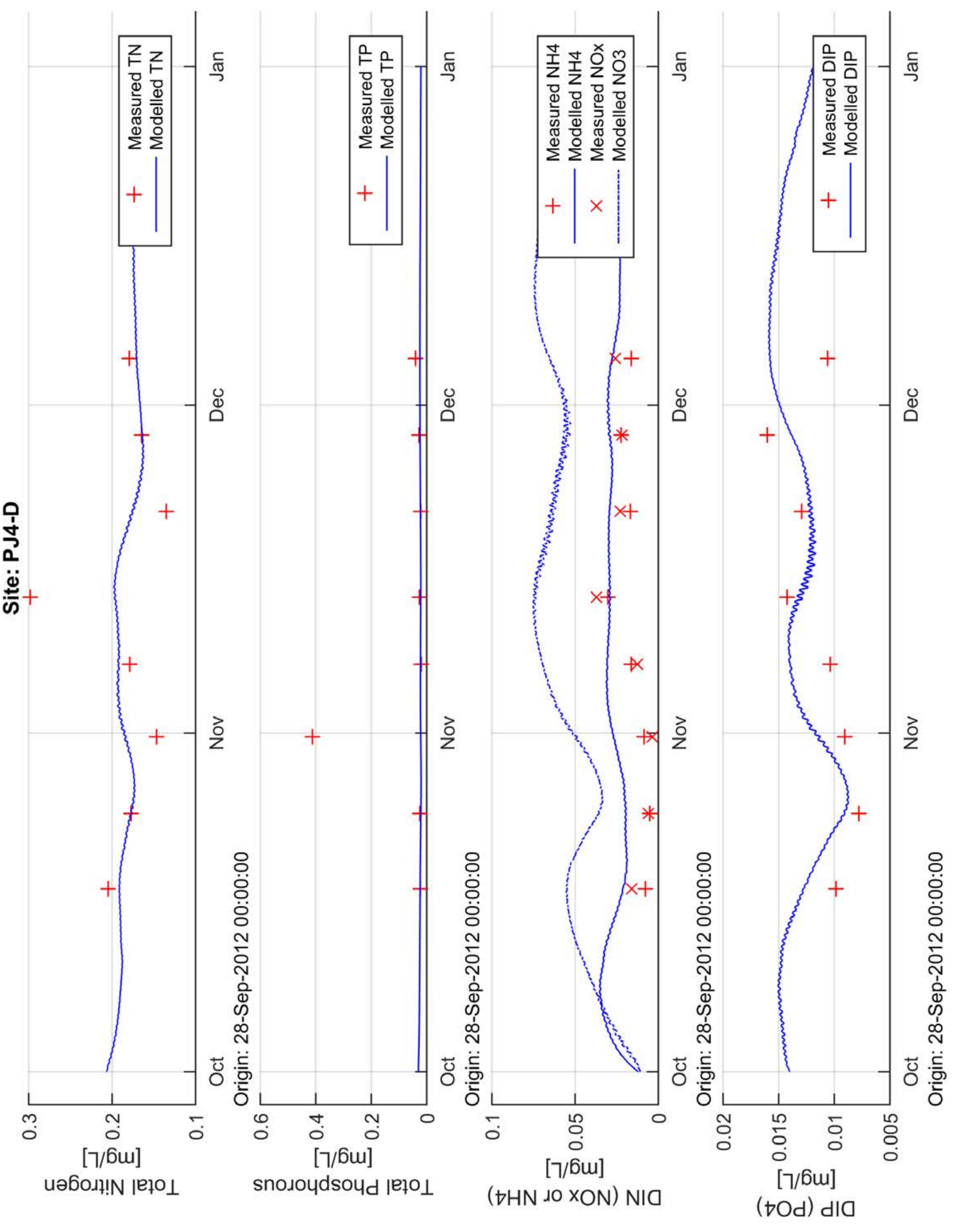
Figure 5.40a


Site: PJ3-D
Total Nitrogen [mg/L]
Measured TN
Modelled TN
Total Phosphorous [mg/L]
Measured TP
Modelled TP
DIN (NOx or NH4) [mg/L]
Measured NH4
Modelled NH4
Measured NOx
Modelled NO3
DIP (PO4) [mg/L]
Measured DIP
Modelled DIP
Oct
Nov
Dec
Jan
Origin: 28-Sep-2012 00:00:00



Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: PJ4

Figure 5.41a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012

DYNAMO Model − Site: PJ4

Figure 5.41b

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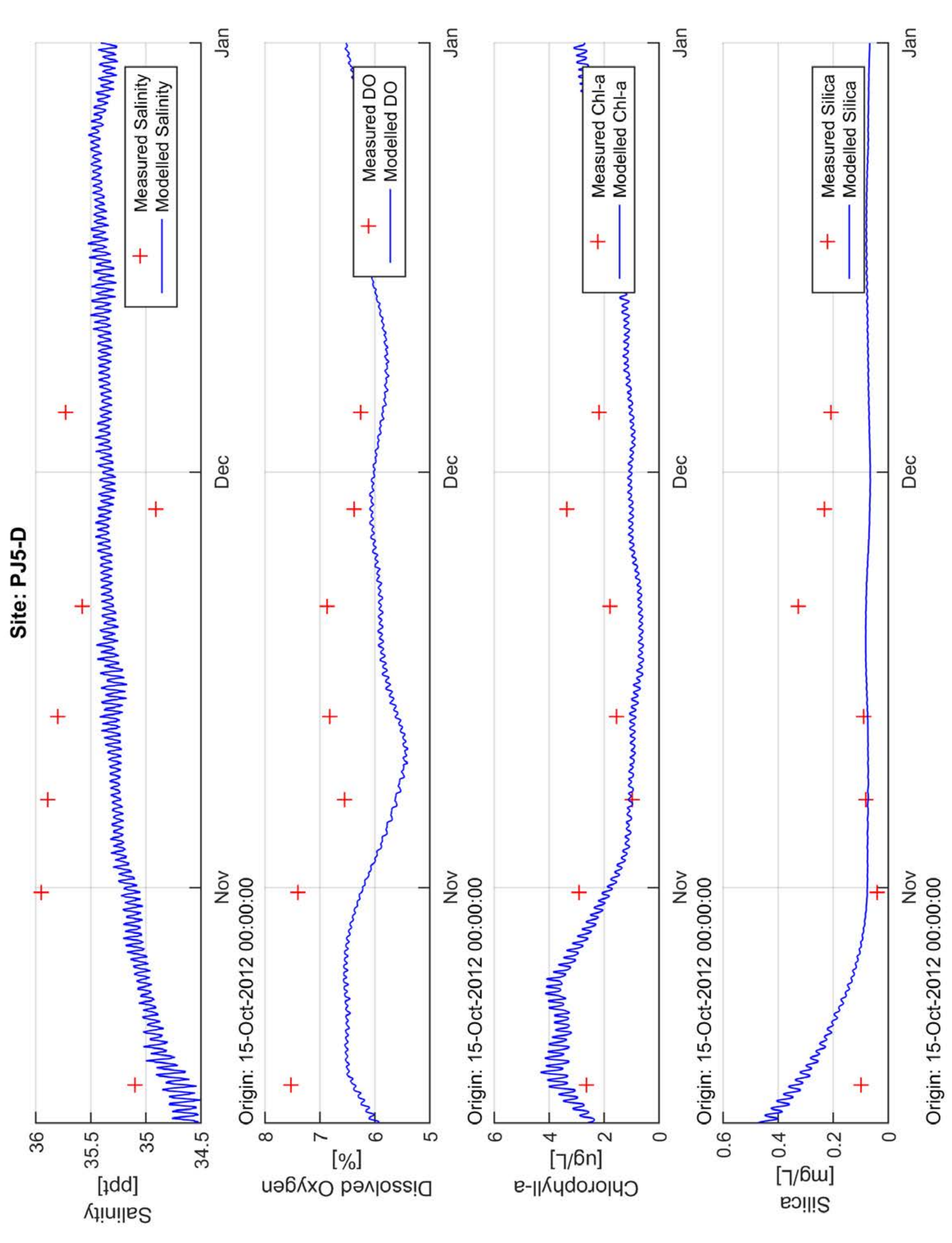

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Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: PJ5

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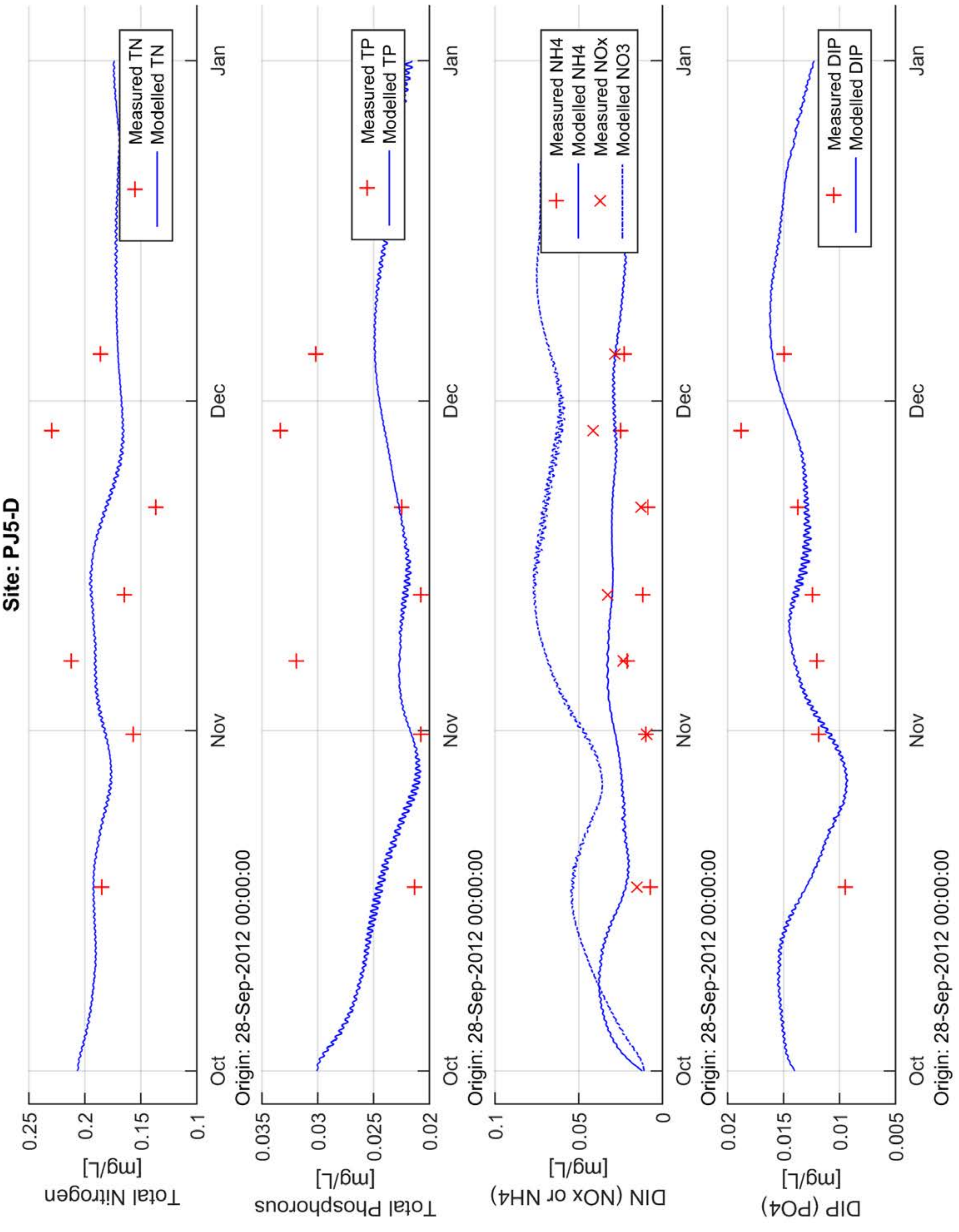
Figure 5.42a

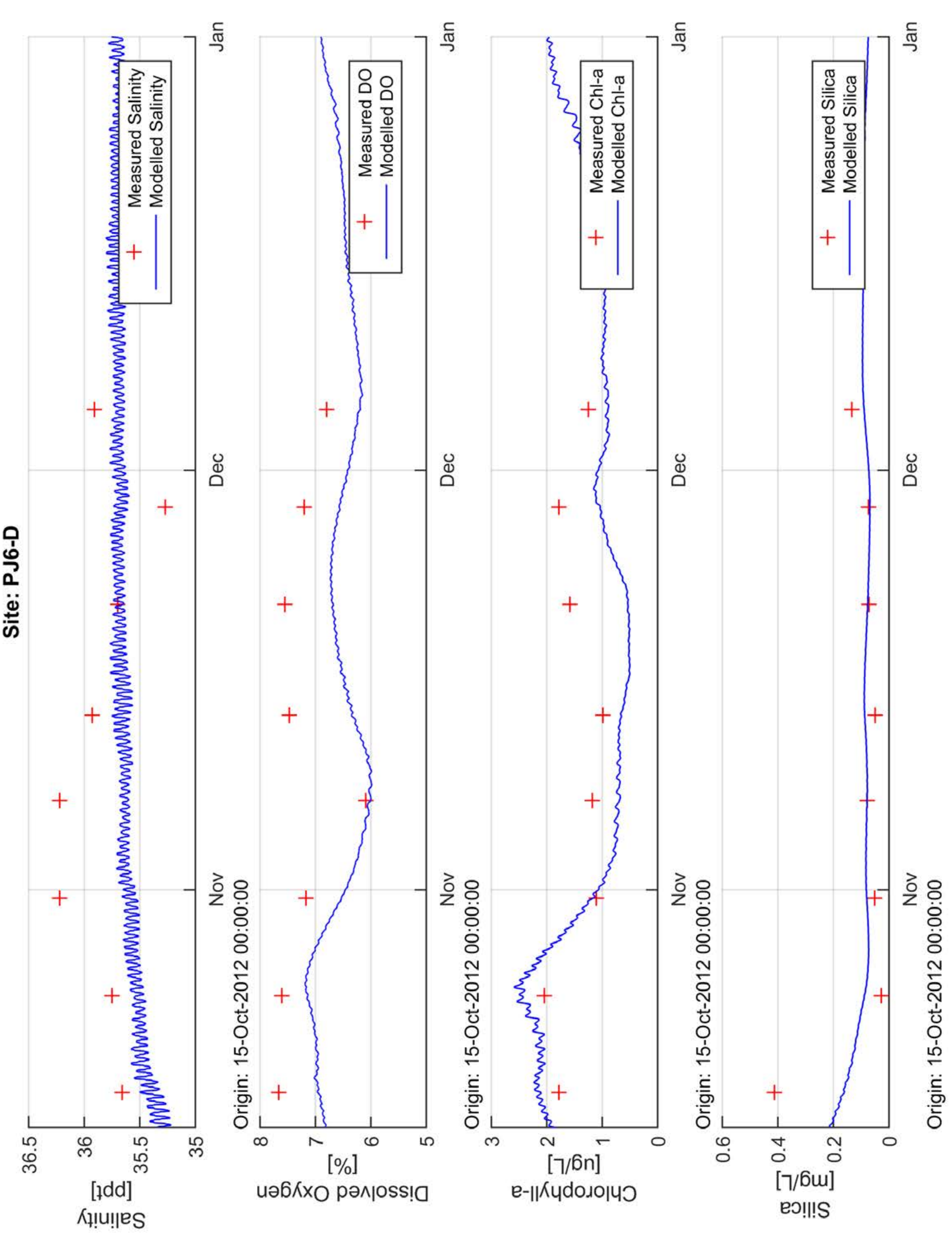


Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012

DYNAMO Model − Site: PJ5

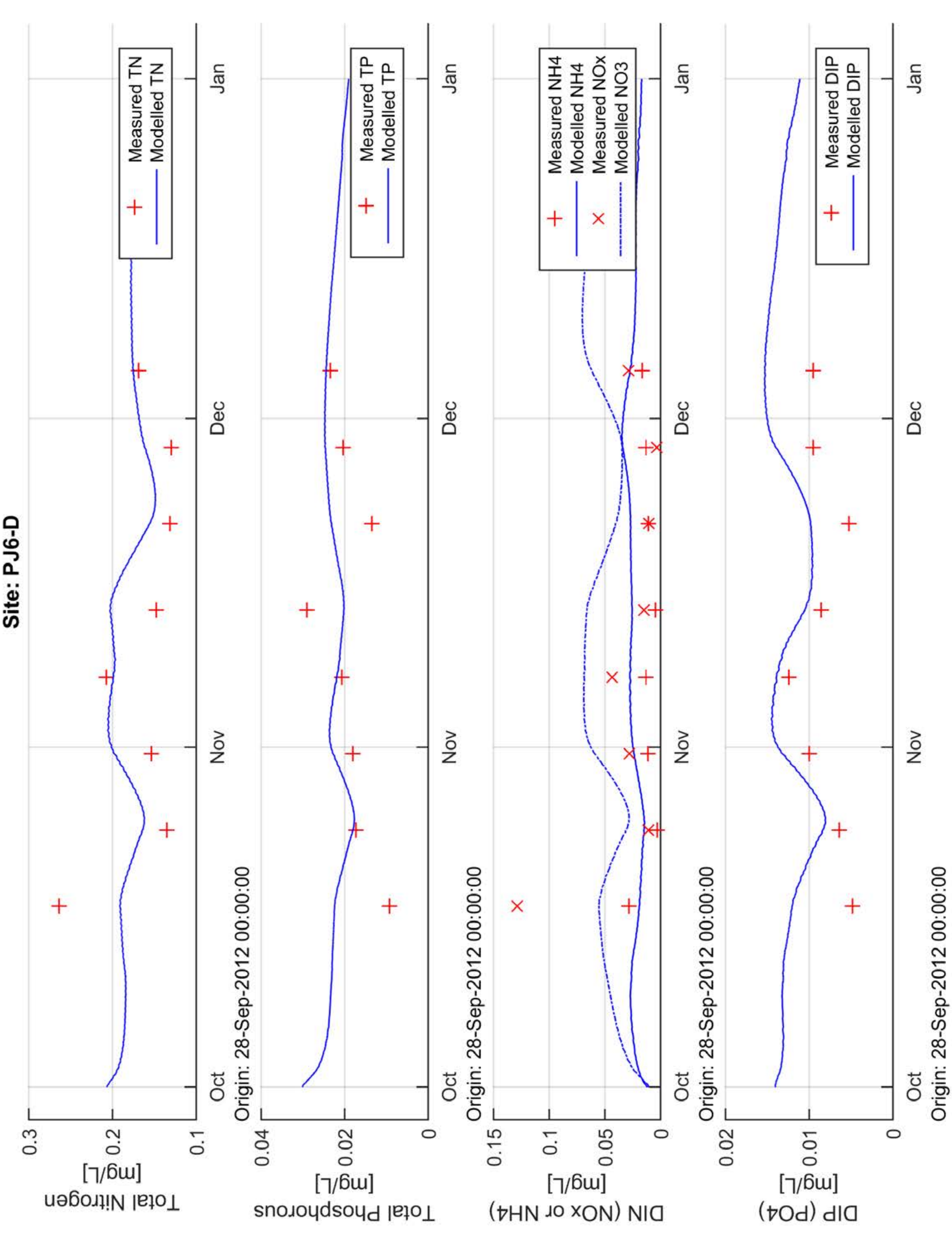
Figure 5.42b



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: PJ6

Figure 5.43a



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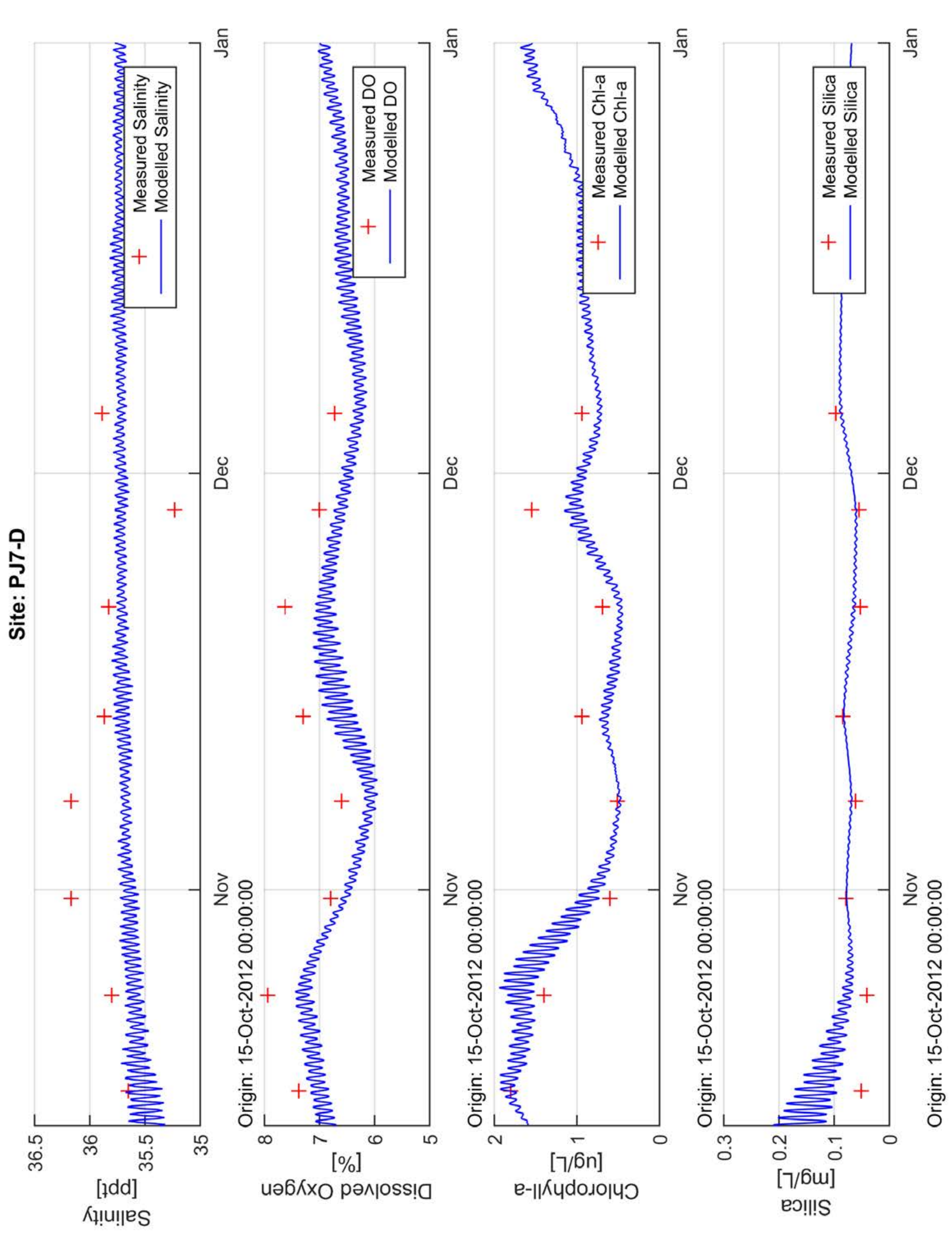
Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: PJ6

Figure 5.43b

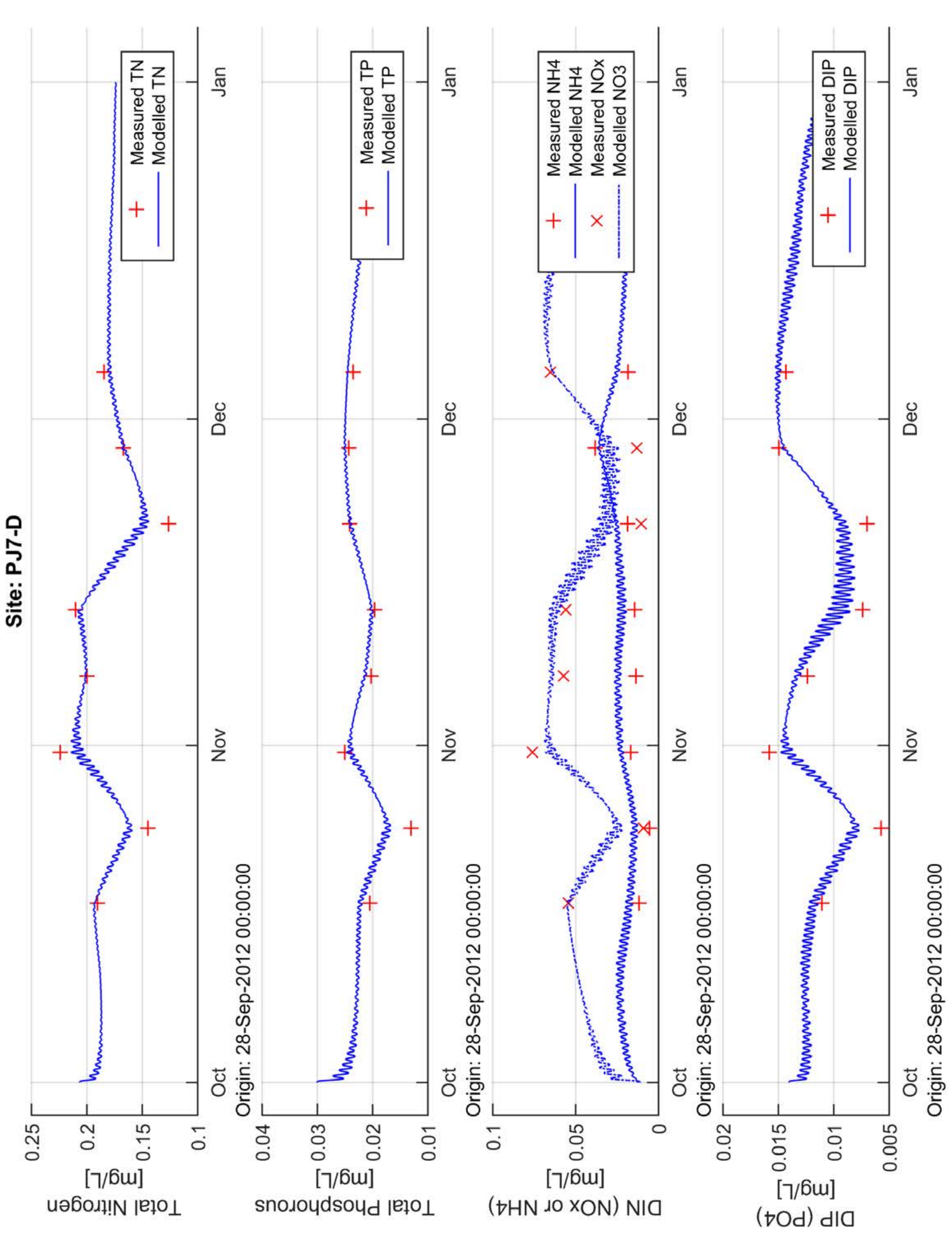


Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012

DYNAMO Model − Site: PJ7

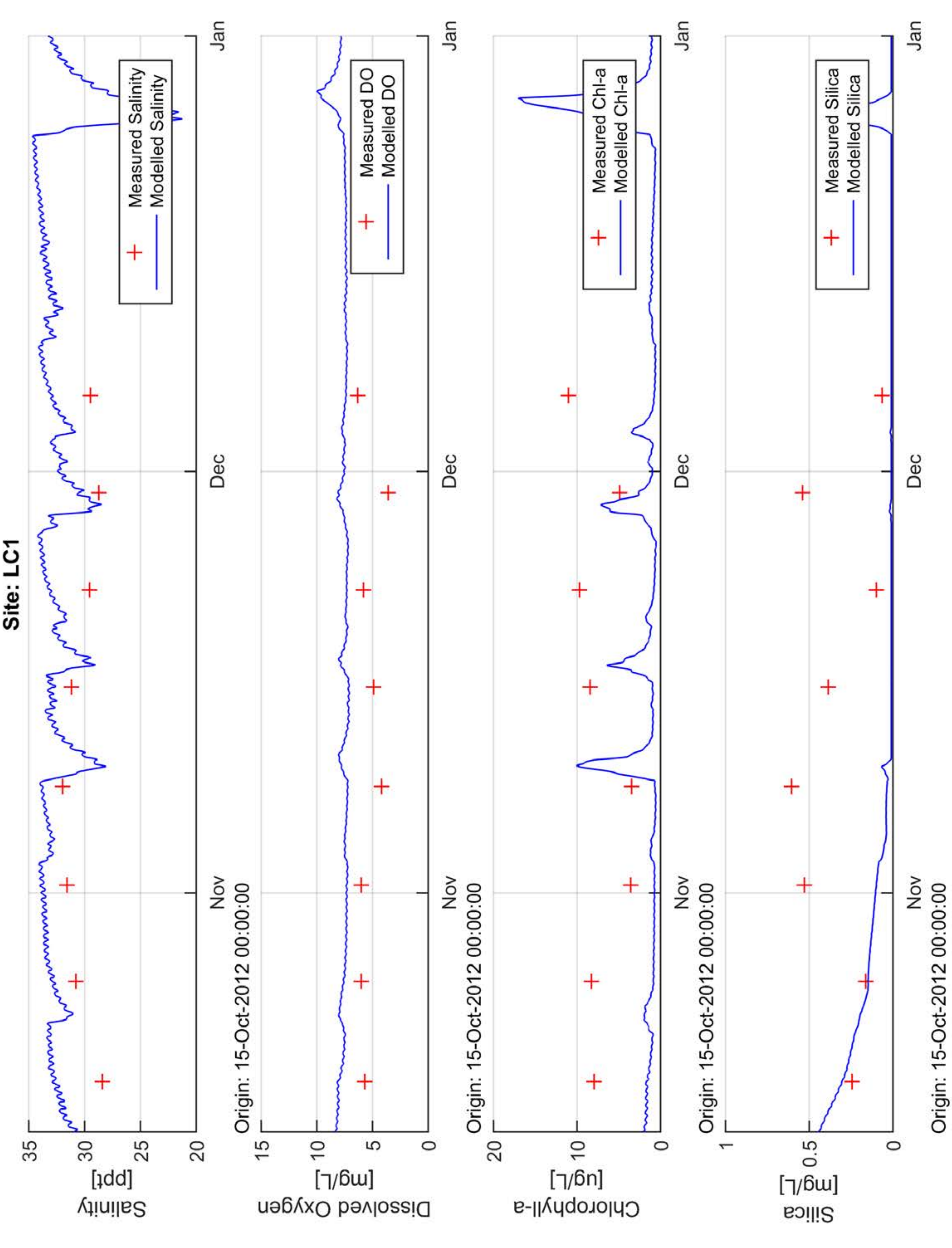
Figure 5.44a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
DYNAMO Model − Site: PJ7

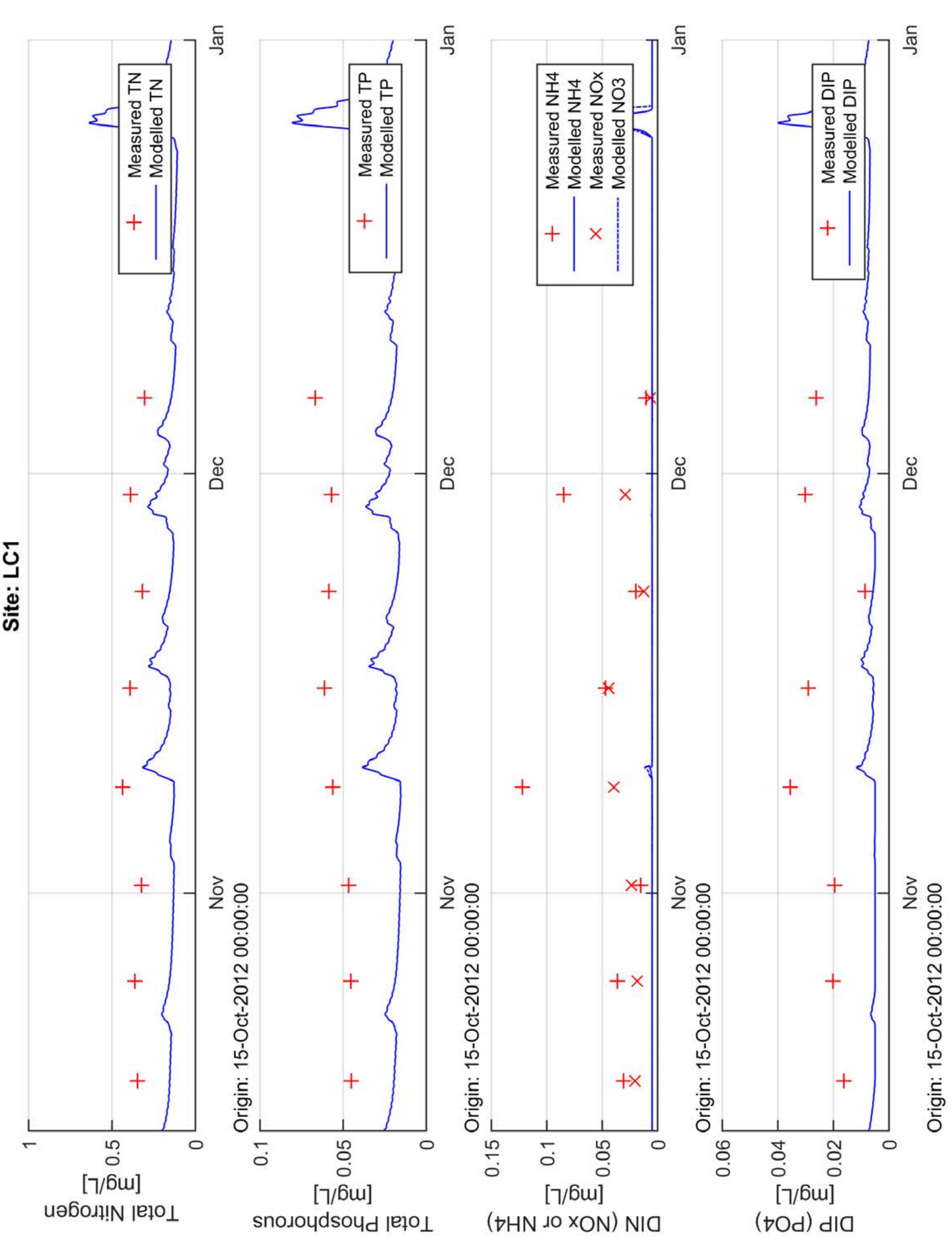
Figure 5.44b



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: LC1

Figure 5.45a



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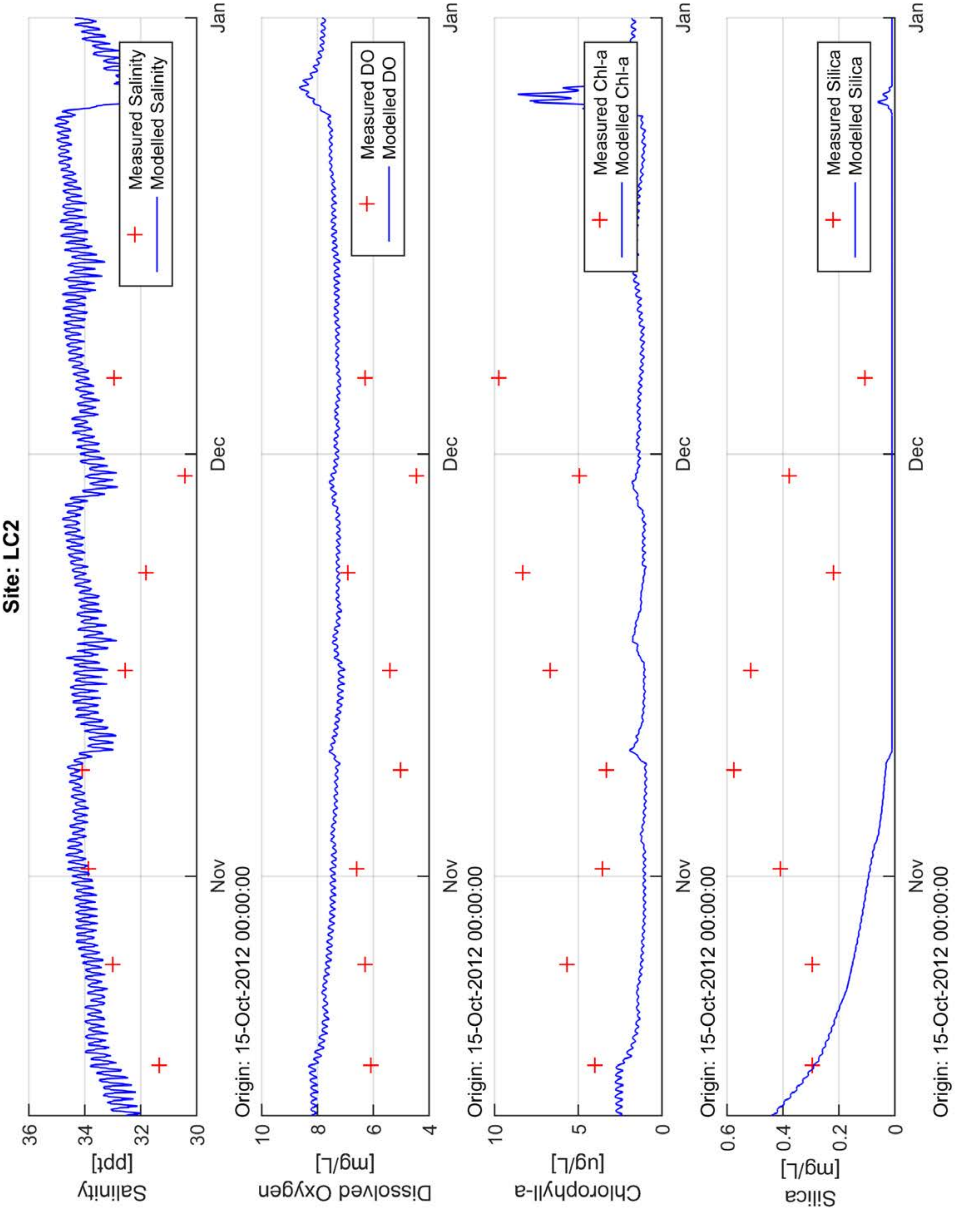
Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: LC1

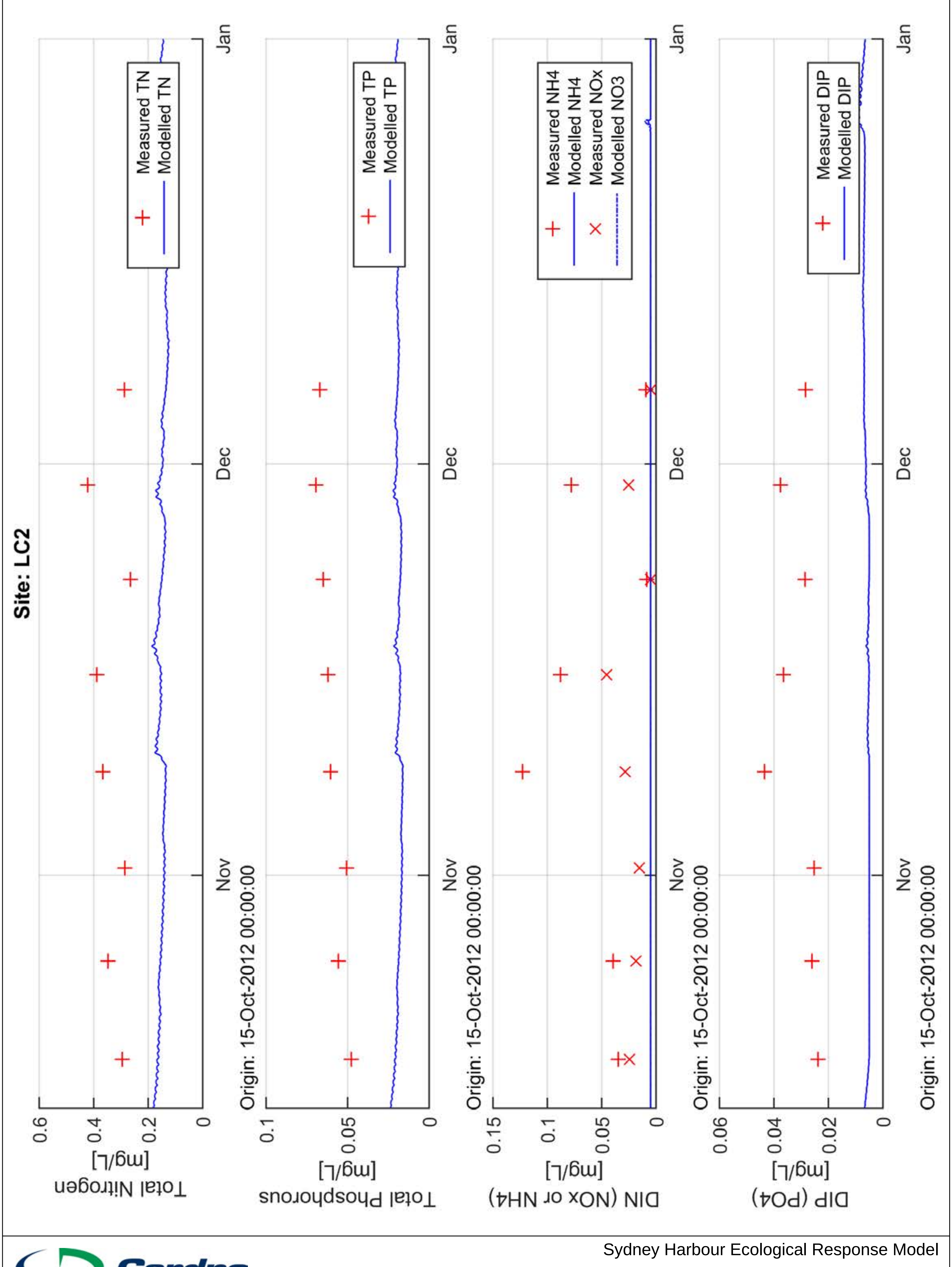
Figure 5.45b



Sydney Harbour Ecological Response Model

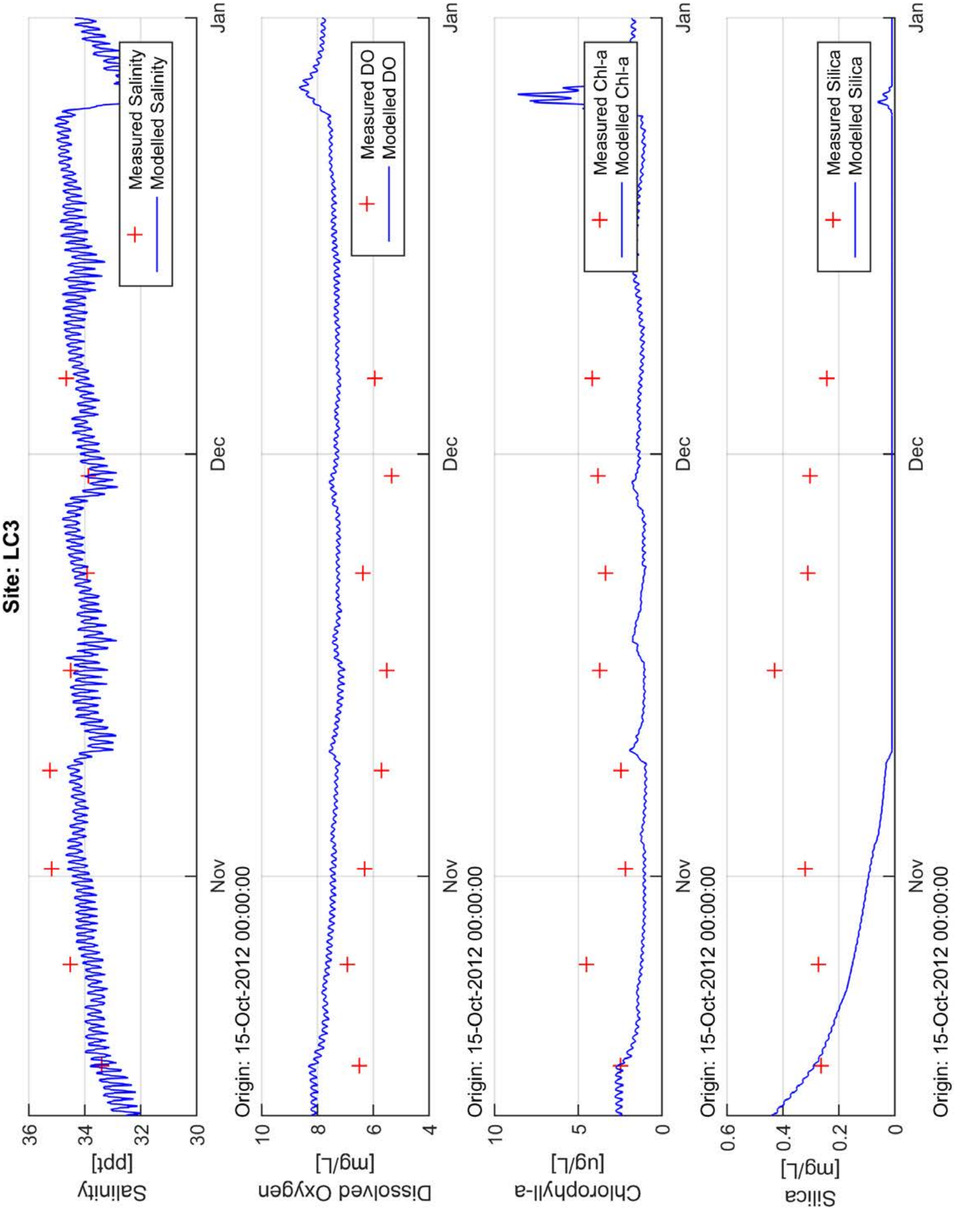
Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: LC2

Figure 5.46a



Site: LC2
Total Nitrogen [mg/L]
Measured TN
Modelled TN
Total Phosphorous [mg/L]
Measured TP
Modelled TP
DIN (NOx or NH4) [mg/L]
Measured NH4
Modelled NH4
Measured NOx
Modelled NO3
DIP (PO4) [mg/L]
Measured DIP
Modelled DIP
Origin: 15-Oct-2012 00:00:00
Nov
Dec
Jan

Figure 5.46b



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Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: LC3

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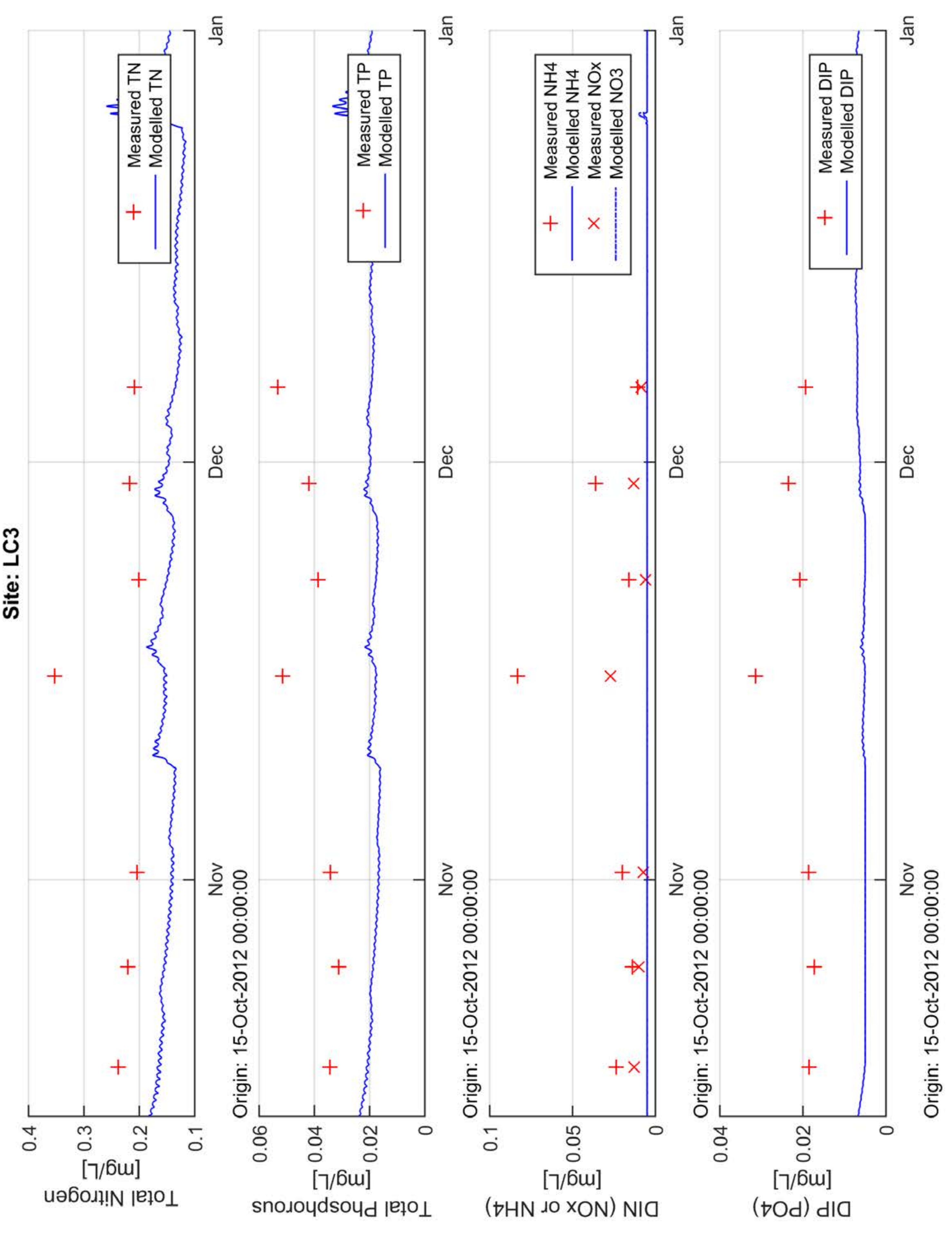
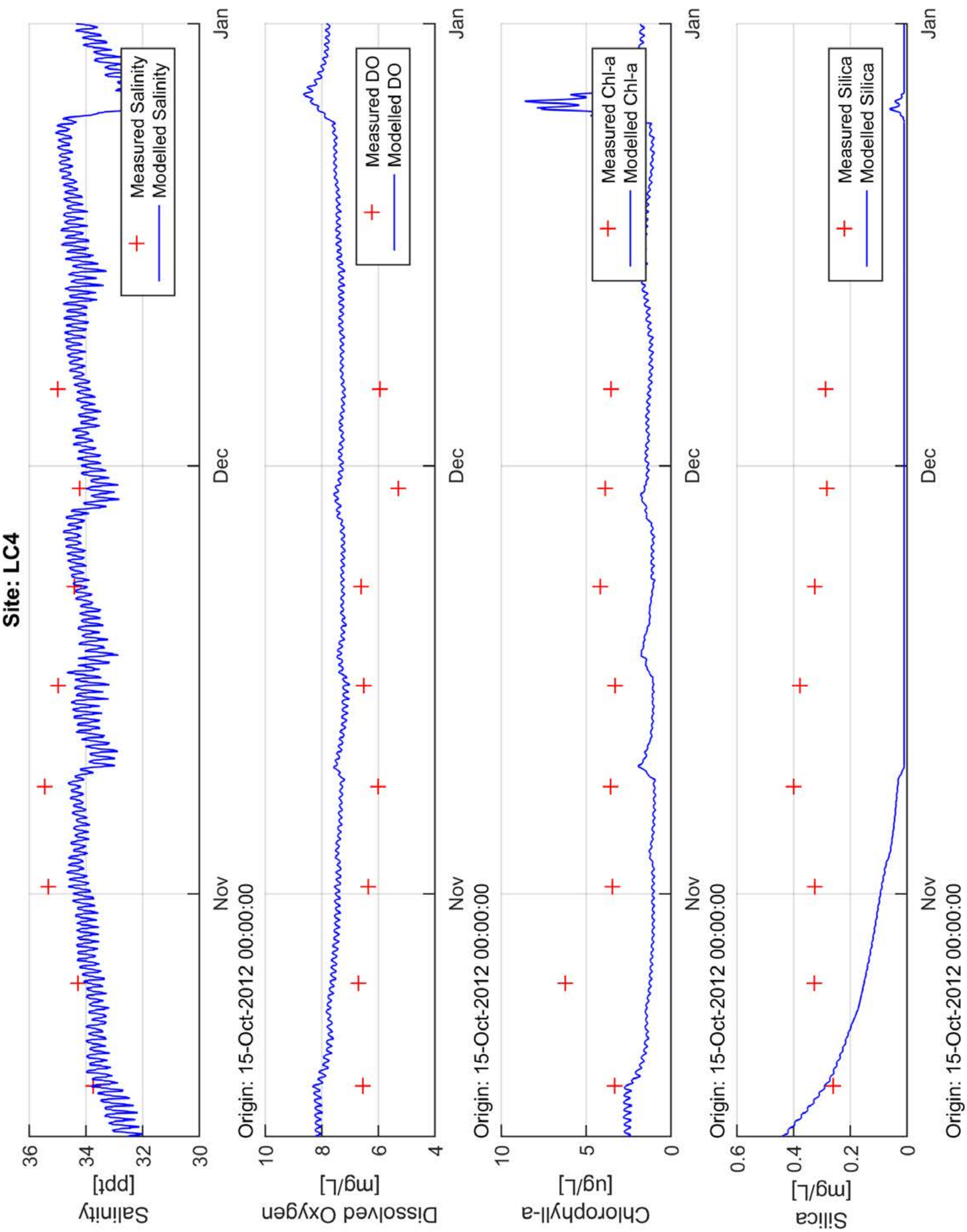
Figure 5.47a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: LC3

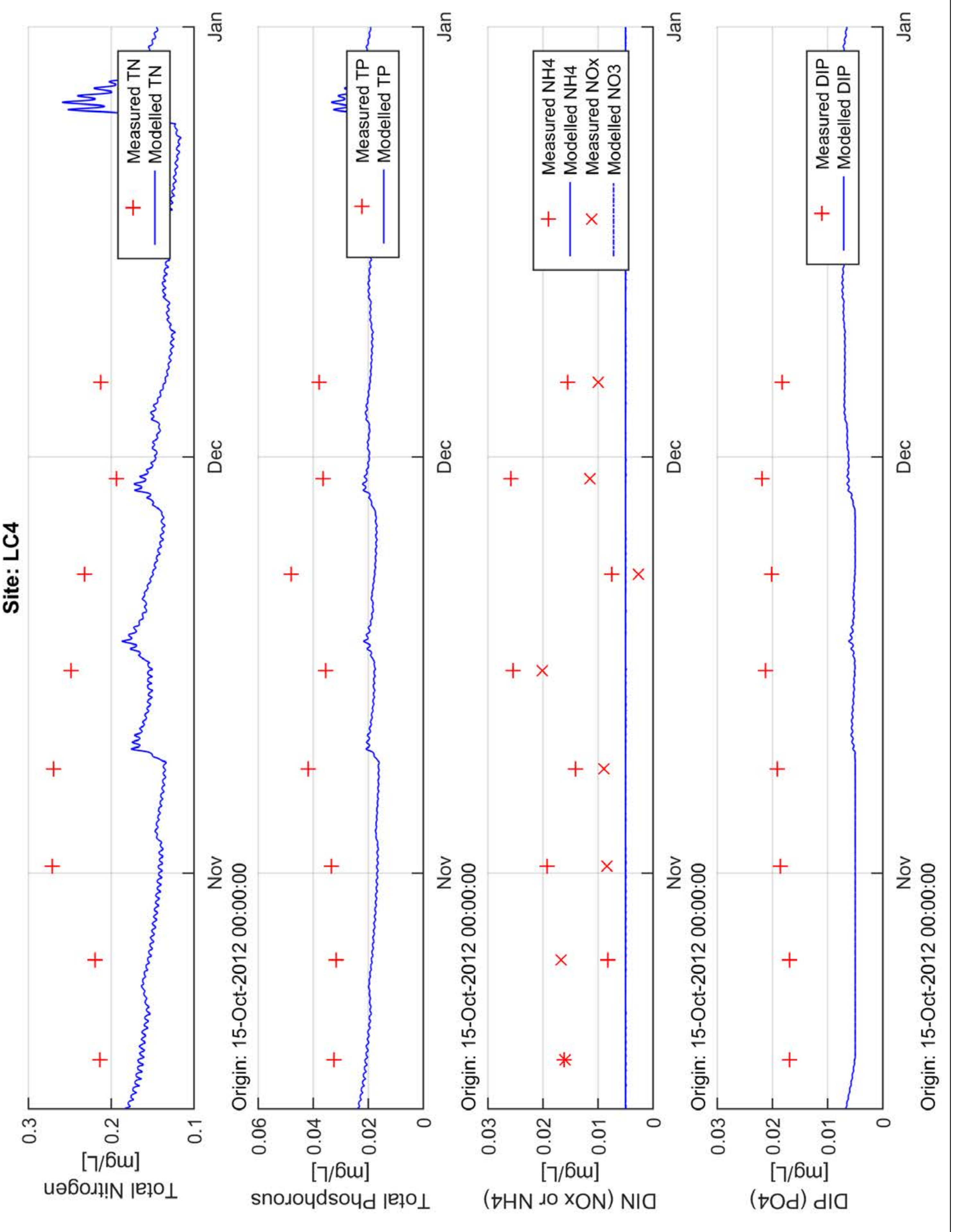
Figure 5.47b



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: LC4

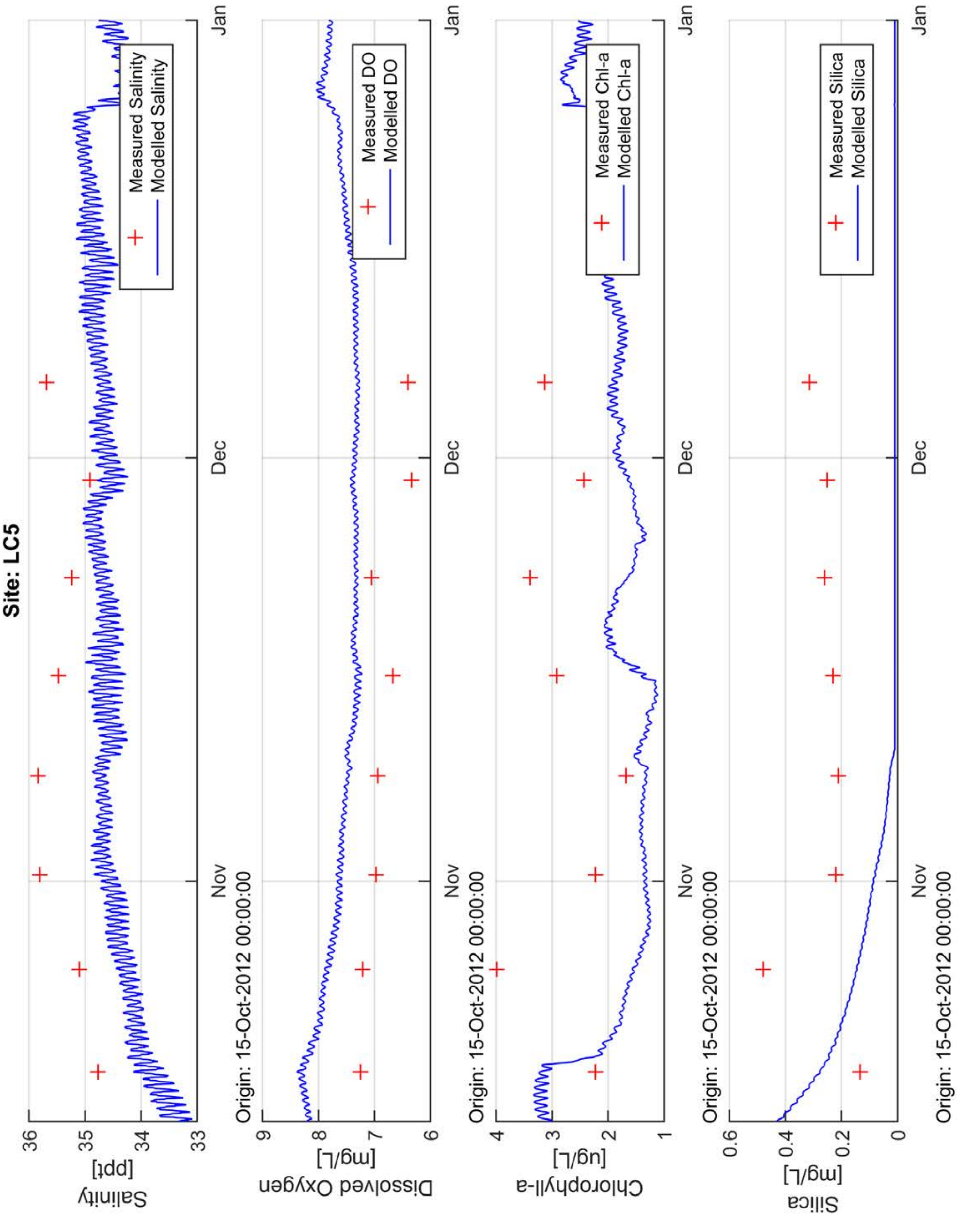
Figure 5.48a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: LC4

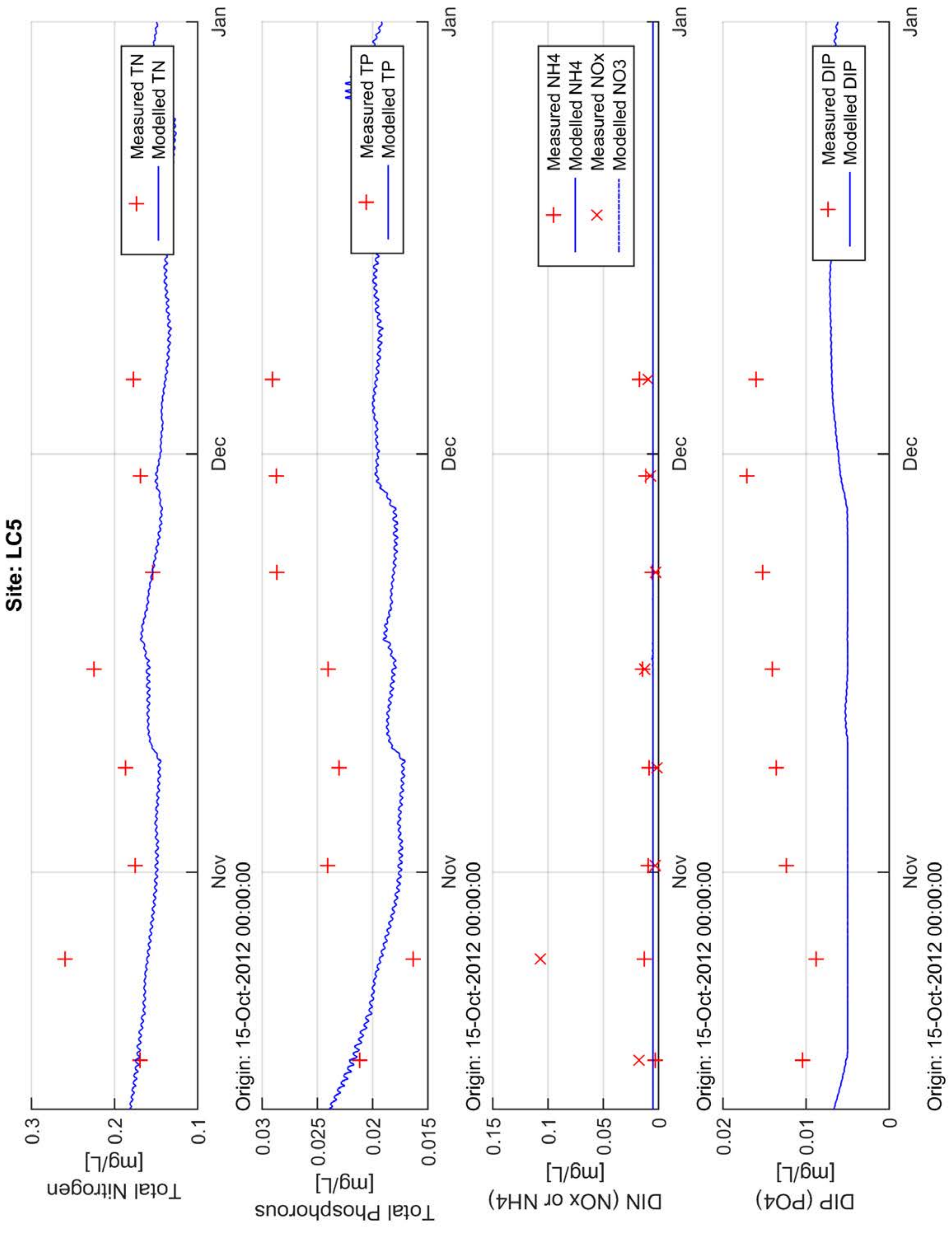
Figure 5.48b



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: LC5

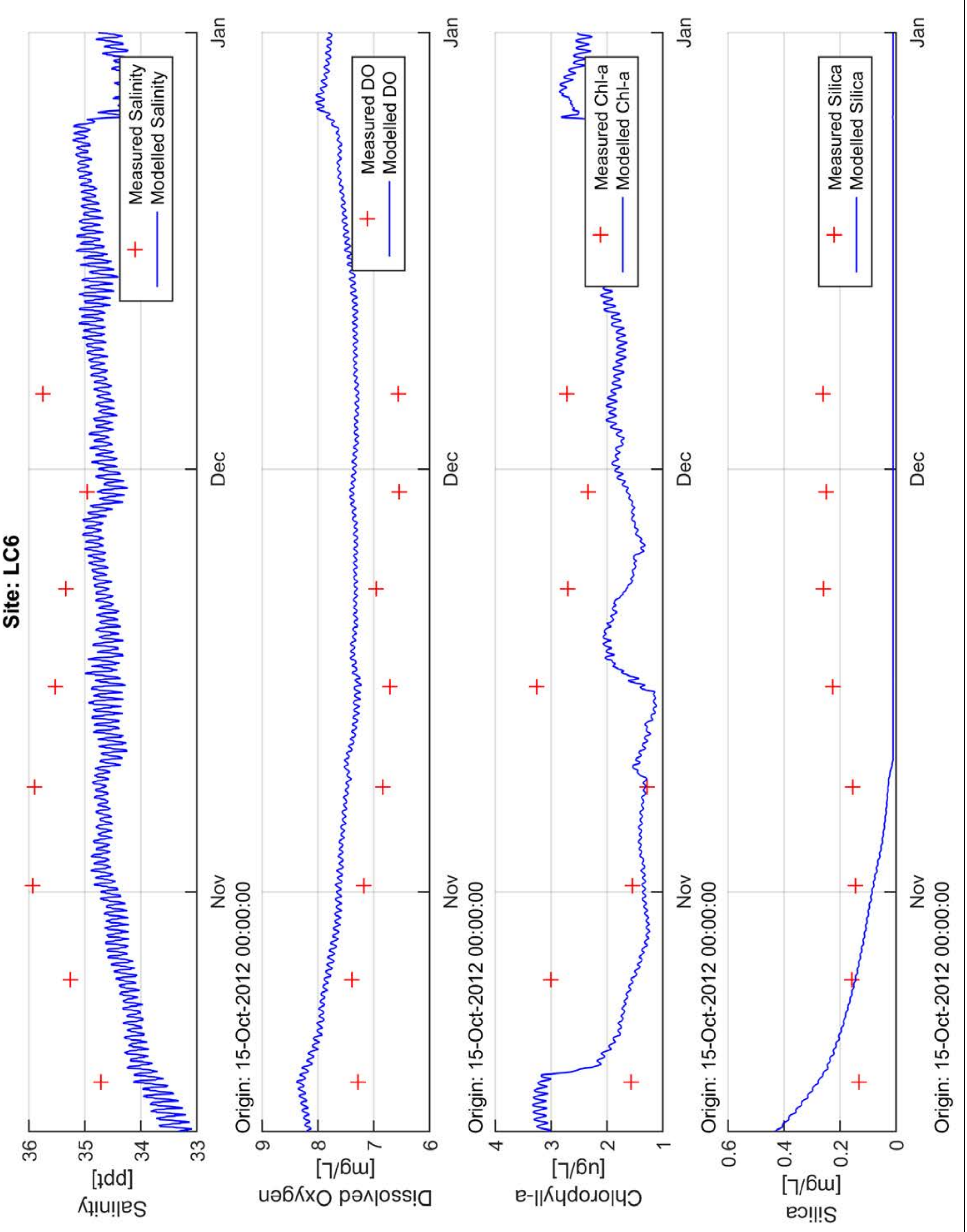
Figure 5.49a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: LC5

Figure 5.49b



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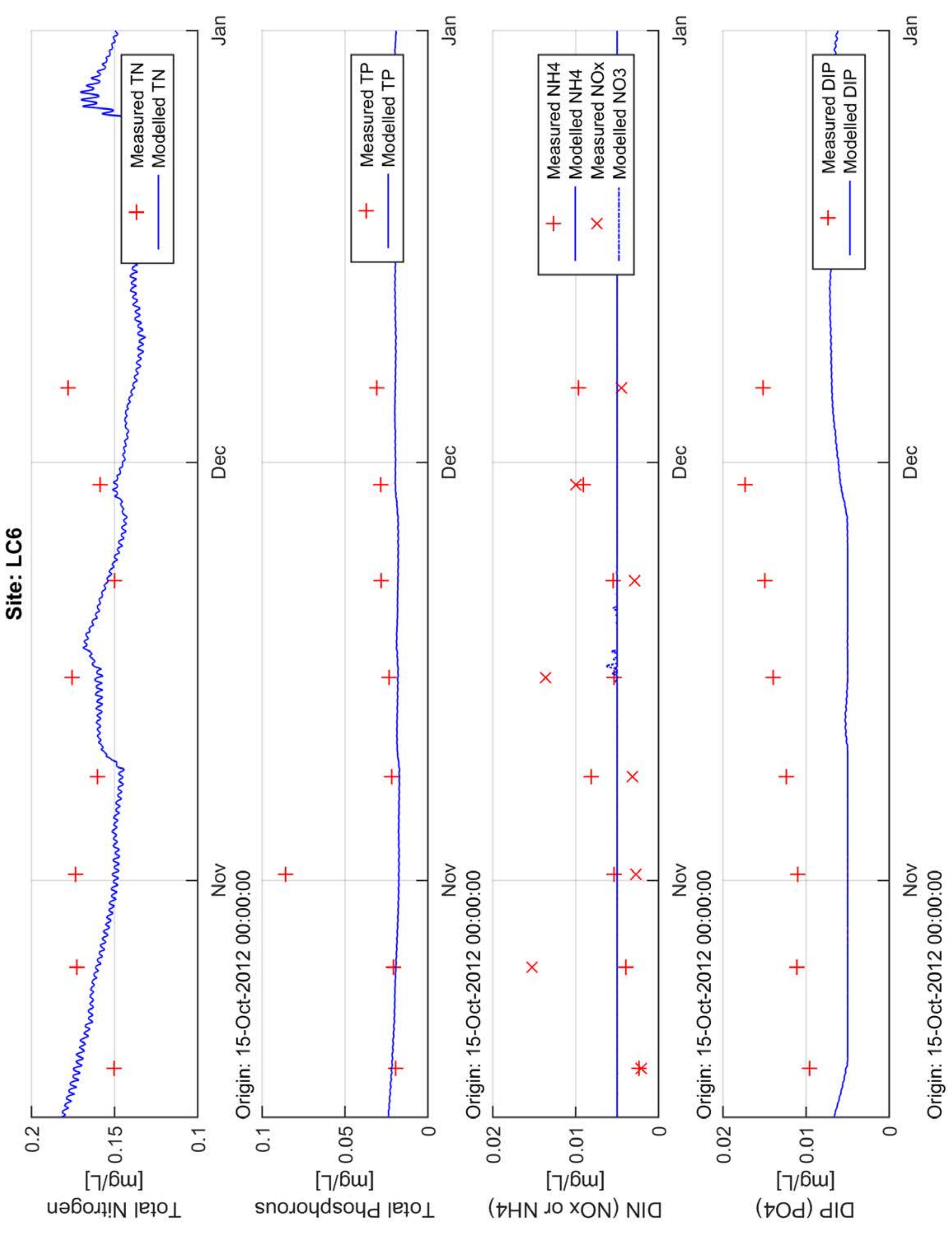
Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: LC6

Figure 5.50a

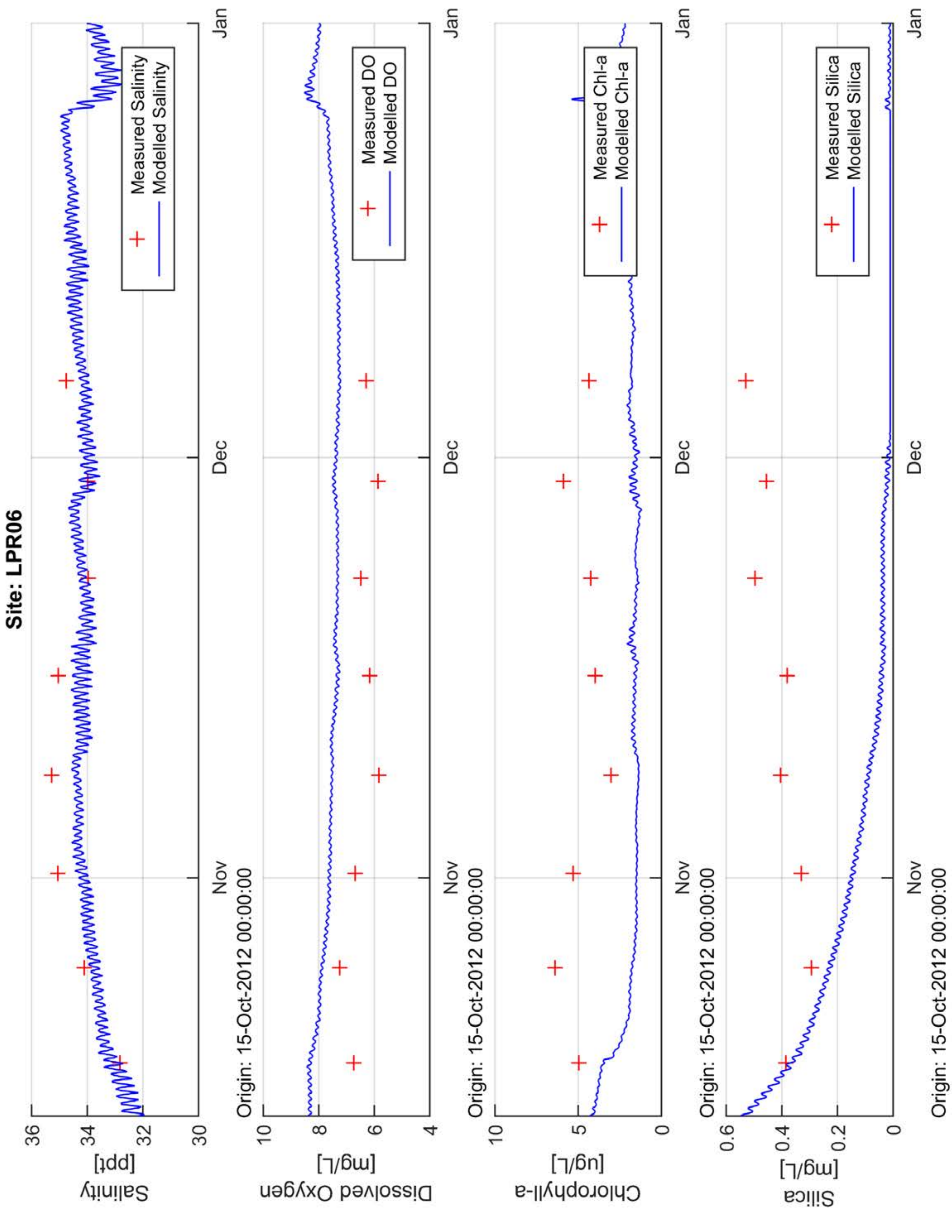


Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012

BLOOM Model − Site: LC6

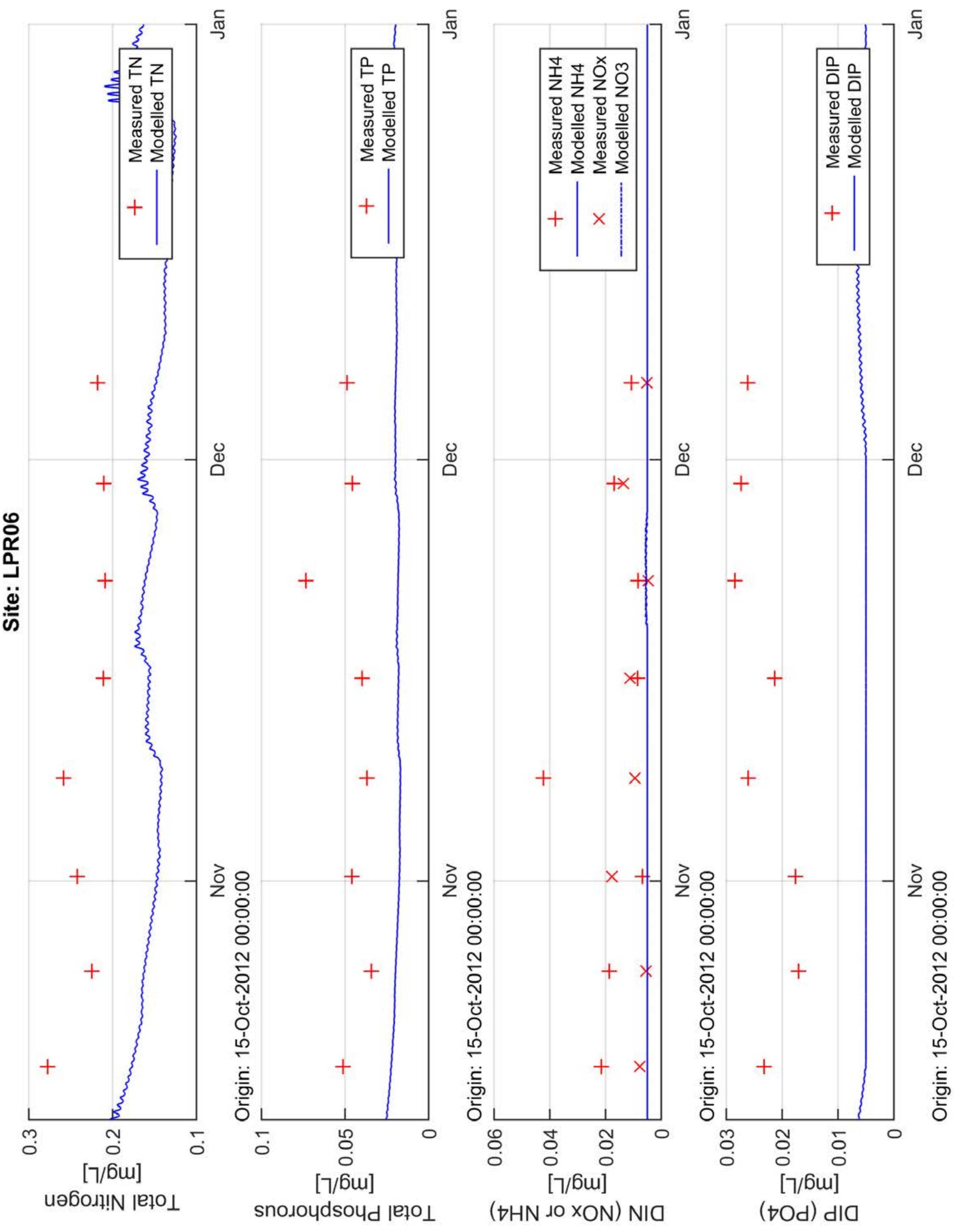
Figure 5.50b



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: LPR06

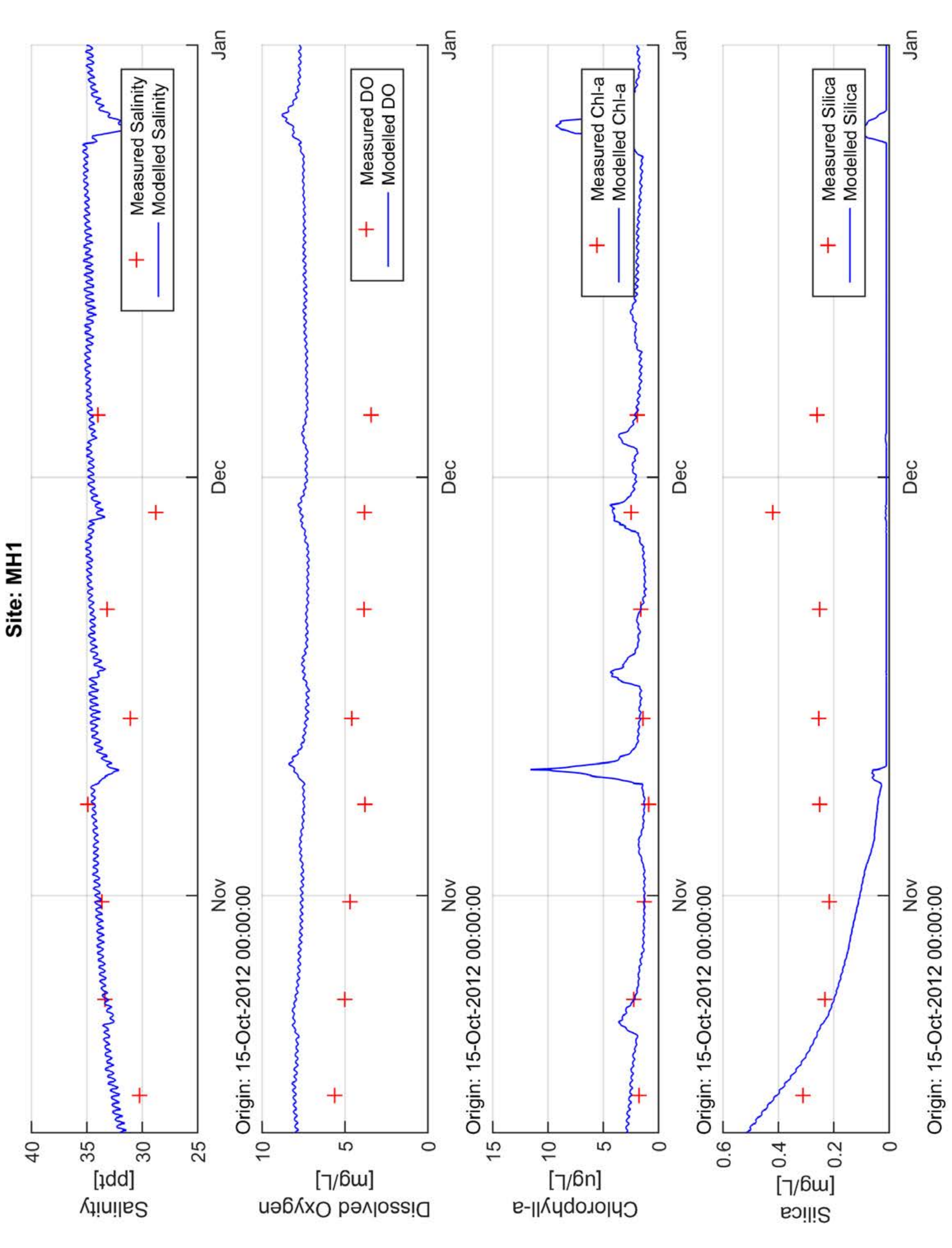
Figure 5.51a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: LPR06

Figure 5.51b



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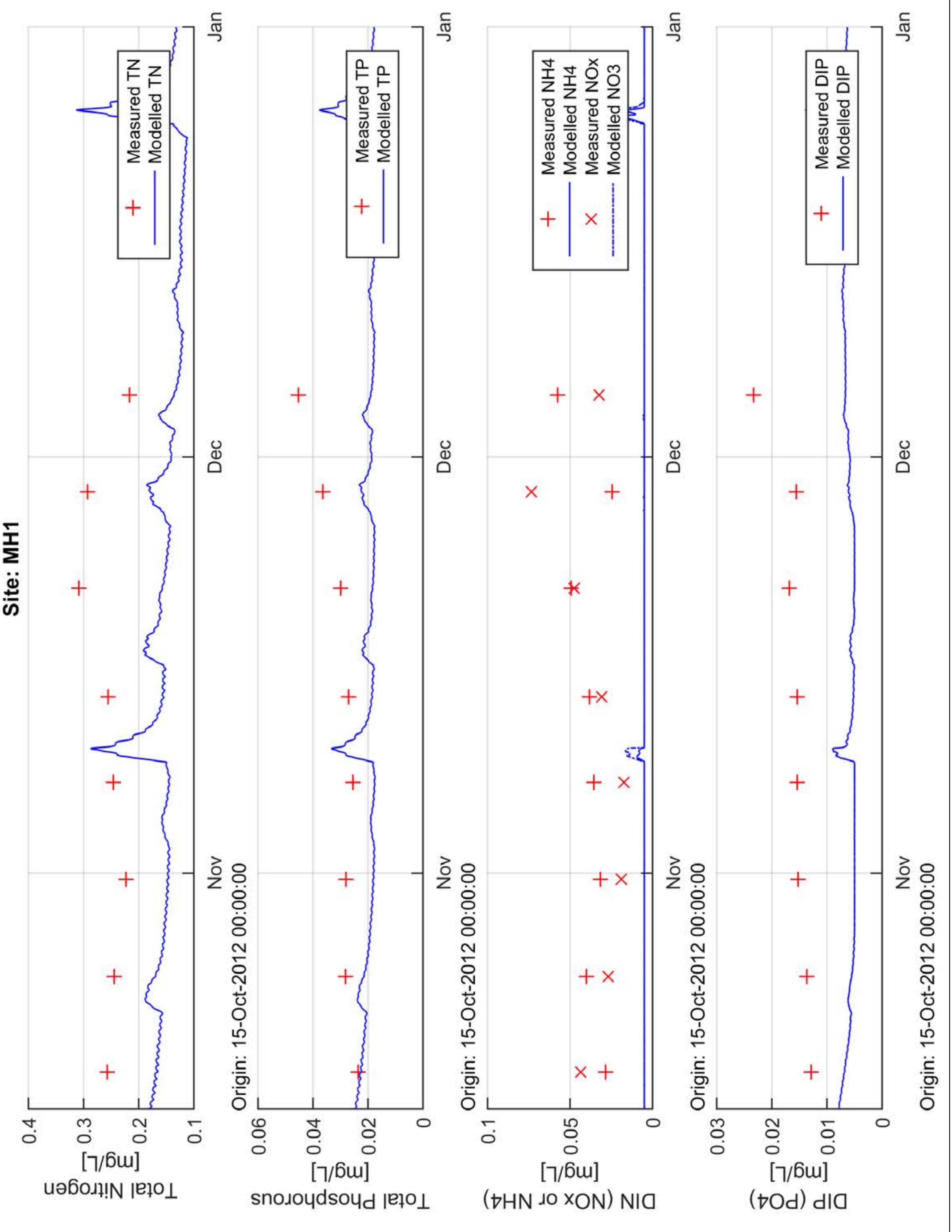
Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: MH1

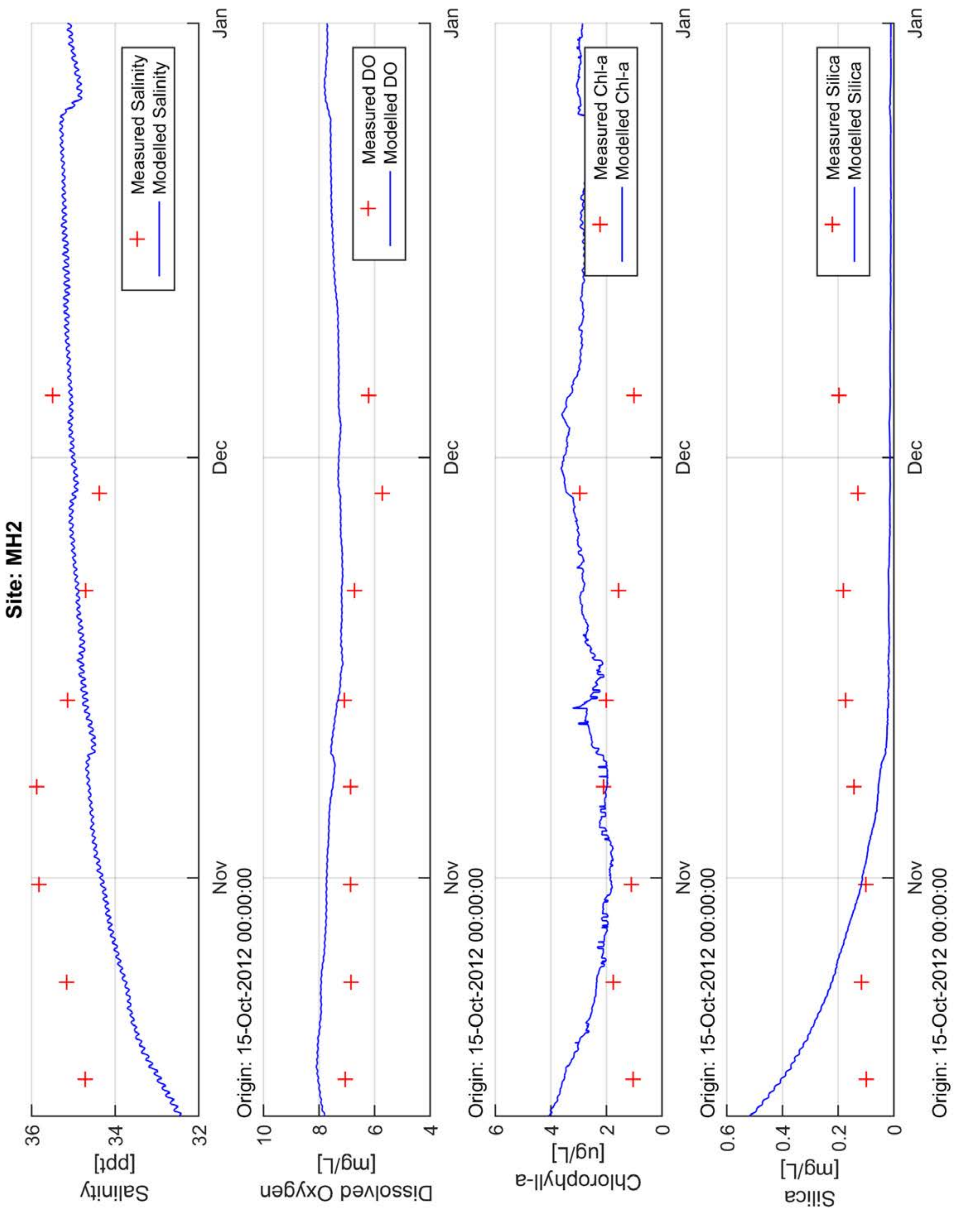
Figure 5.52a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: MH1

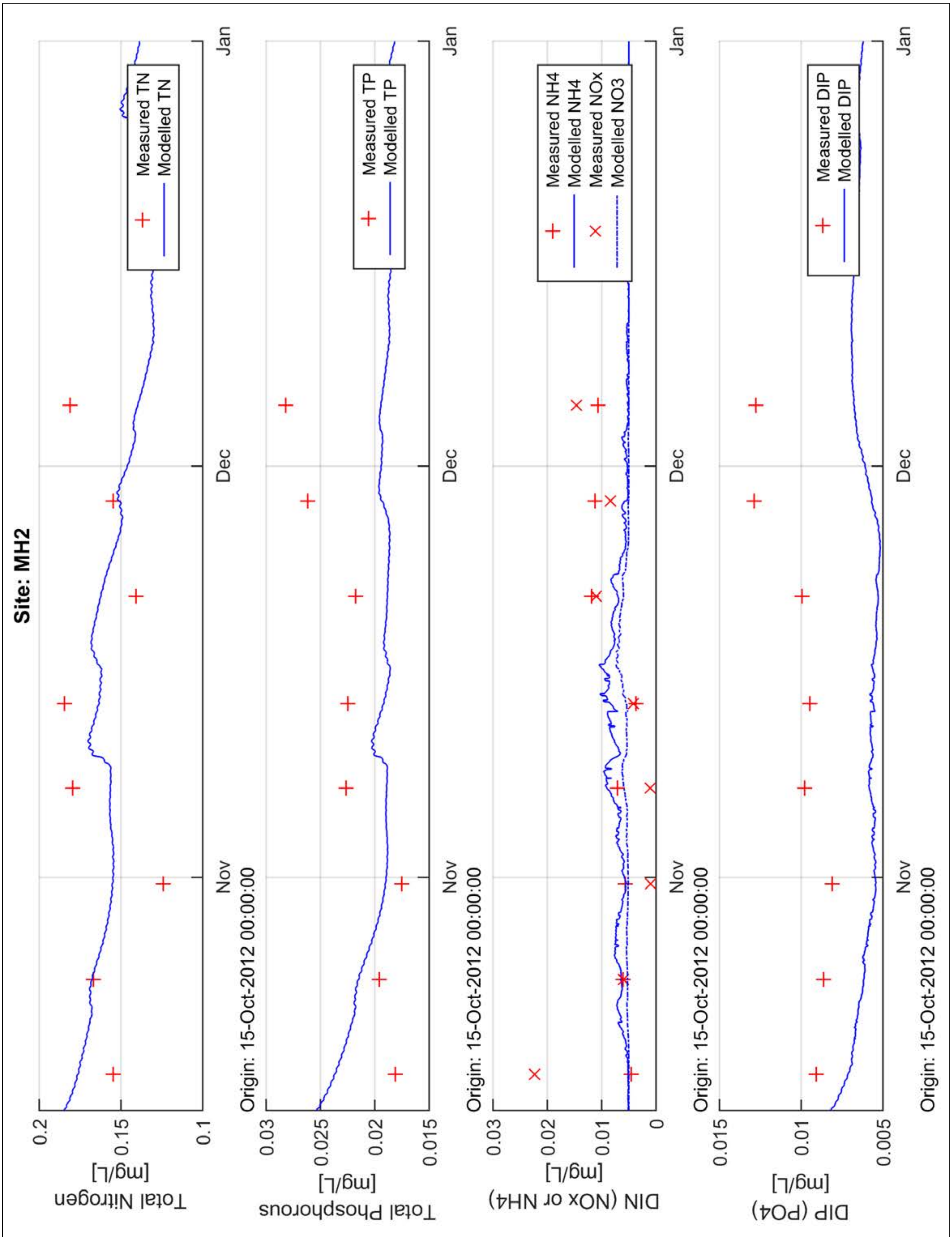
Figure 5.52b



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: MH2

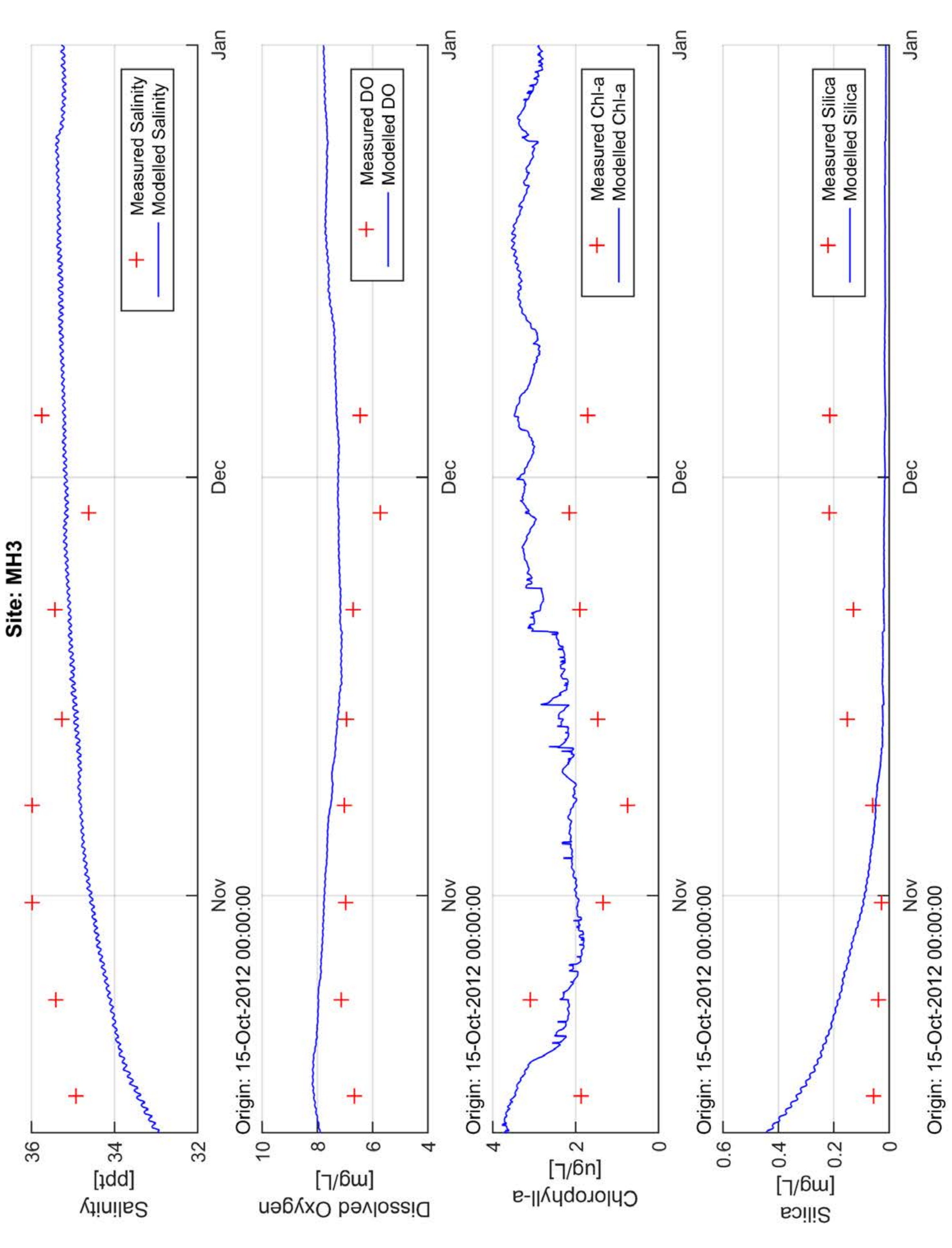
Figure 5.53a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: MH2

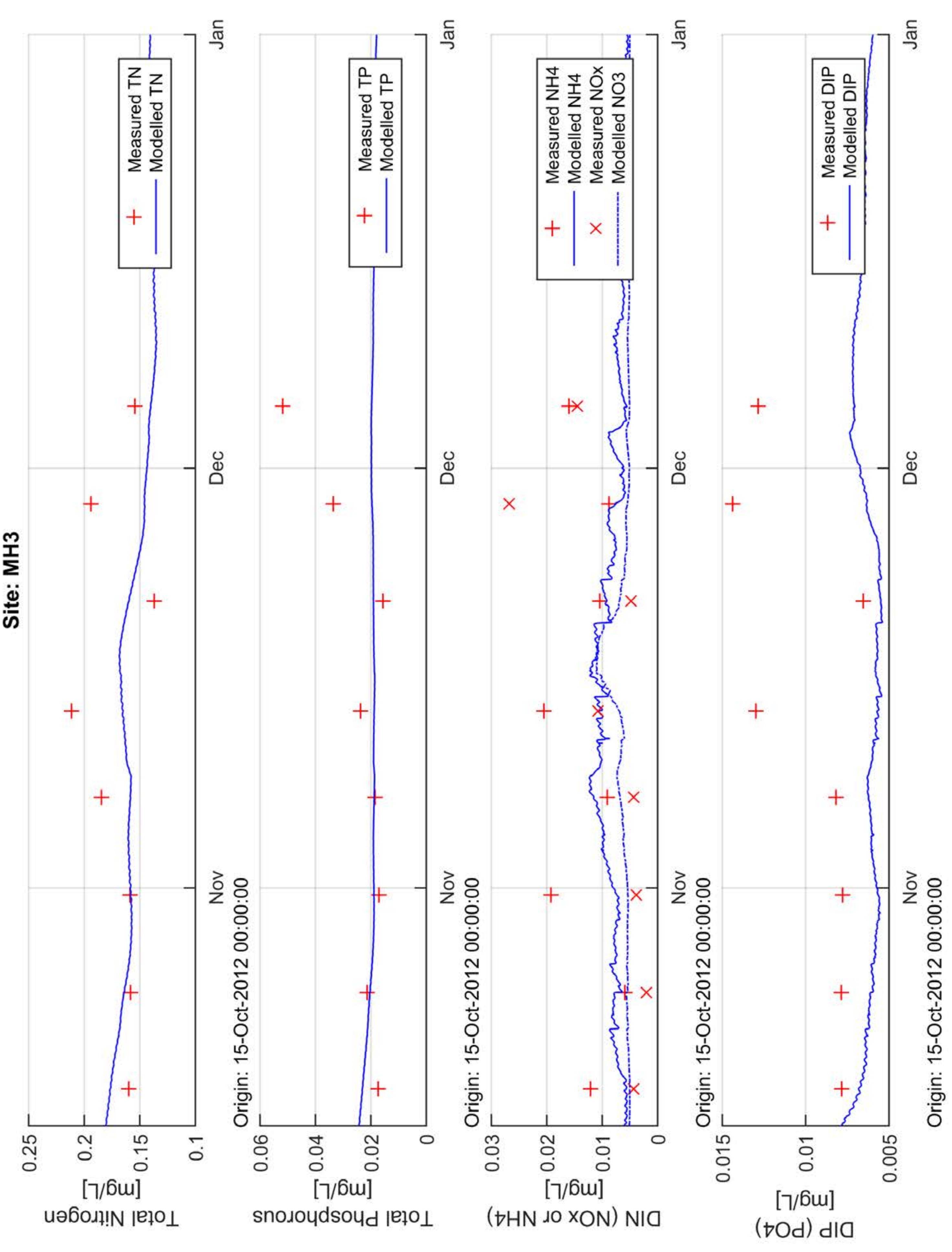
Figure 5.53b



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: MH3

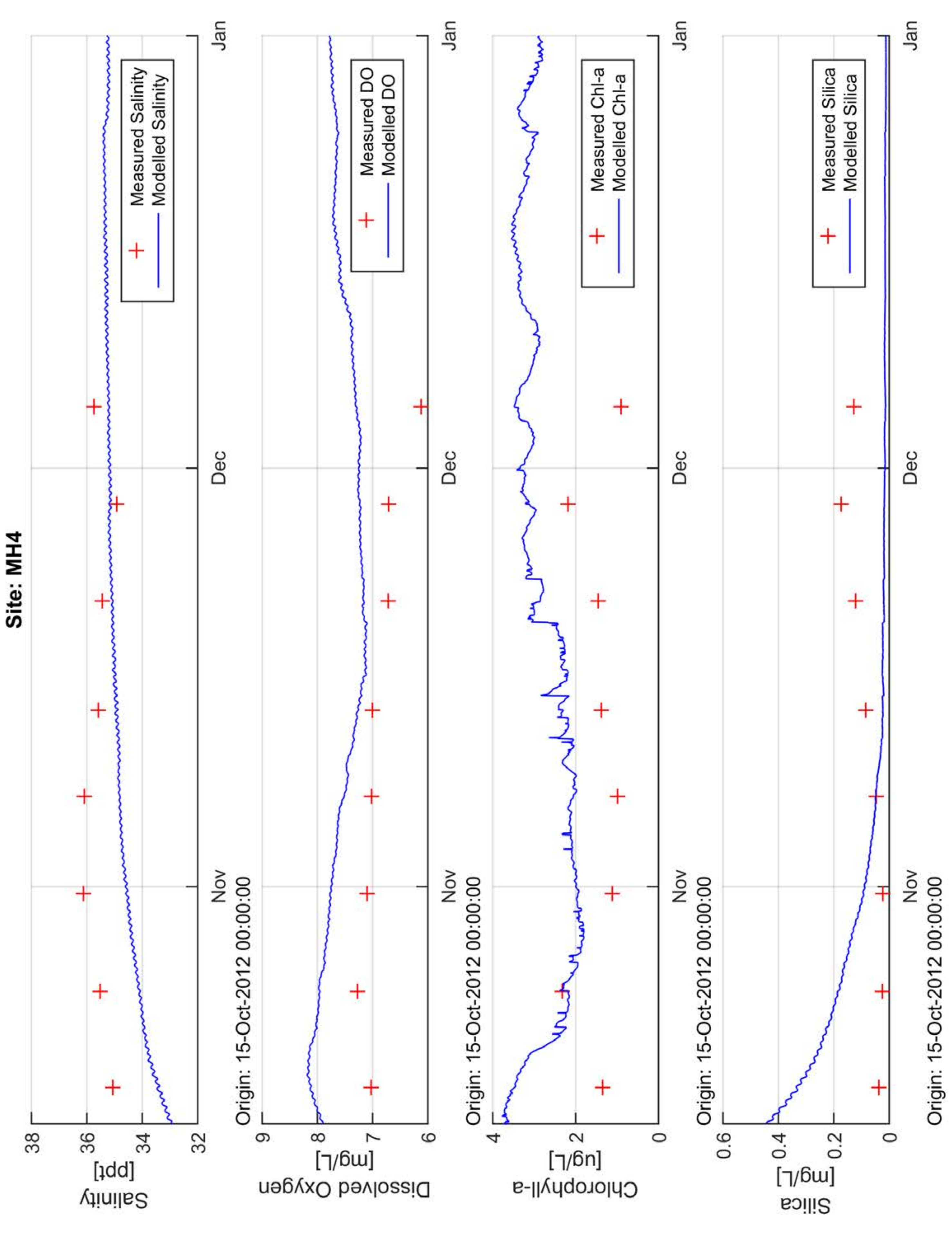
Figure 5.54a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: MH3

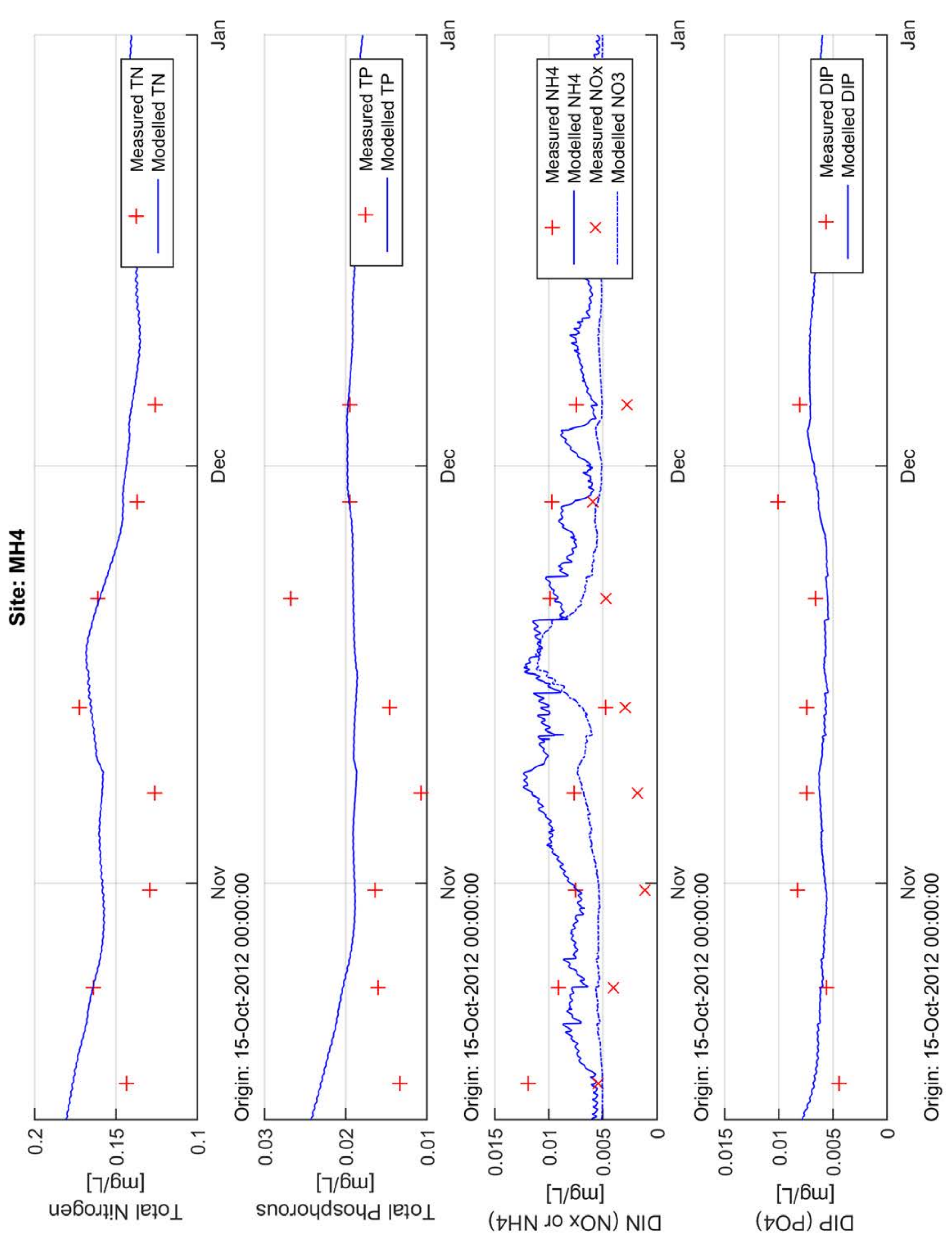
Figure 5.54b



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: MH4

Figure 5.55a



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Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: MH4

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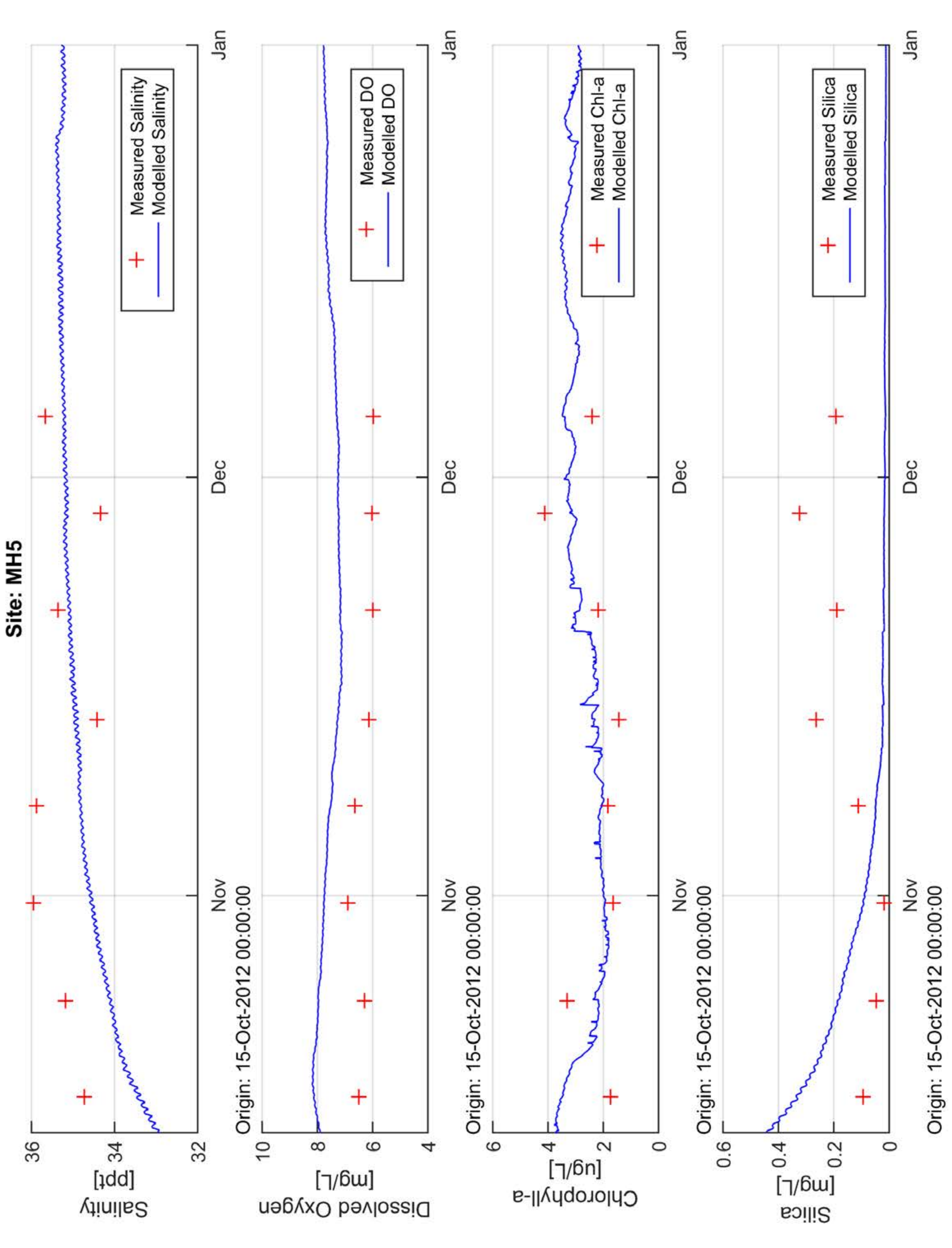
Figure 5.55b

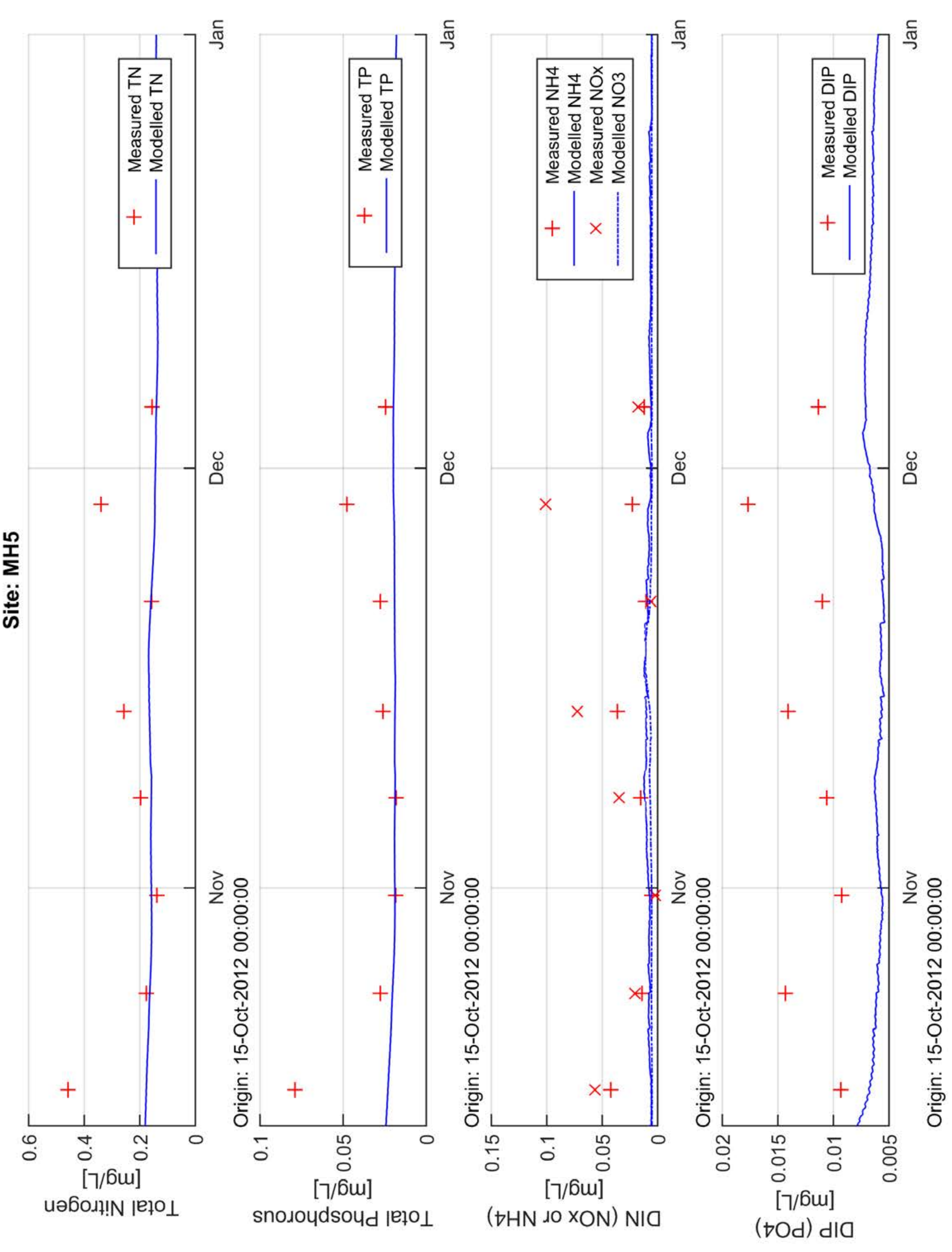


Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012

BLOOM Model − Site: MH5

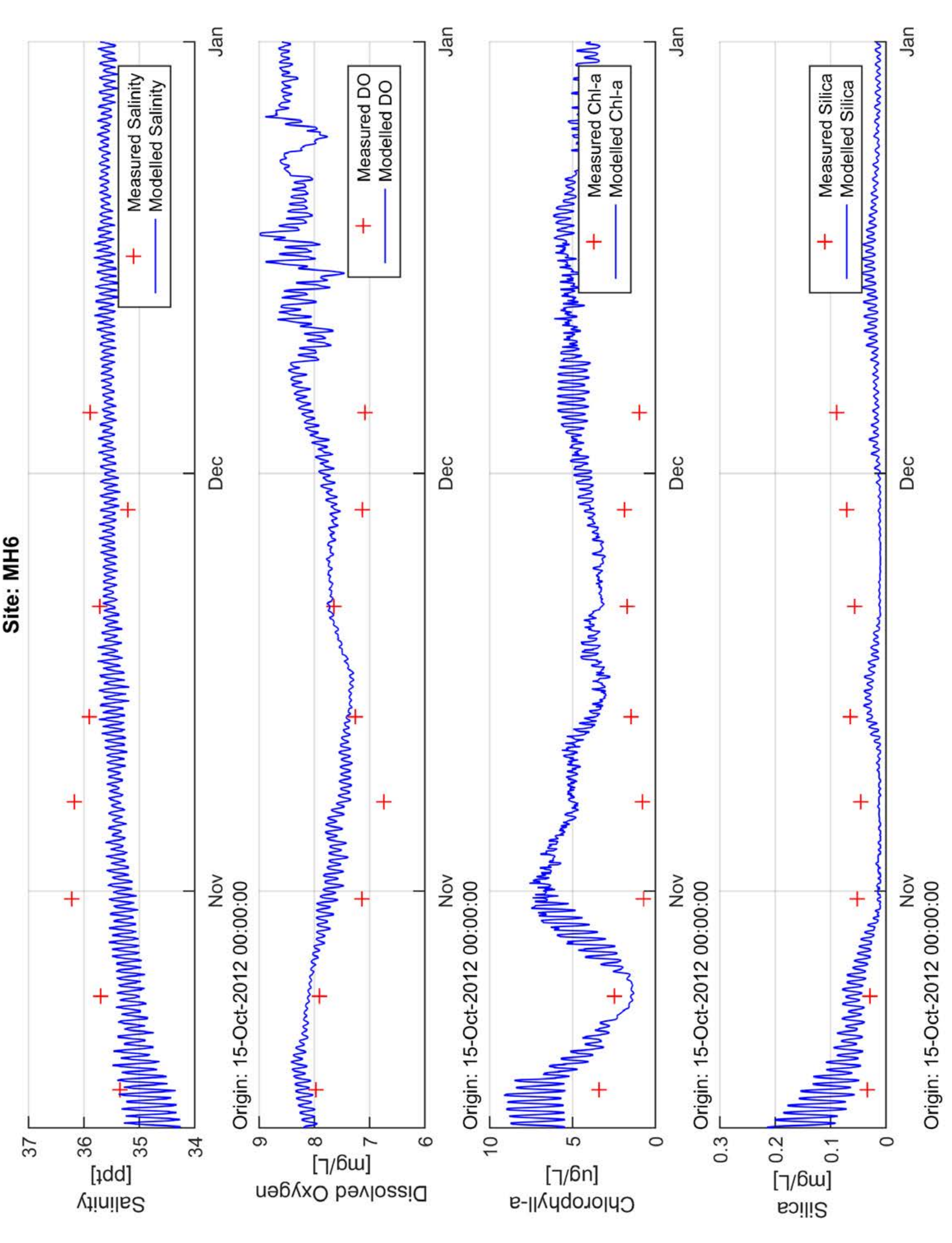
Figure 5.56a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: MH5

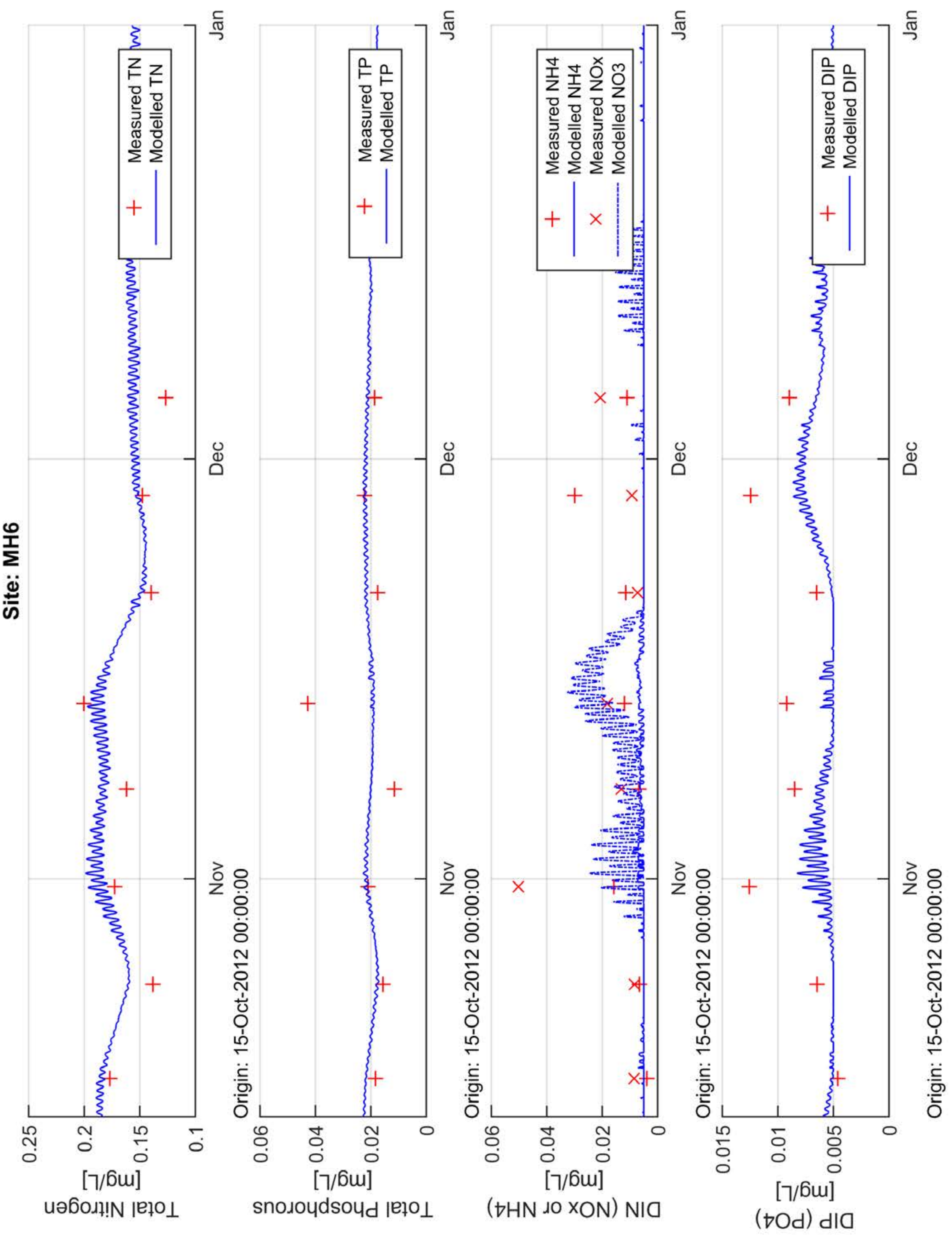
Figure 5.56b



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: MH6

Figure 5.57a



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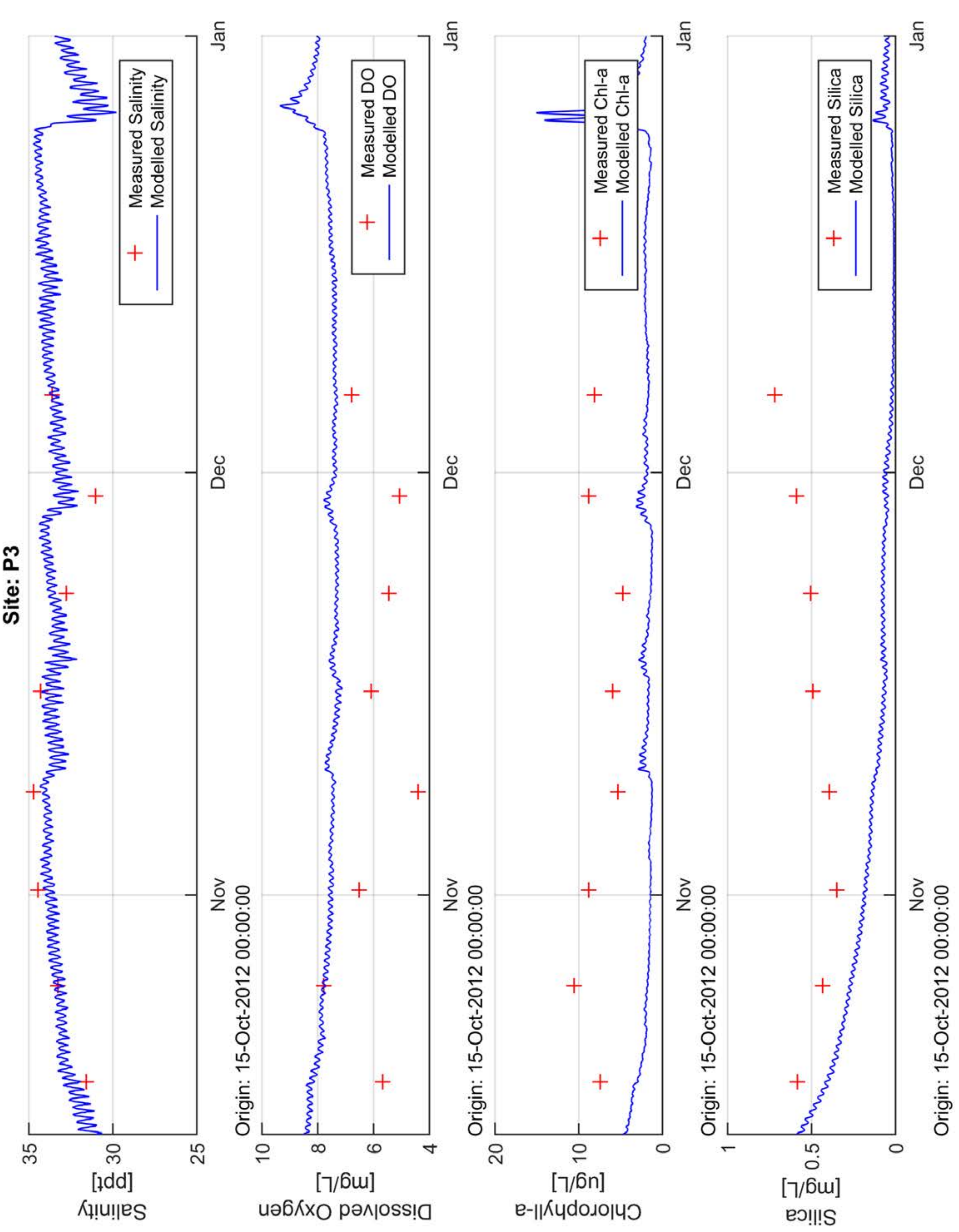
Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012

BLOOM Model − Site: MH6

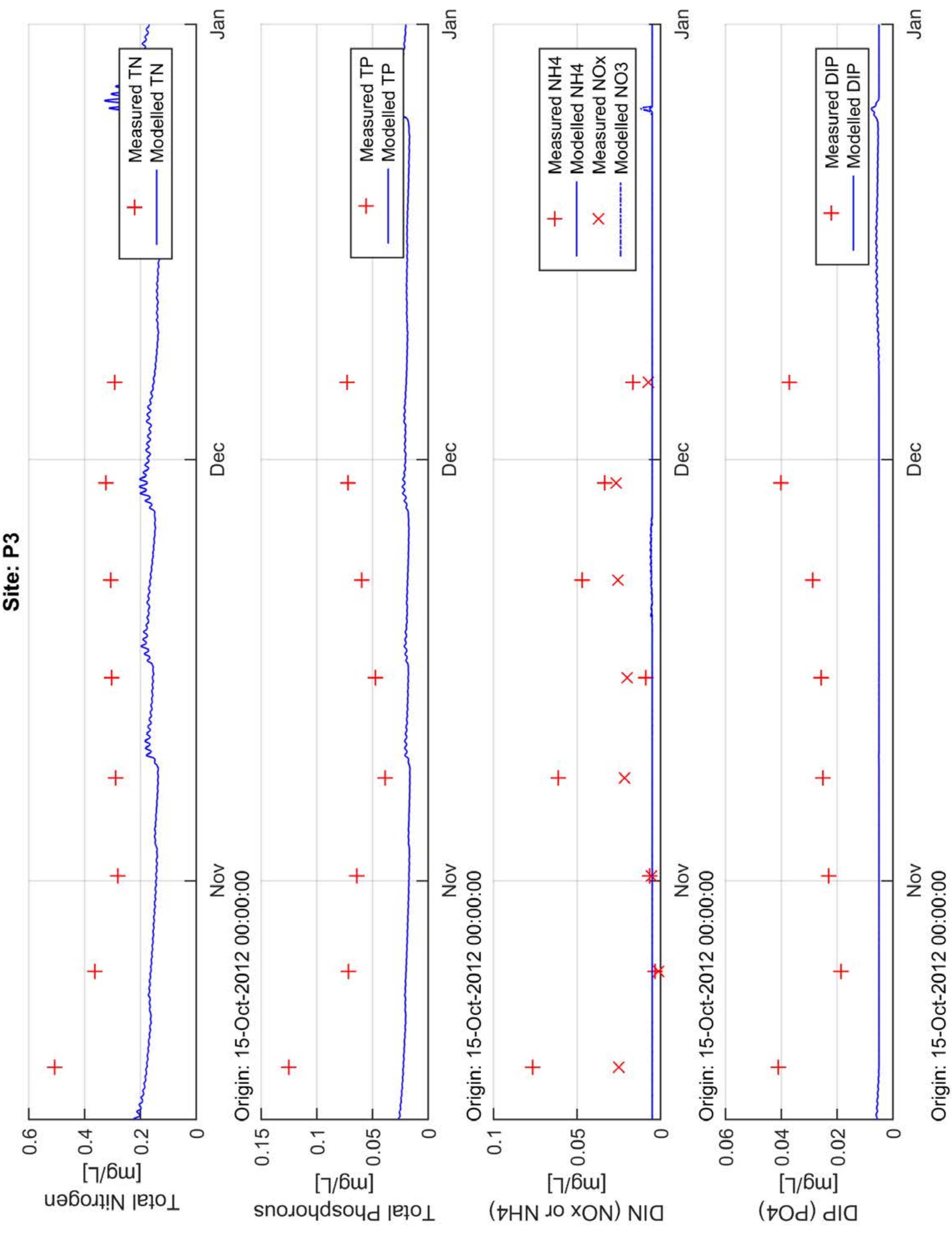
Figure 5.57b



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: P3

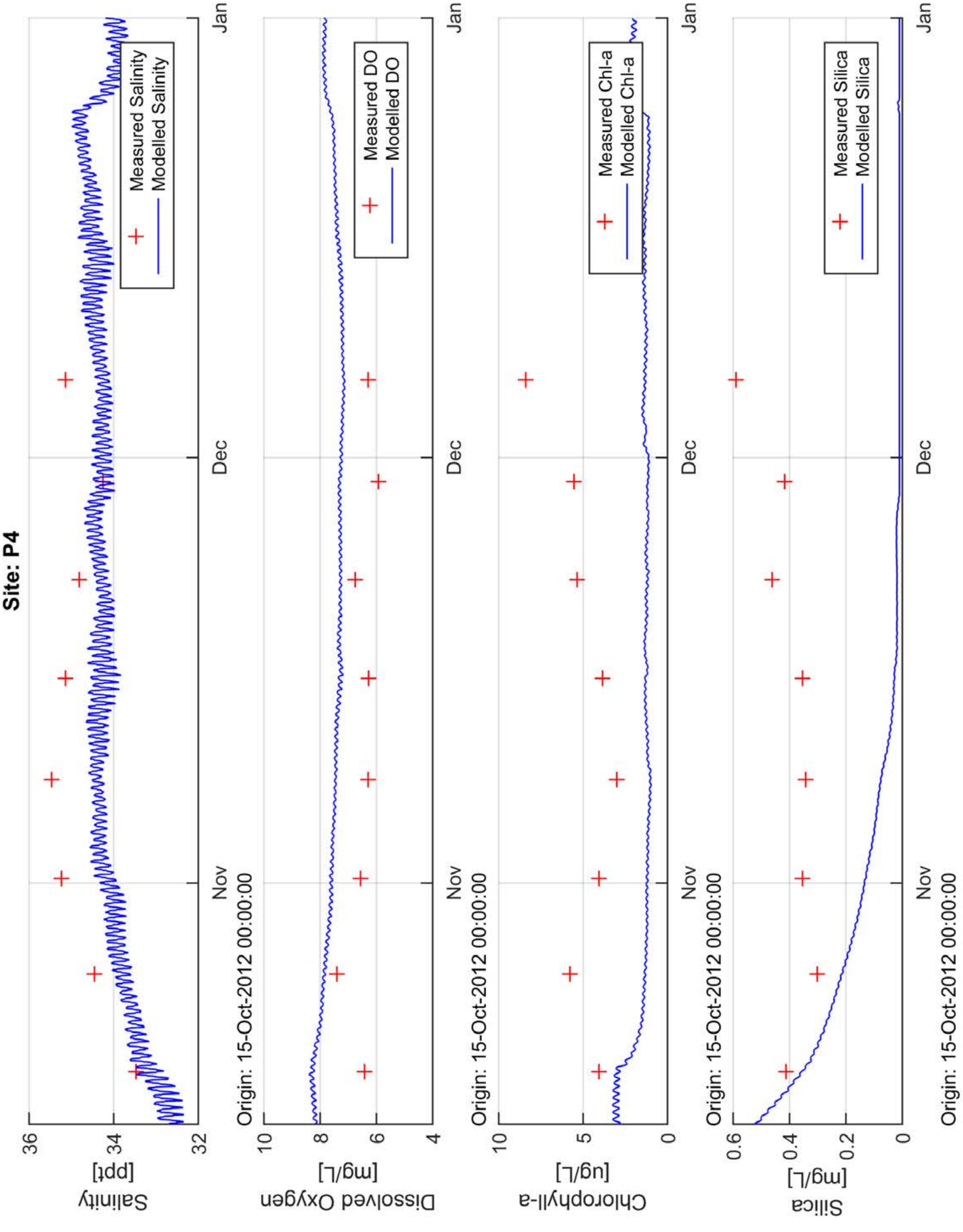
Figure 5.58a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: P3

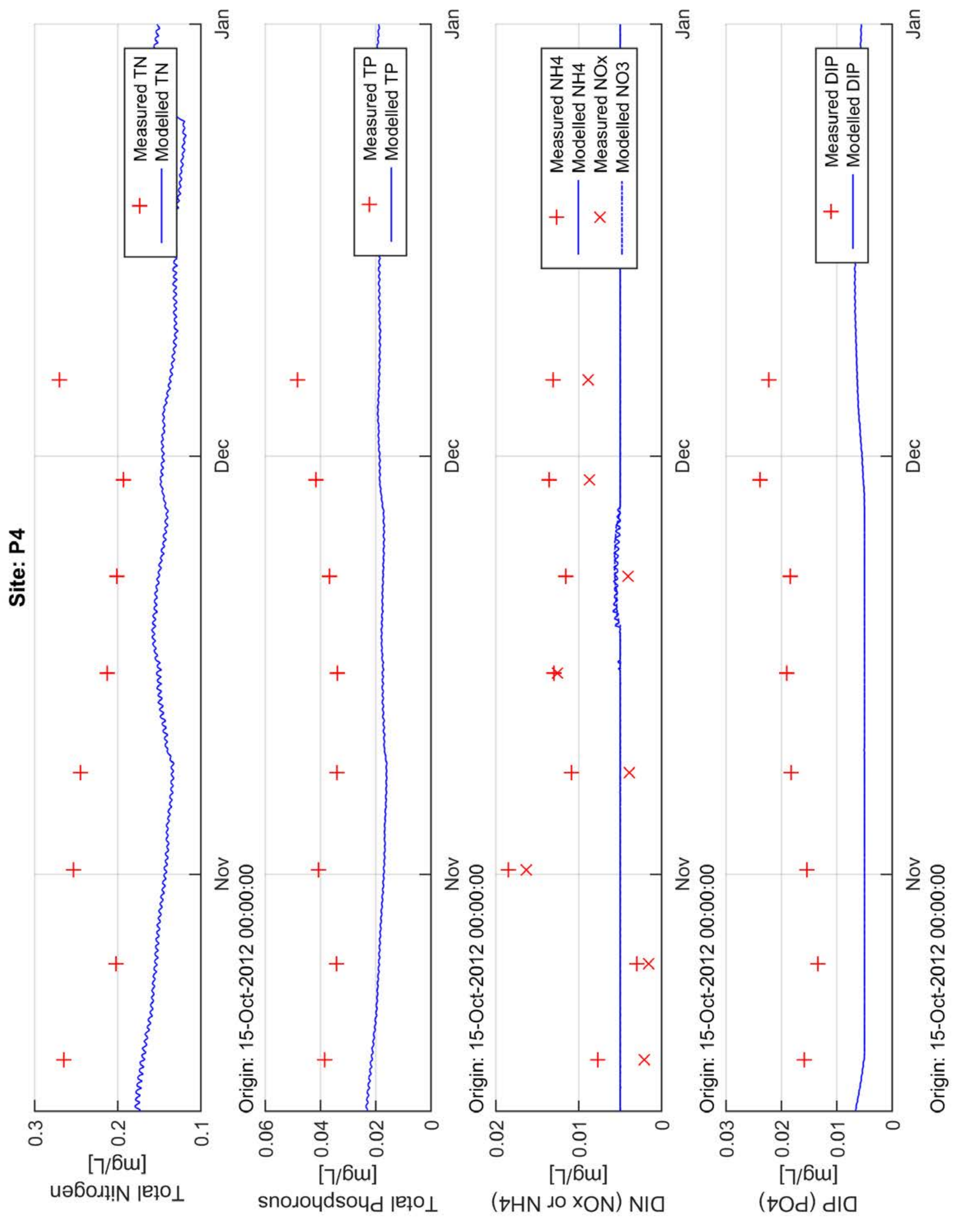
Figure 5.58b



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: P4

Figure 5.59a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: P4

Figure 5.59b

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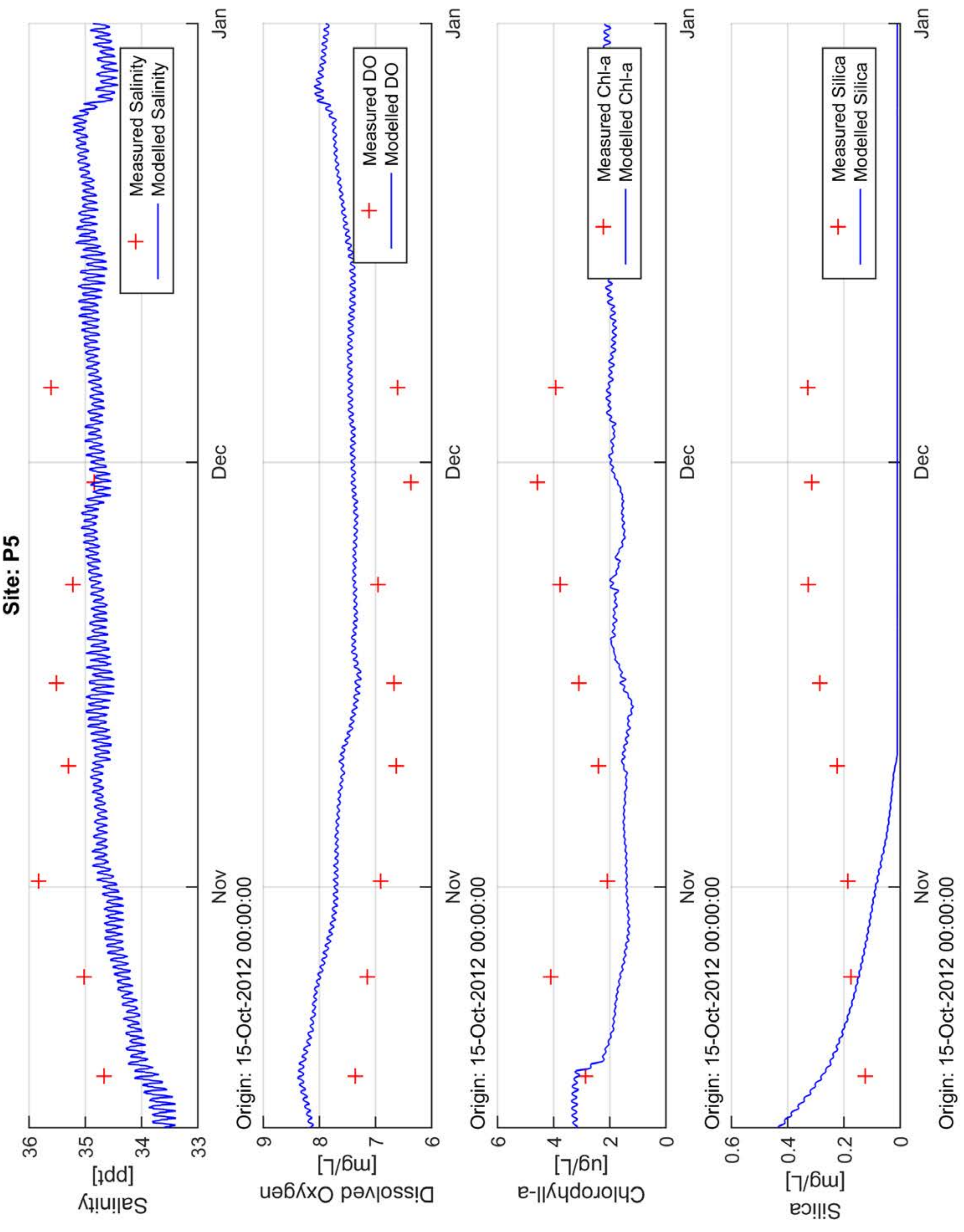
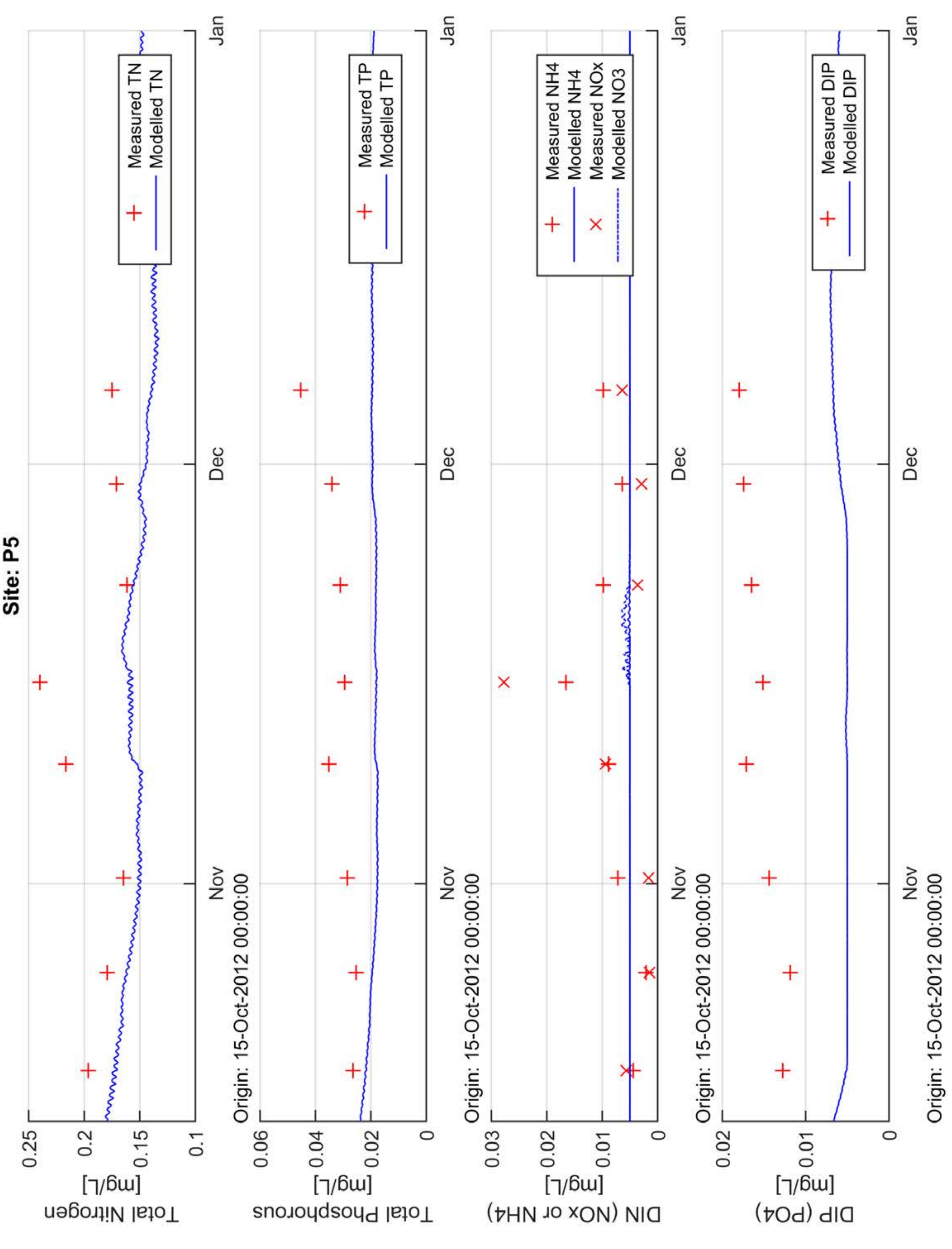


Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012

BLOOM Model − Site: P5

Figure 5.60a

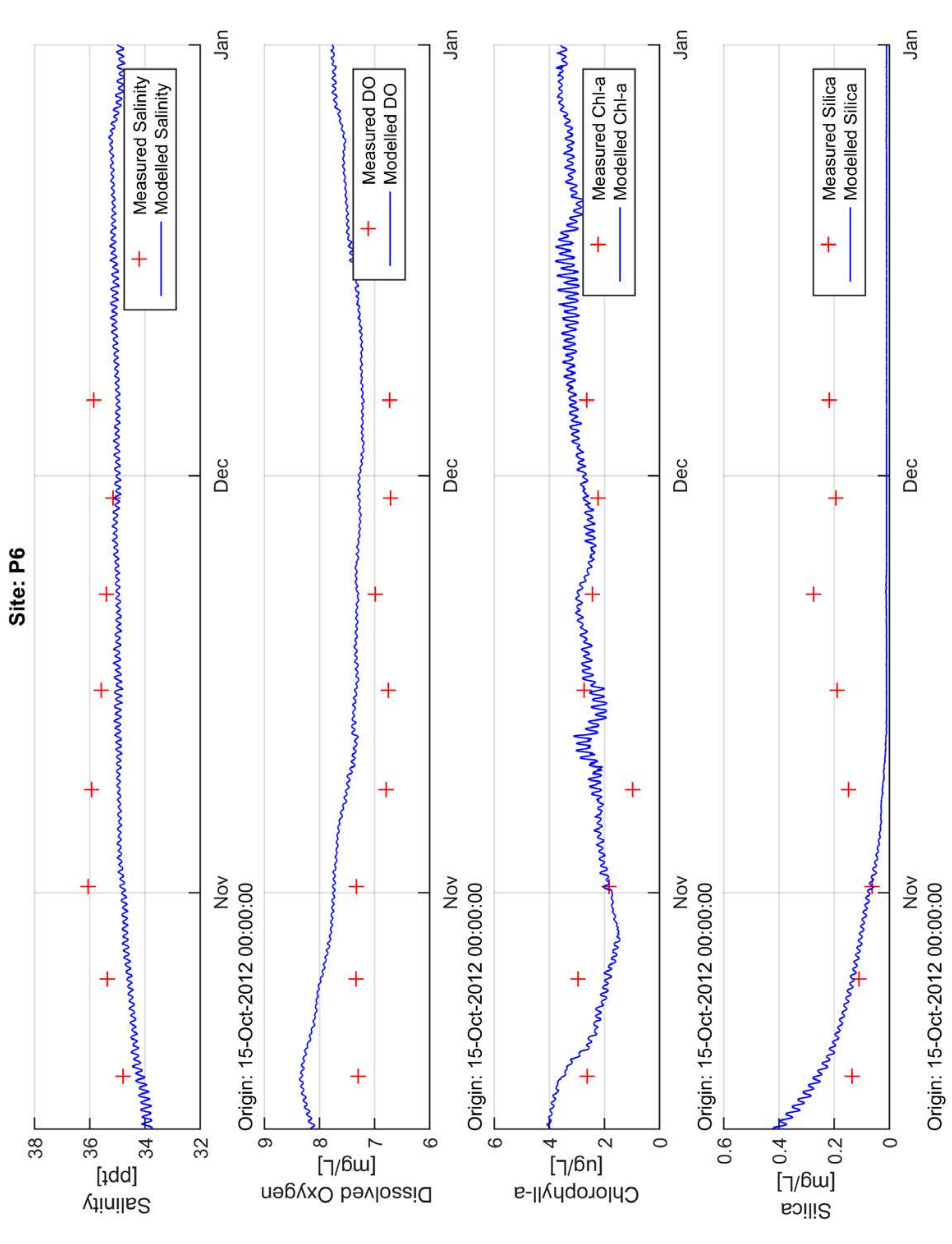


Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012

BLOOM Model − Site: P5

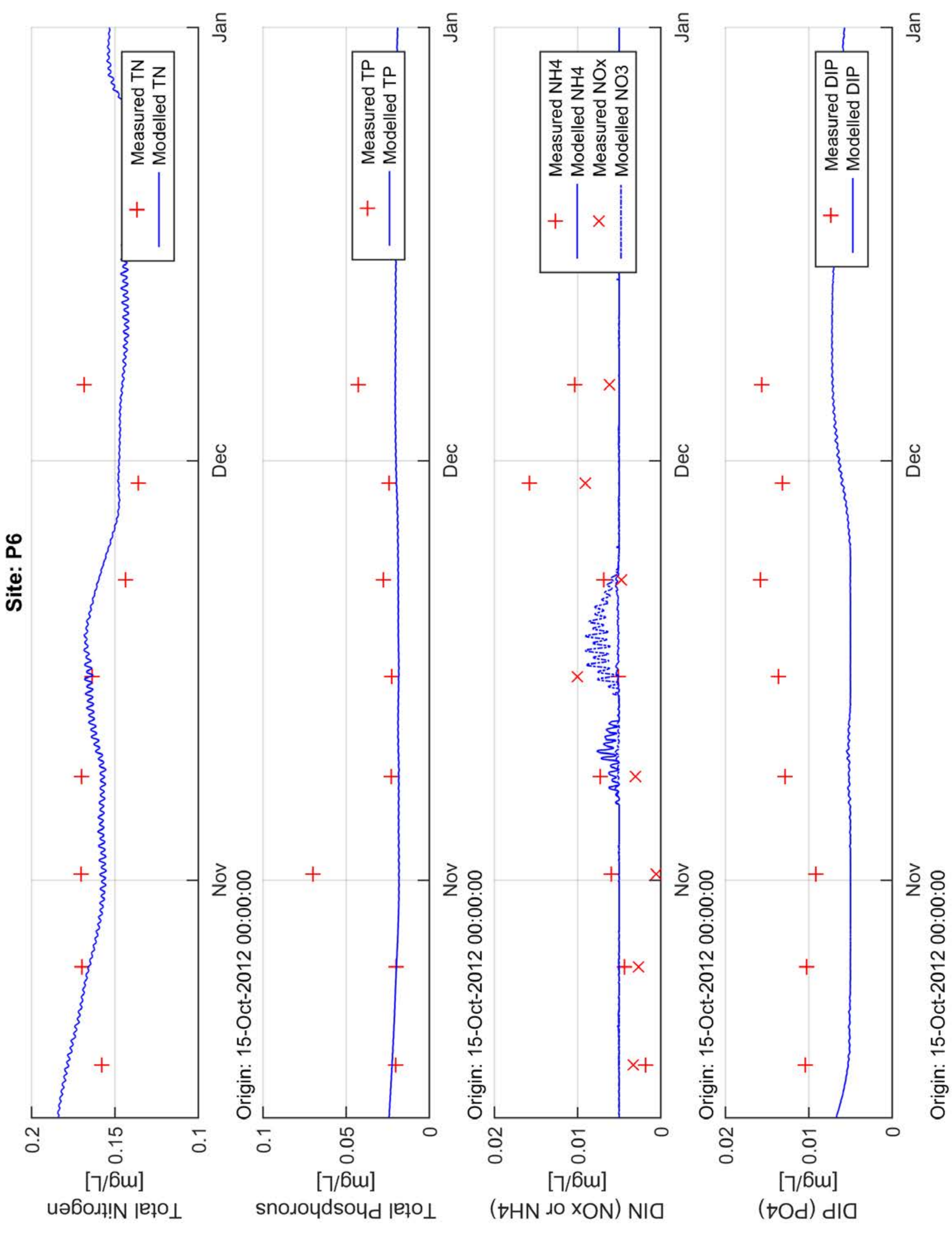
Figure 5.60b



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: P6

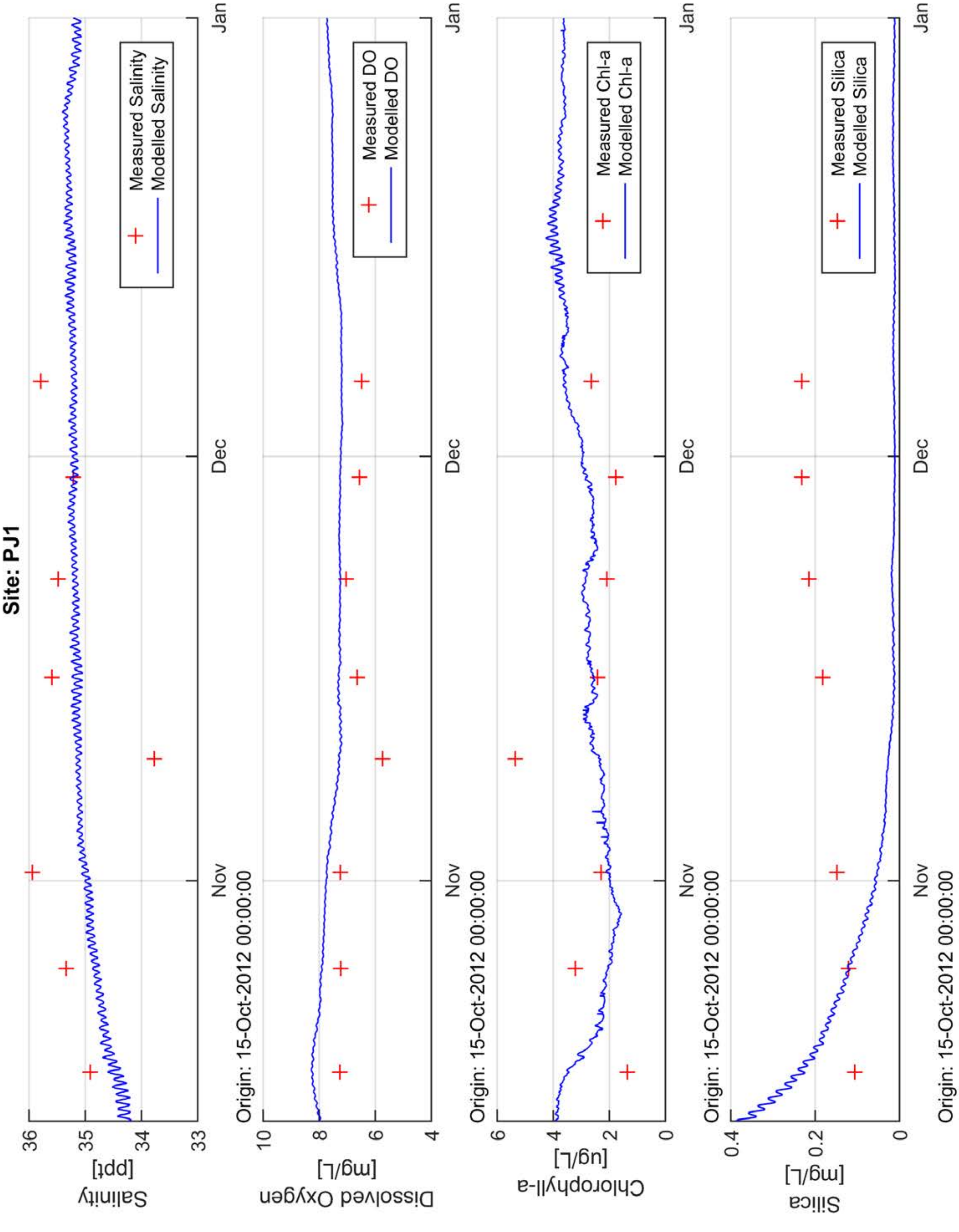
Figure 5.61a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: P6

Figure 5.61b



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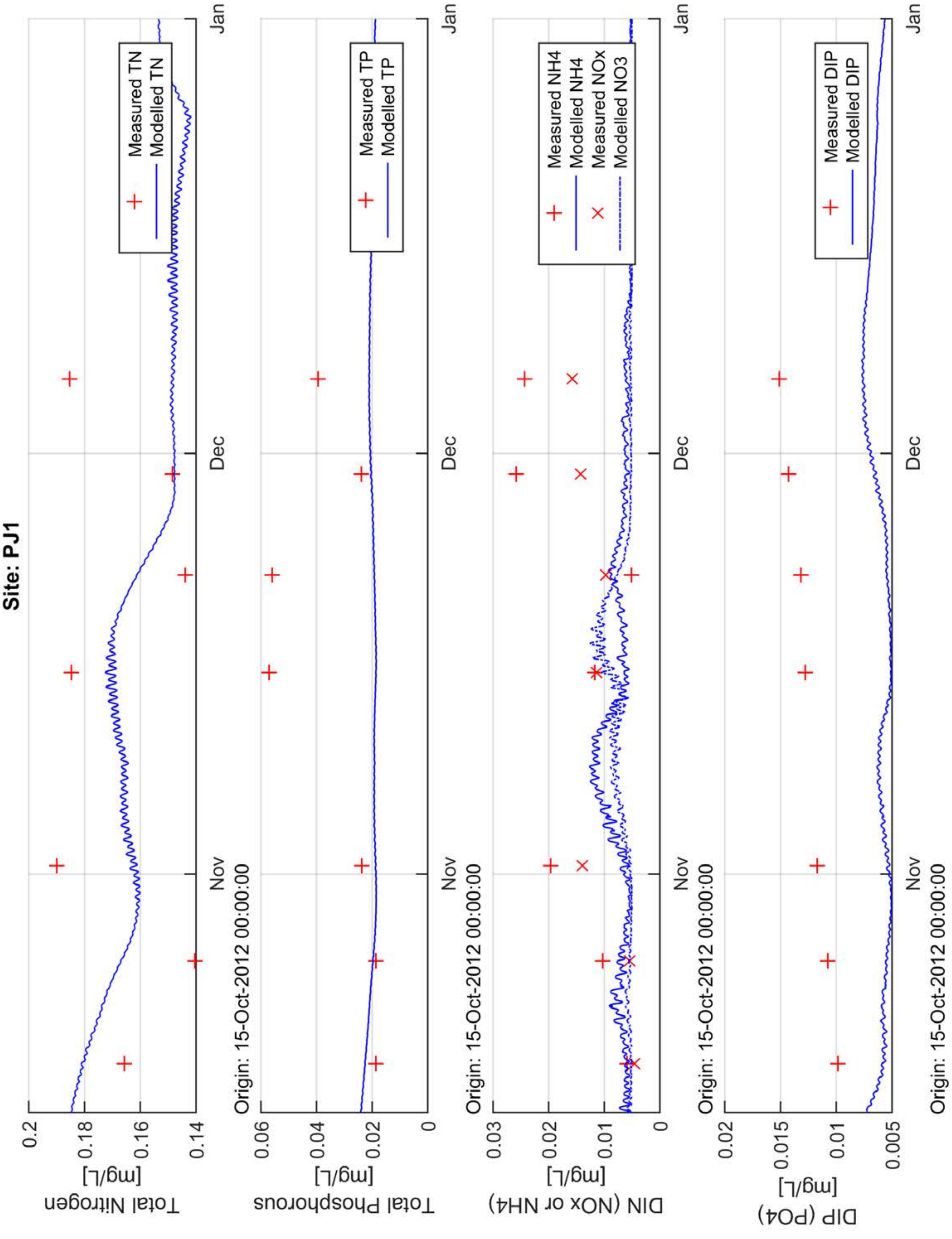
Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: PJ1

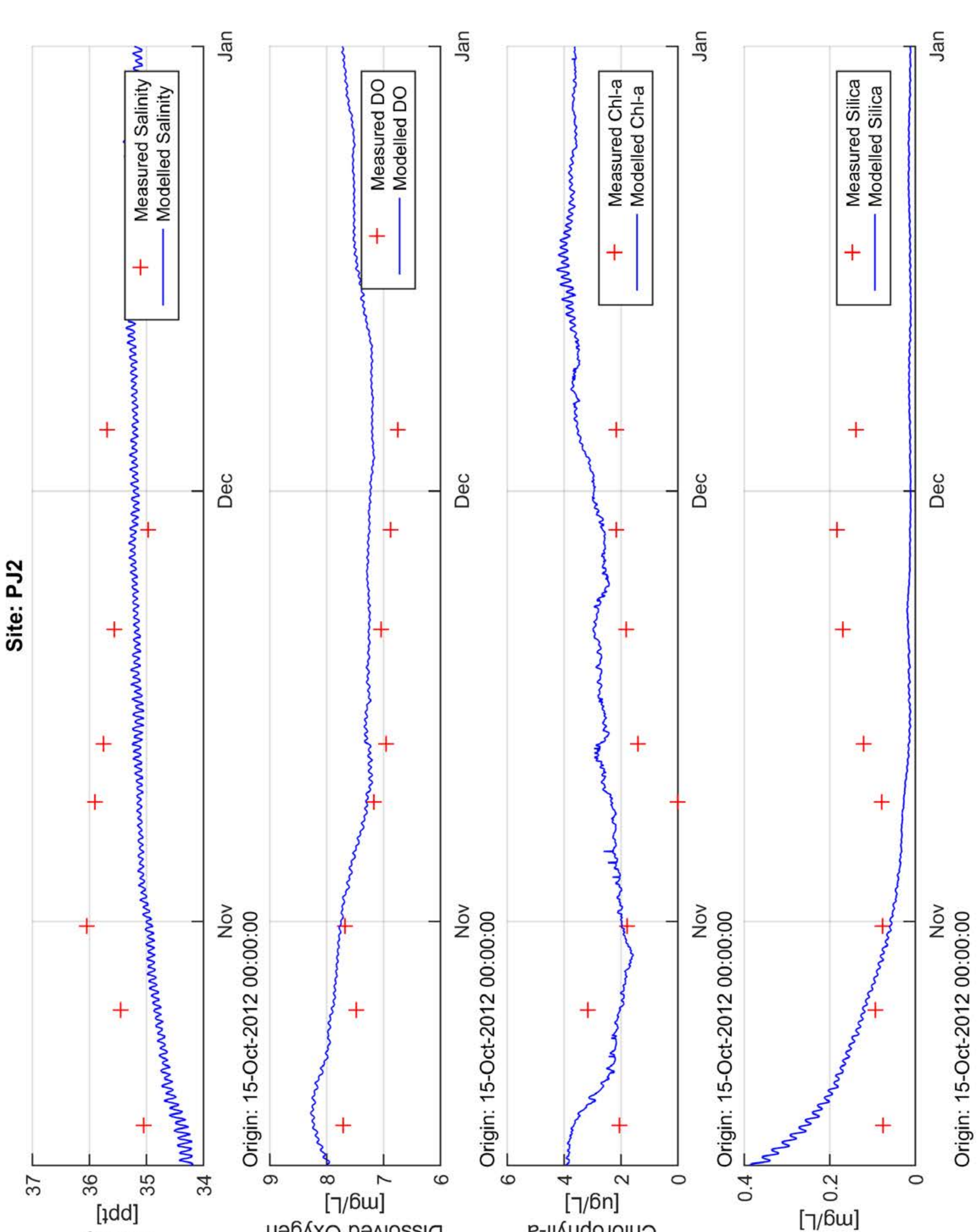
Figure 5.62a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: PJ1

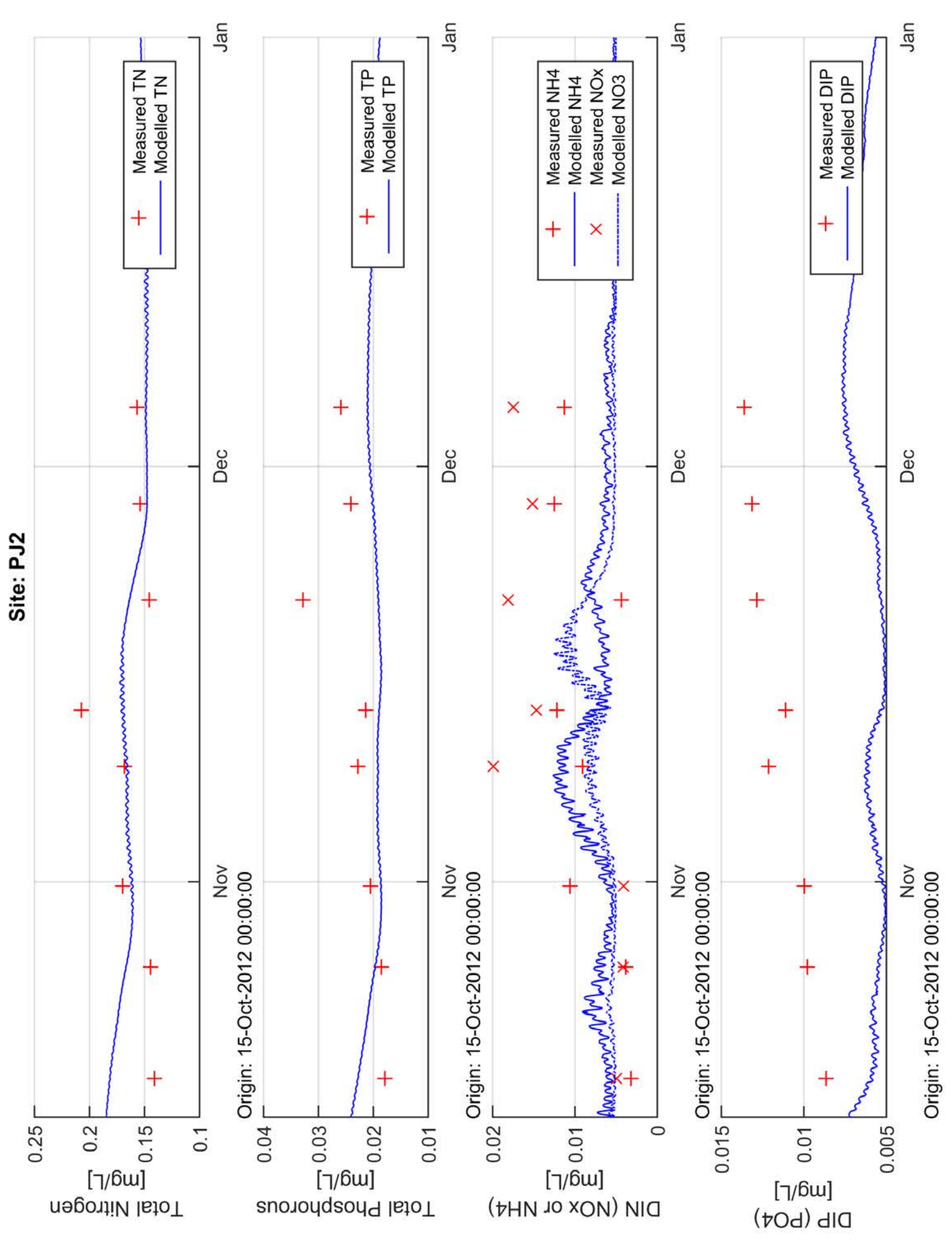
Figure 5.62b



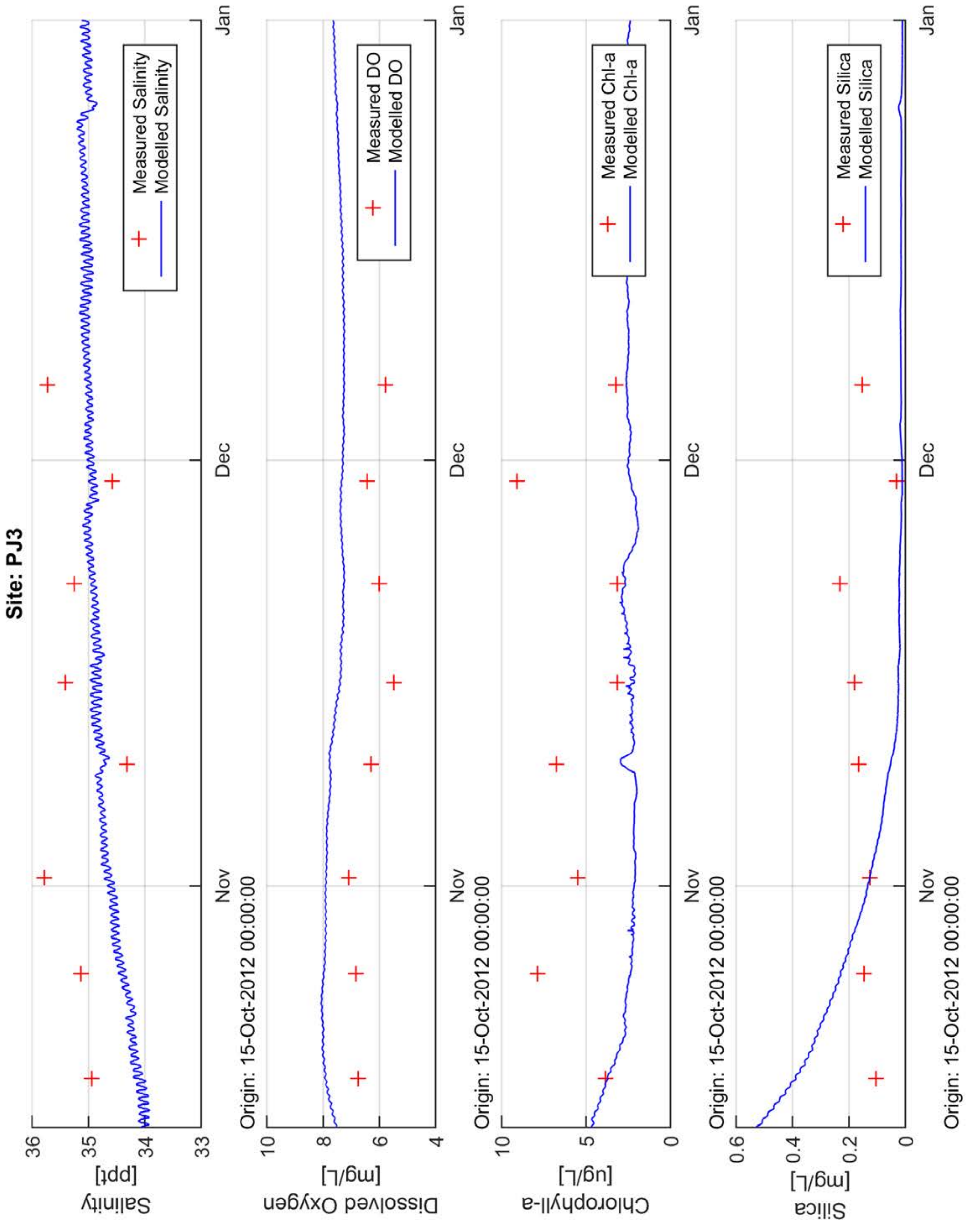
Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: PJ2

Figure 5.63a



Sydney Harbour Ecological Response Model
Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: PJ2
Figure 5.63b



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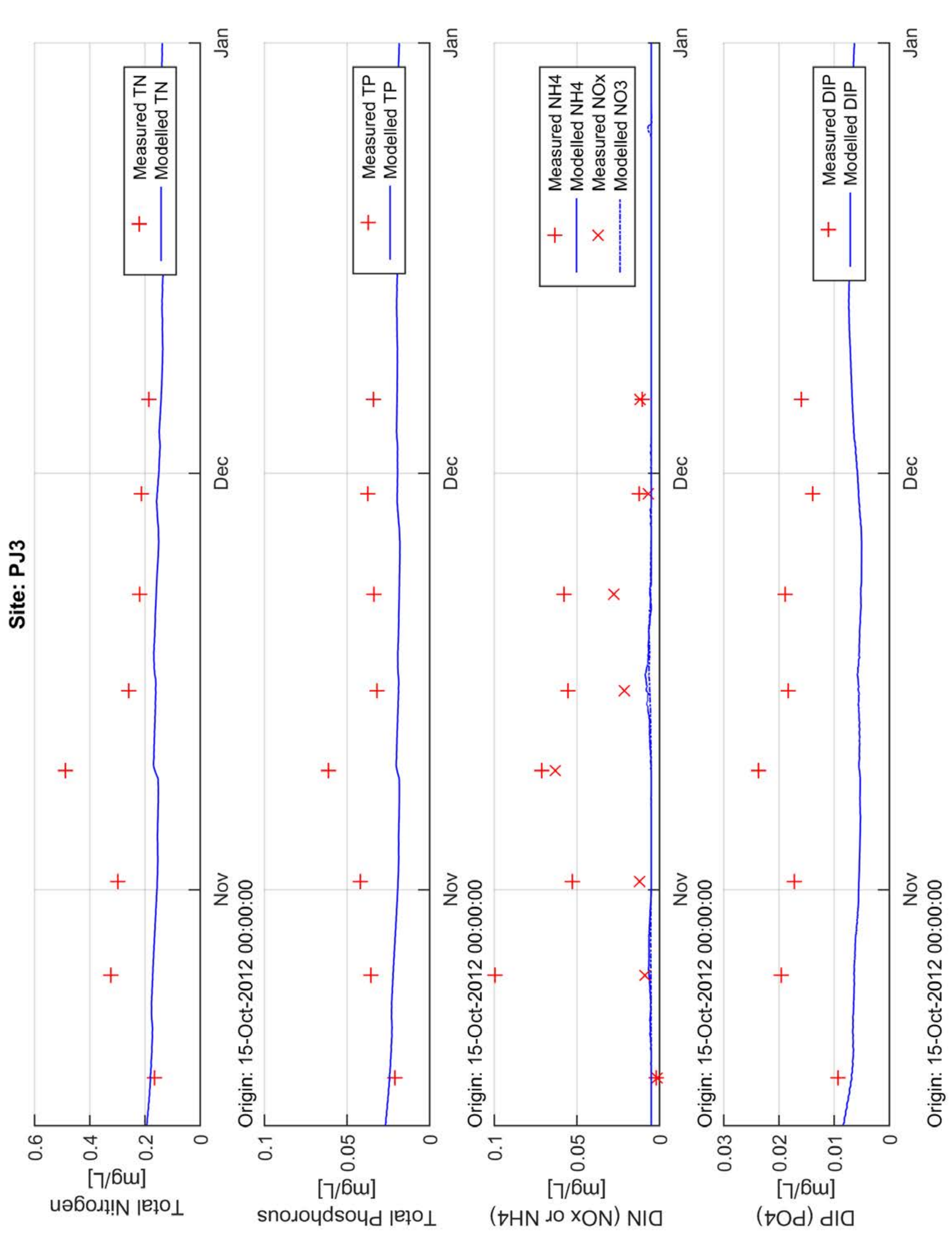
Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: PJ3

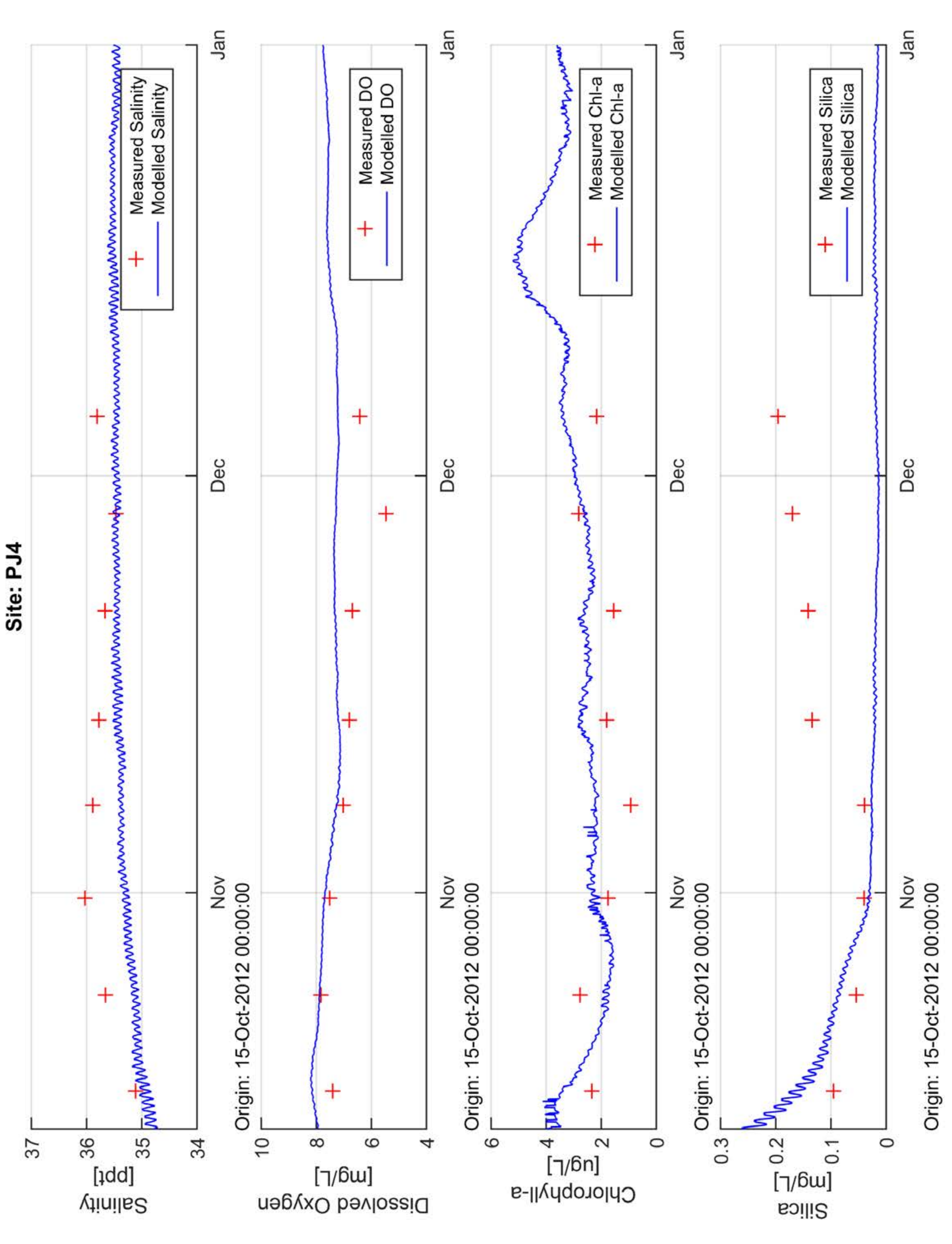
Figure 5.64a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: PJ3

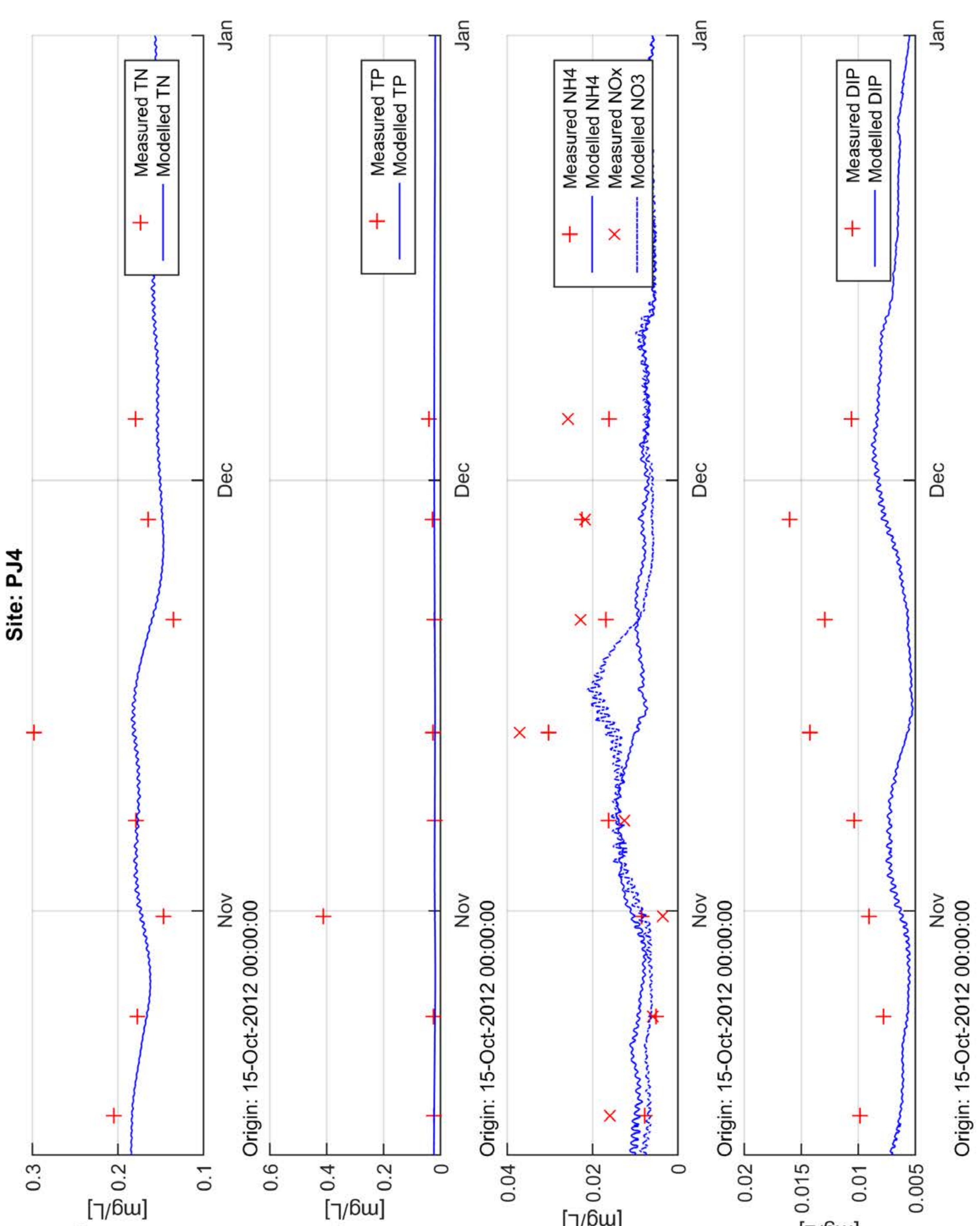
Figure 5.64b



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: PJ4

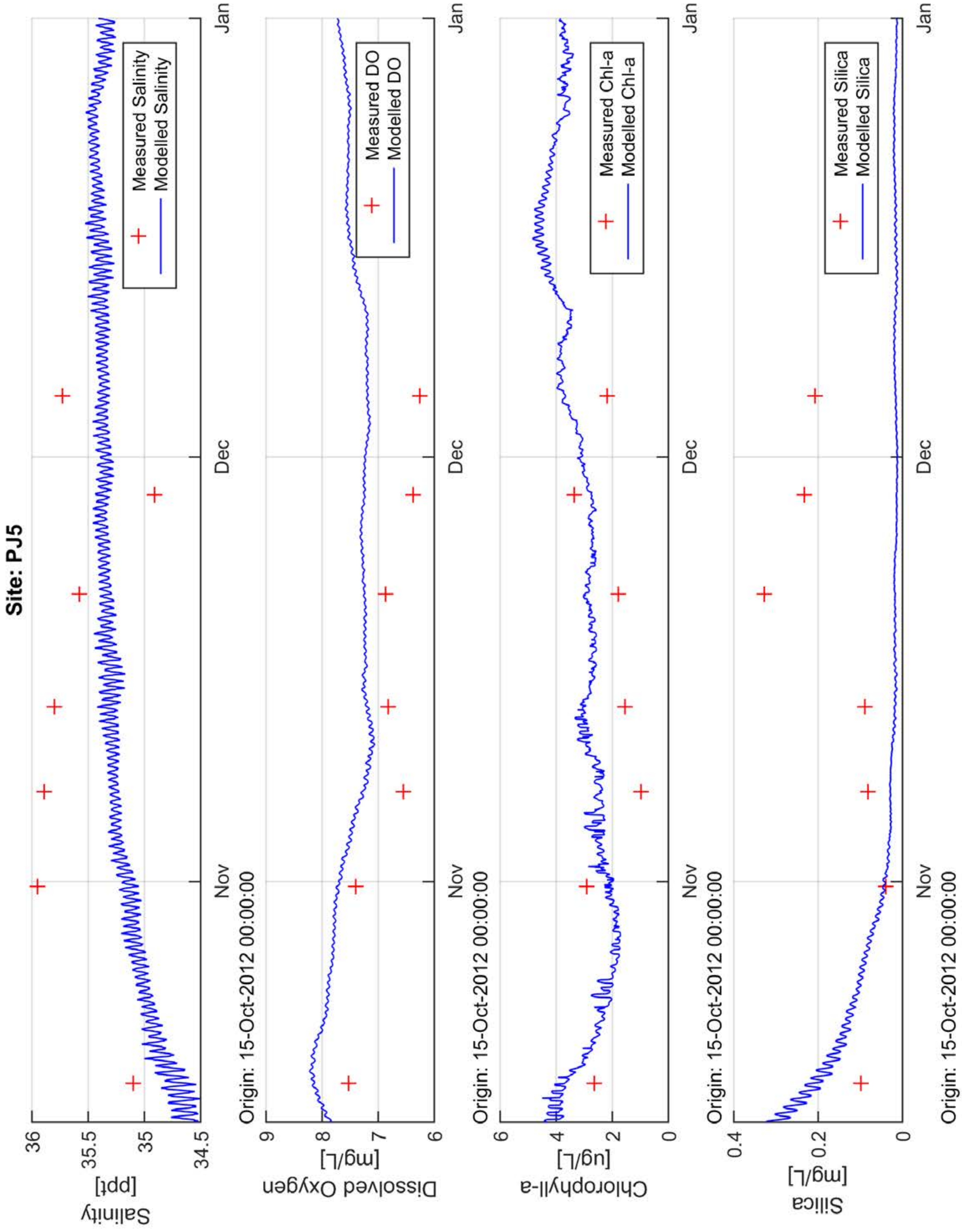
Figure 5.65a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: PJ4

Figure 5.65b



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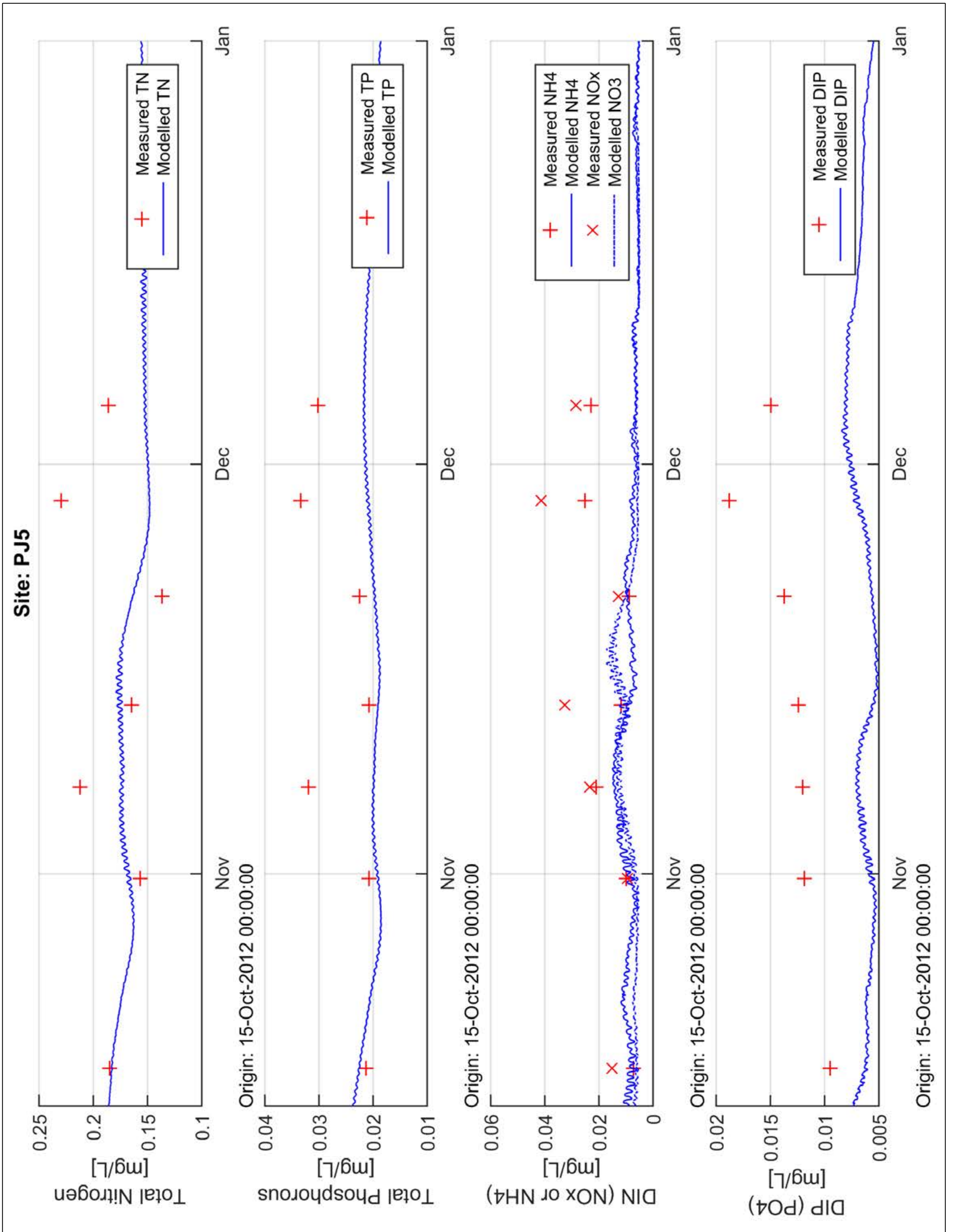
Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: PJ5

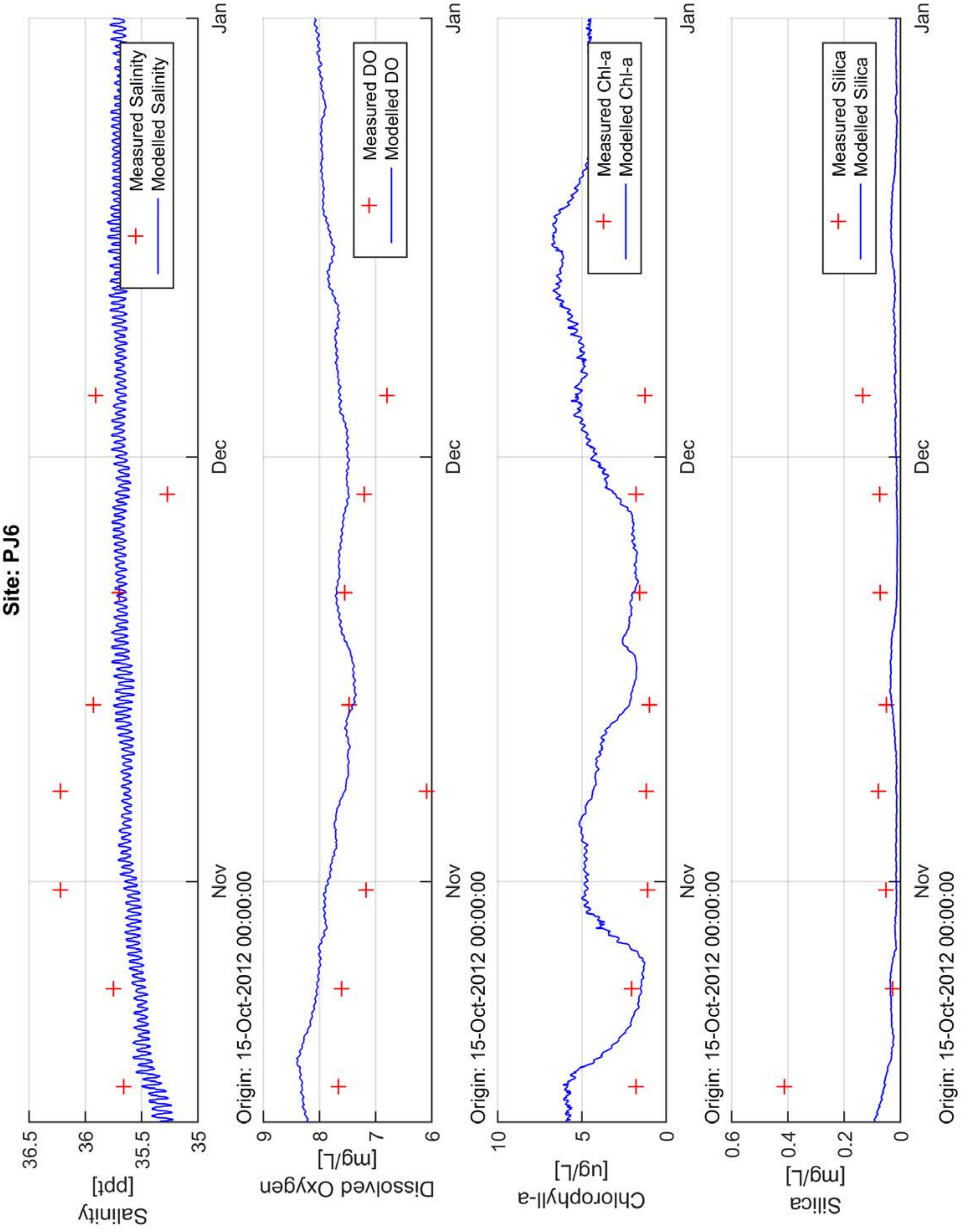
Figure 5.66a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: PJ5

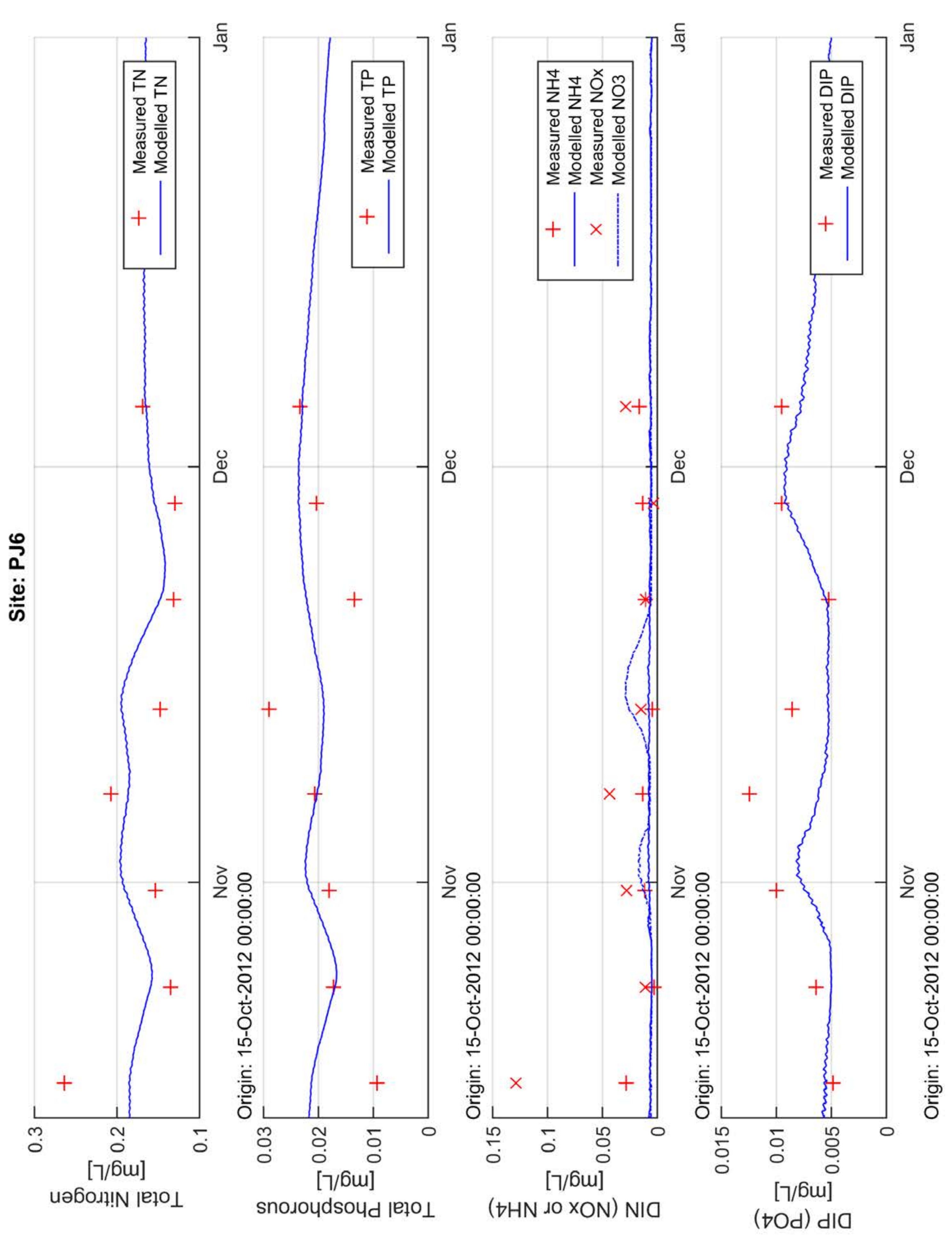
Figure 5.66b



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: PJ6

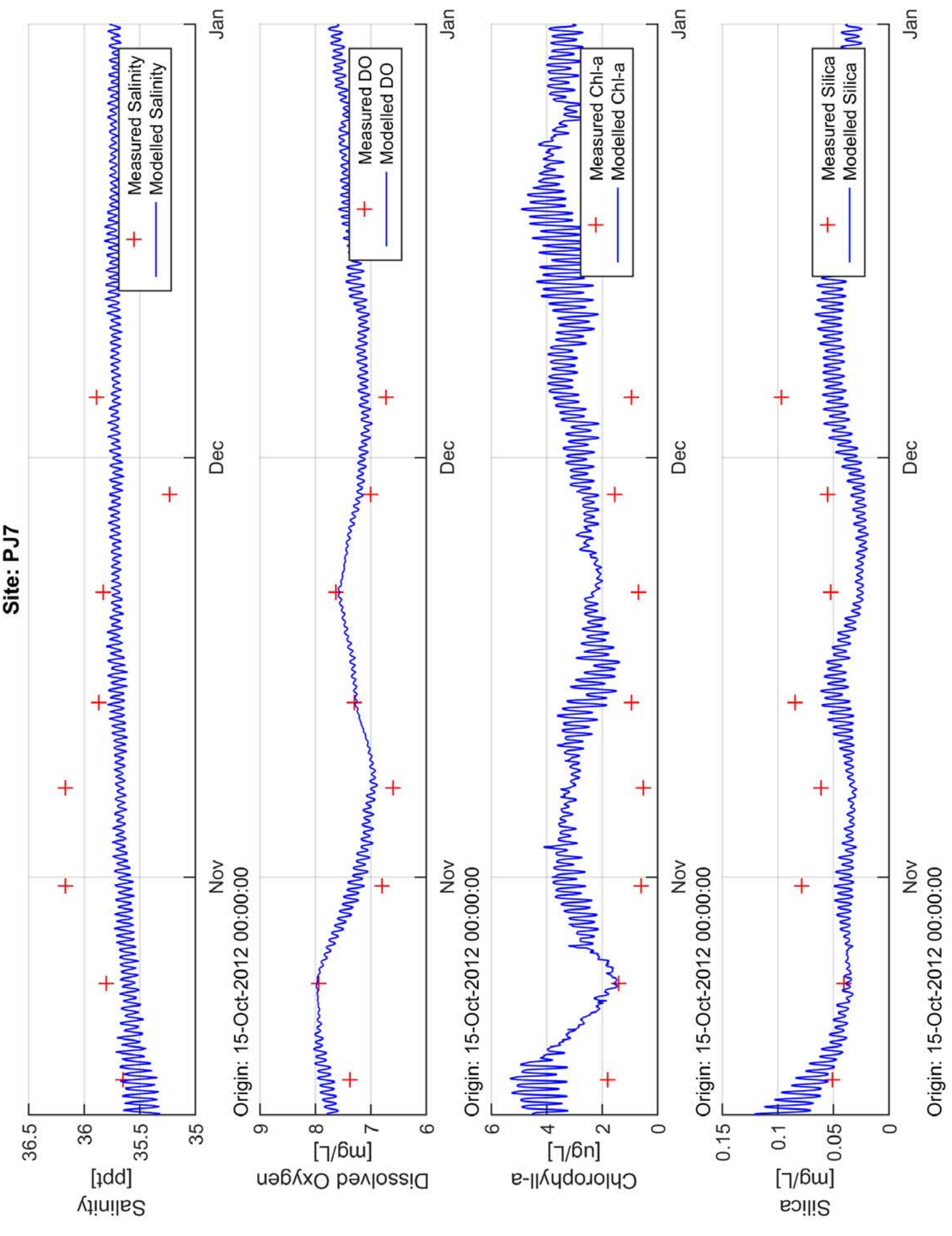
Figure 5.67a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: PJ6

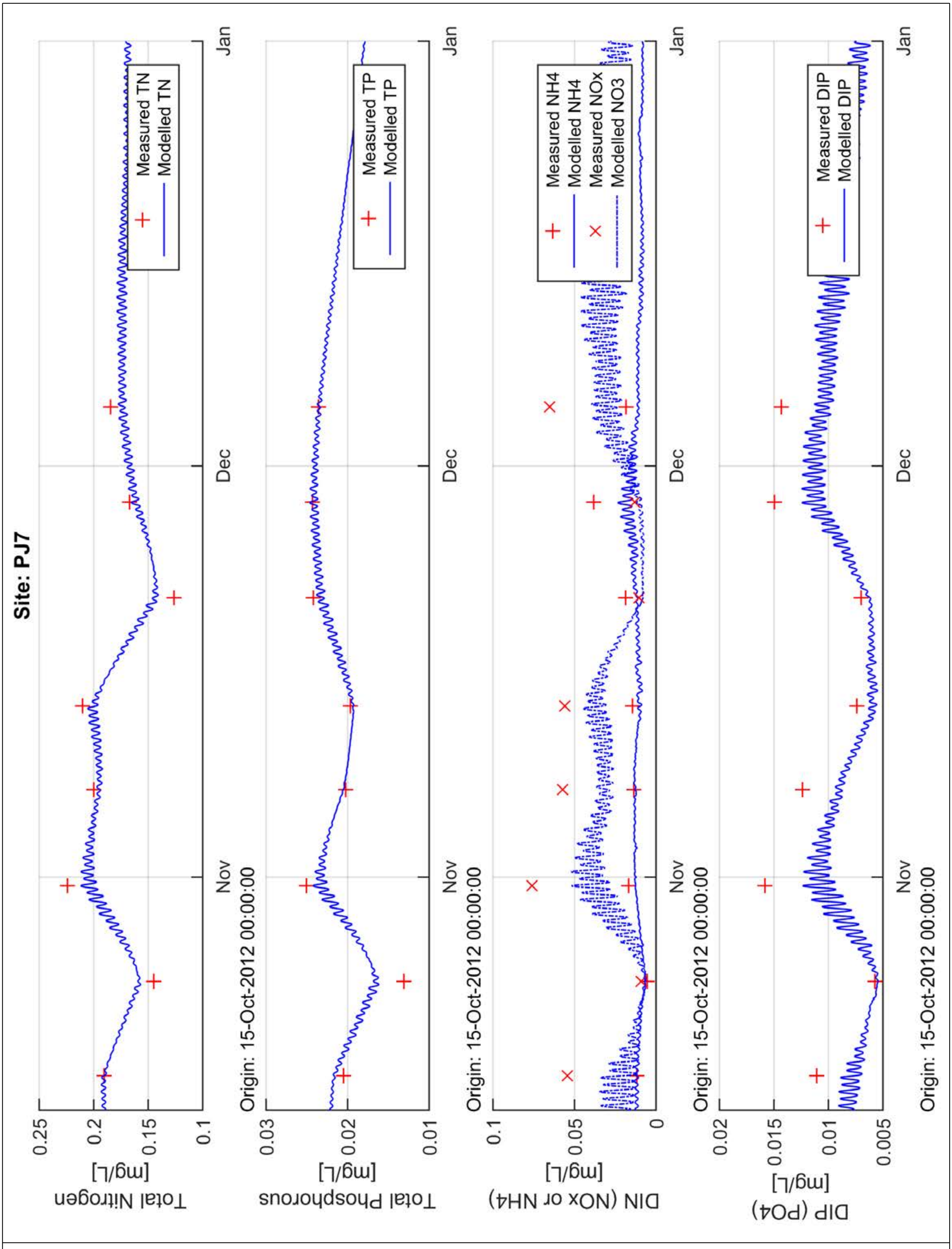
Figure 5.67b



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: PJ7

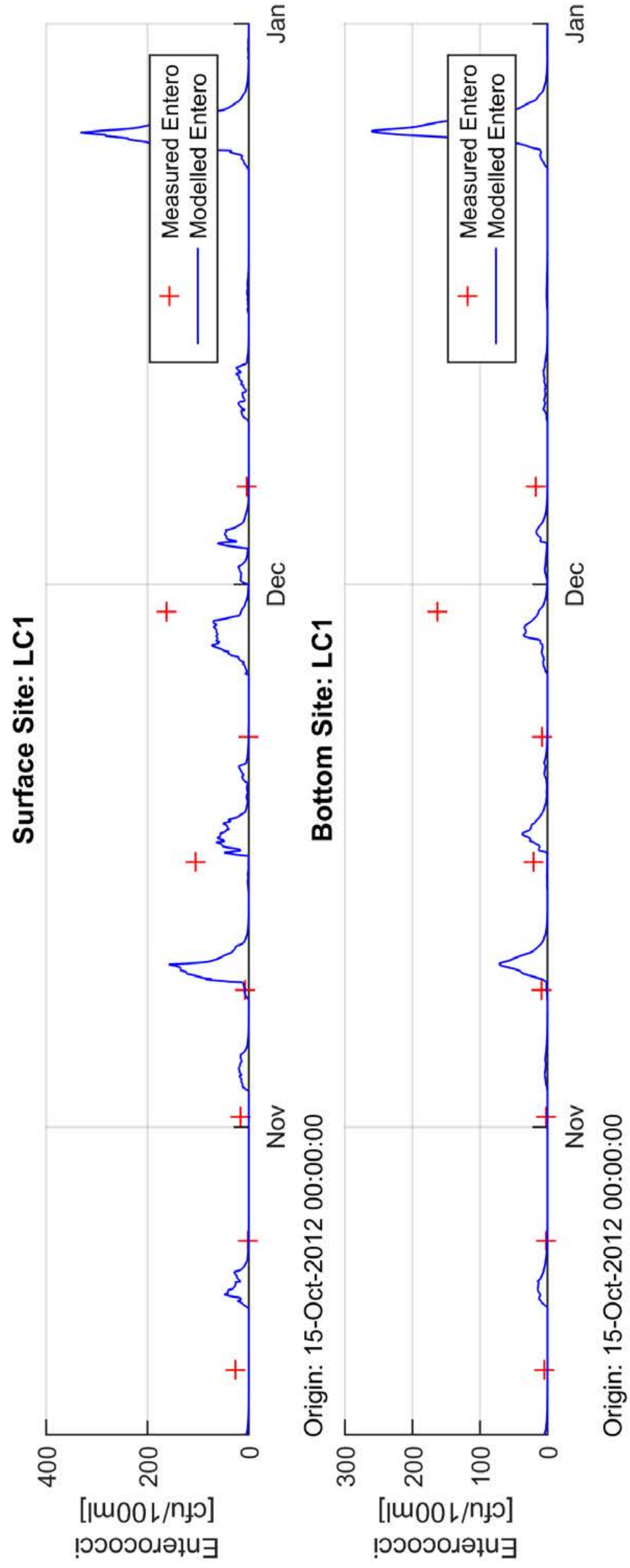
Figure 5.68a



Sydney Harbour Ecological Response Model

Water Quality Parameter Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: PJ7

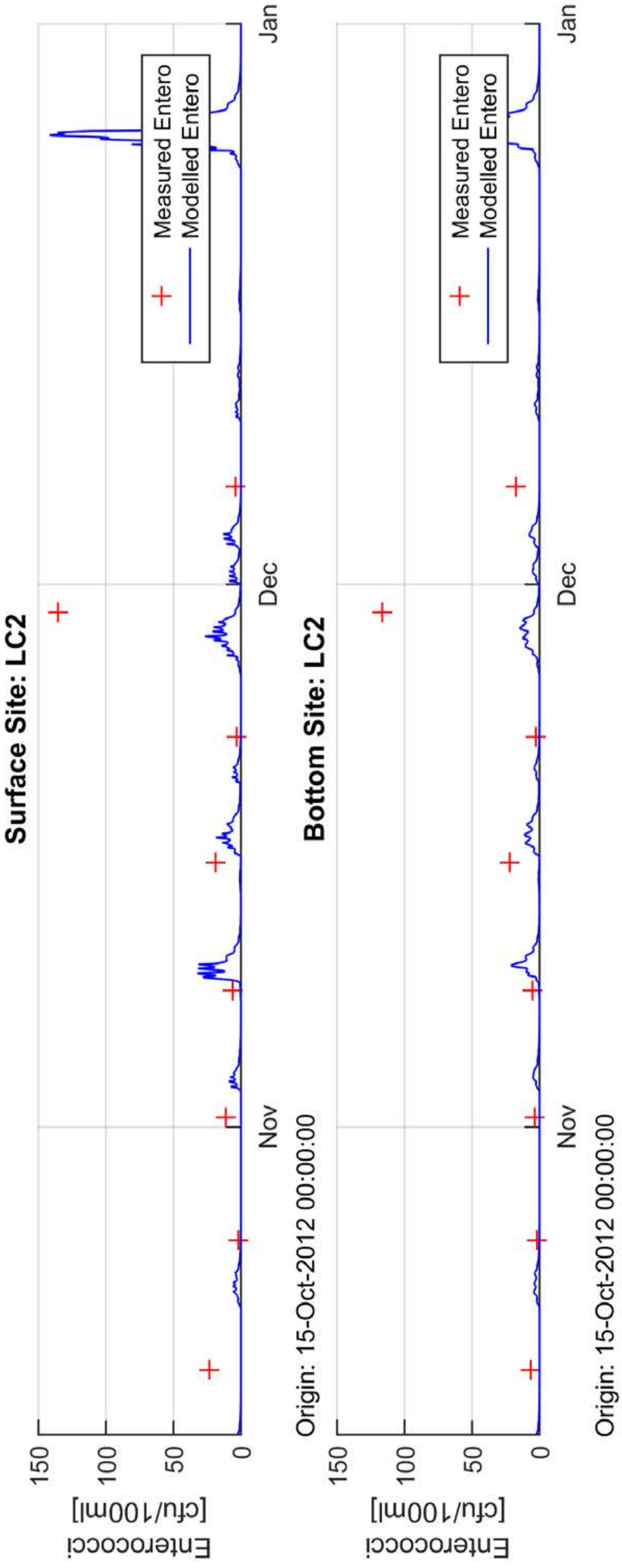
Figure 5.68b



Sydney Harbour Ecological Response Model

Enterococci Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: LC1

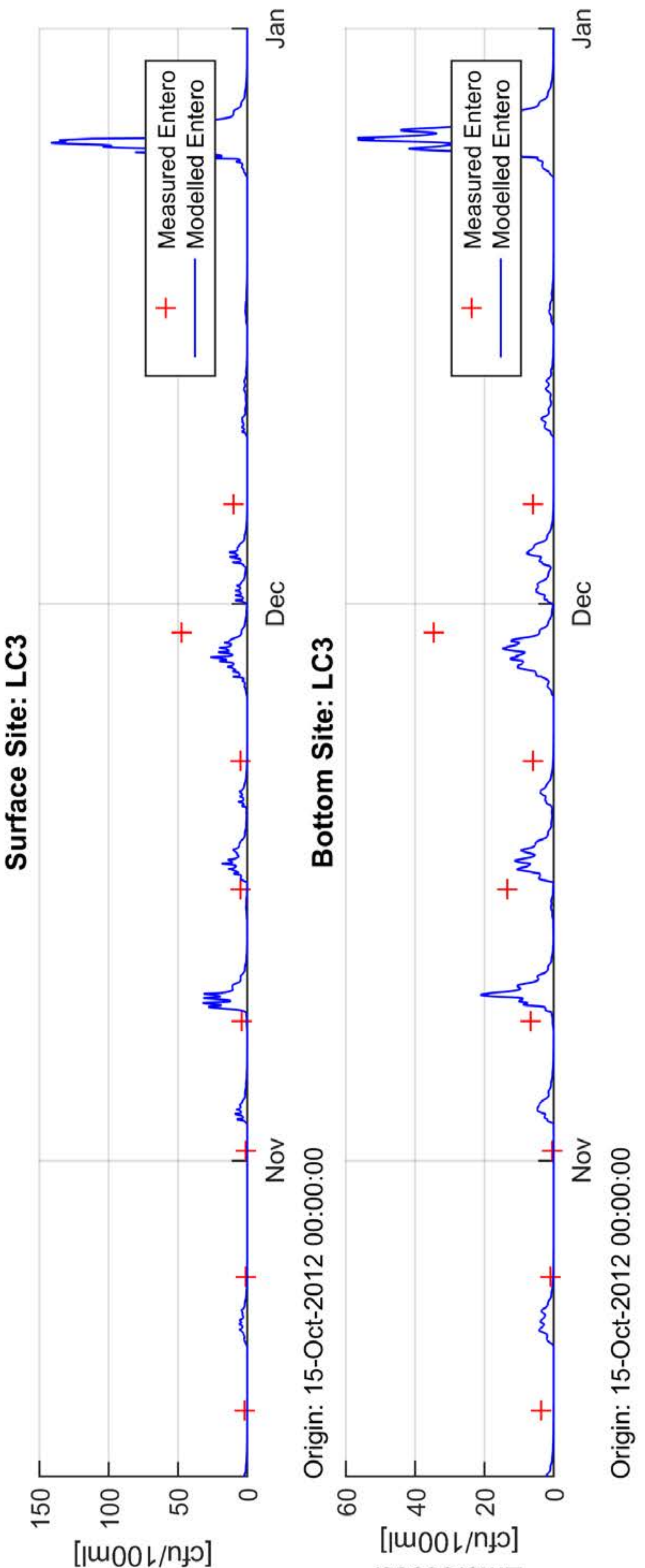
Figure 5.69



Sydney Harbour Ecological Response Model

Enterococci Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: LC2

Figure 5.70



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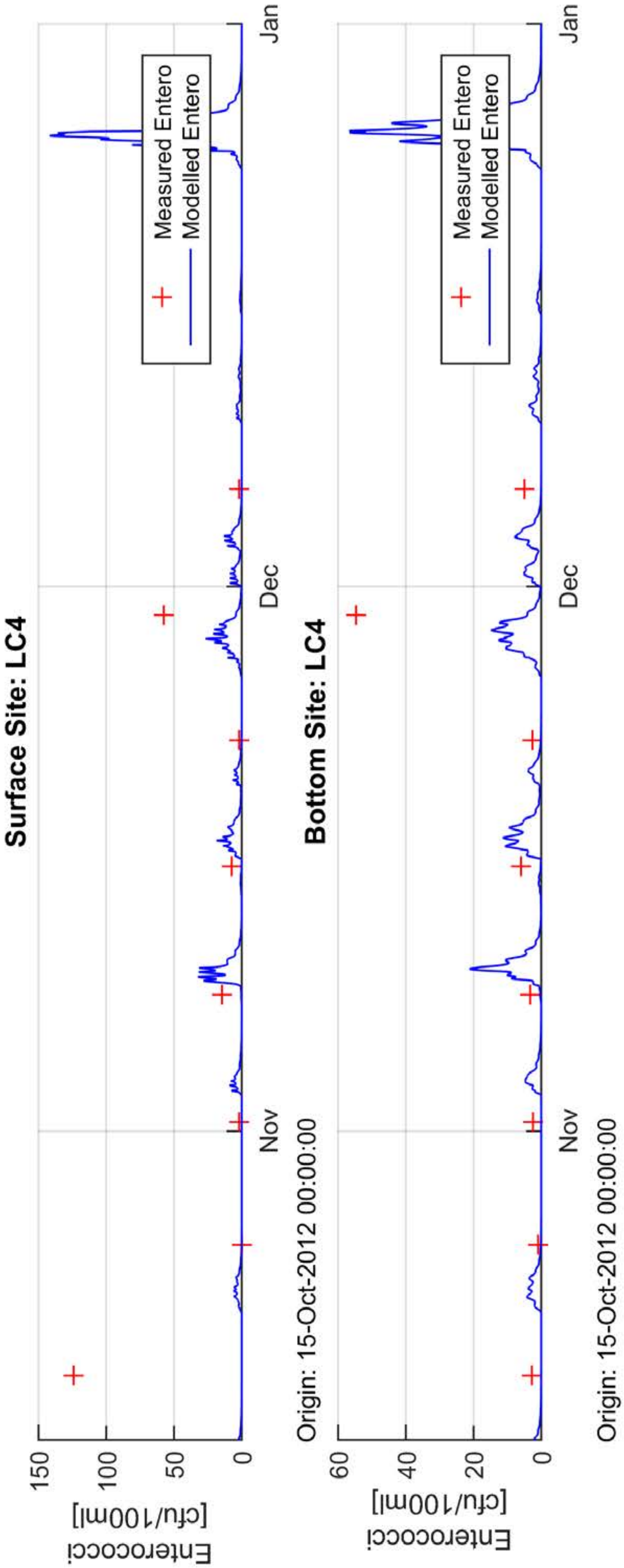
Sydney Harbour Ecological Response Model

Enterococci Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: LC3

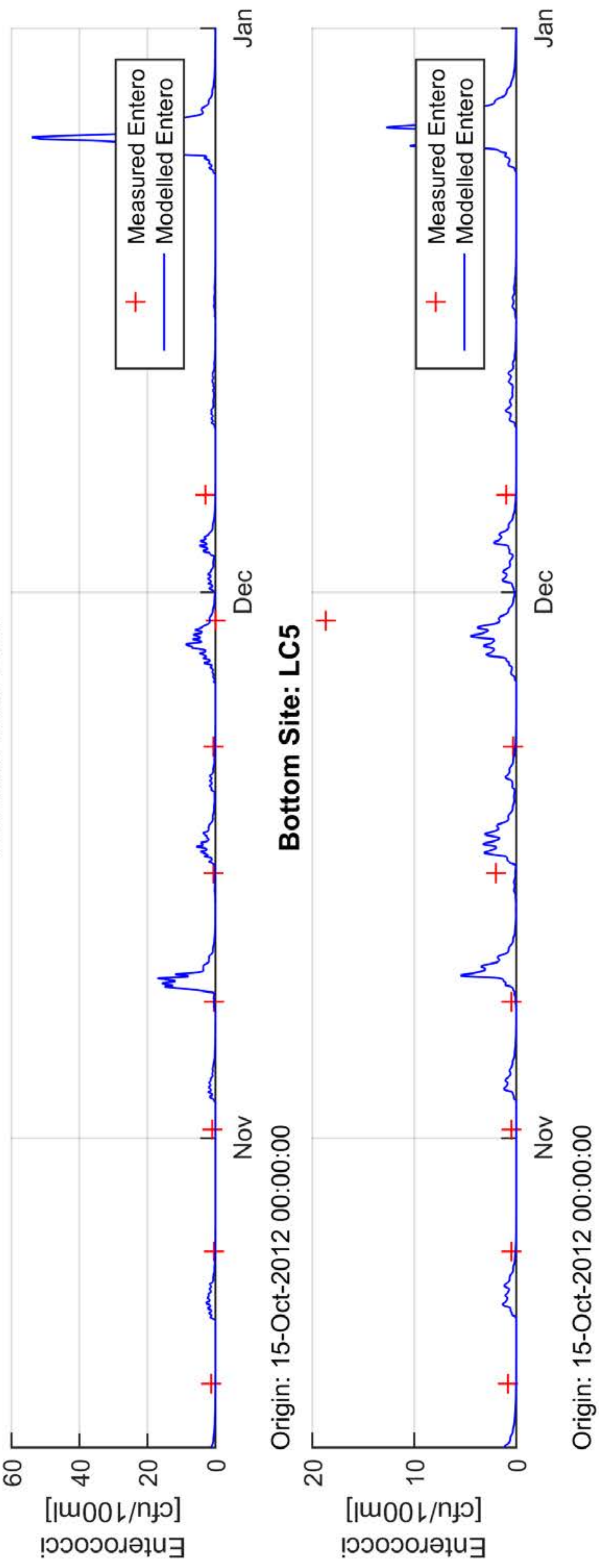
Figure 5.71



Sydney Harbour Ecological Response Model

Enterococci Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: LC4

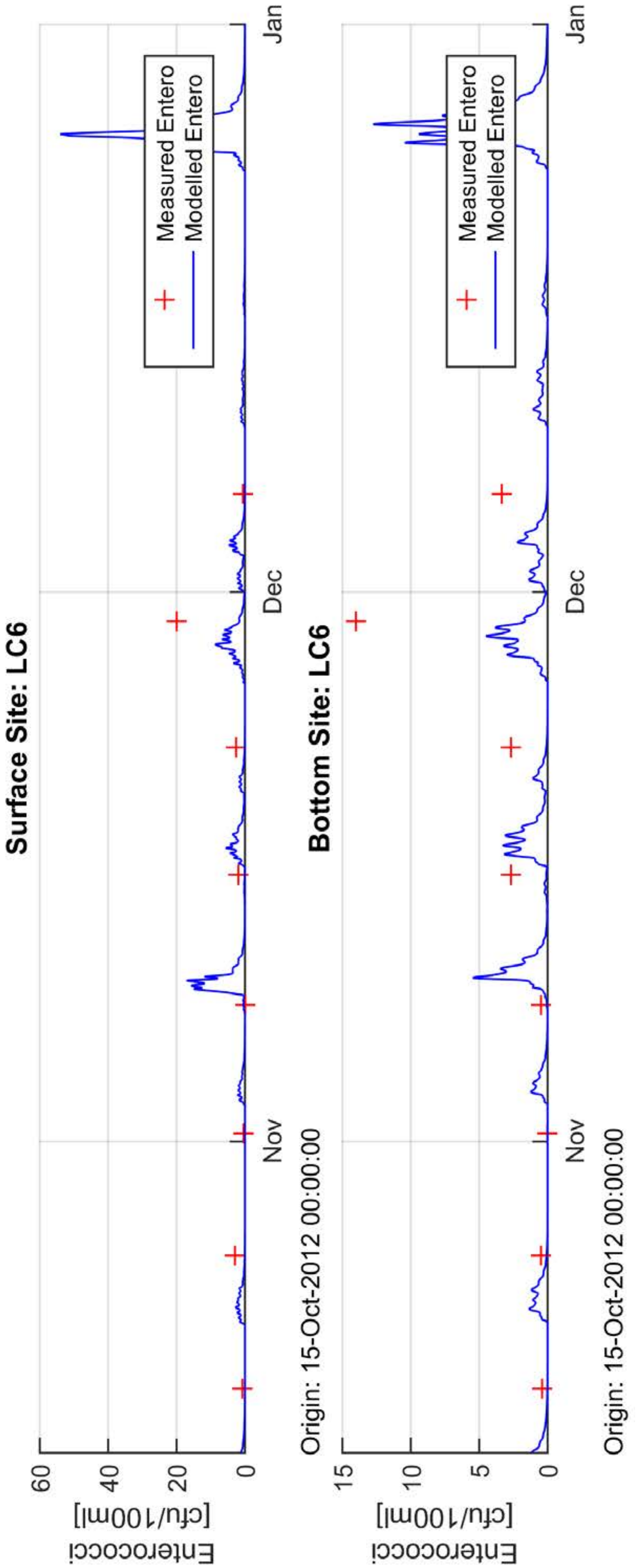
Figure 5.72



Sydney Harbour Ecological Response Model

Enterococci Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: LC5

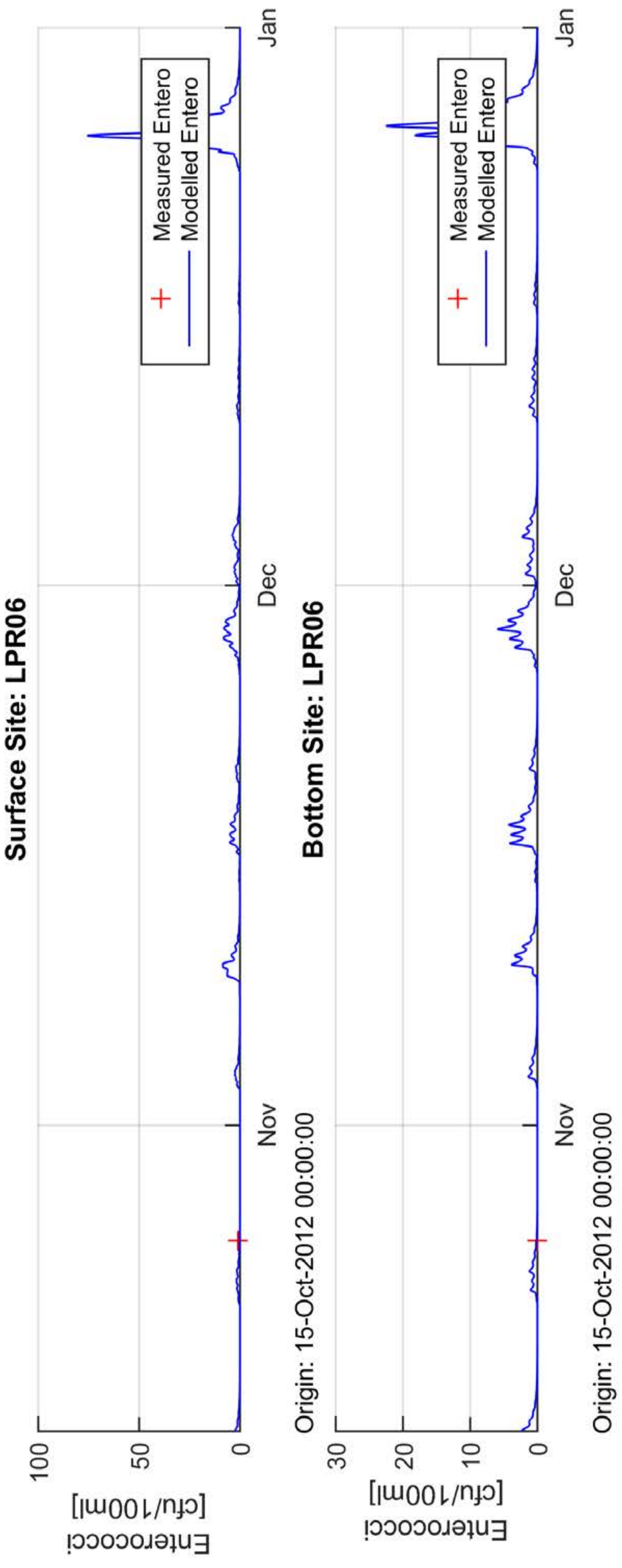
Figure 5.73



Sydney Harbour Ecological Response Model

Enterococci Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: LC6

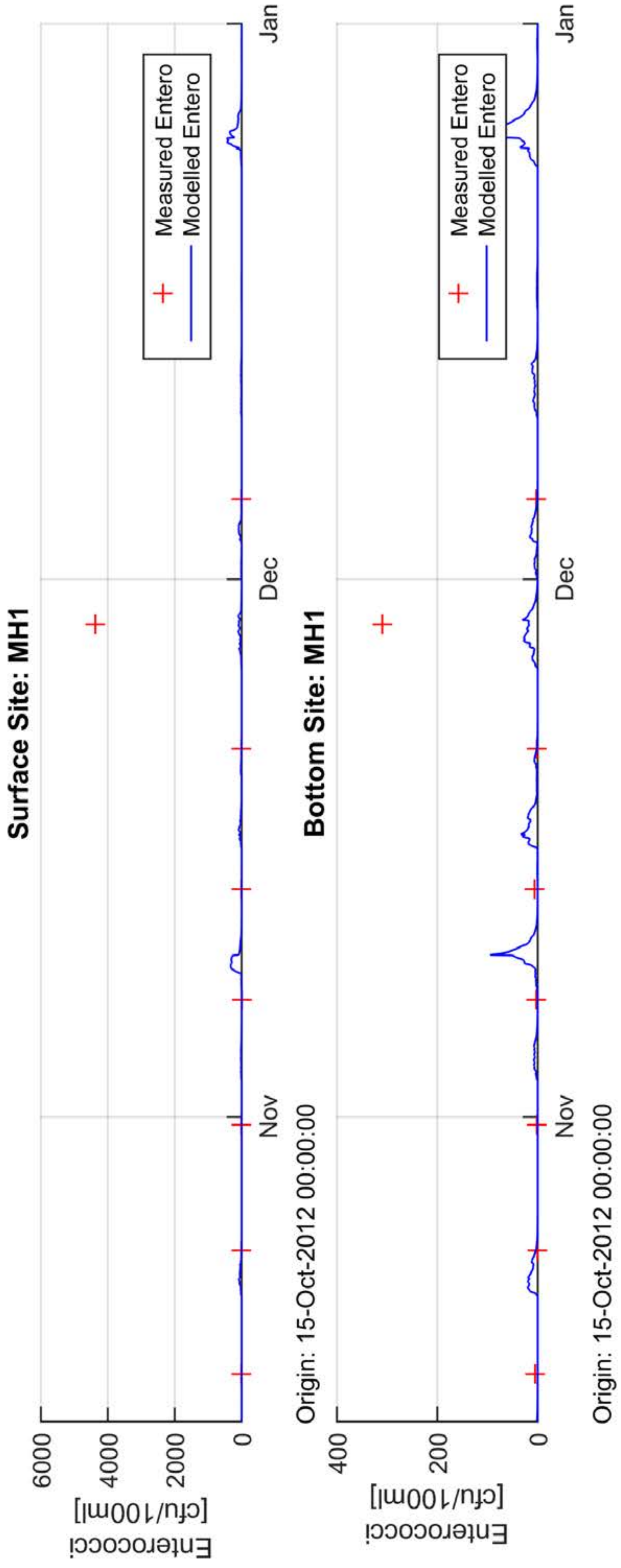
Figure 5.74



Sydney Harbour Ecological Response Model

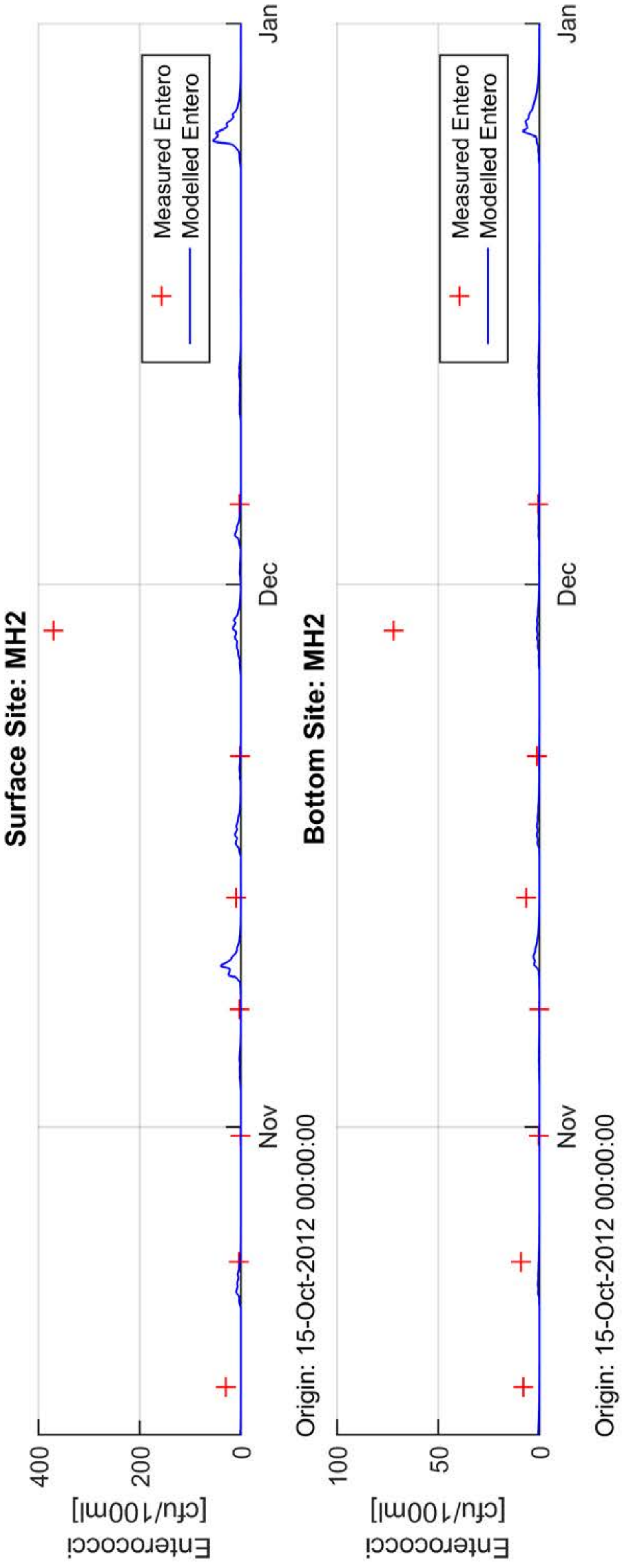
Enterococci Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: LPR06

Figure 5.75



Enterococci Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: MH1

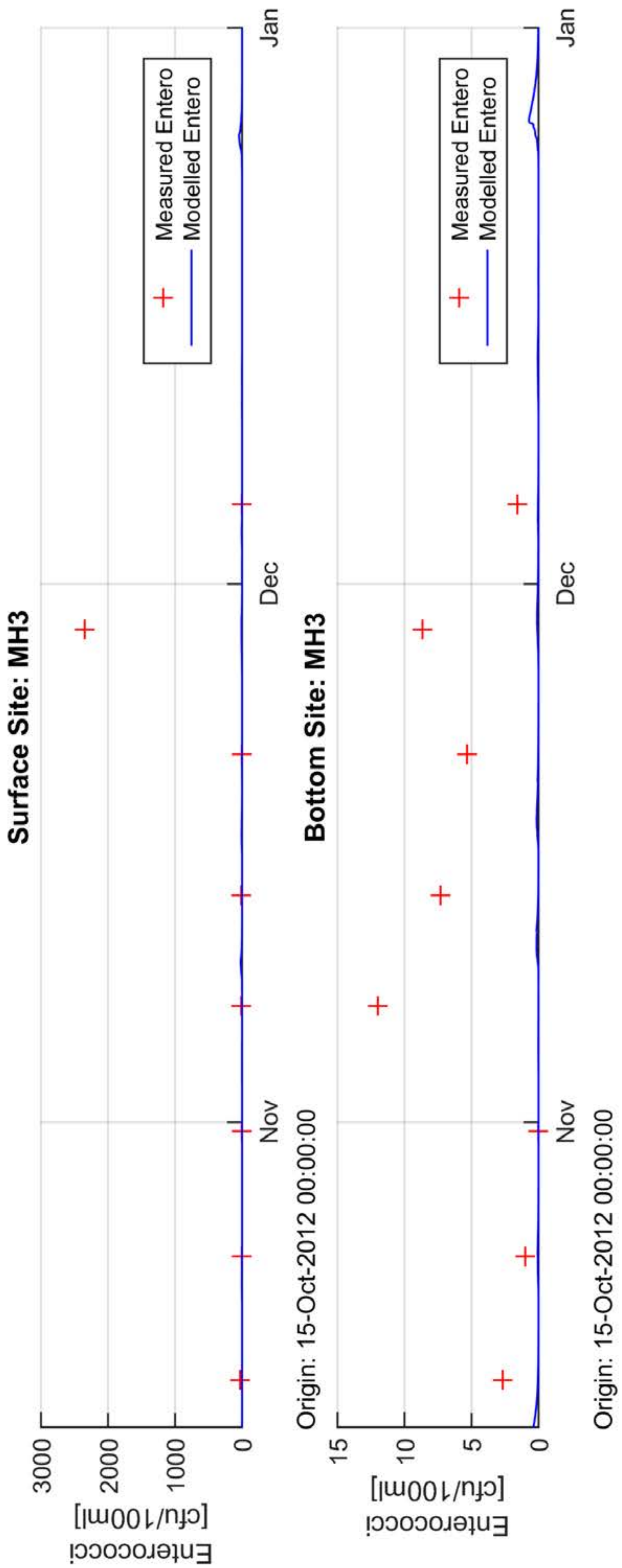
Figure 5.76



Sydney Harbour Ecological Response Model

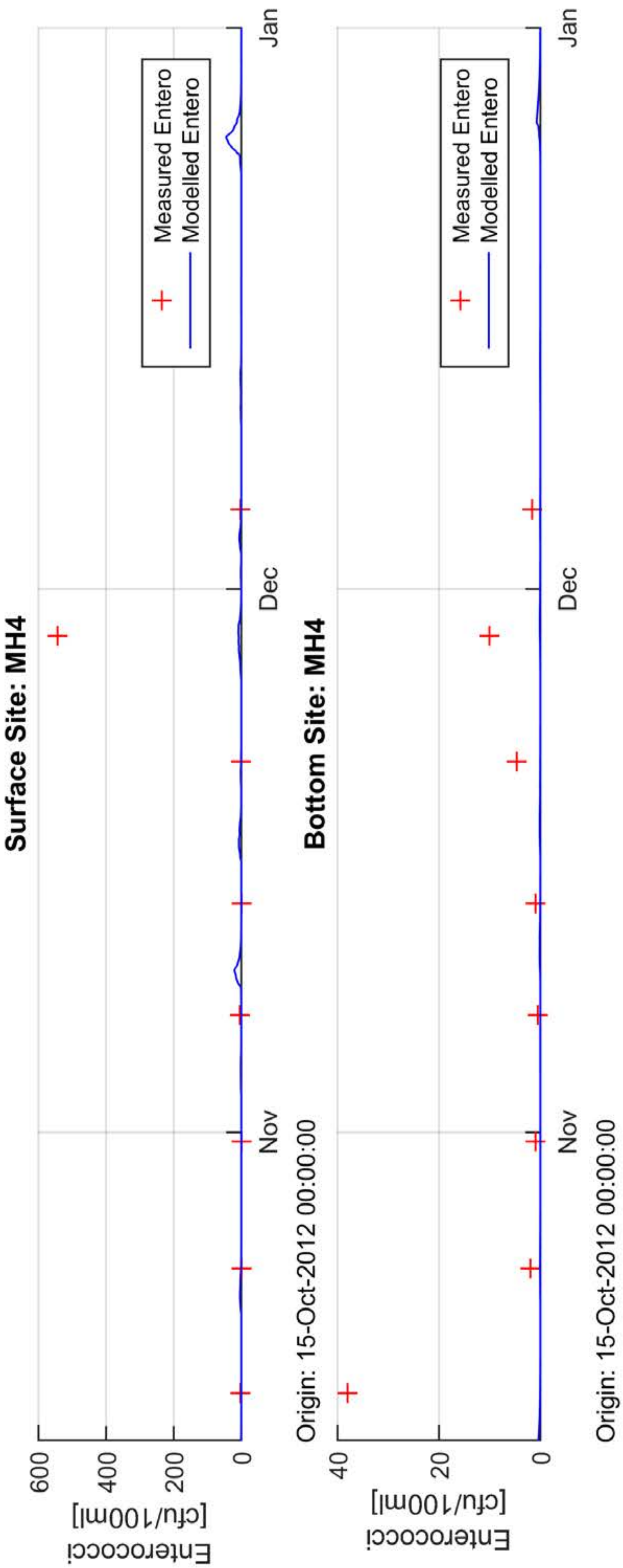
Enterococci Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: MH2

Figure 5.77



Enterococci Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: MH3

Figure 5.78



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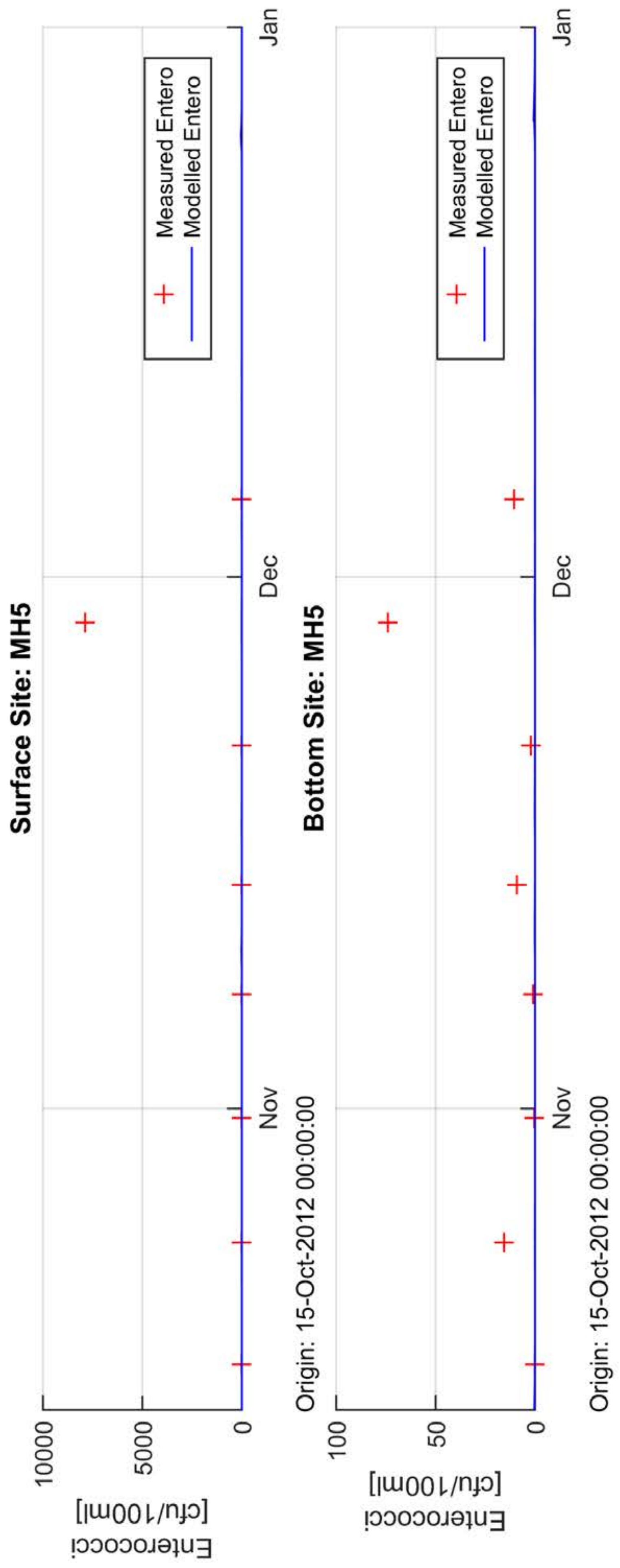
Sydney Harbour Ecological Response Model

Enterococci Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: MH4

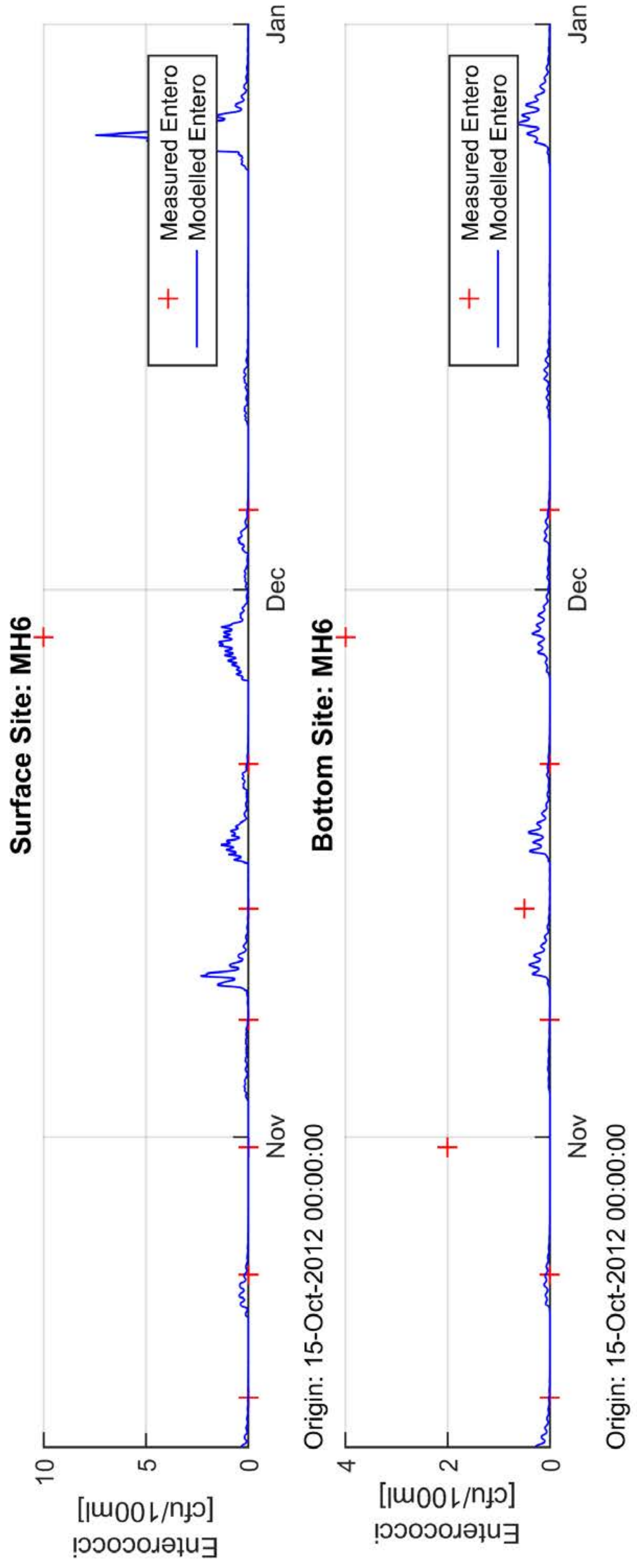
Figure 5.79



Sydney Harbour Ecological Response Model

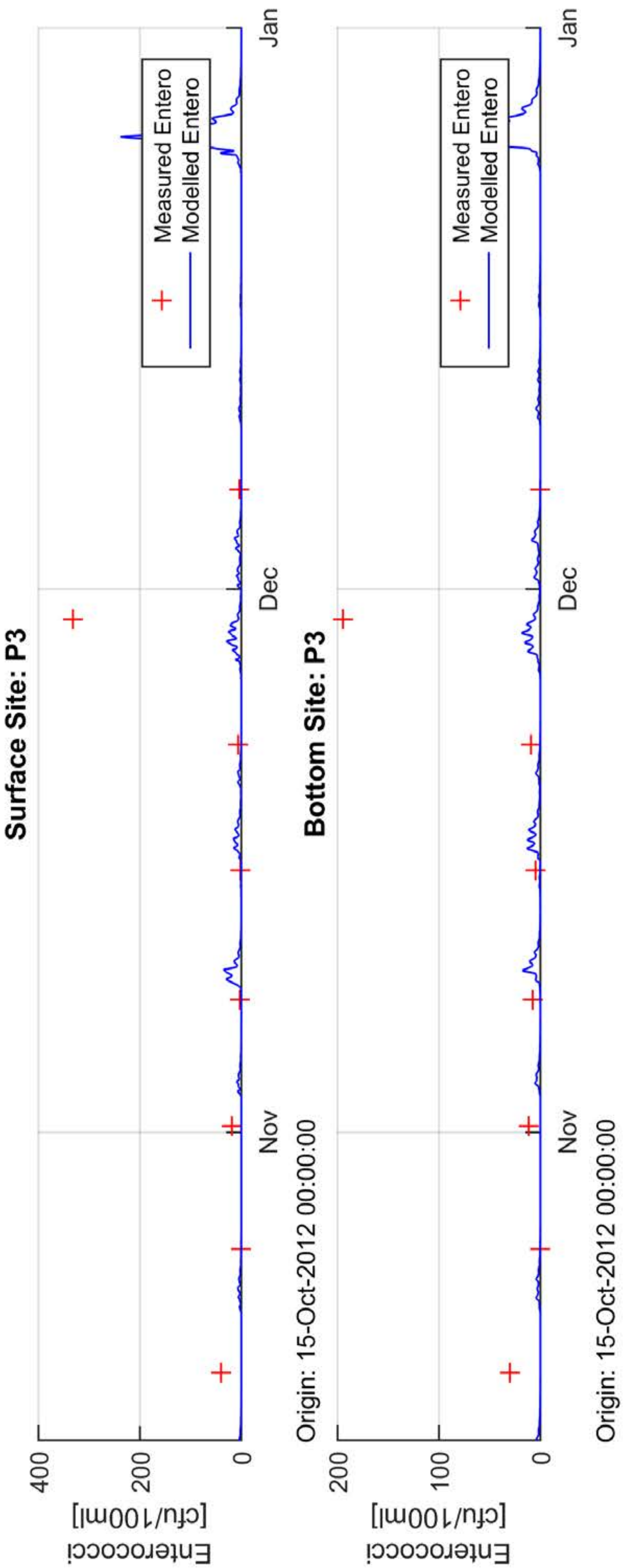
Enterococci Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: MH5

Figure 5.80



Enterococci Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: MH6

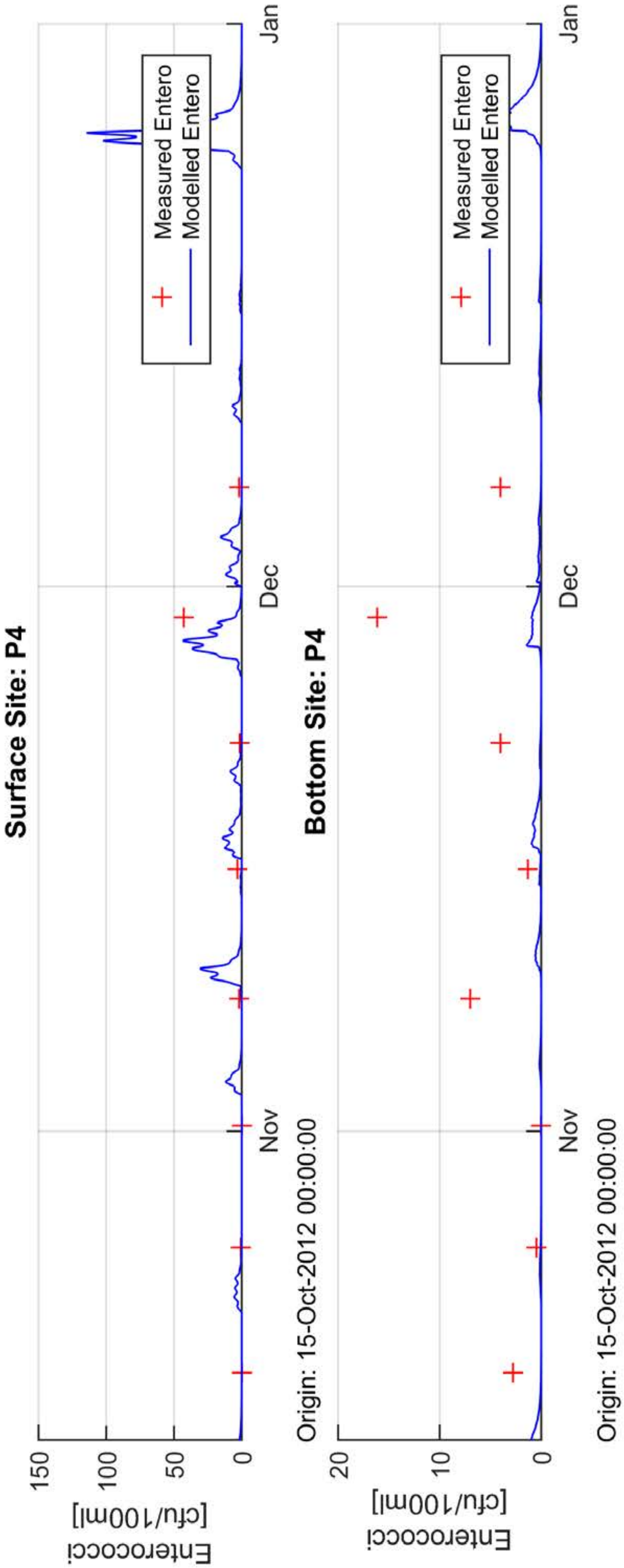
Figure 5.81



Sydney Harbour Ecological Response Model

Enterococci Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: P3

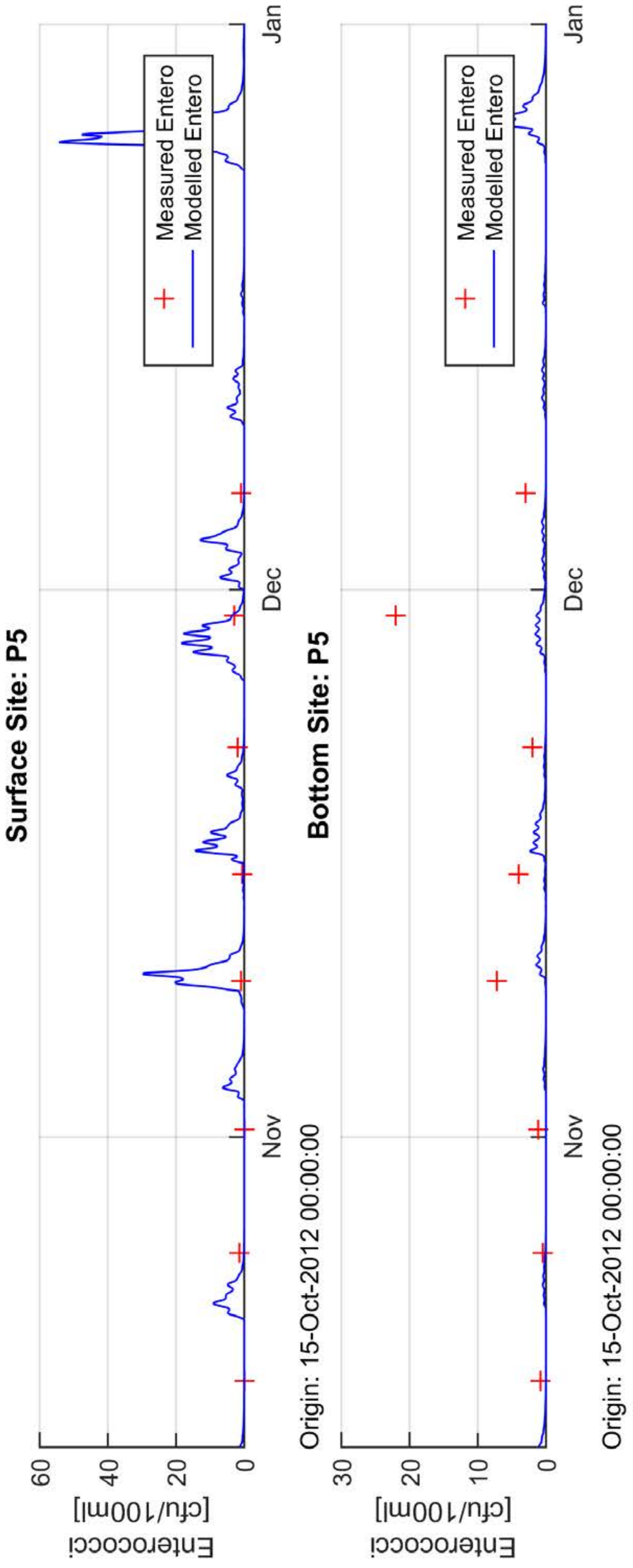
Figure 5.82



Sydney Harbour Ecological Response Model

Enterococci Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: P4

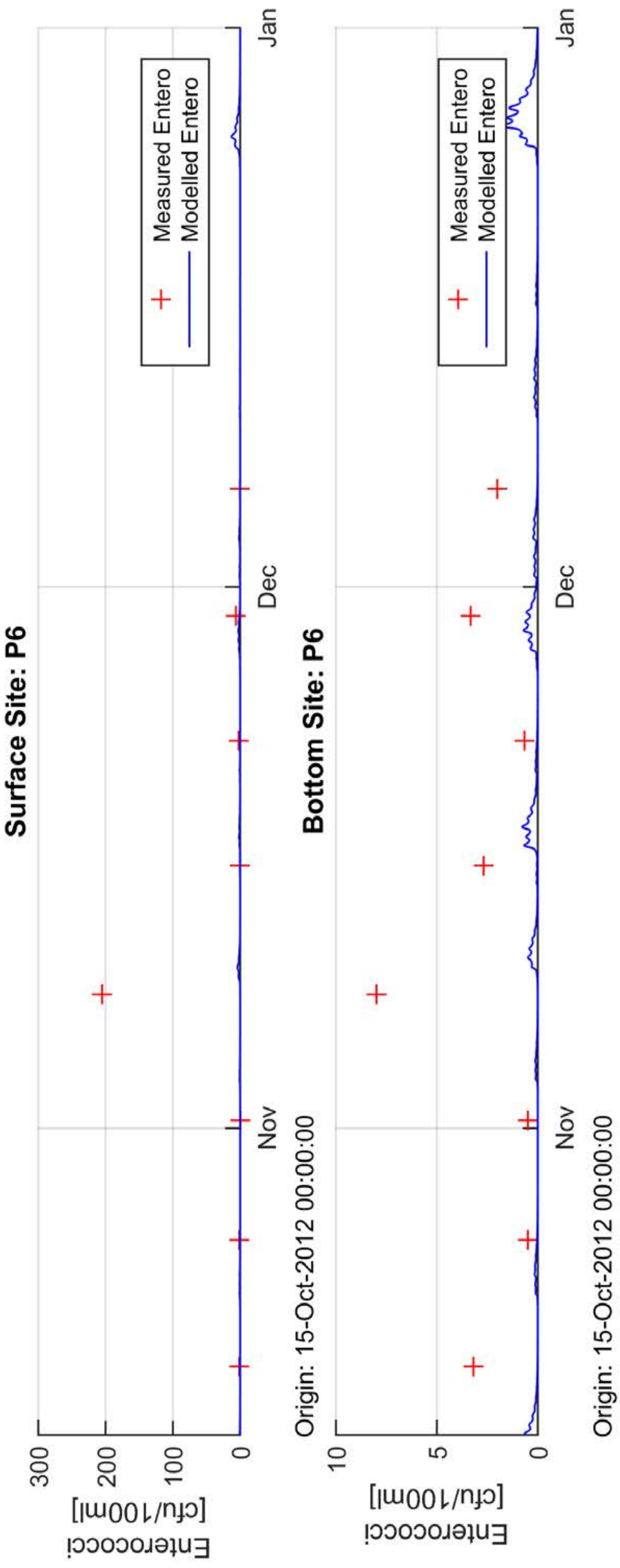
Figure 5.83



Sydney Harbour Ecological Response Model

Enterococci Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: P5

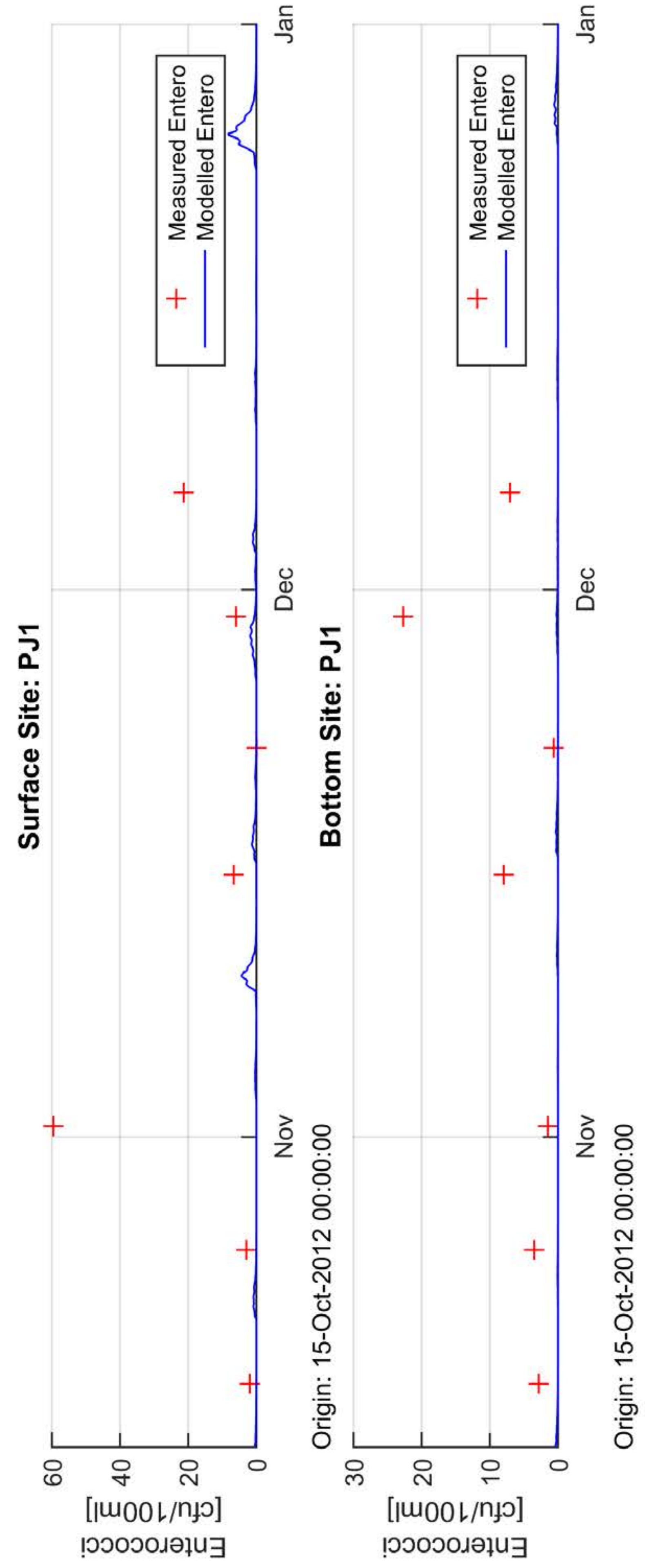
Figure 5.84



Sydney Harbour Ecological Response Model

Enterococci Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: P6

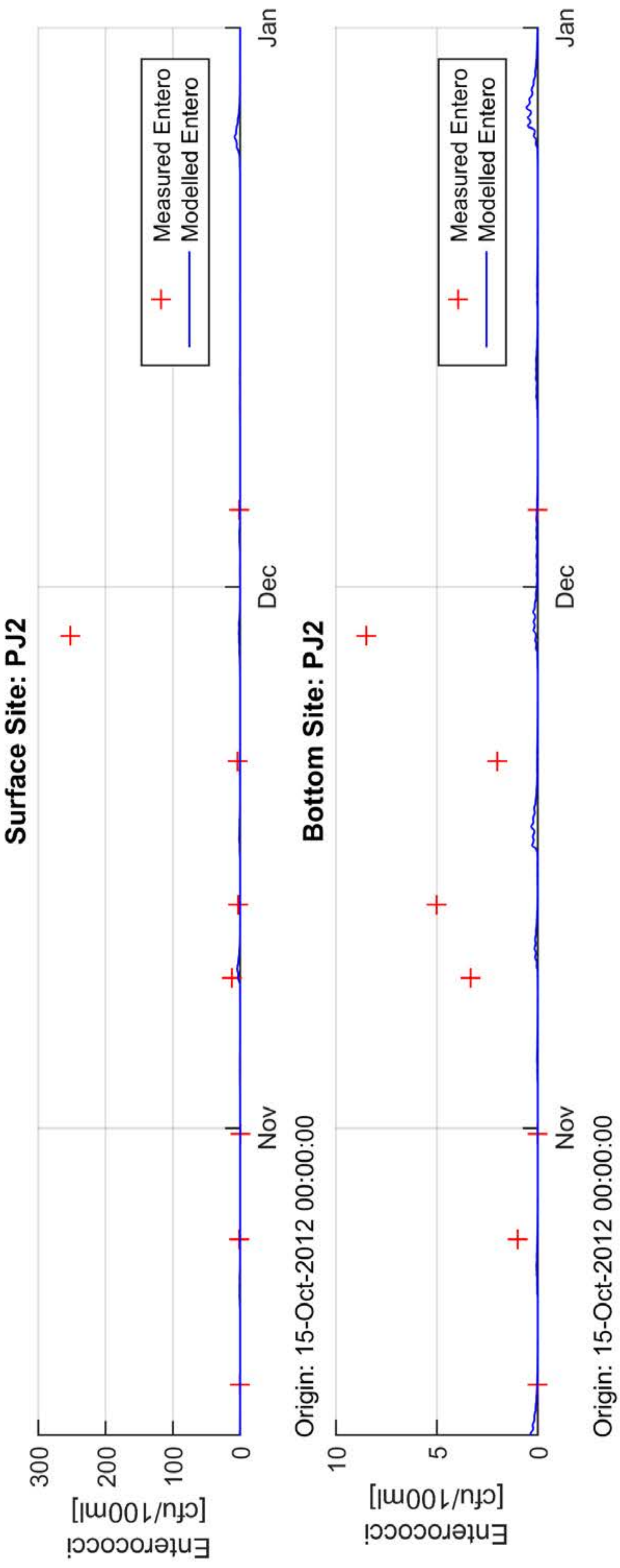
Figure 5.85



Sydney Harbour Ecological Response Model

Enterococci Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: PJ1

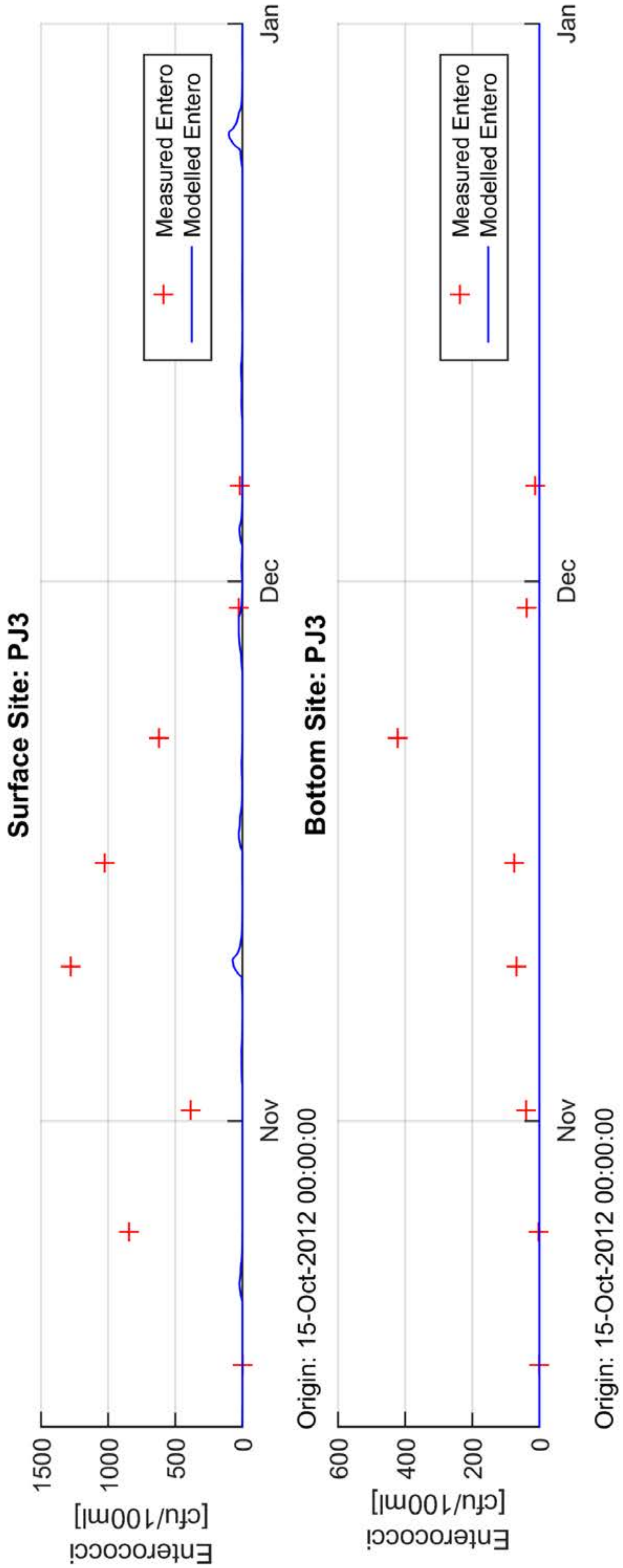
Figure 5.86



Sydney Harbour Ecological Response Model

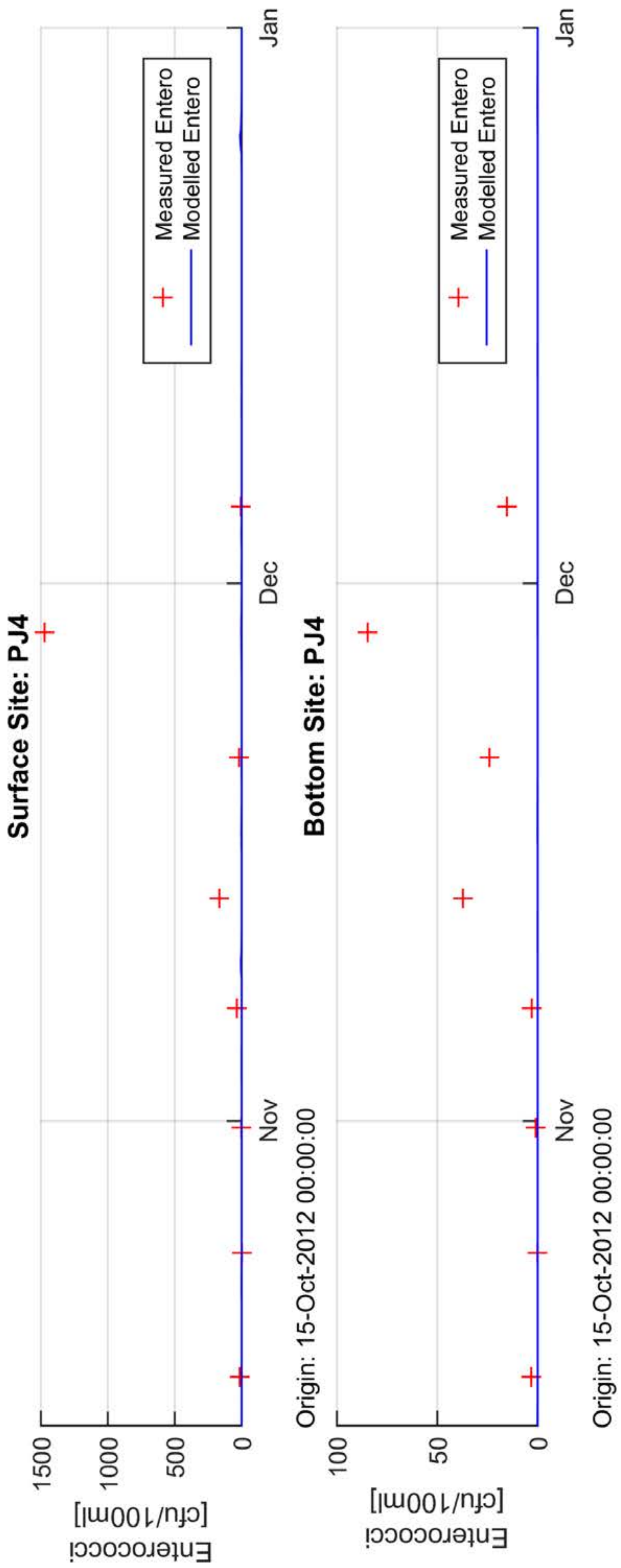
Enterococci Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: PJ2

Figure 5.87



Enterococci Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: PJ3

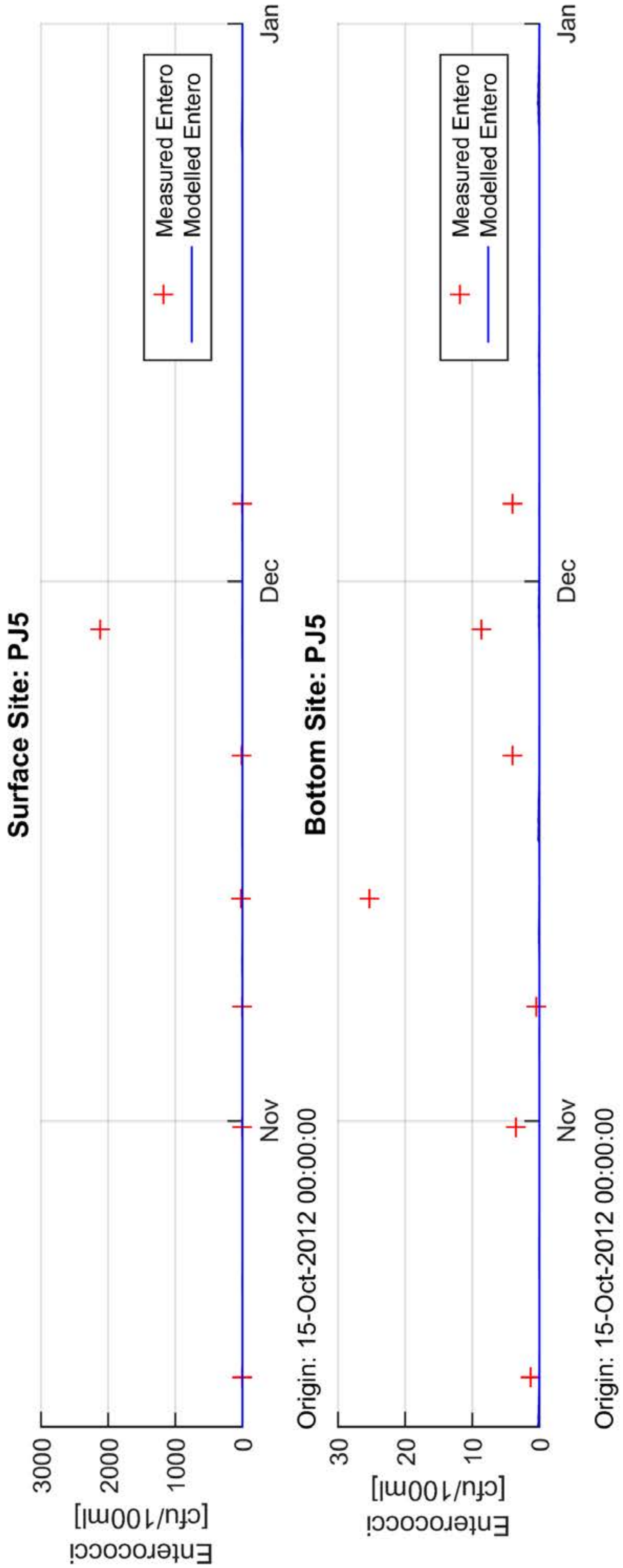
Figure 5.88



Sydney Harbour Ecological Response Model

Enterococci Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: PJ4

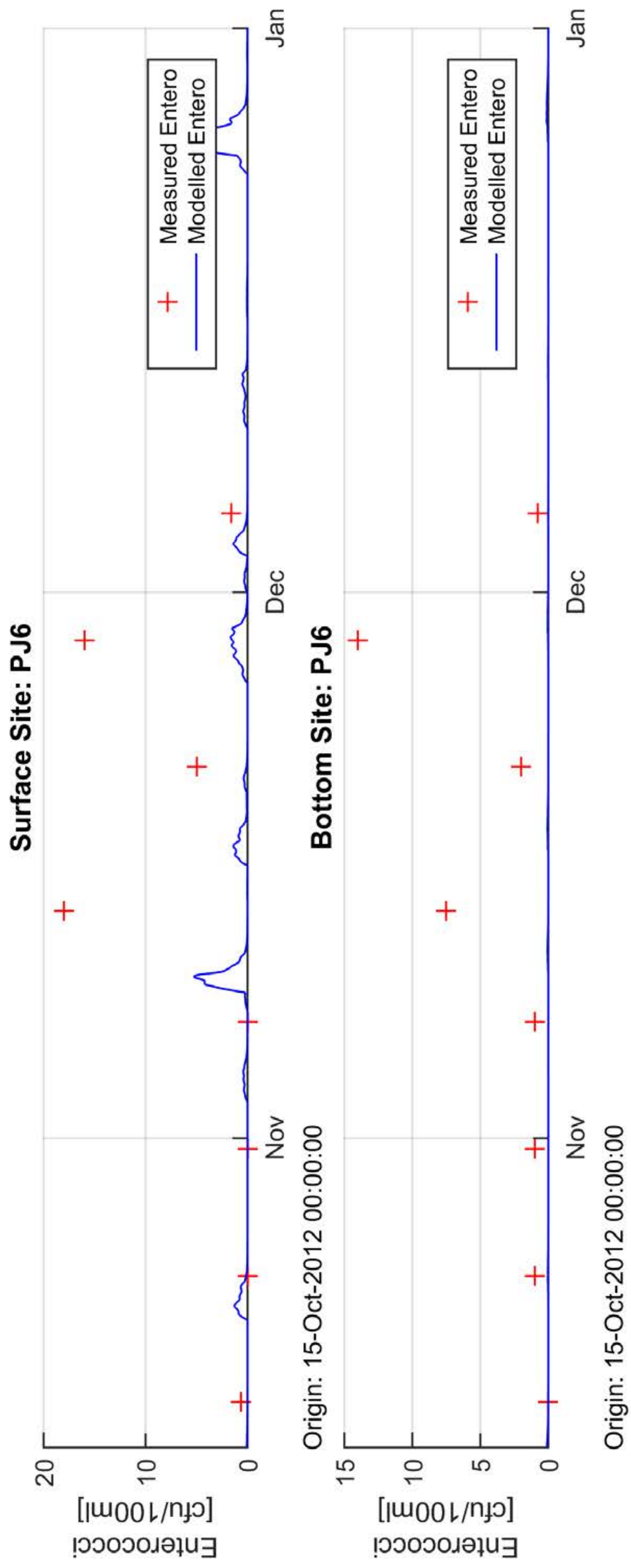
Figure 5.89



Sydney Harbour Ecological Response Model

Enterococci Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: PJ5

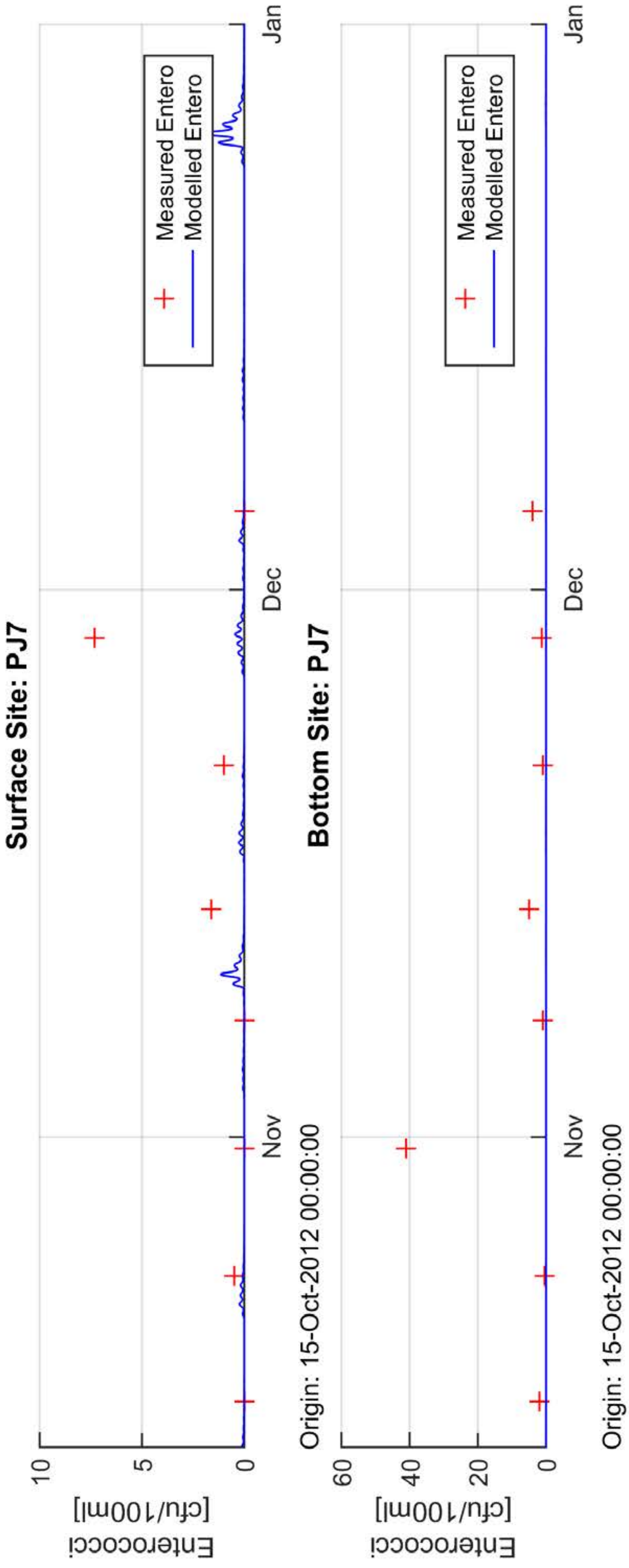
Figure 5.90



Sydney Harbour Ecological Response Model

Enterococci Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: PJ6

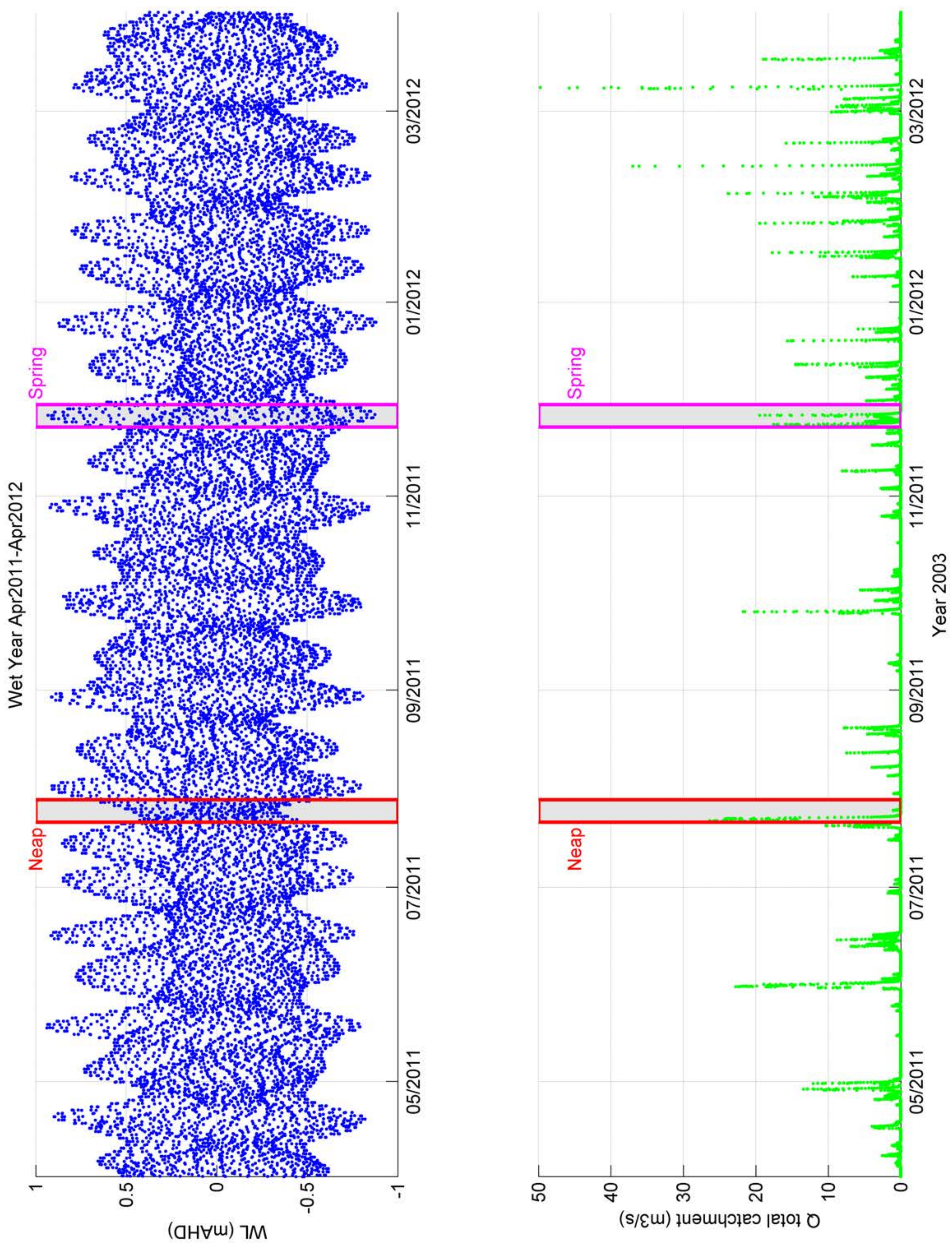
Figure 5.91



Sydney Harbour Ecological Response Model

Enterococci Time−Series 3D Box Model: Oct−Dec 2012
BLOOM Model − Site: PJ7

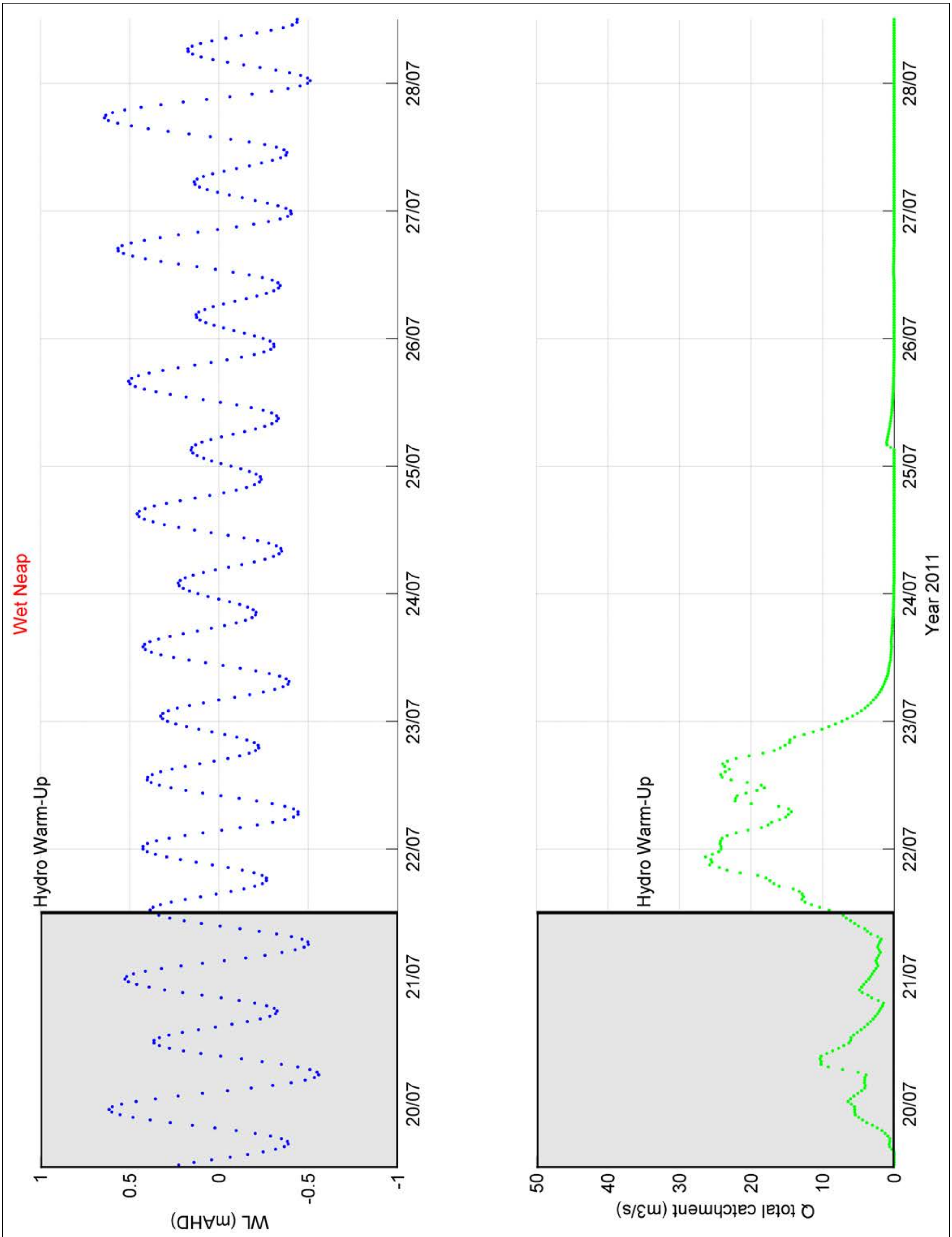
Figure 5.92



Sydney Harbour Ecological Response Model

Time−Series of Water Level and Total Catchment Discharge
Wet Year

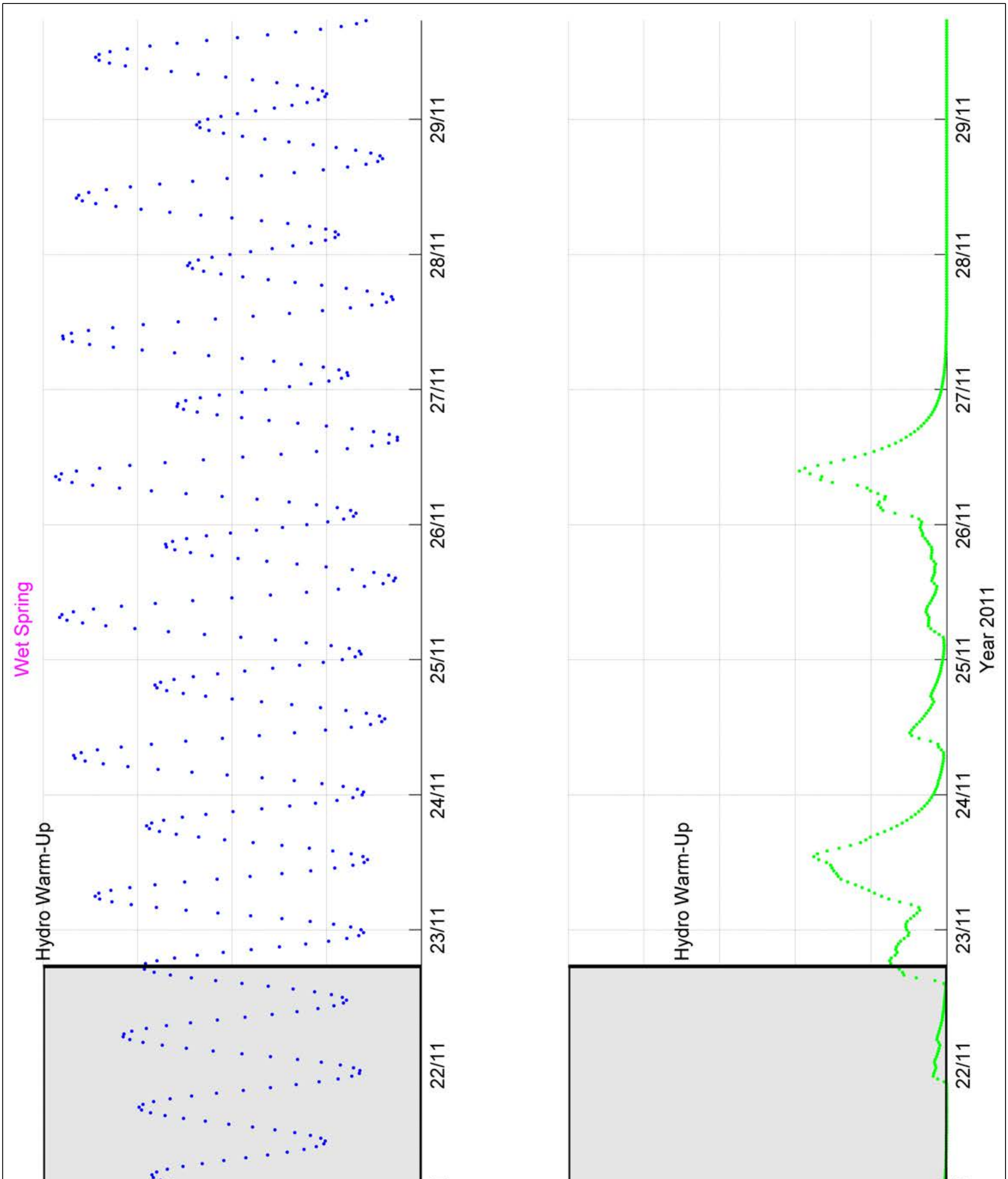
Figure 6.1a



Sydney Harbour Ecological Response Model

Time−Series of Water Level and Total Catchment Discharge
Wet Neap

Figure 6.1b



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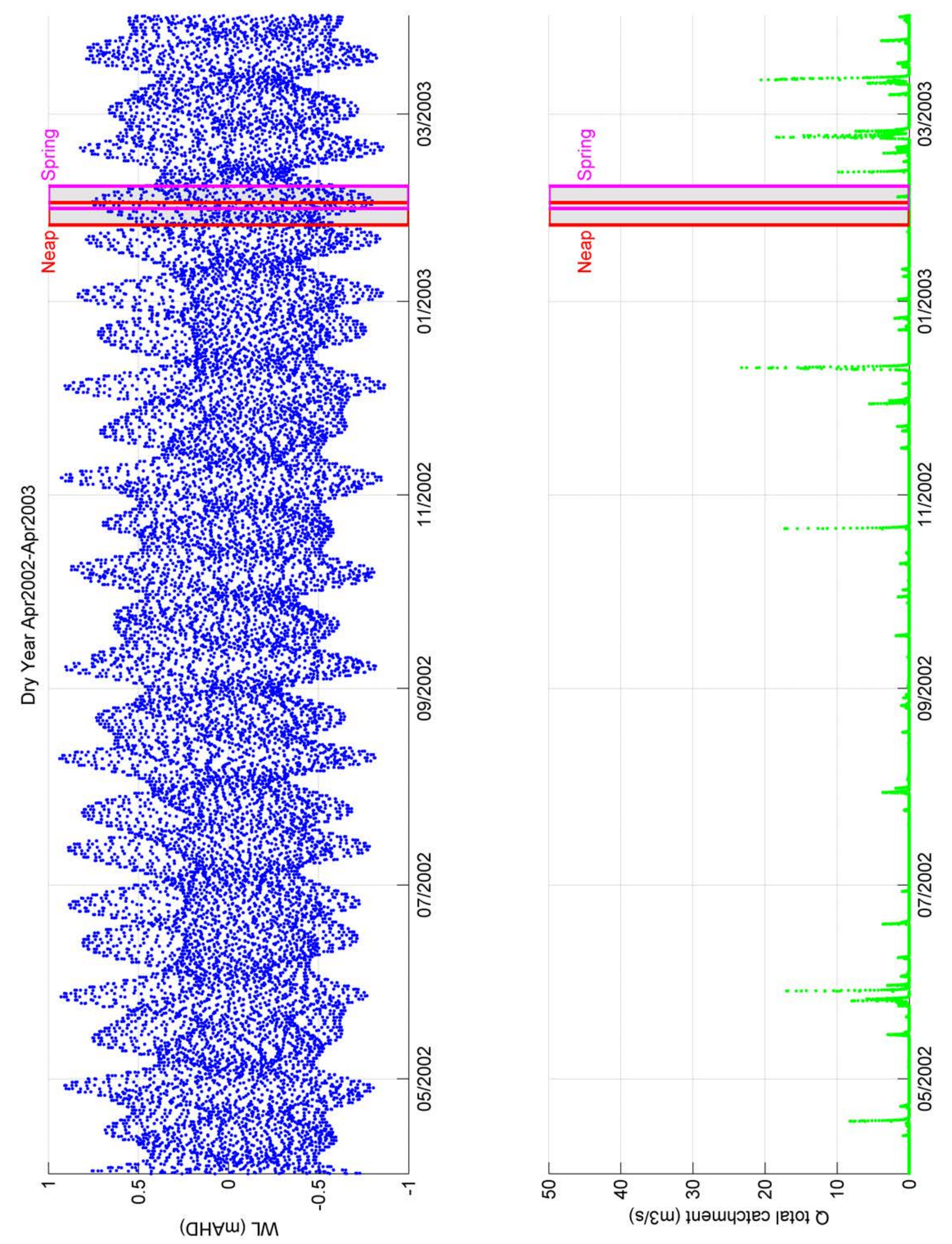
Sydney Harbour Ecological Response Model

Time−Series of Water Level and Total Catchment Discharge
Wet Spring

Figure 6.1c



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Sydney Harbour Ecological Response Model

Time−Series of Water Level and Total Catchment Discharge
Dry Year

Figure 6.2a

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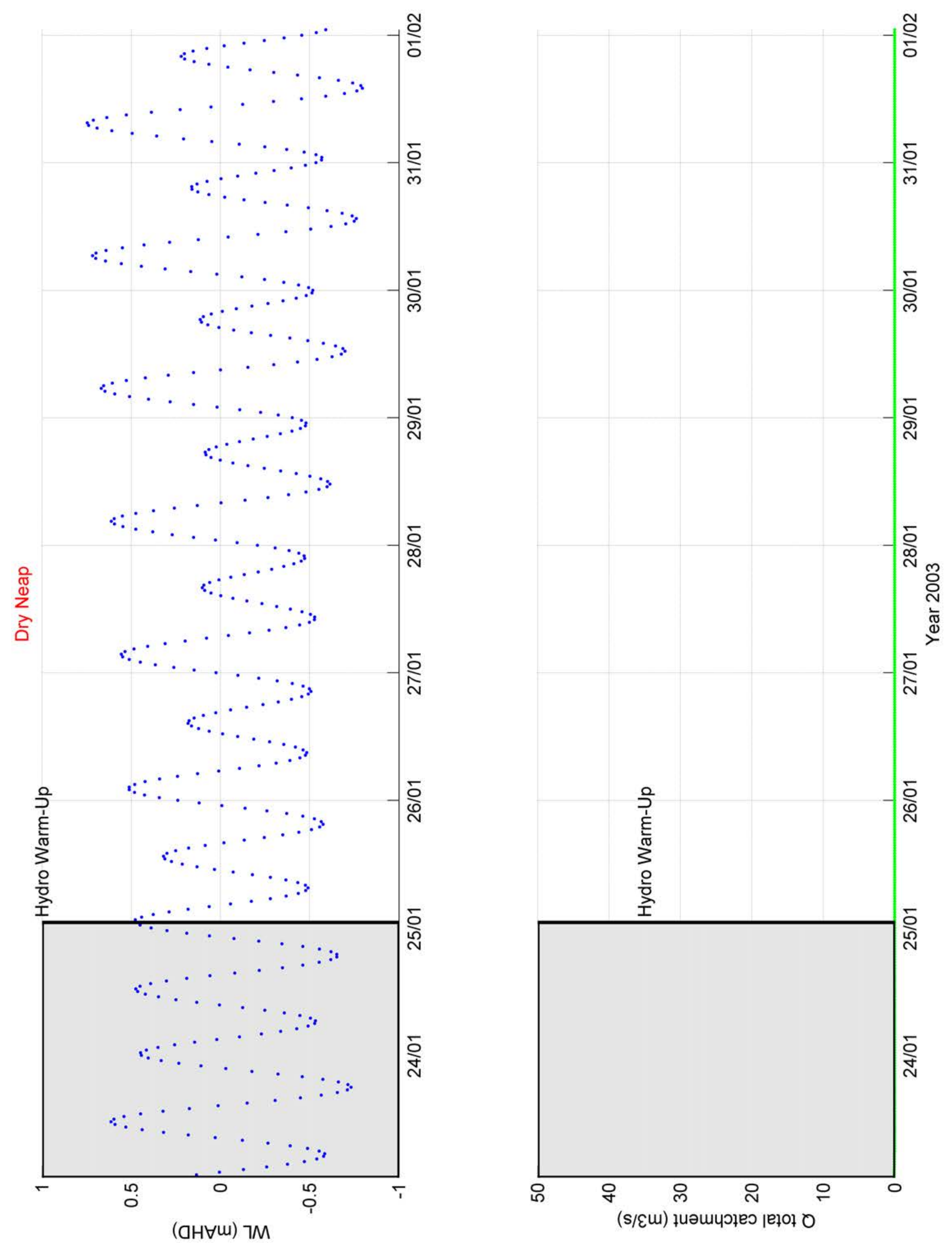

Sydney Harbour Ecological Response Model

Time−Series of Water Level and Total Catchment Discharge
Dry Neap

Figure 6.2b

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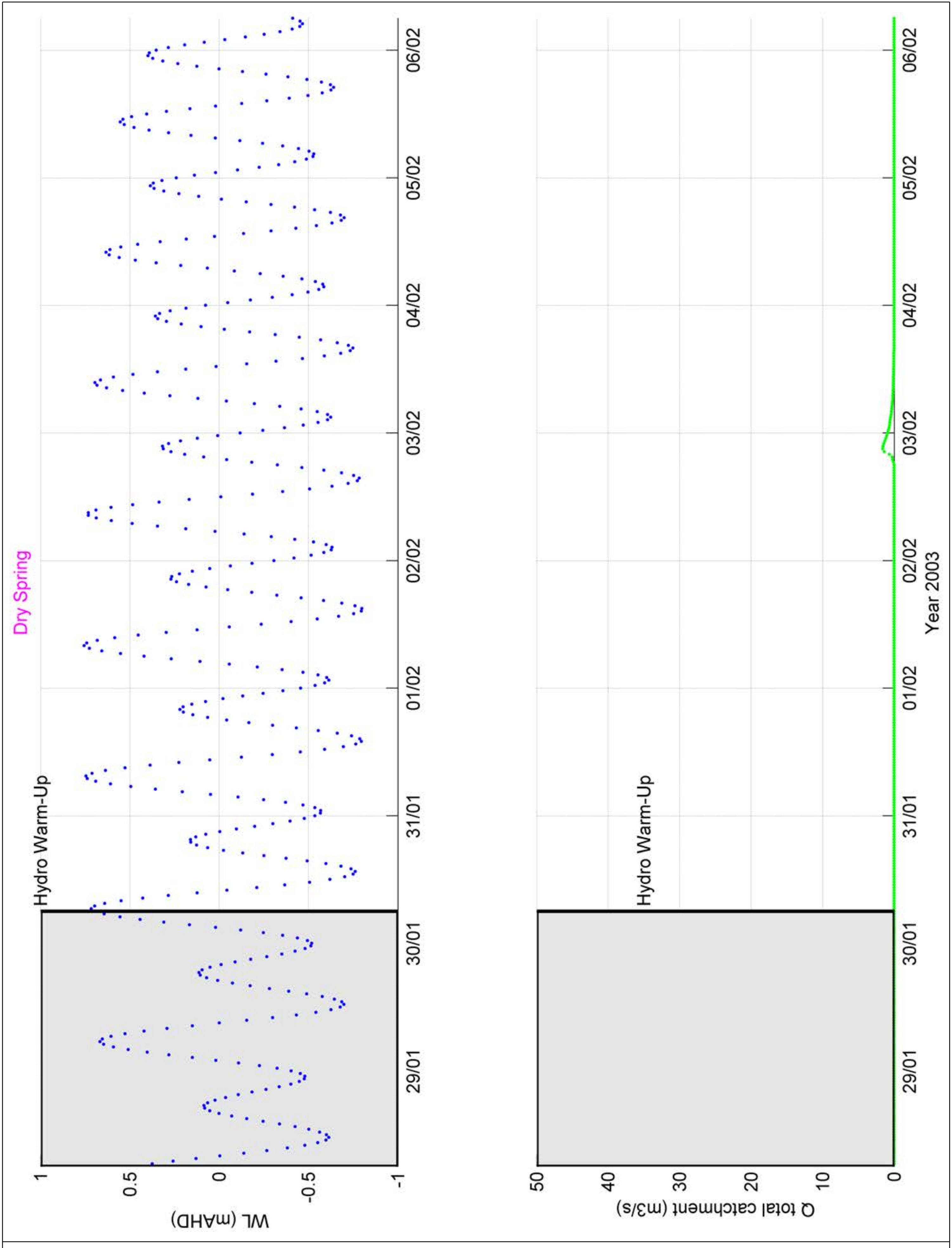
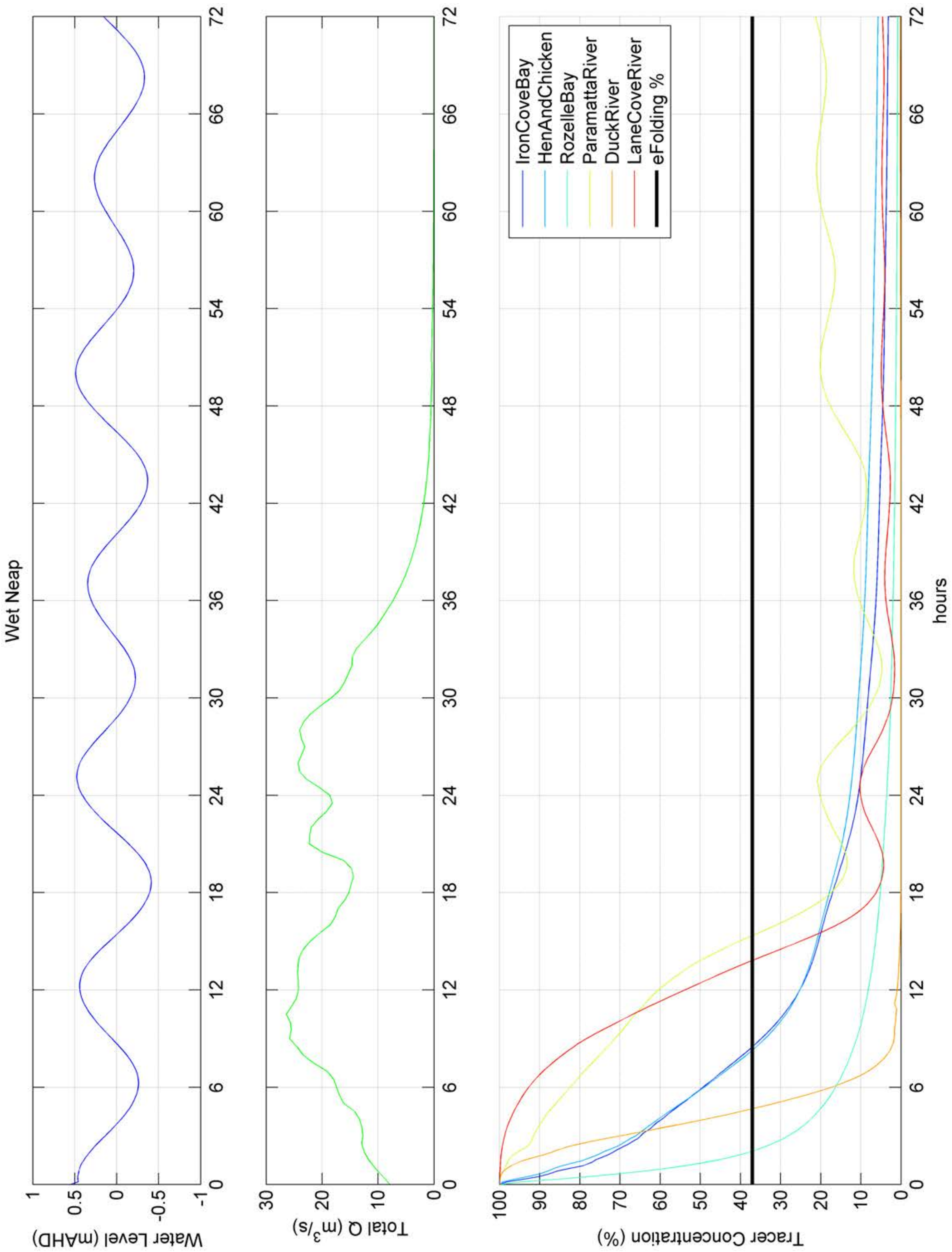


Sydney Harbour Ecological Response Model

Time−Series of Water Level and Total Catchment Discharge
Dry Spring

Figure 6.2c



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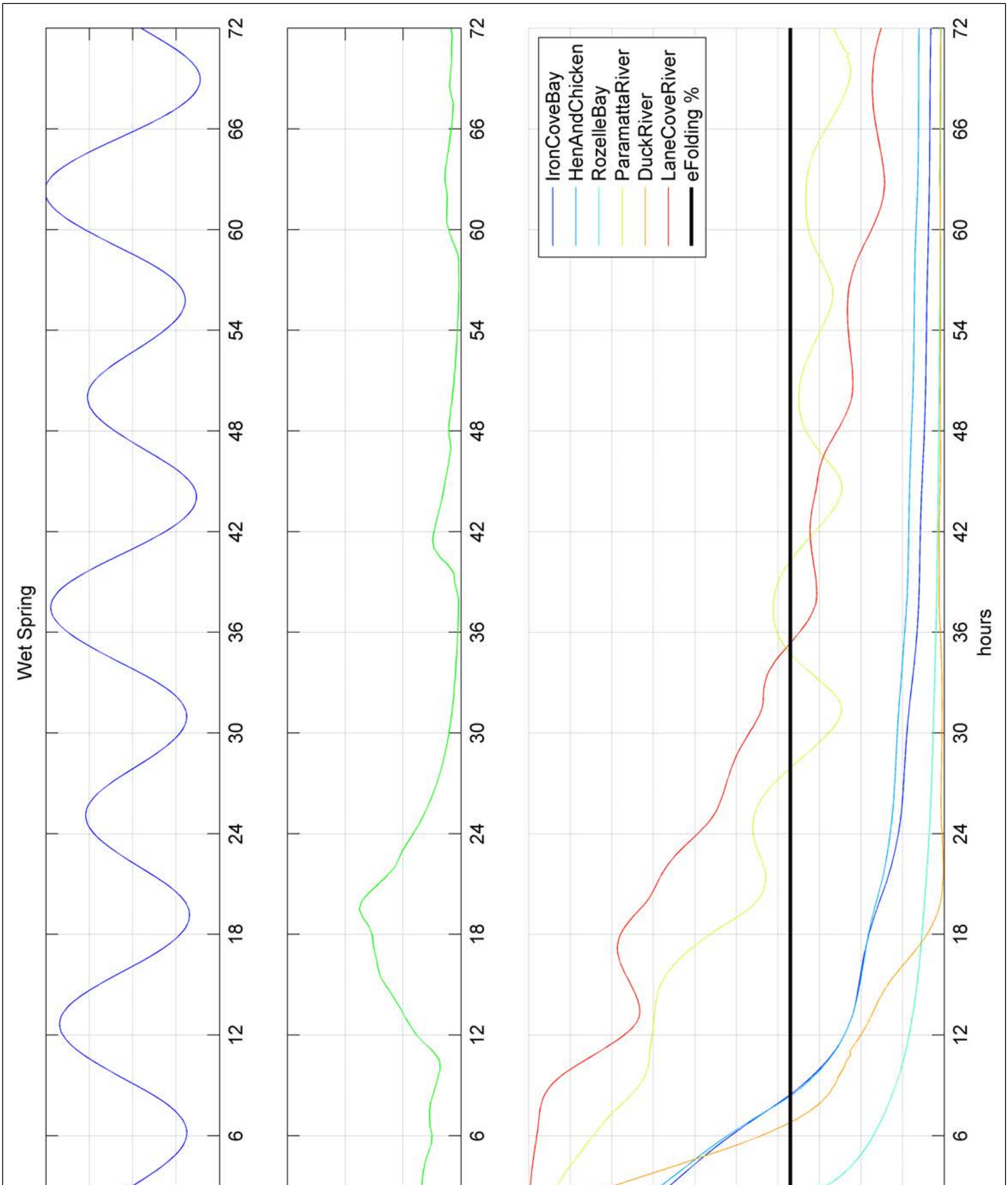
Sydney Harbour Ecological Response Model

Time−Series of Tracer Concentration and Efolding Time
Wet Neap

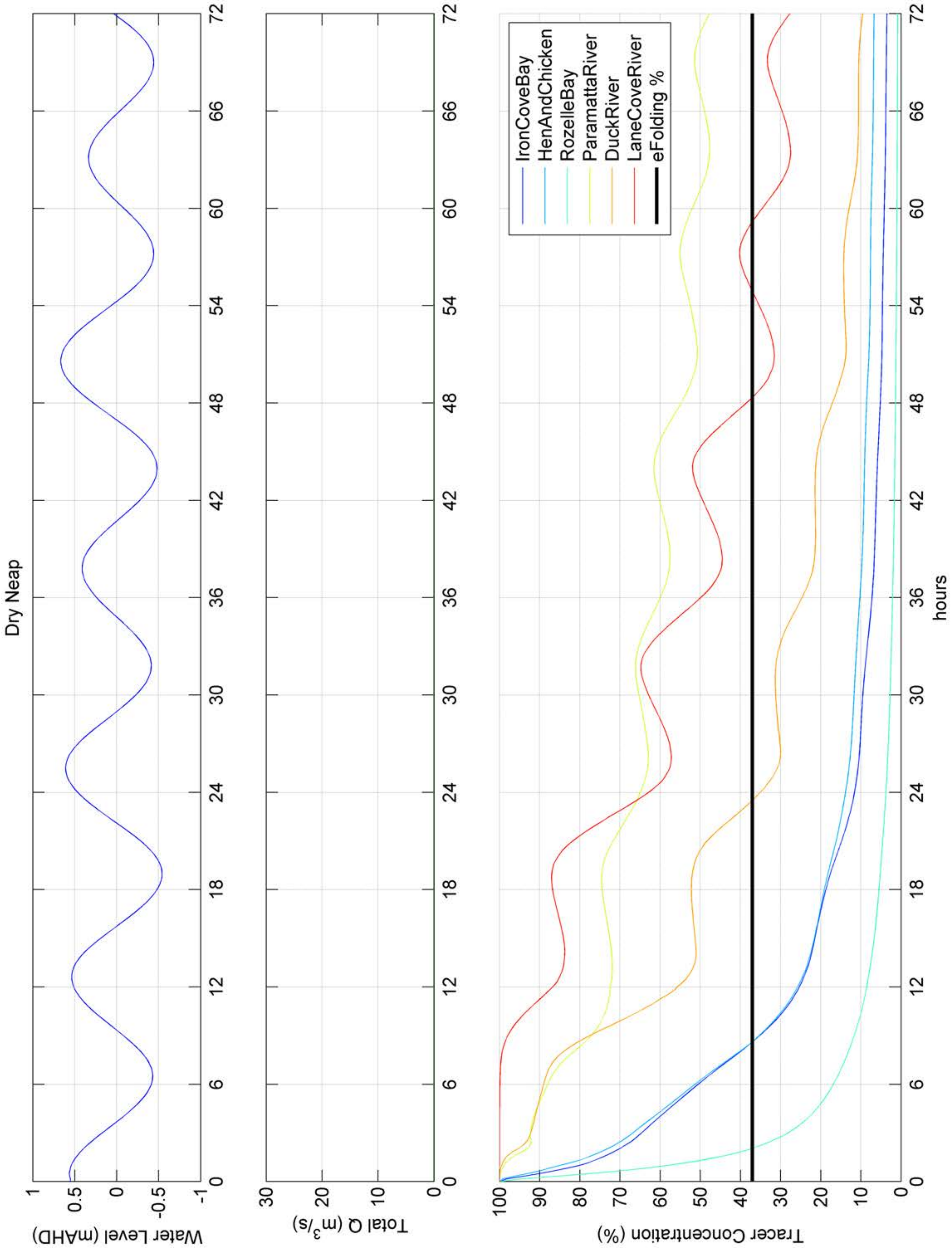
Figure 6.3a



Sydney Harbour Ecological Response Model

Time−Series of Tracer Concentration and Efolding Time
Wet Spring

Figure 6.3b



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Sydney Harbour Ecological Response Model

Time−Series of Tracer Concentration and Efolding Time
Dry Year

Figure 6.3c

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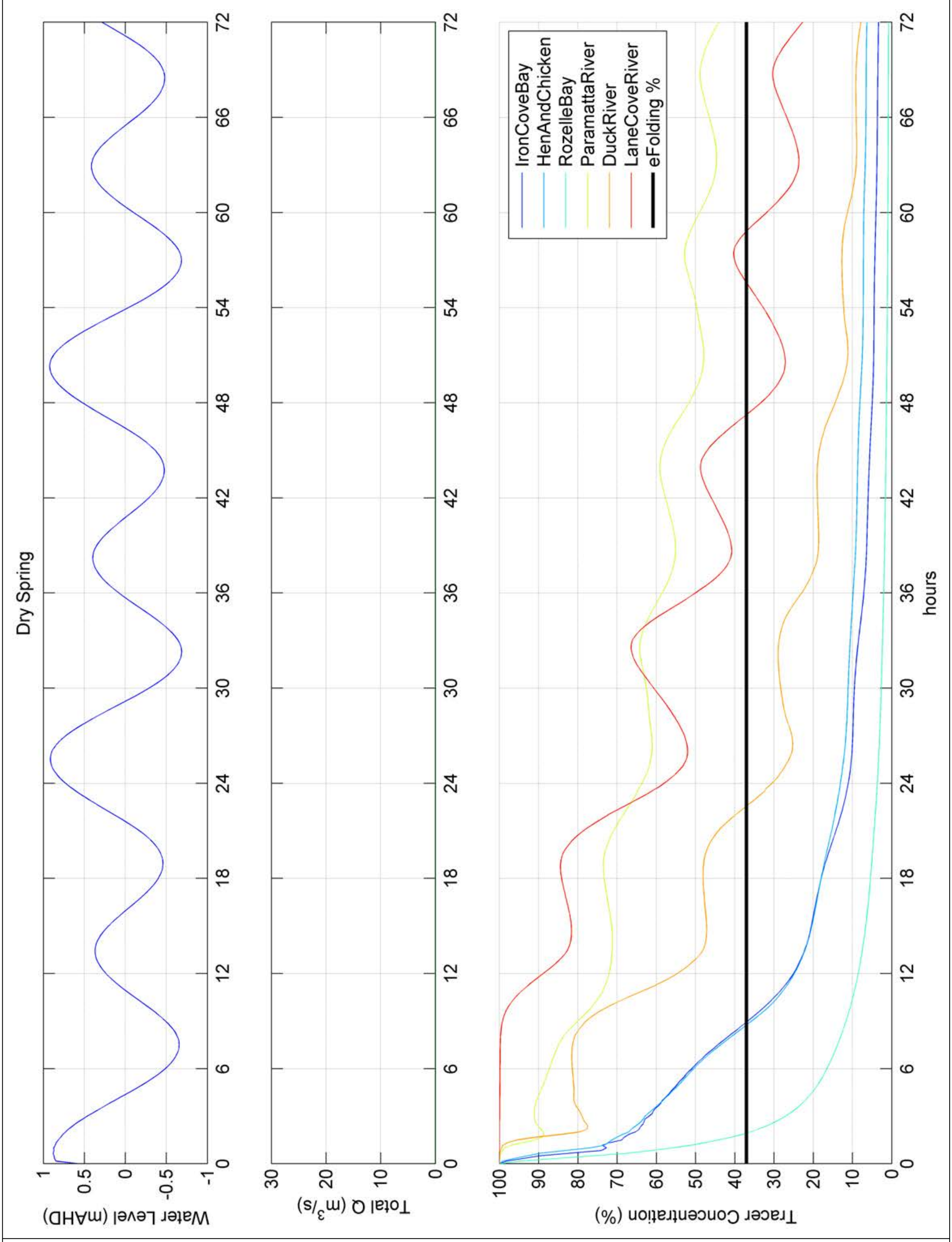
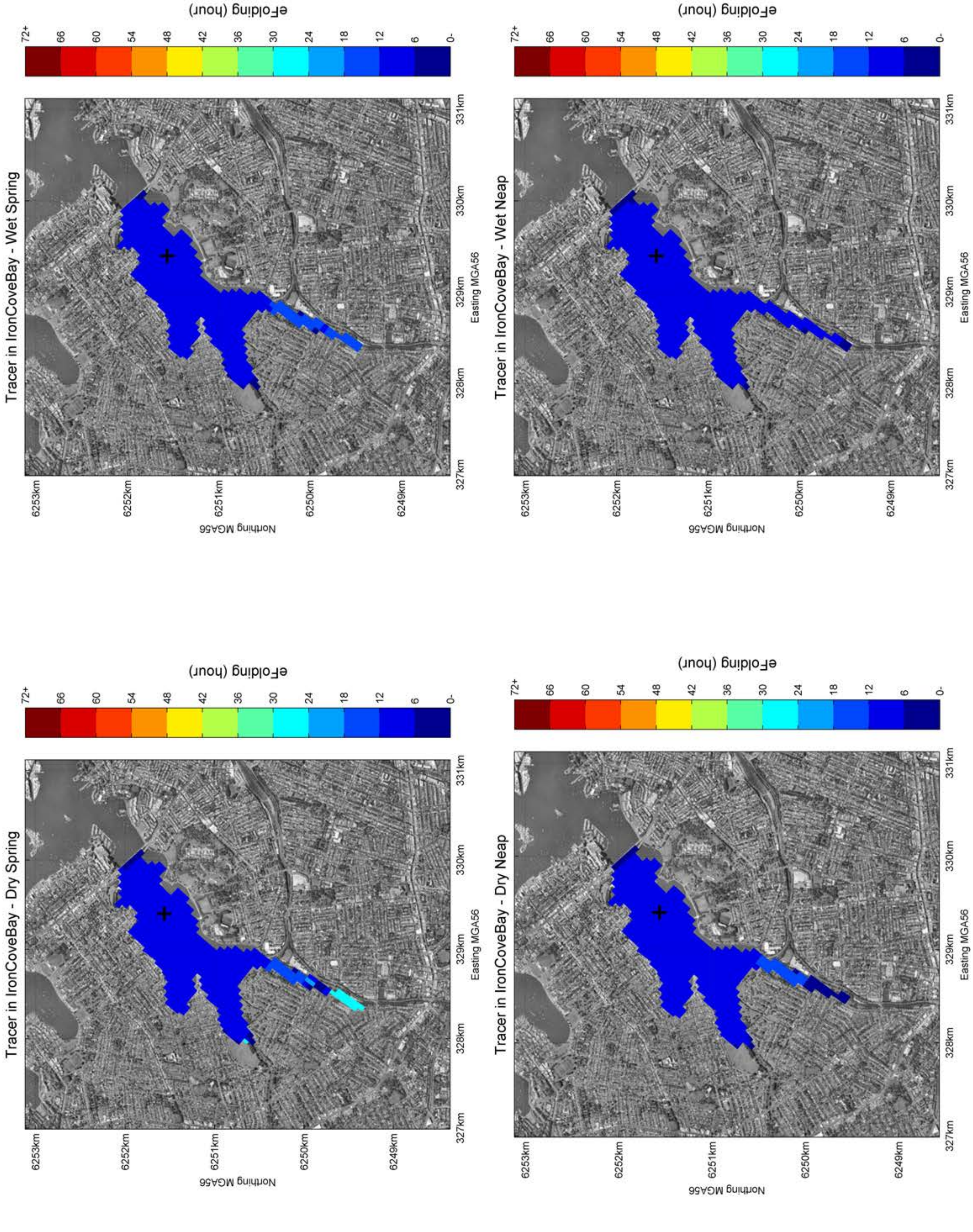


Sydney Harbour Ecological Response Model

Time−Series of Tracer Concentration and Efolding Time
Dry Neap

Figure 6.3d



Sydney Harbour Ecological Response Model

E−Folding Map
Iron Cove

Figure 6.4a

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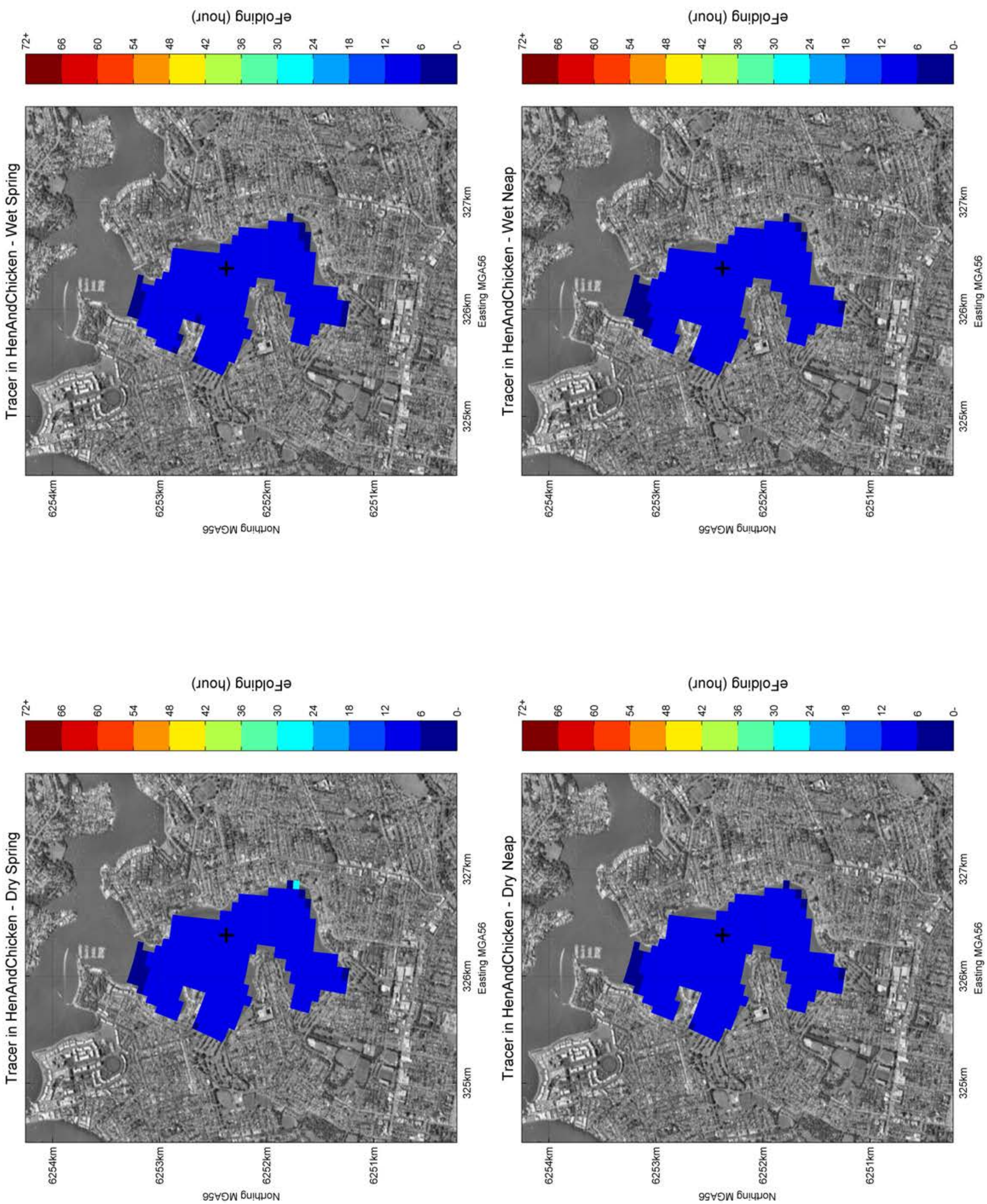
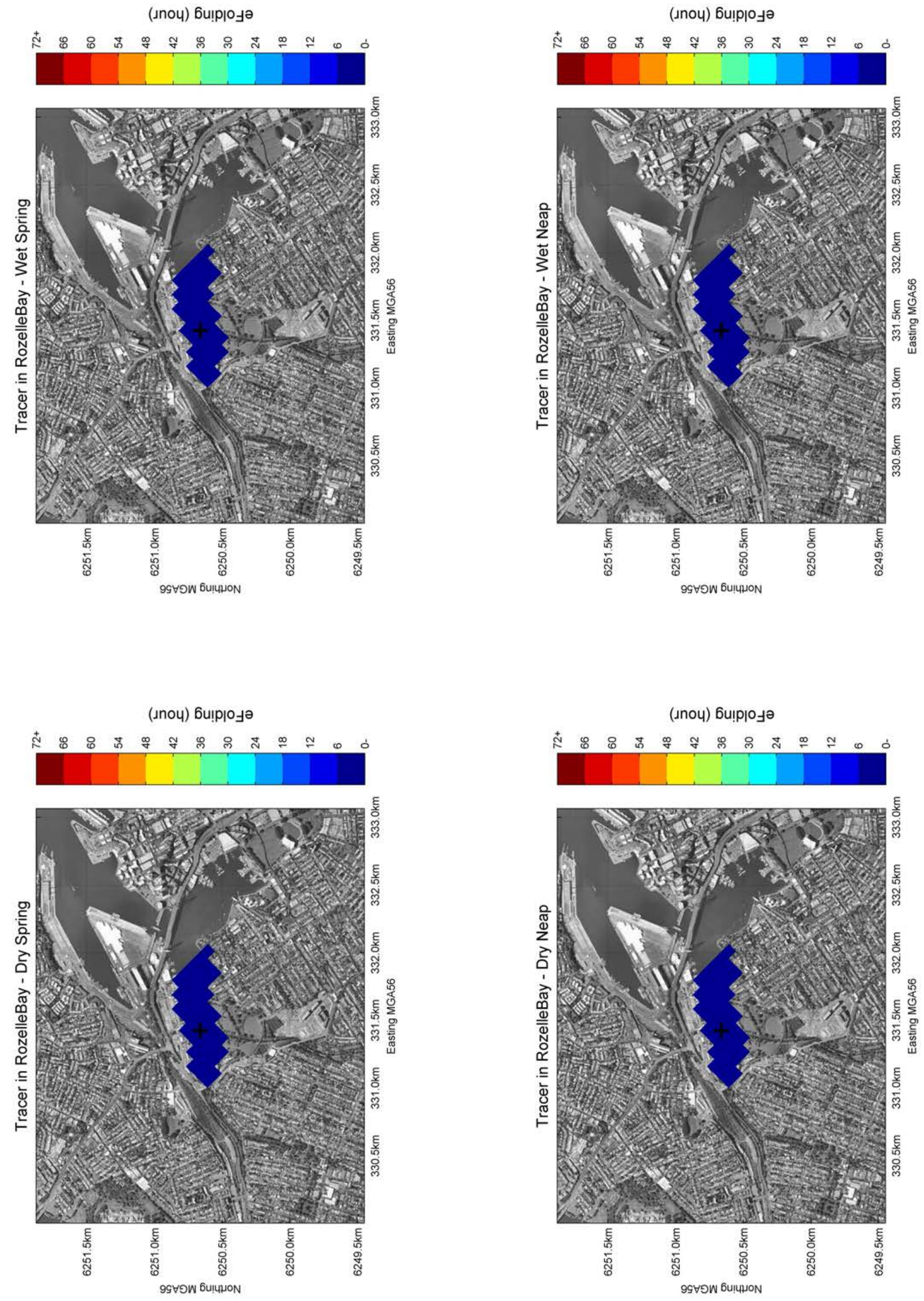


Sydney Harbour Ecological Response Model

E−Folding Map
Hen and Chicken

Figure 6.4b



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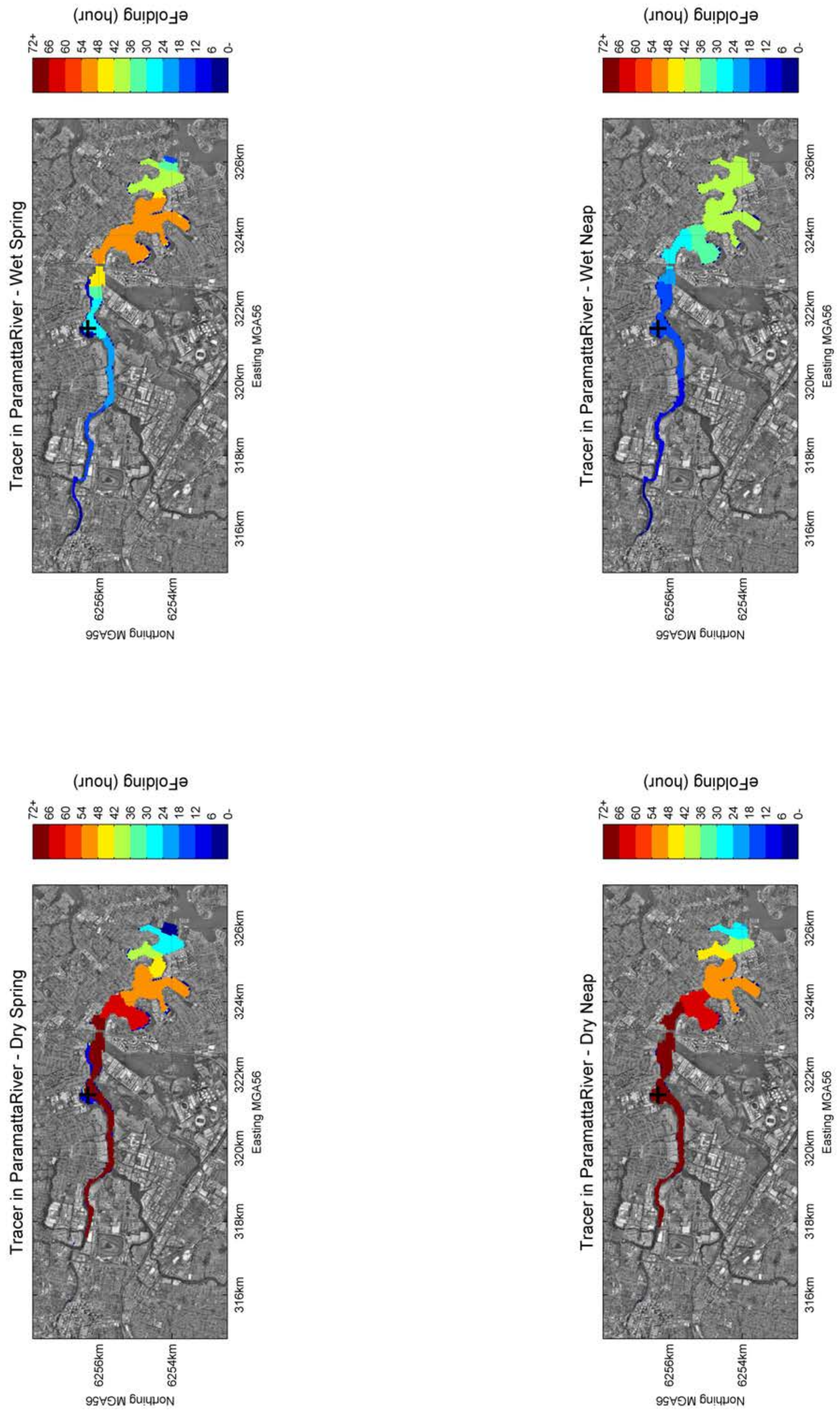
Sydney Harbour Ecological Response Model

E−Folding Map
Rozelle Bay

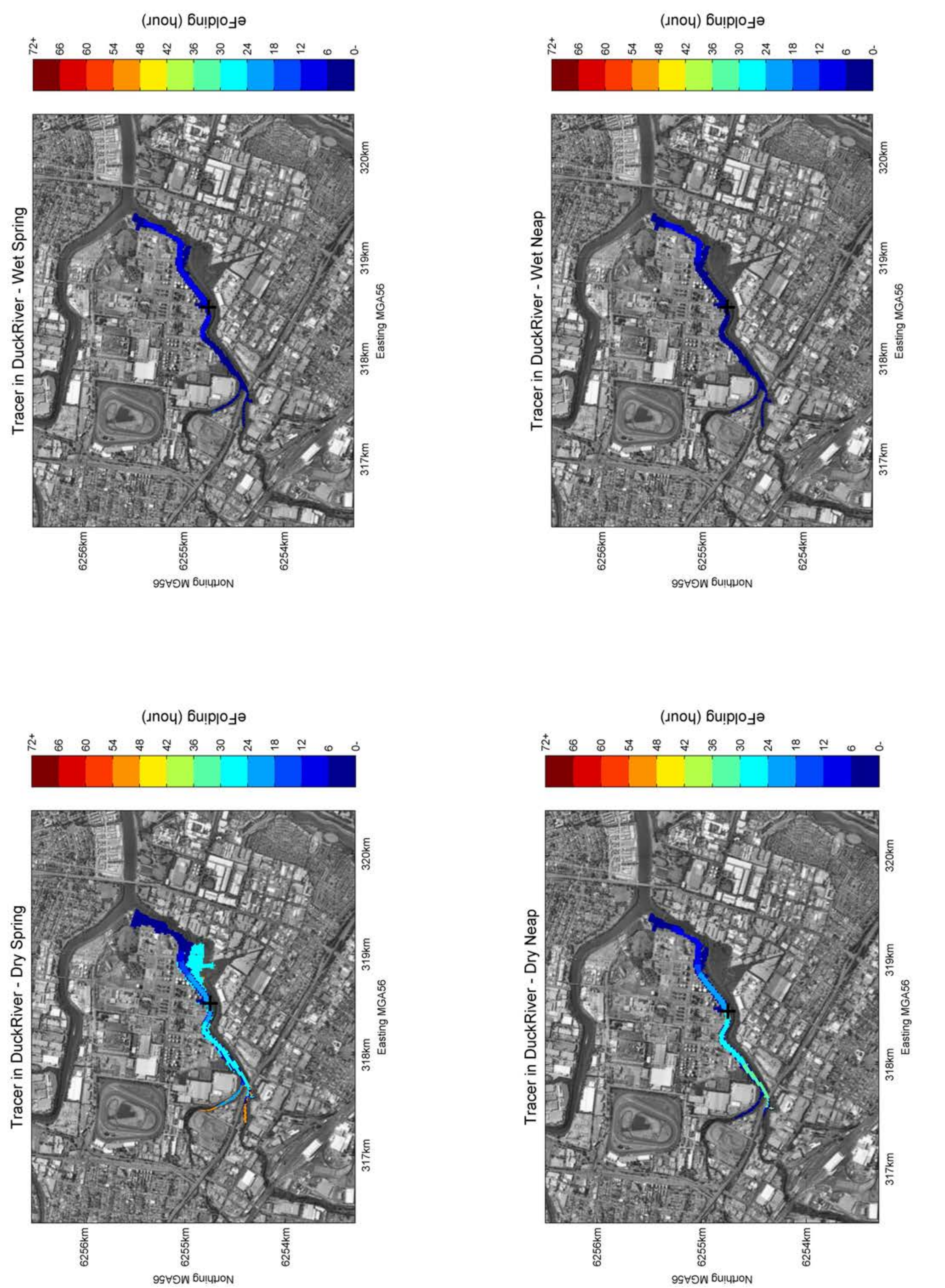
Figure 6.4c



Sydney Harbour Ecological Response Model

E−Folding Map
Parramatta River

Figure 6.4d



Sydney Harbour Ecological Response Model

E−Folding Map
Duck River

Figure 6.4e

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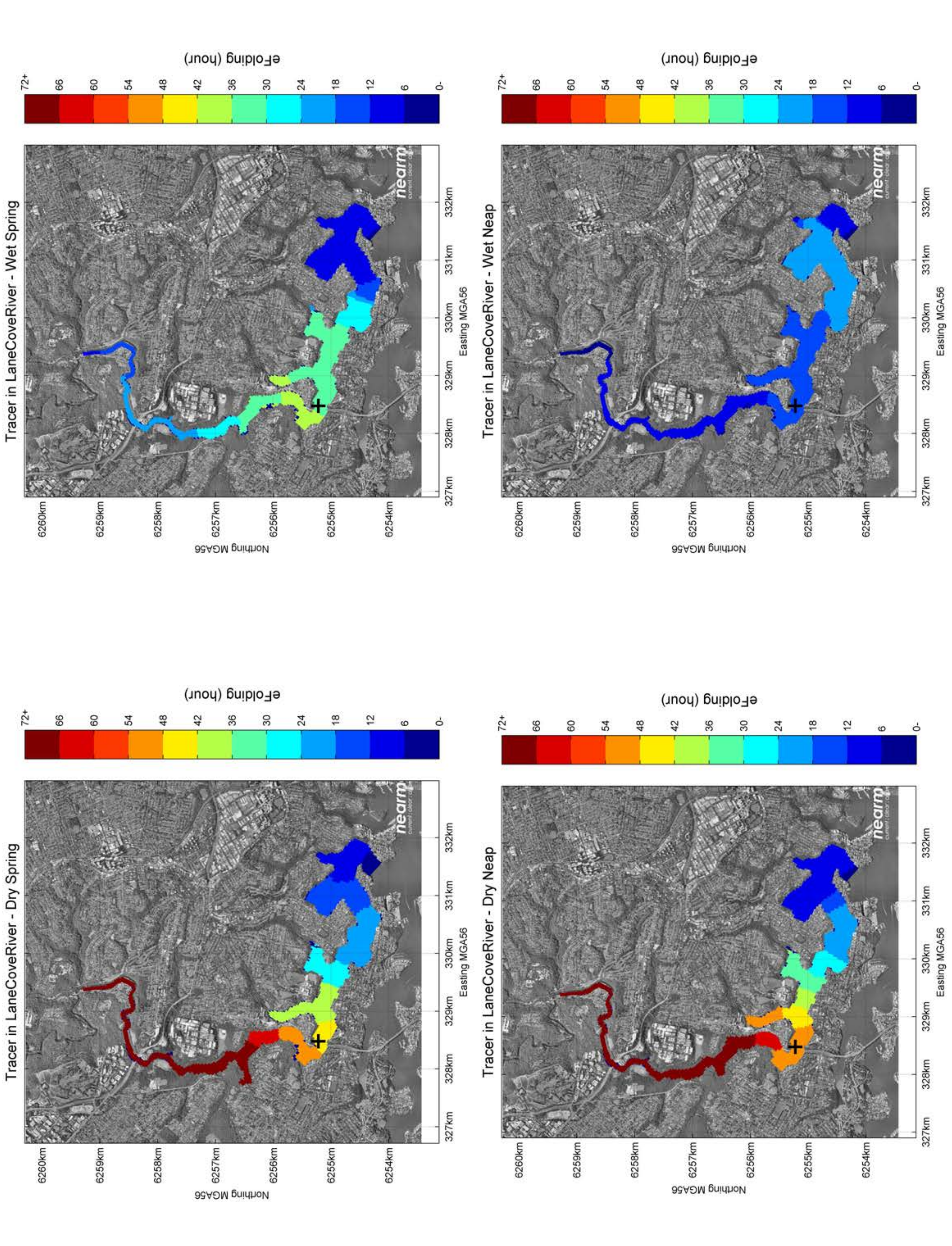

Sydney Harbour Ecological Response Model

E−Folding Map
Lane Cove River

Figure 6.4f

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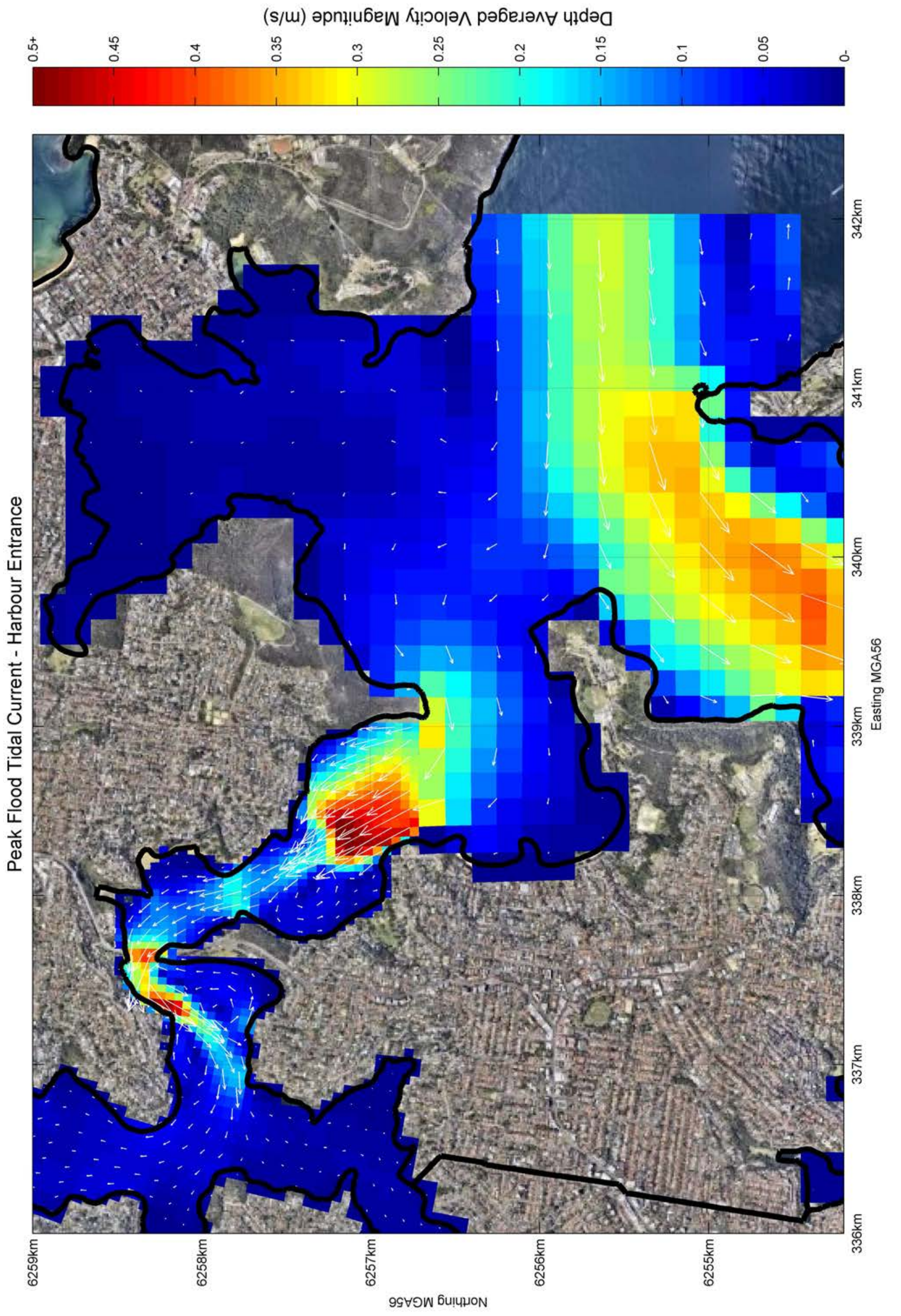

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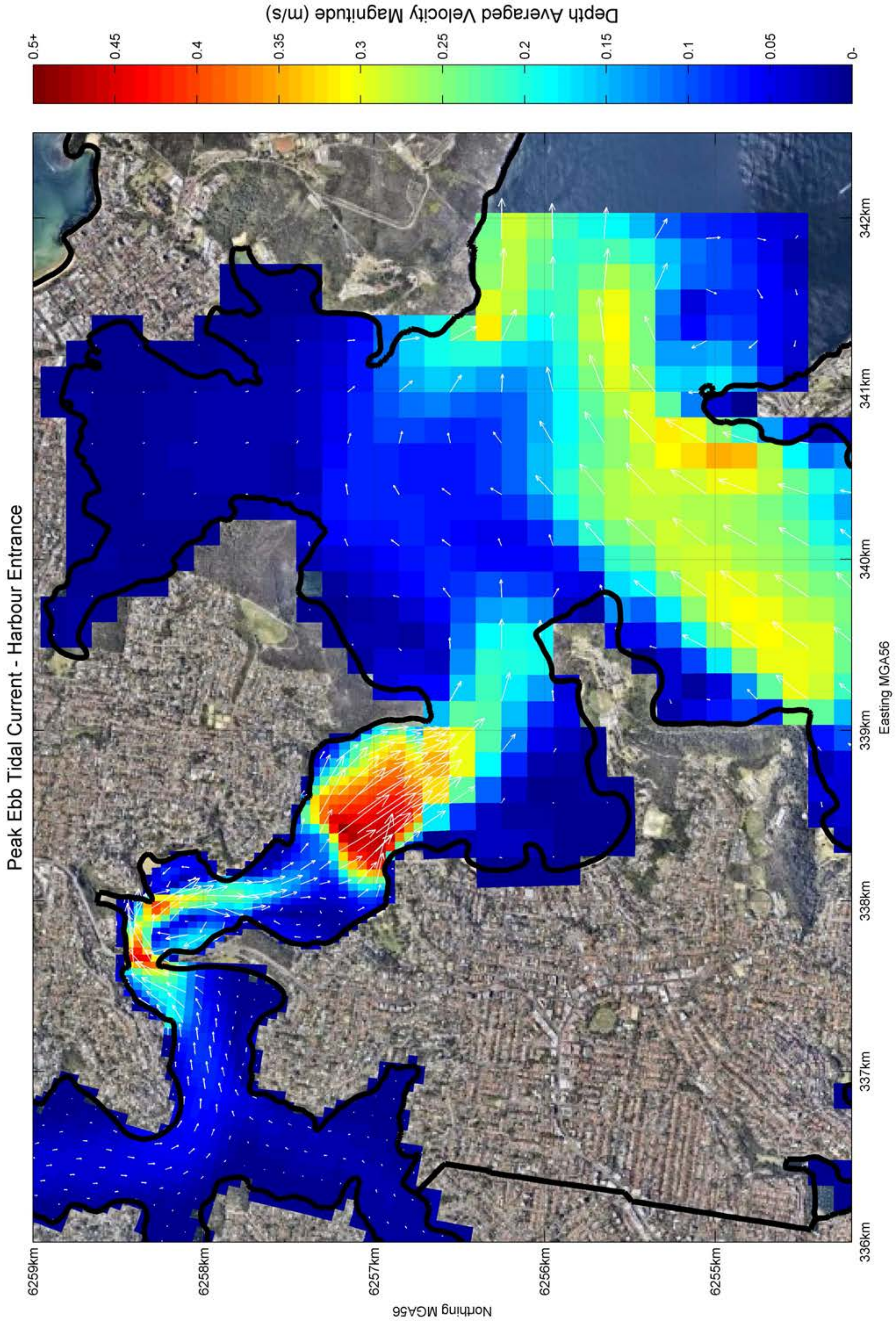
Sydney Harbour Ecological Response Model

Map of Peak Depth Averaged Current
Harbour Entrance – Spring Flood

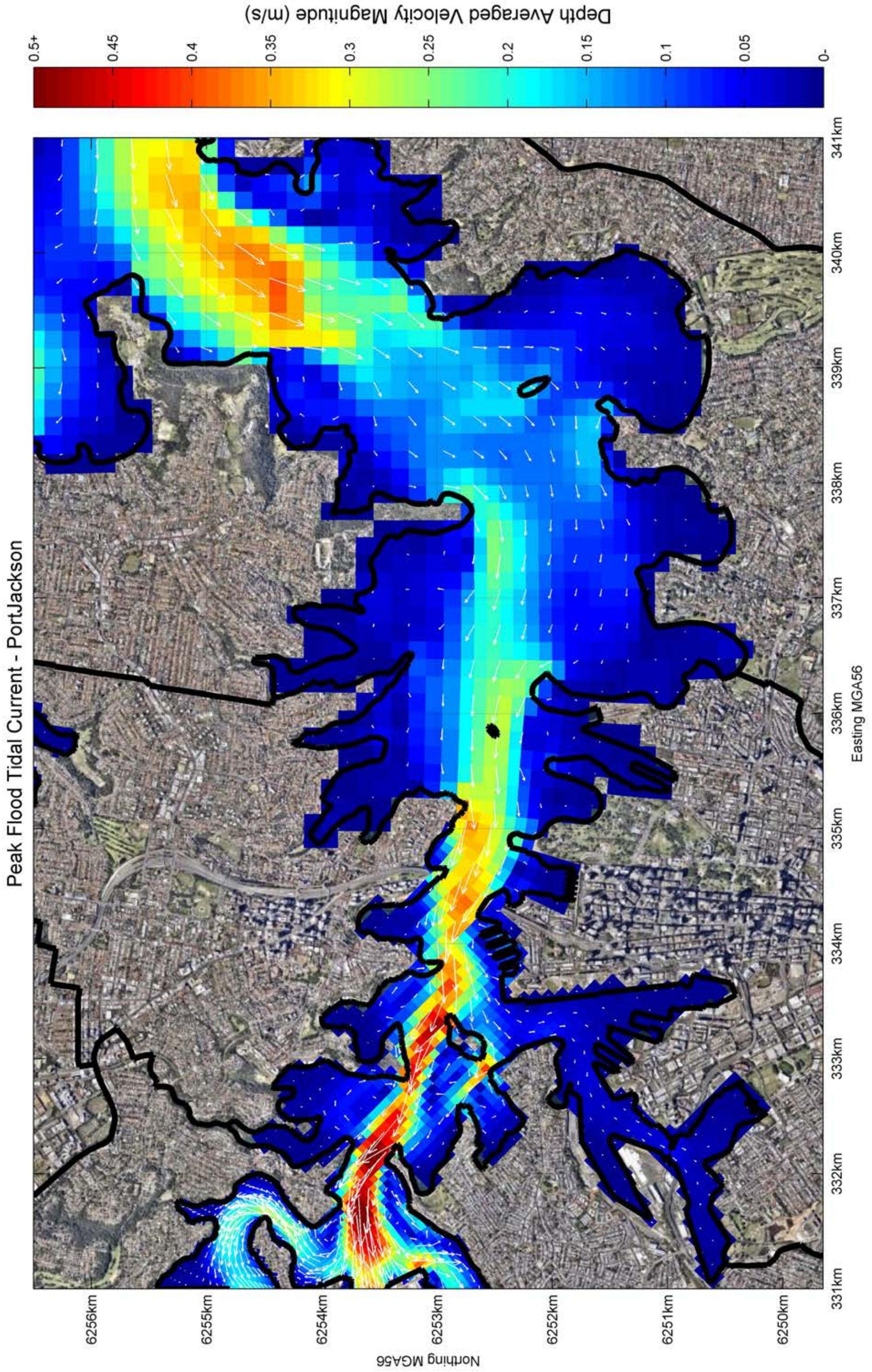
Figure 8.1a



Sydney Harbour Ecological Response Model

Map of Peak Depth Averaged Current
Harbour Entrance − Spring Ebb

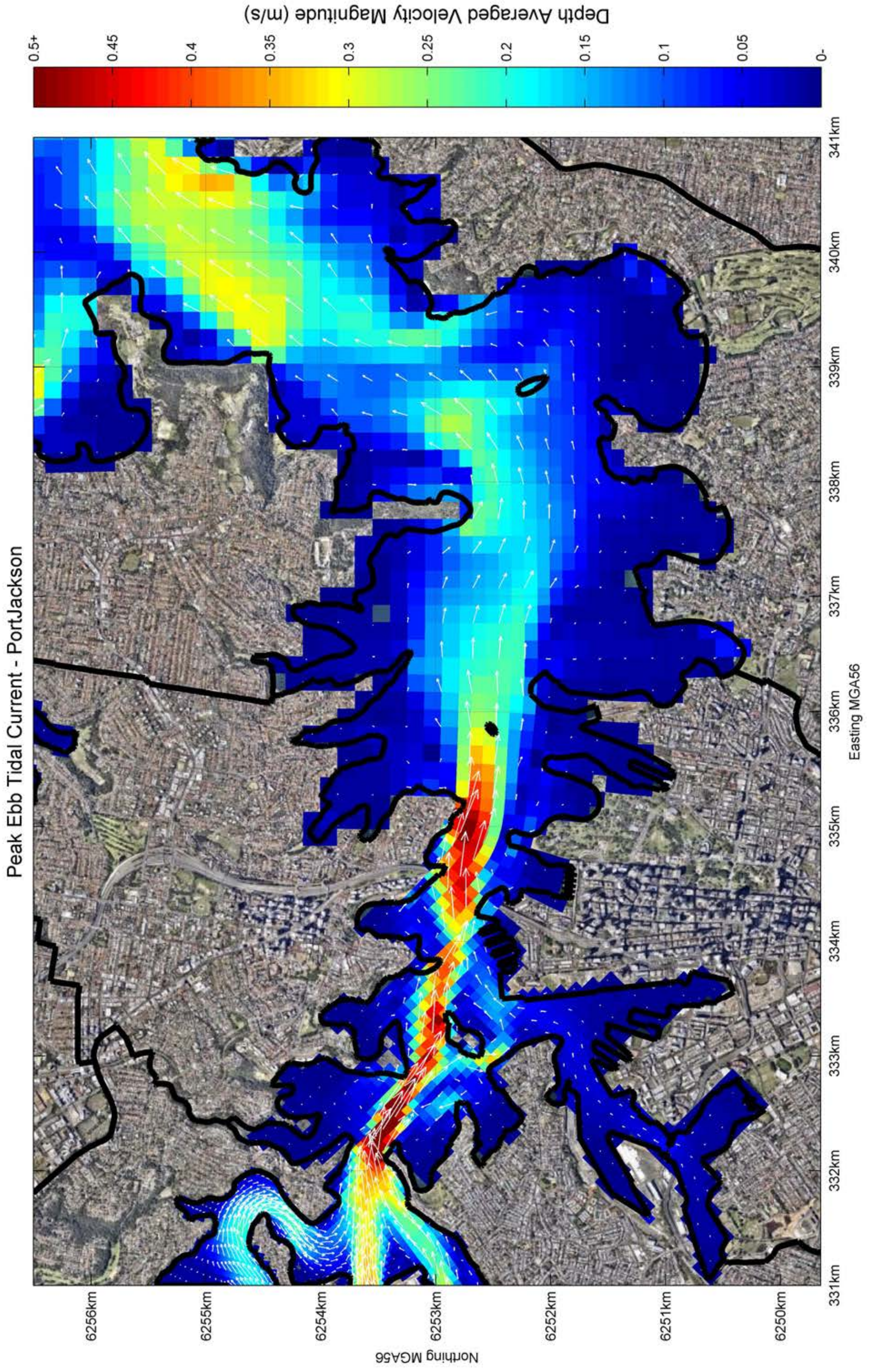
Figure 8.1b



Sydney Harbour Ecological Response Model

Map of Peak Depth Averaged Current
Port Jackson − Spring Flood

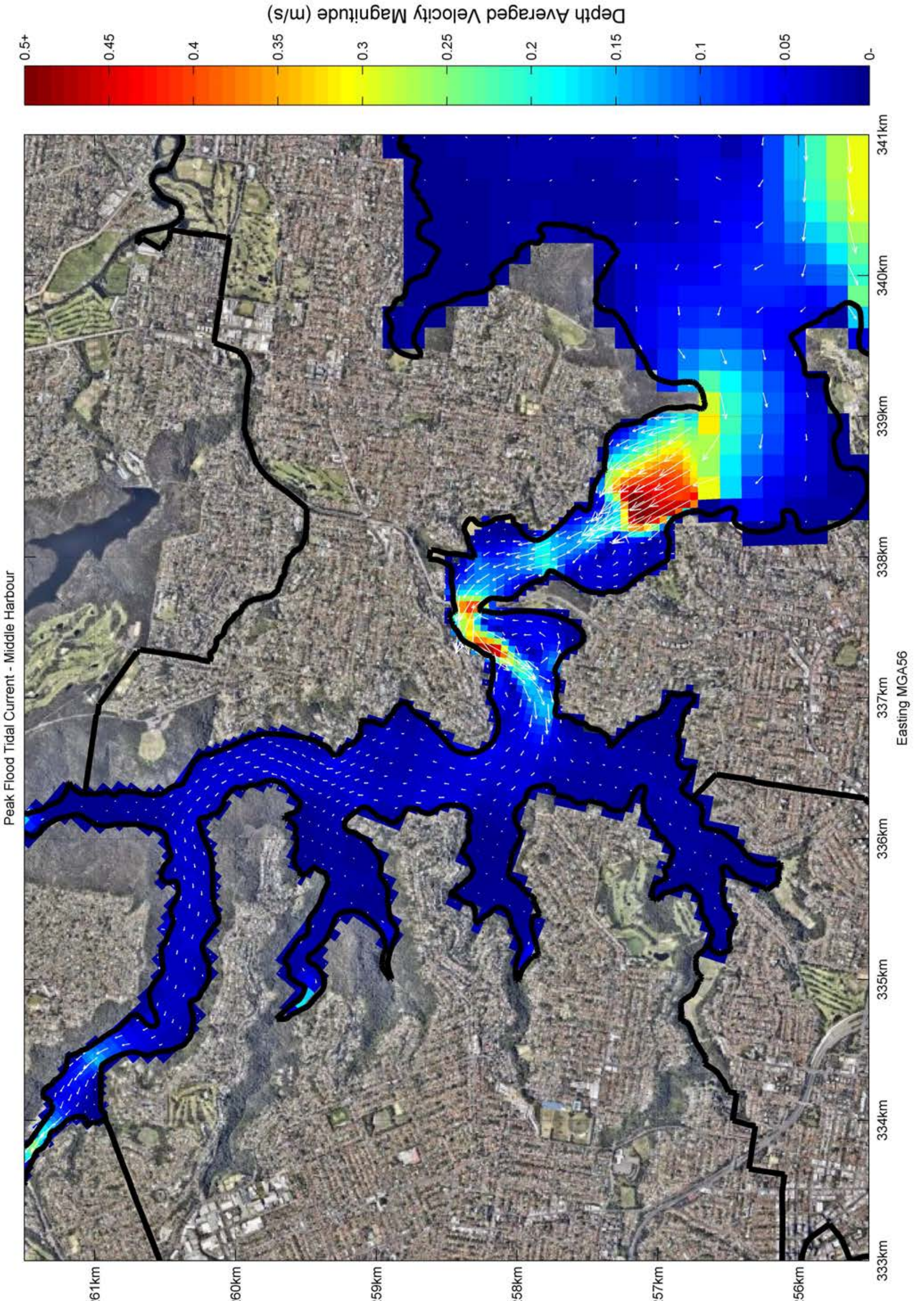
Figure 8.2a



Sydney Harbour Ecological Response Model

Map of Peak Depth Averaged Current
Port Jackson − Spring Ebb

Figure 8.2b



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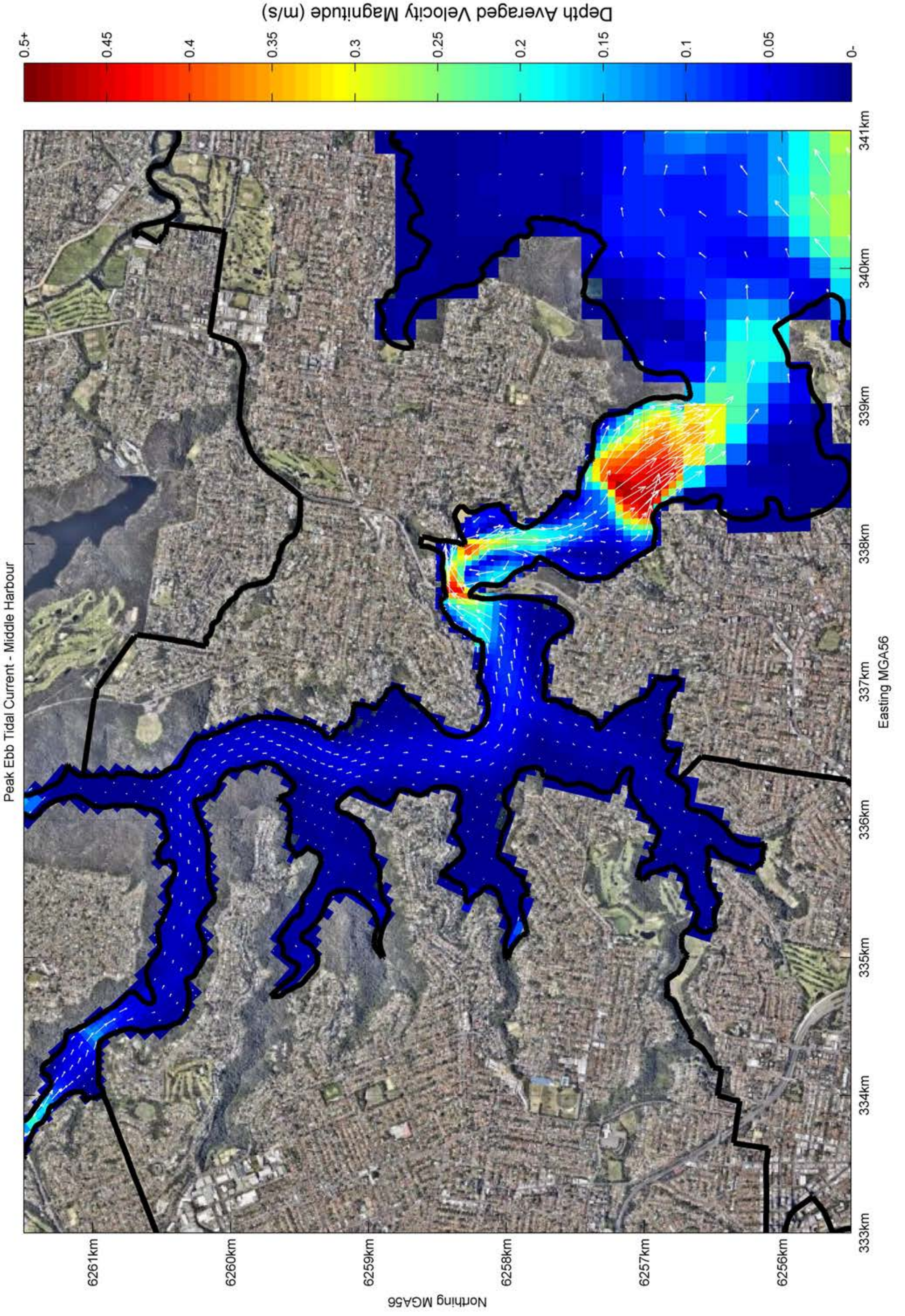
Sydney Harbour Ecological Response Model

Map of Peak Depth Averaged Current
Middle Harbour − Spring Flood

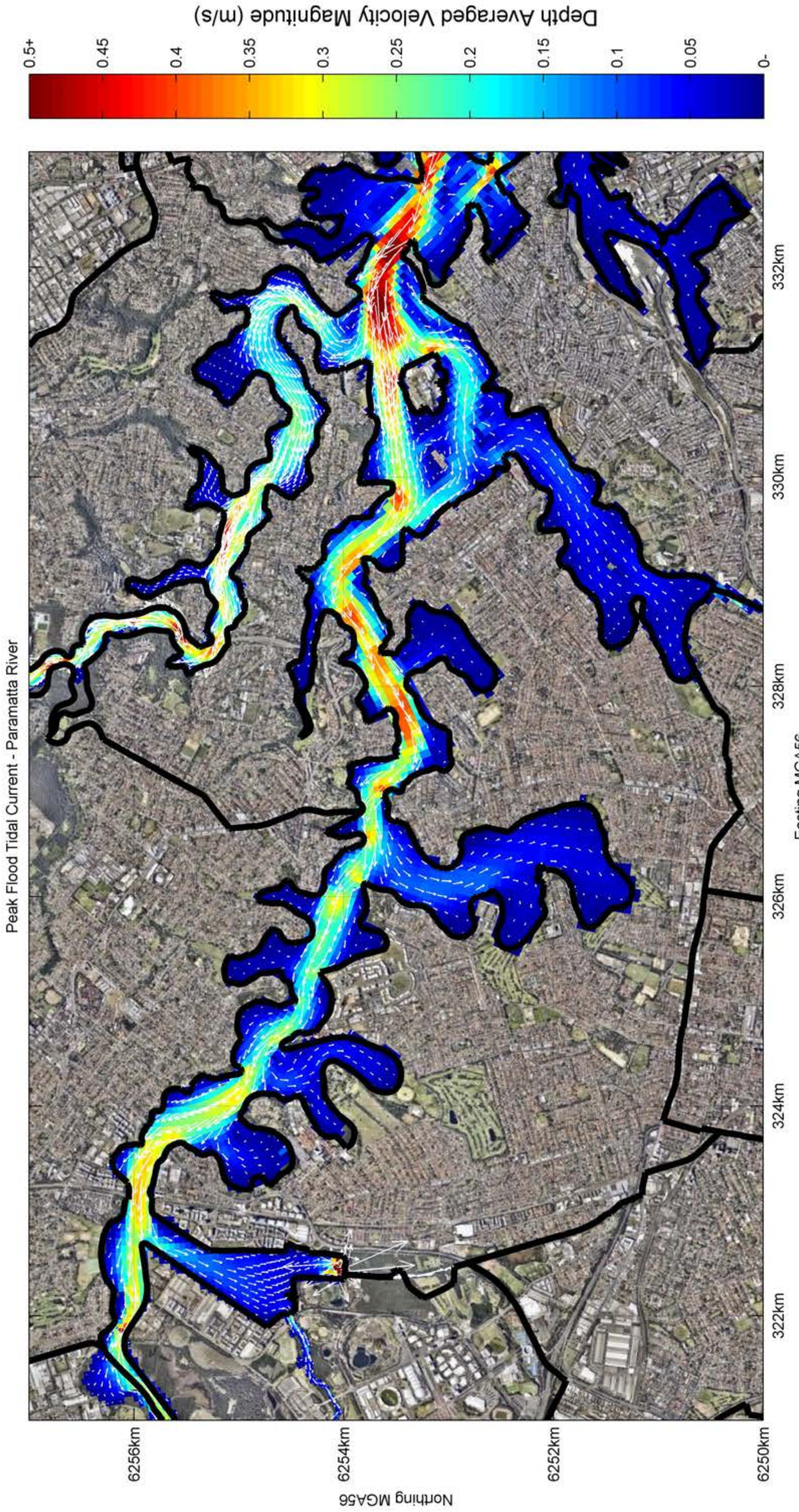
Figure 8.3a



Sydney Harbour Ecological Response Model

Map of Peak Depth Averaged Current
Middle Harbour − Spring Ebb

Figure 8.3b



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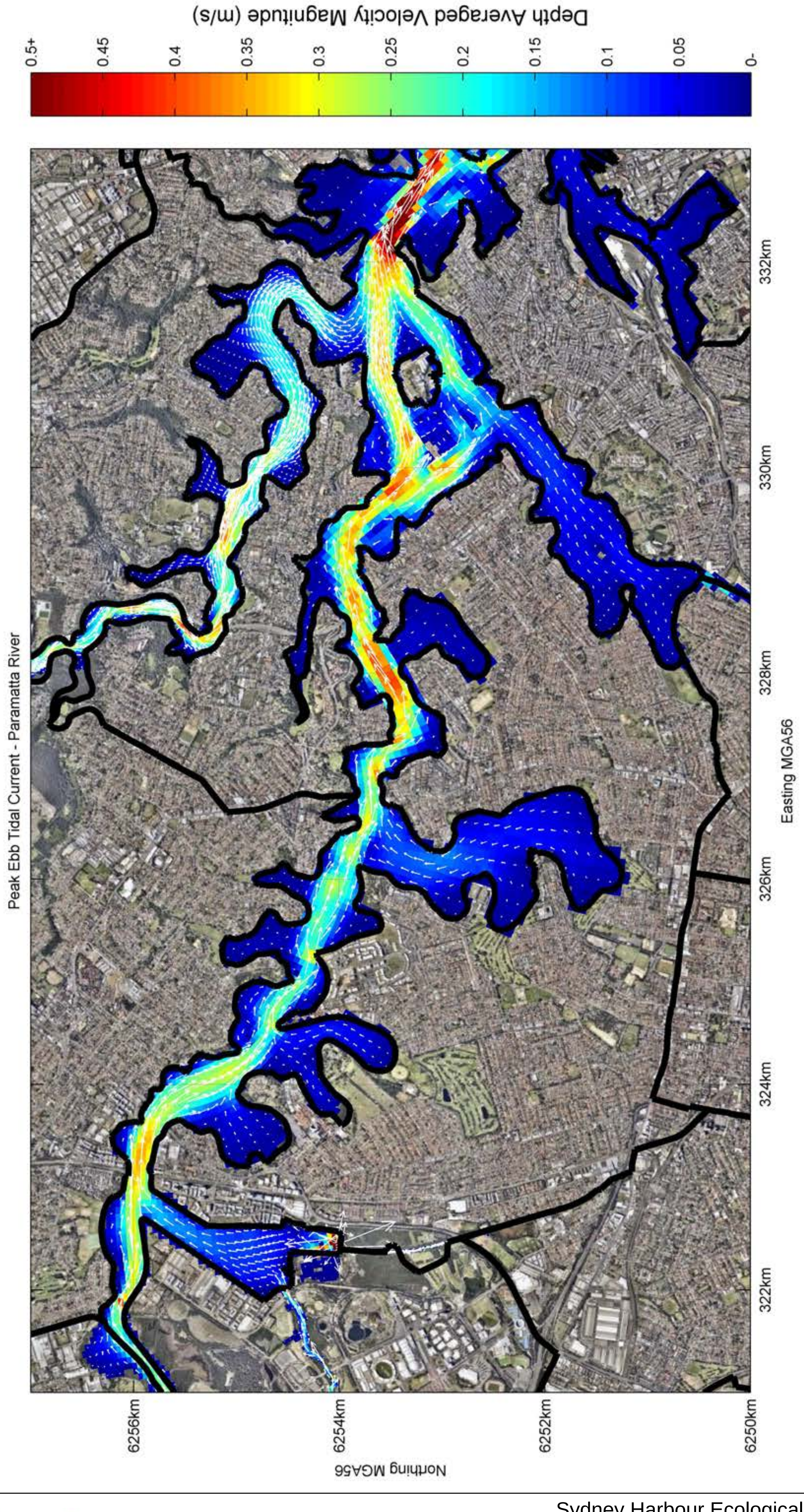
Sydney Harbour Ecological Response Model

Map of Peak Depth Averaged Current
Parramatta River − Spring Flood

Figure 8.4a



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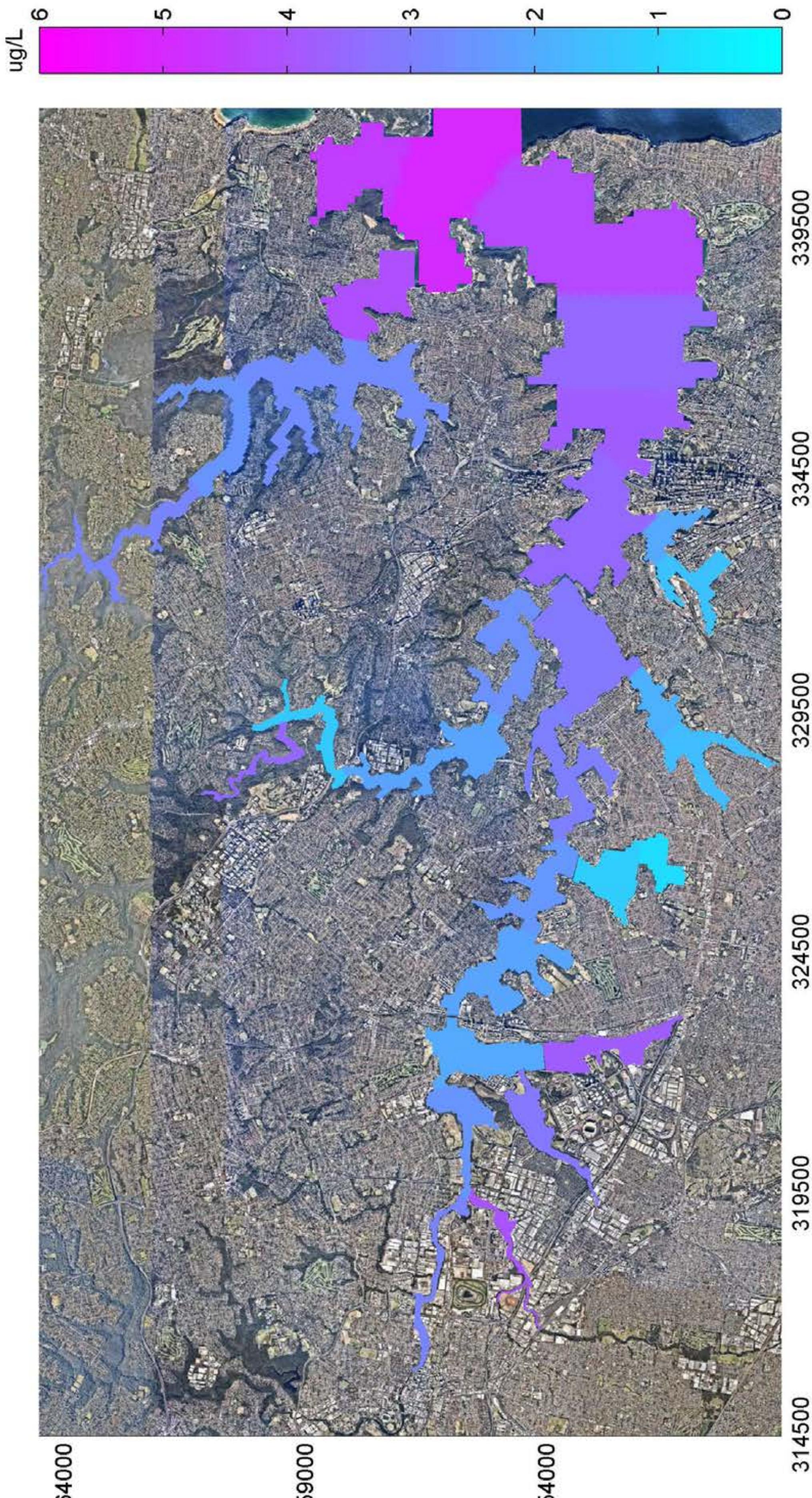
Sydney Harbour Ecological Response Model

Map of Peak Depth Averaged Current
Parramatta River − Spring Ebb

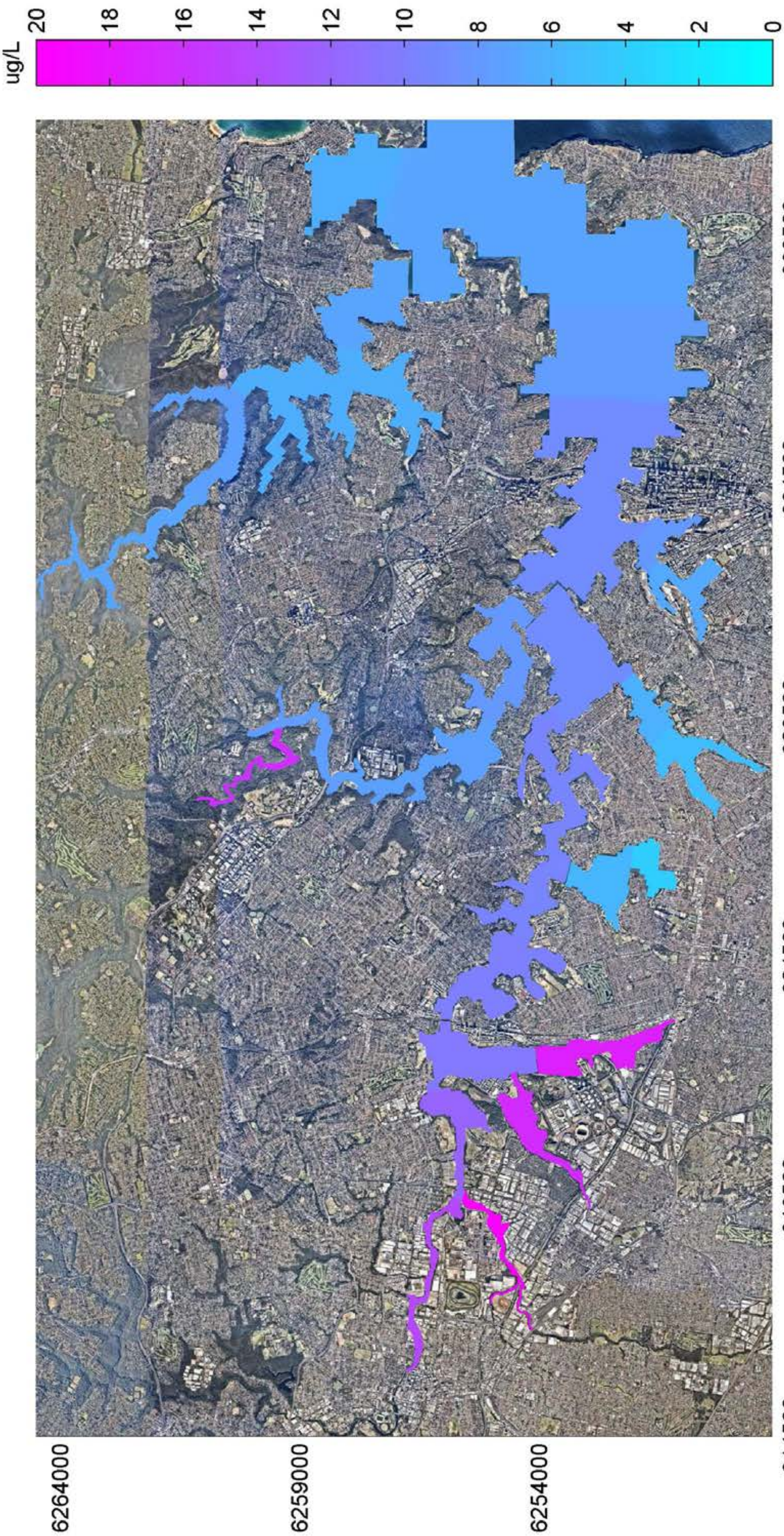
Figure 8.4b



Sydney Harbour Ecological Response Model

Cardno Water Quality 3D Box Model: Surface Layer 50% Chl−a Concentration (ug/L)
BLOOM Model − Average Year (Apr 2012 − Mar 2013)

Figure 9.1a



Sydney Harbour Ecological Response Model

Cardno Water Quality 3D Box Model: Surface Layer 90% Chl−a Concentration (ug/L)
BLOOM Model − Average Year (Apr 2012 − Mar 2013)

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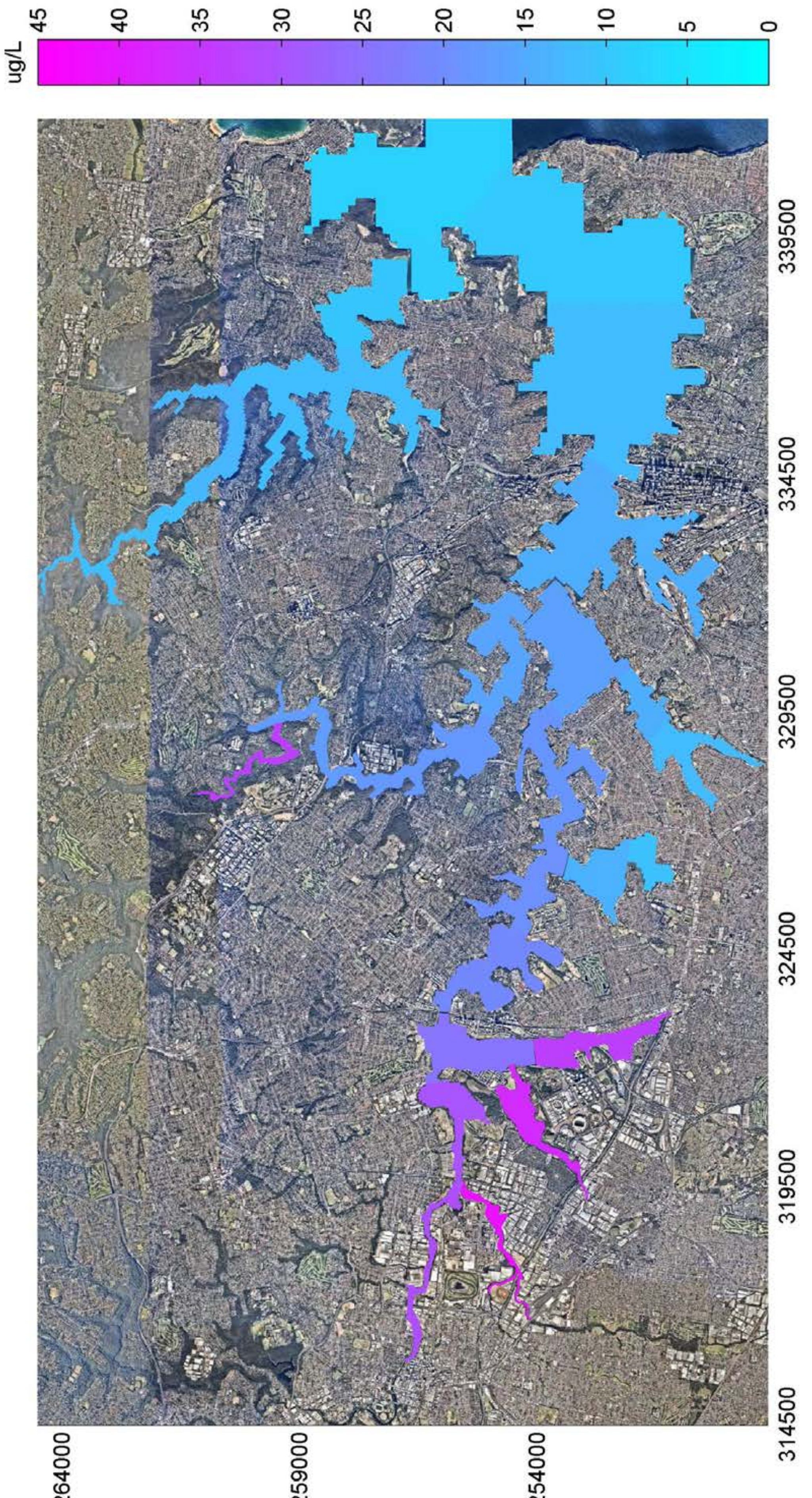
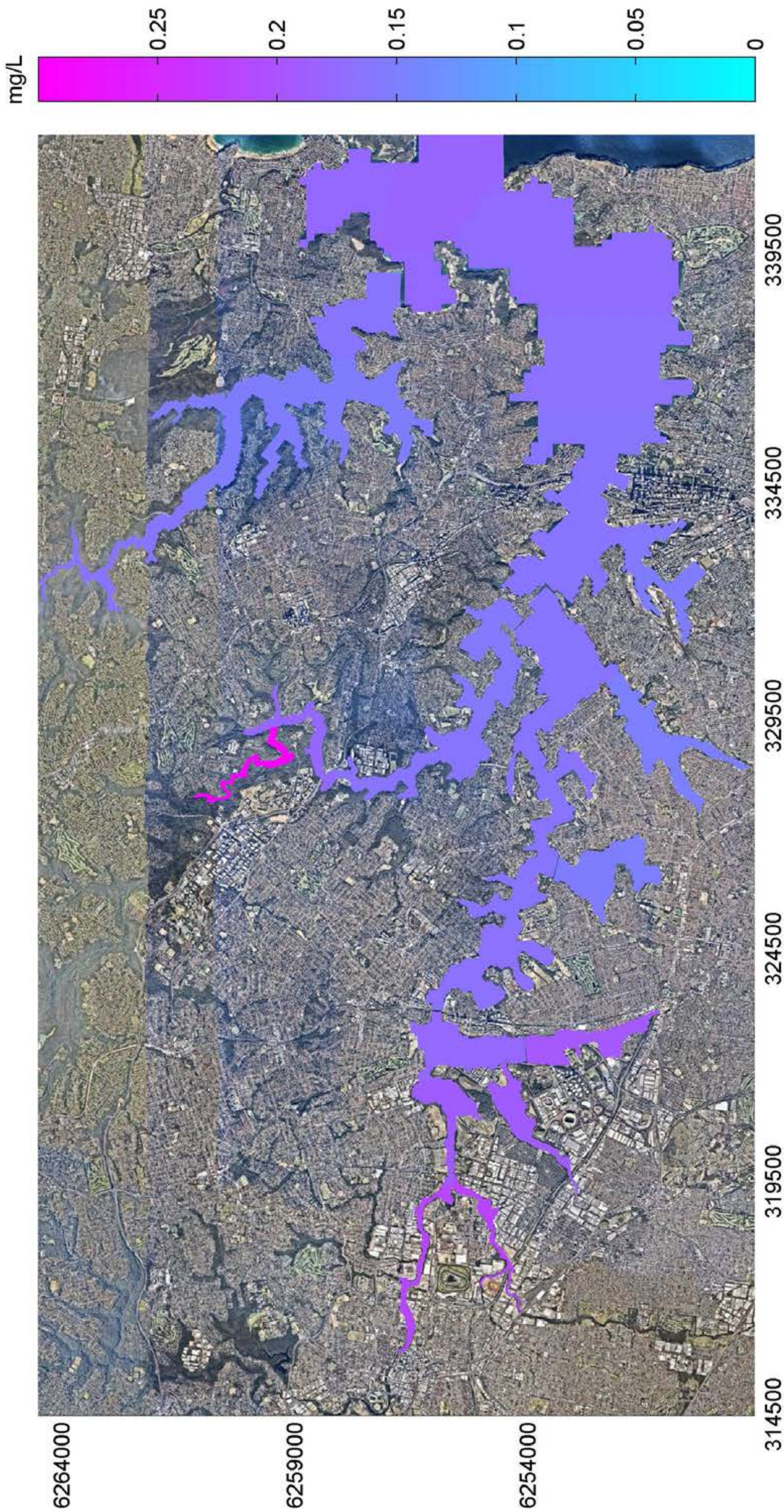
Figure 9.1b



Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 99% Chl−a Concentration (ug/L)
BLOOM Model − Average Year (Apr 2012 − Mar 2013)

Figure 9.1c



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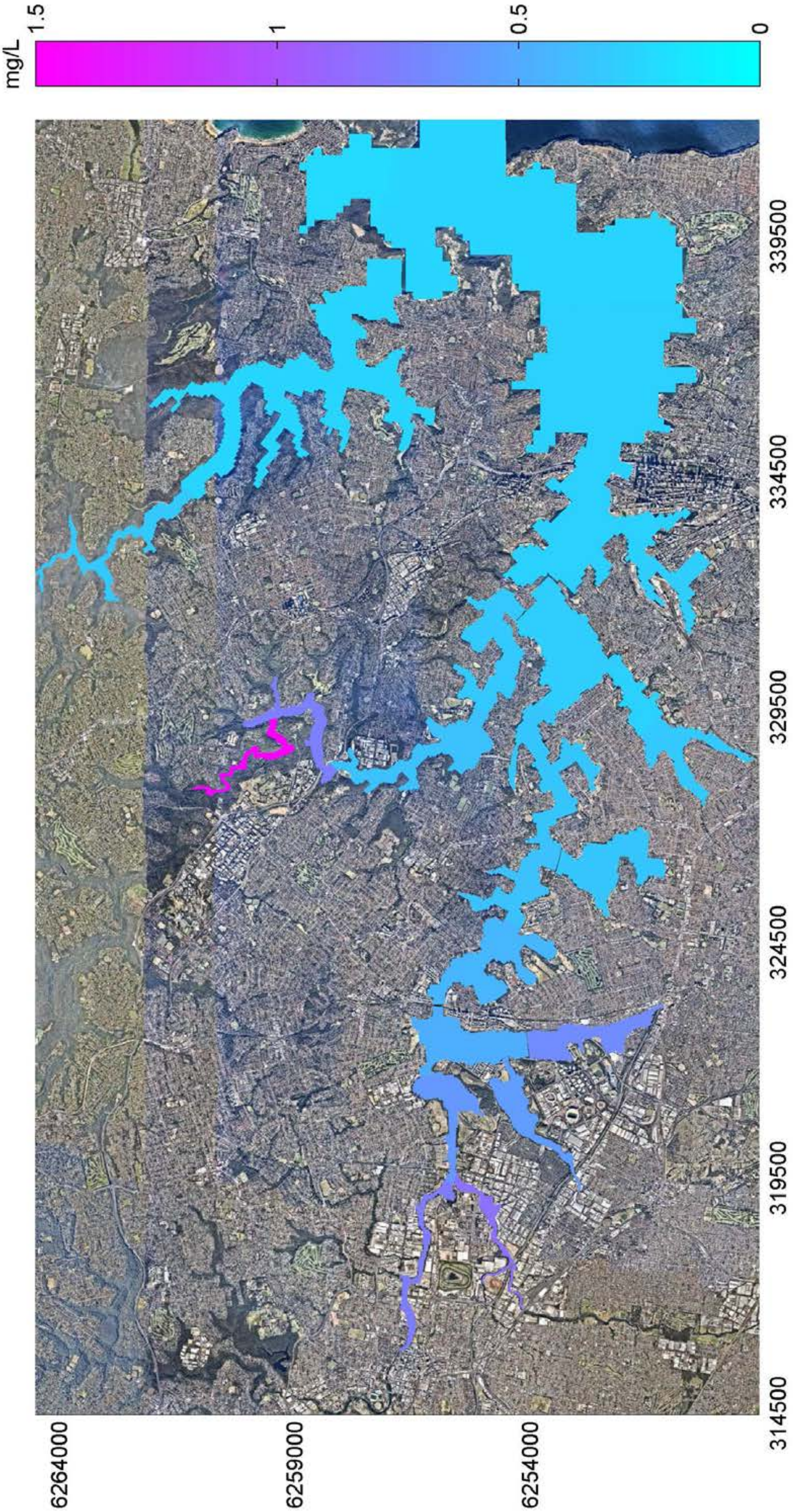
Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 50% Total Nitrogen (mg/L)
BLOOM Model − Average Year (Apr 2012 − Mar 2013)

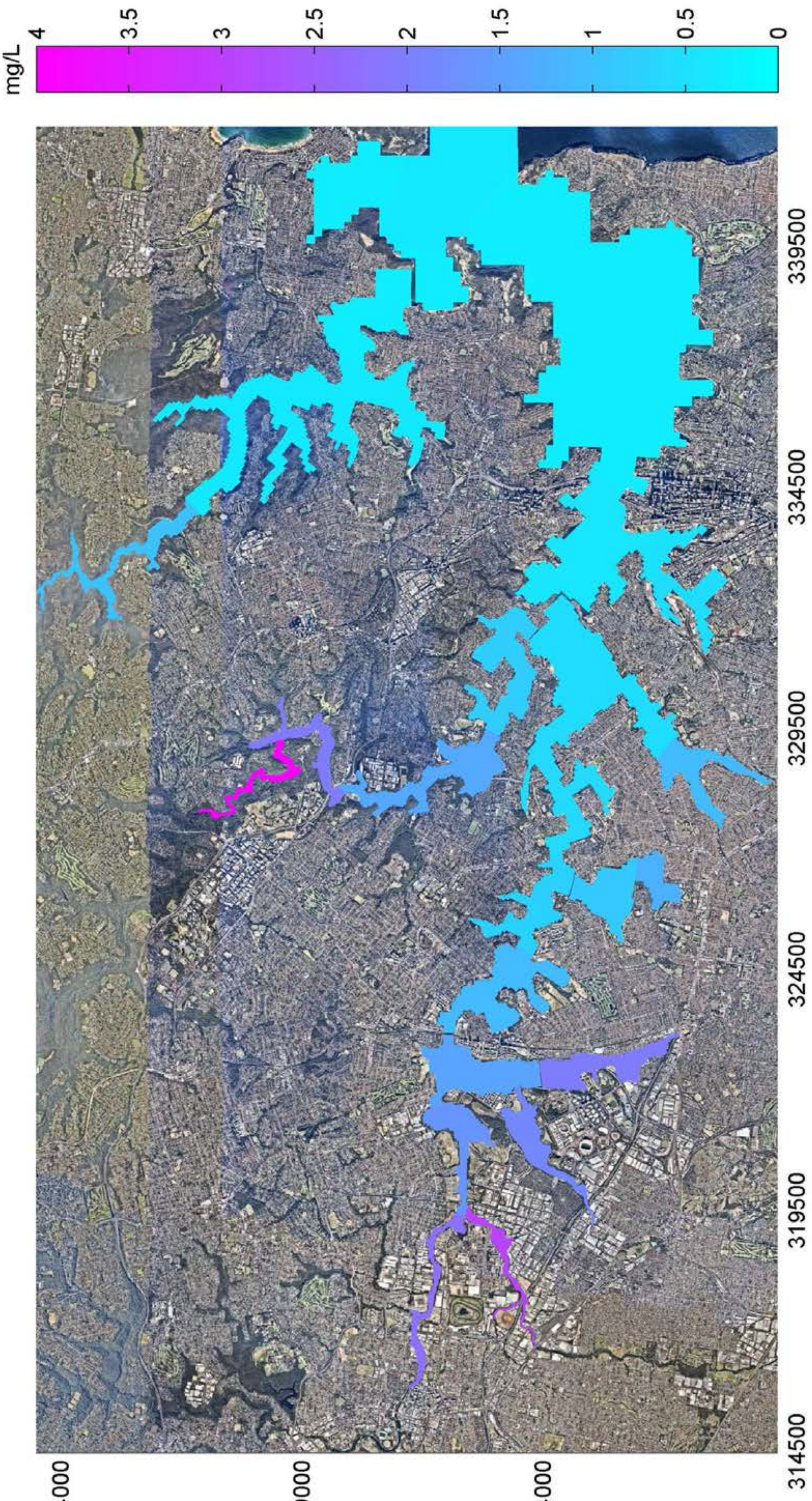
Figure 9.2a



Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 90% Total Nitrogen (mg/L)
BLOOM Model − Average Year (Apr 2012 − Mar 2013)

Figure 9.2b



Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 99% Total Nitrogen (mg/L)
BLOOM Model − Average Year (Apr 2012 − Mar 2013)

Figure 9.2c

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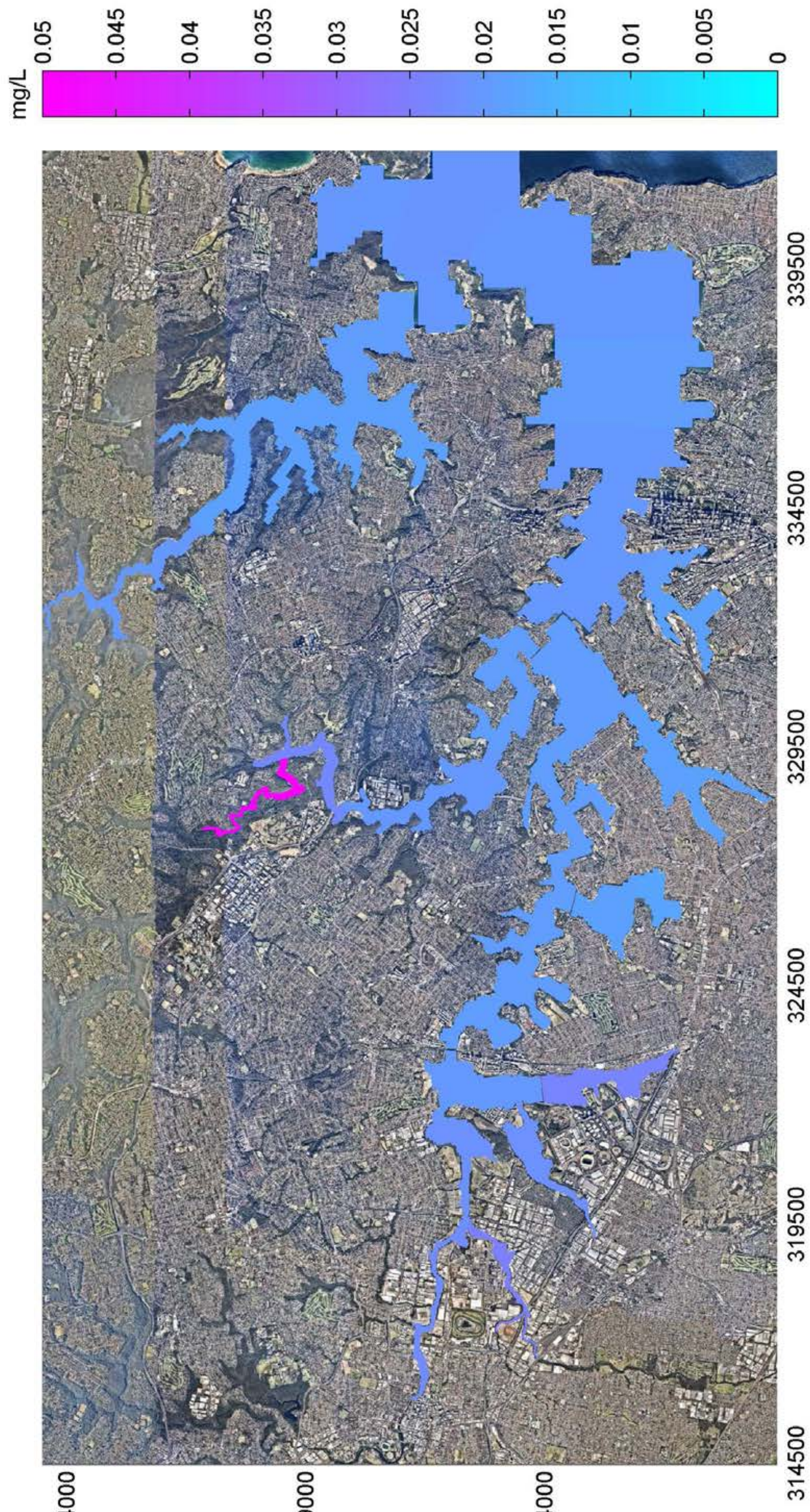

Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 50% Total Phosphorus (mg/L)
BLOOM Model − Average Year (Apr 2012 − Mar 2013)

Figure 9.3a

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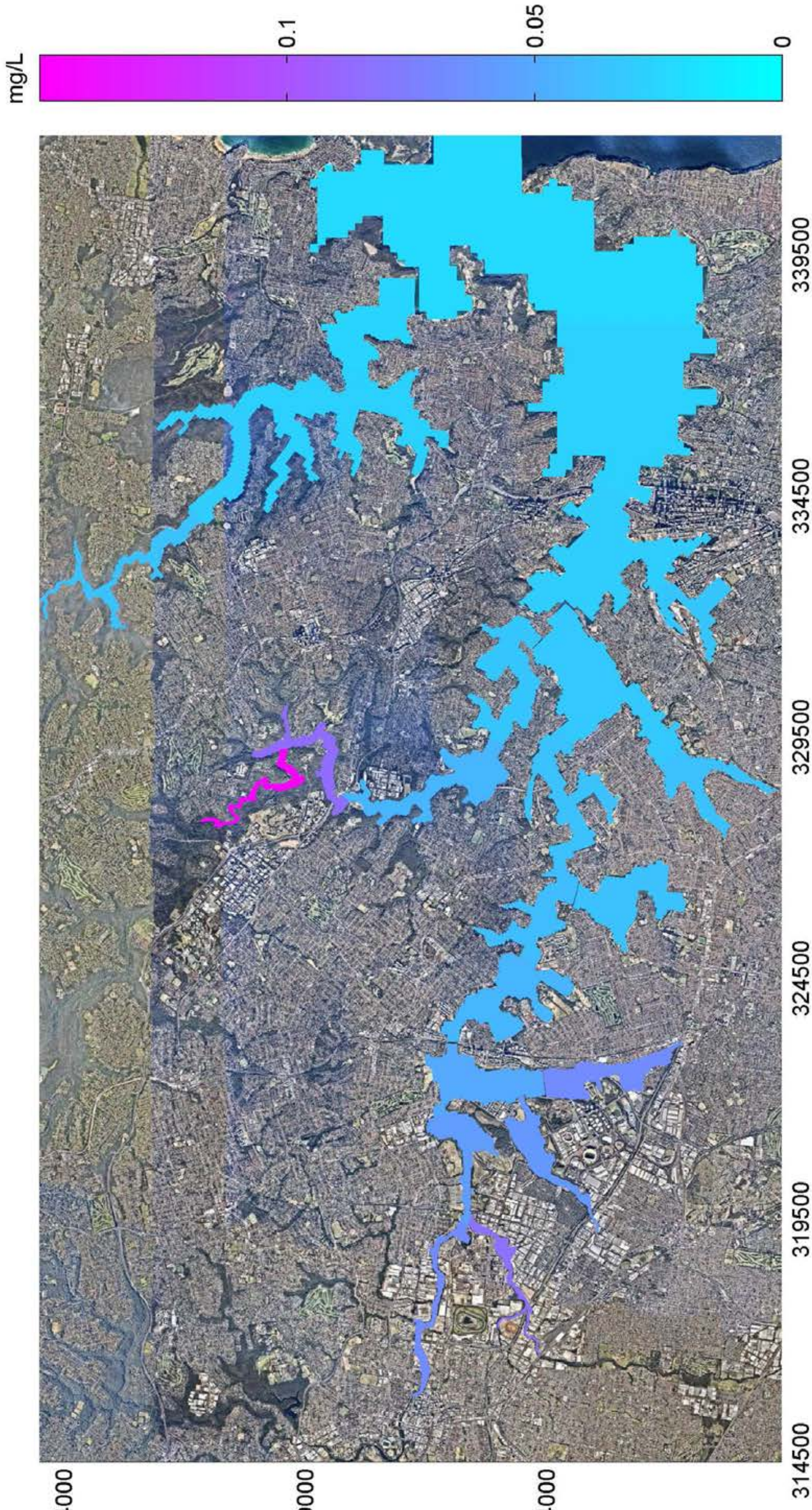
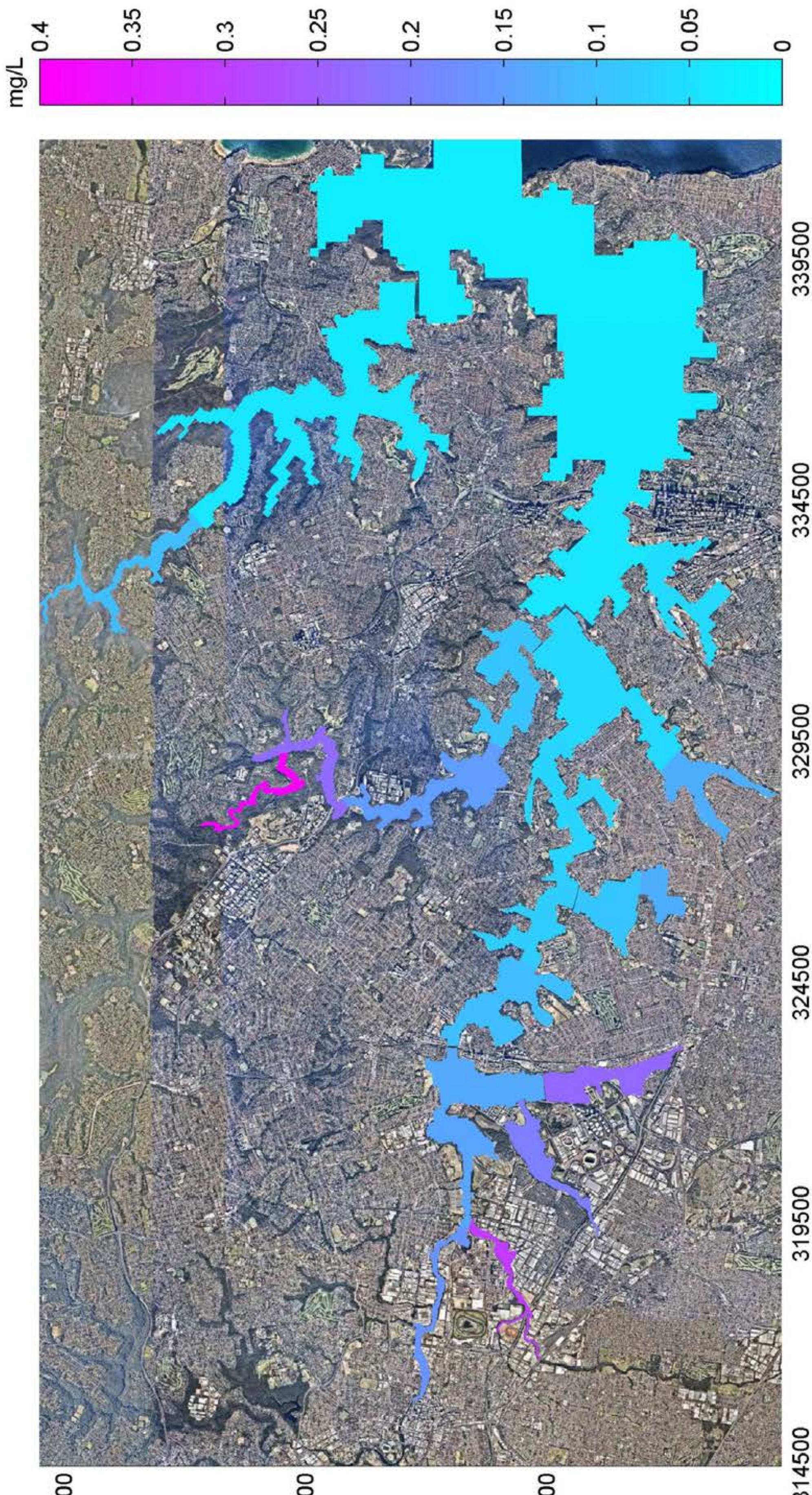


Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 90% Total Phosphorus (mg/L)
BLOOM Model − Average Year (Apr 2012 − Mar 2013)

Figure 9.3b



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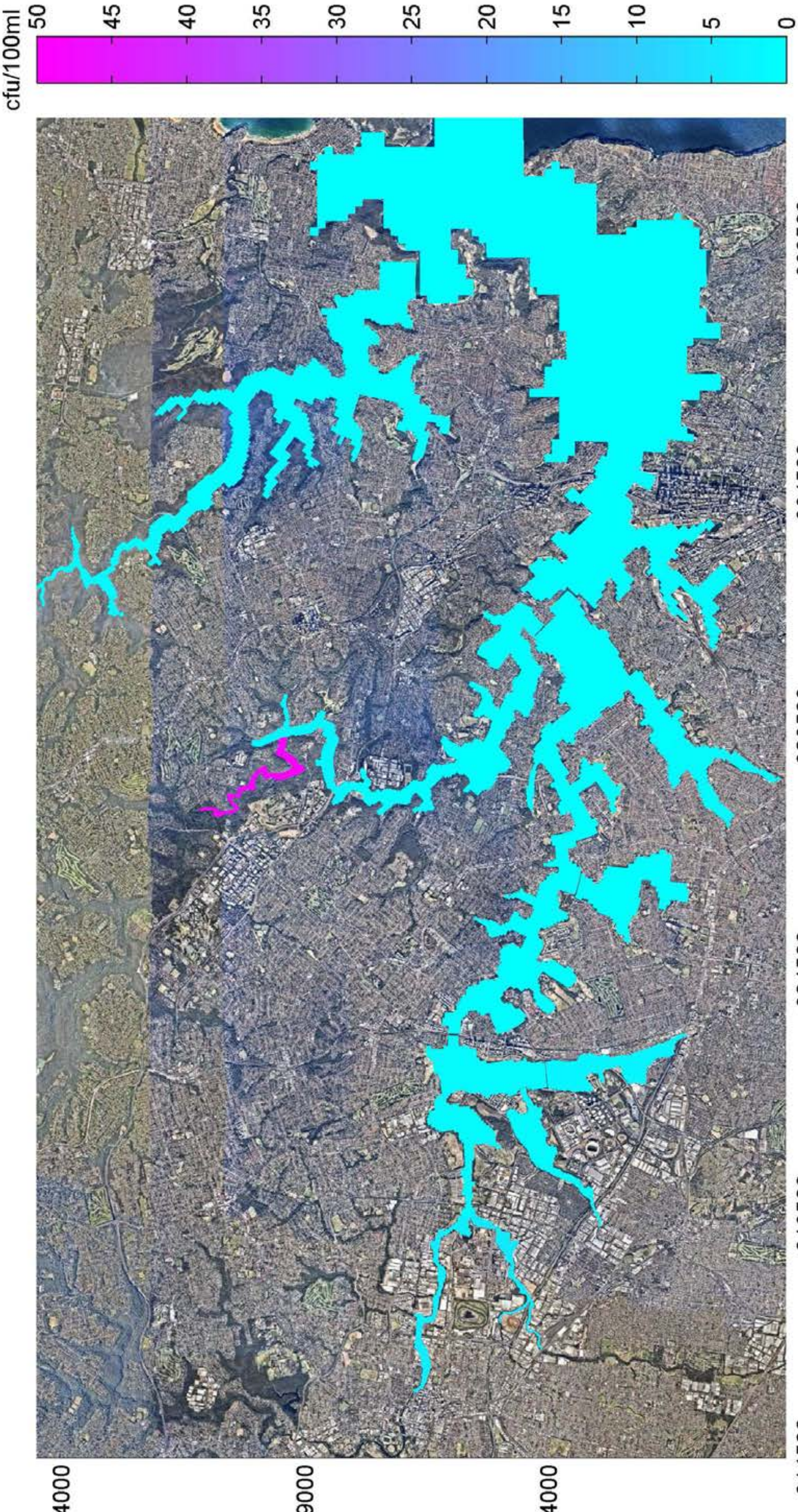
Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 99% Total Phosphorus (mg/L)
BLOOM Model − Average Year (Apr 2012 − Mar 2013)

Figure 9.3c



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Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 50% Enterococci (cfu/100ml)
BLOOM Model − Average Year (Apr 2012 − Mar 2013)

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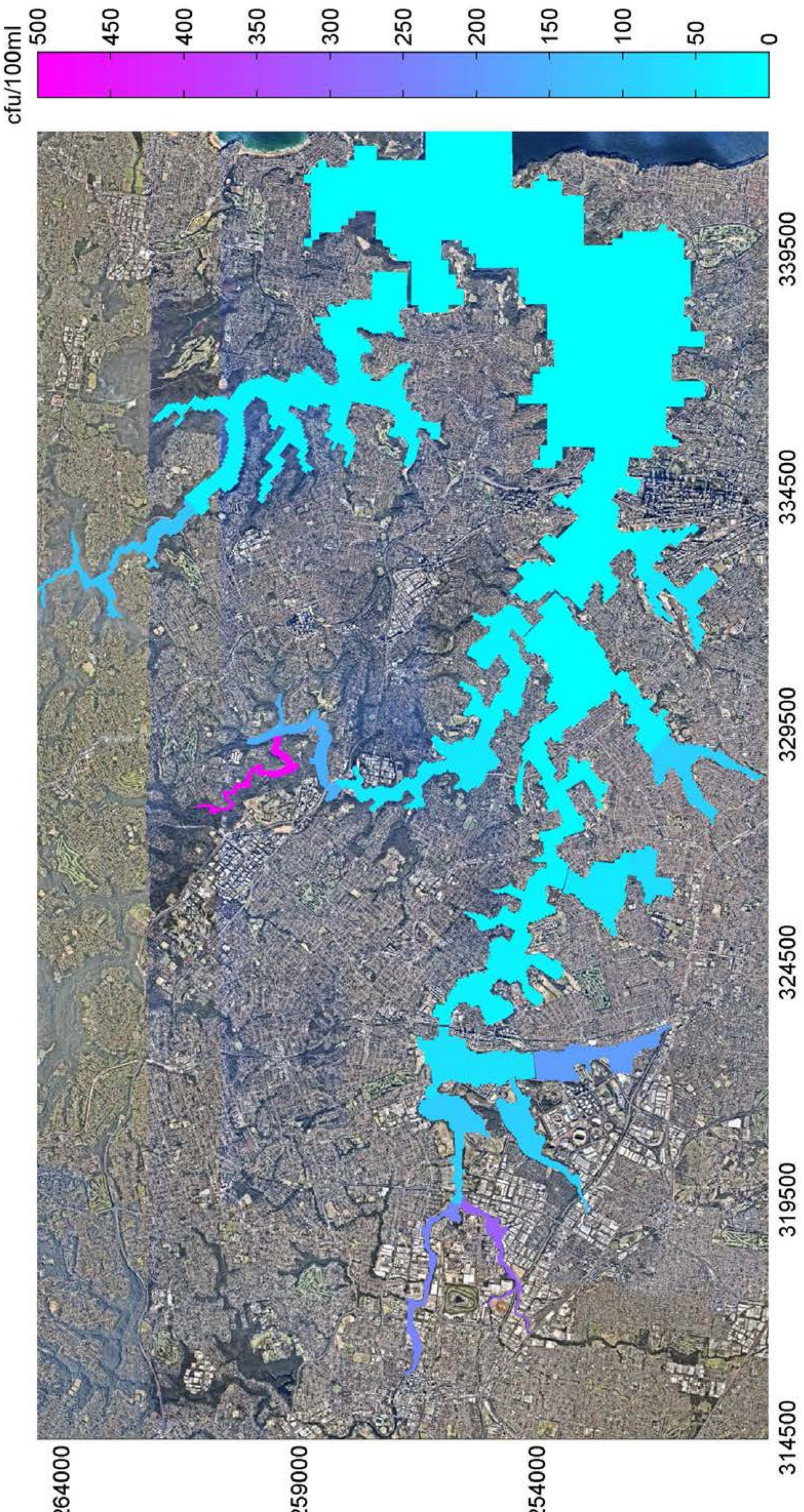
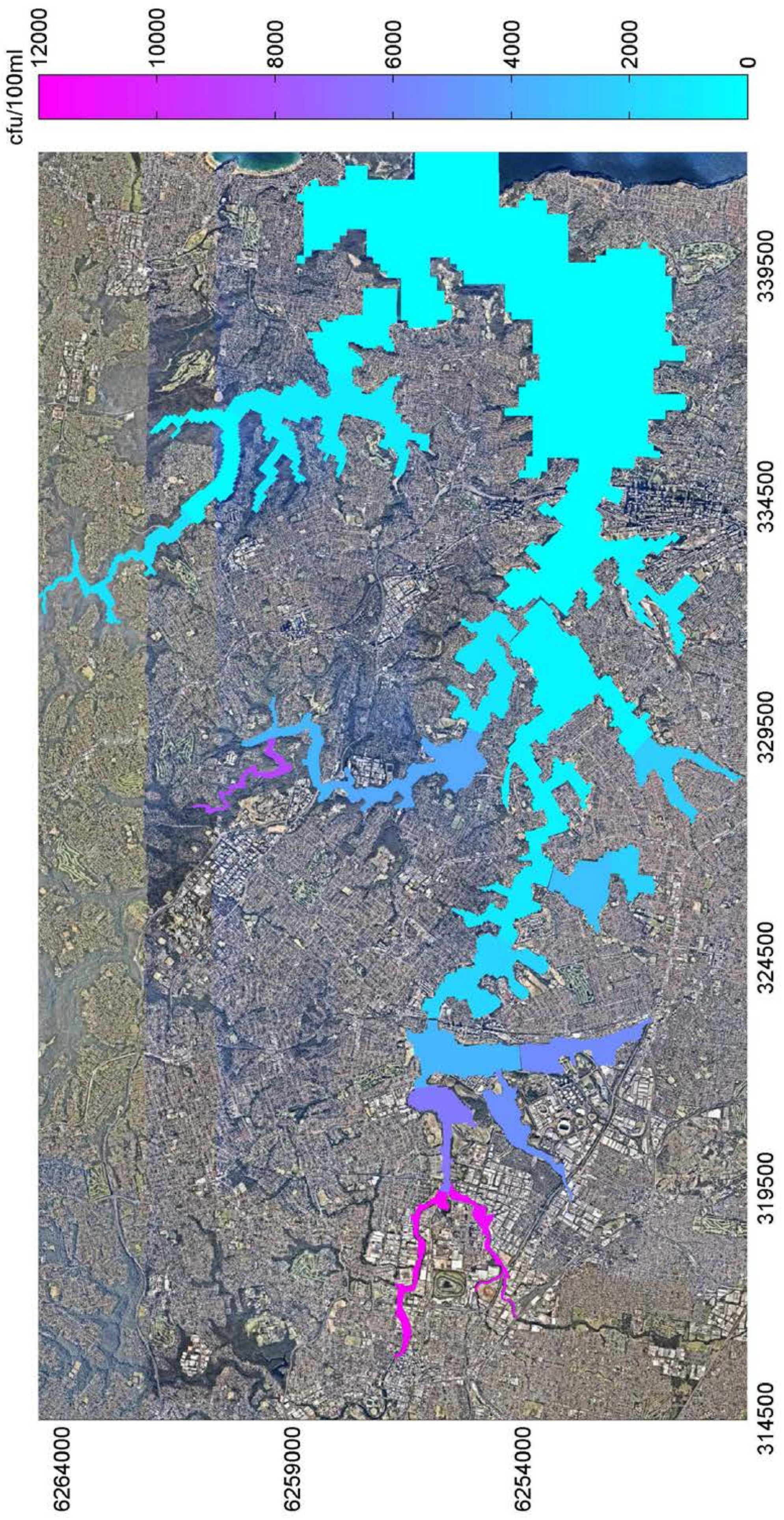
Figure 9.4a



Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 90% Enterococci (cfu/100ml)
BLOOM Model − Average Year (Apr 2012 − Mar 2013)

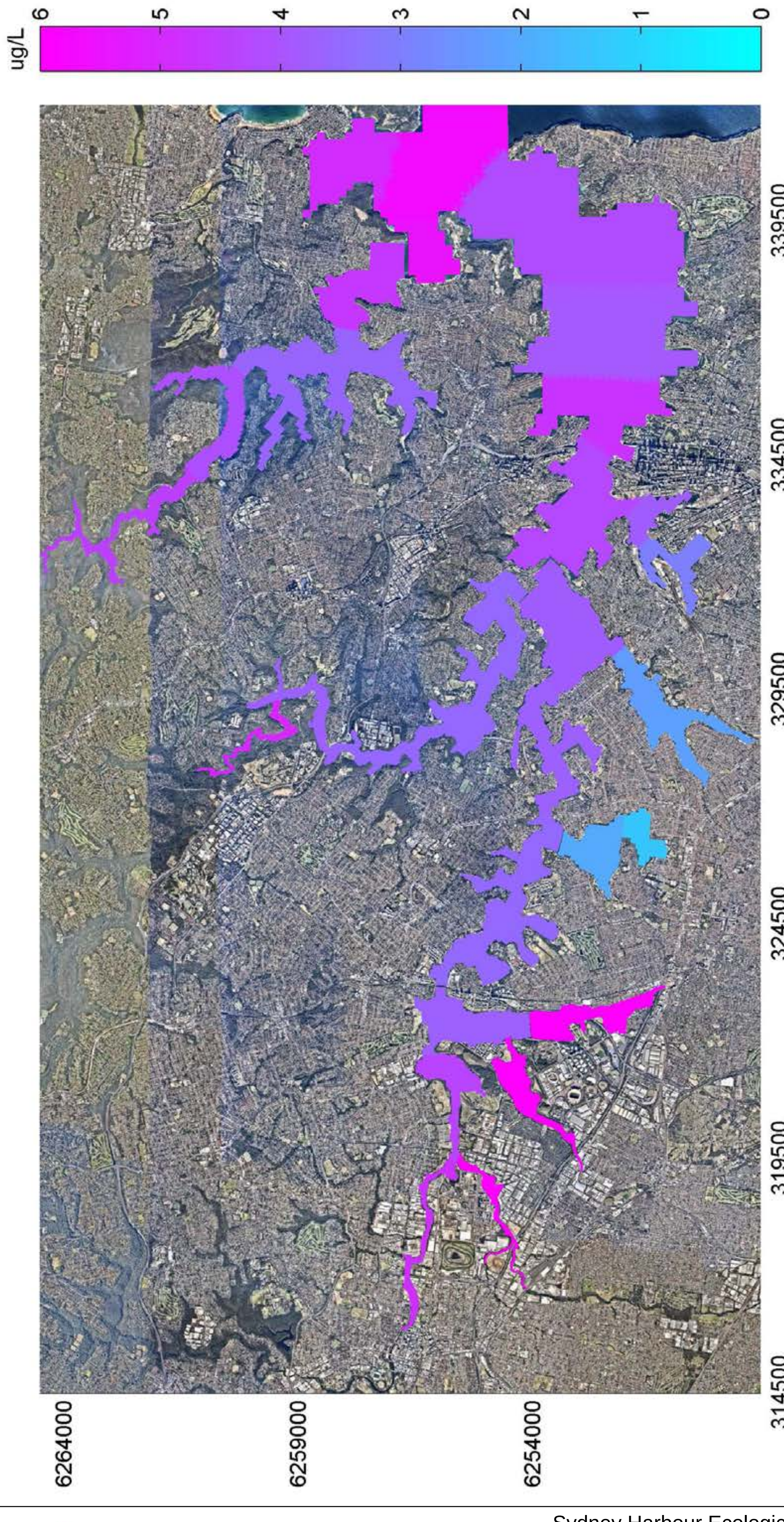
Figure 9.4b



Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 99% Enterococci (cfu/100ml)
BLOOM Model − Average Year (Apr 2012 − Mar 2013)

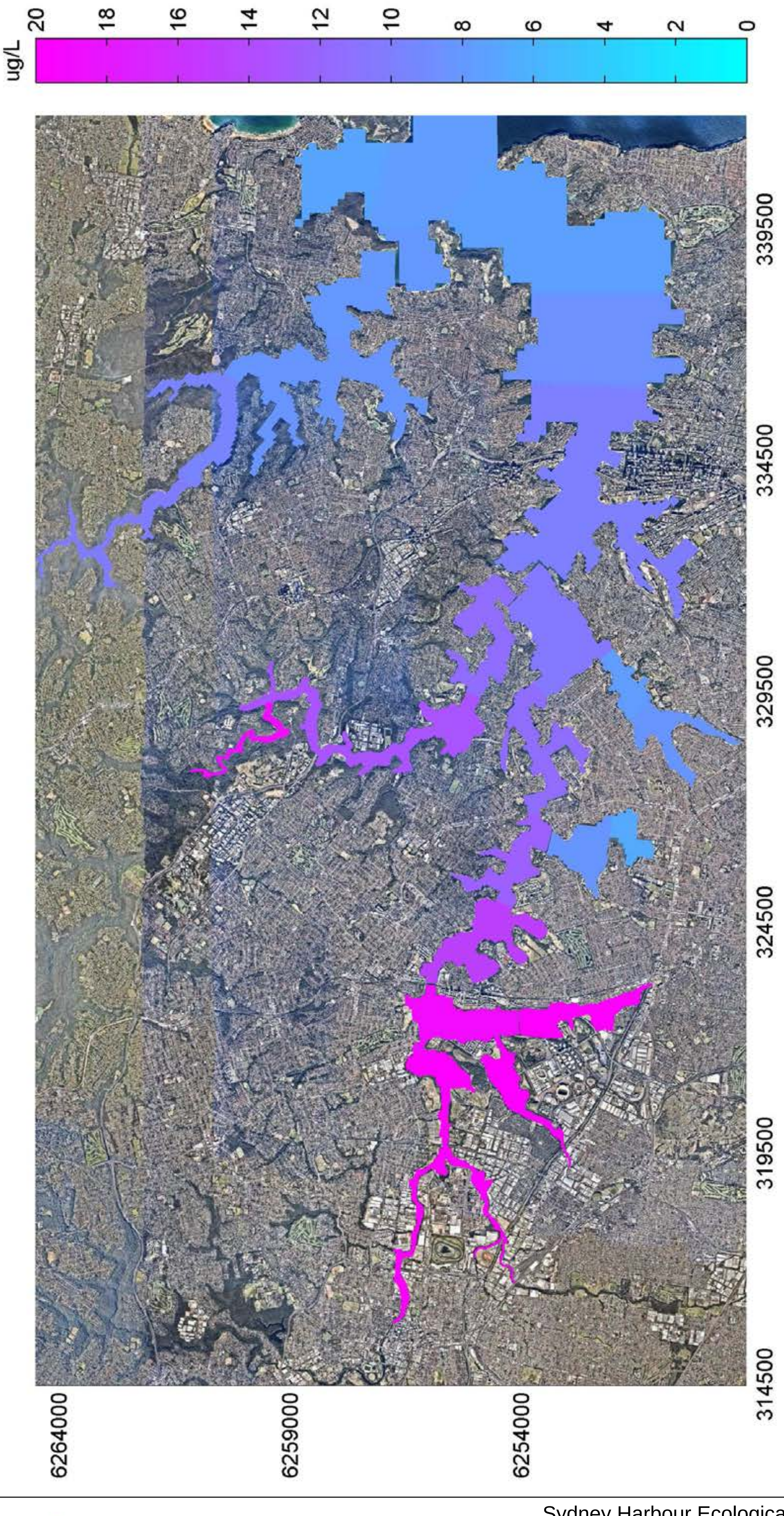
Figure 9.4c



Sydney Harbour Ecological Response Model

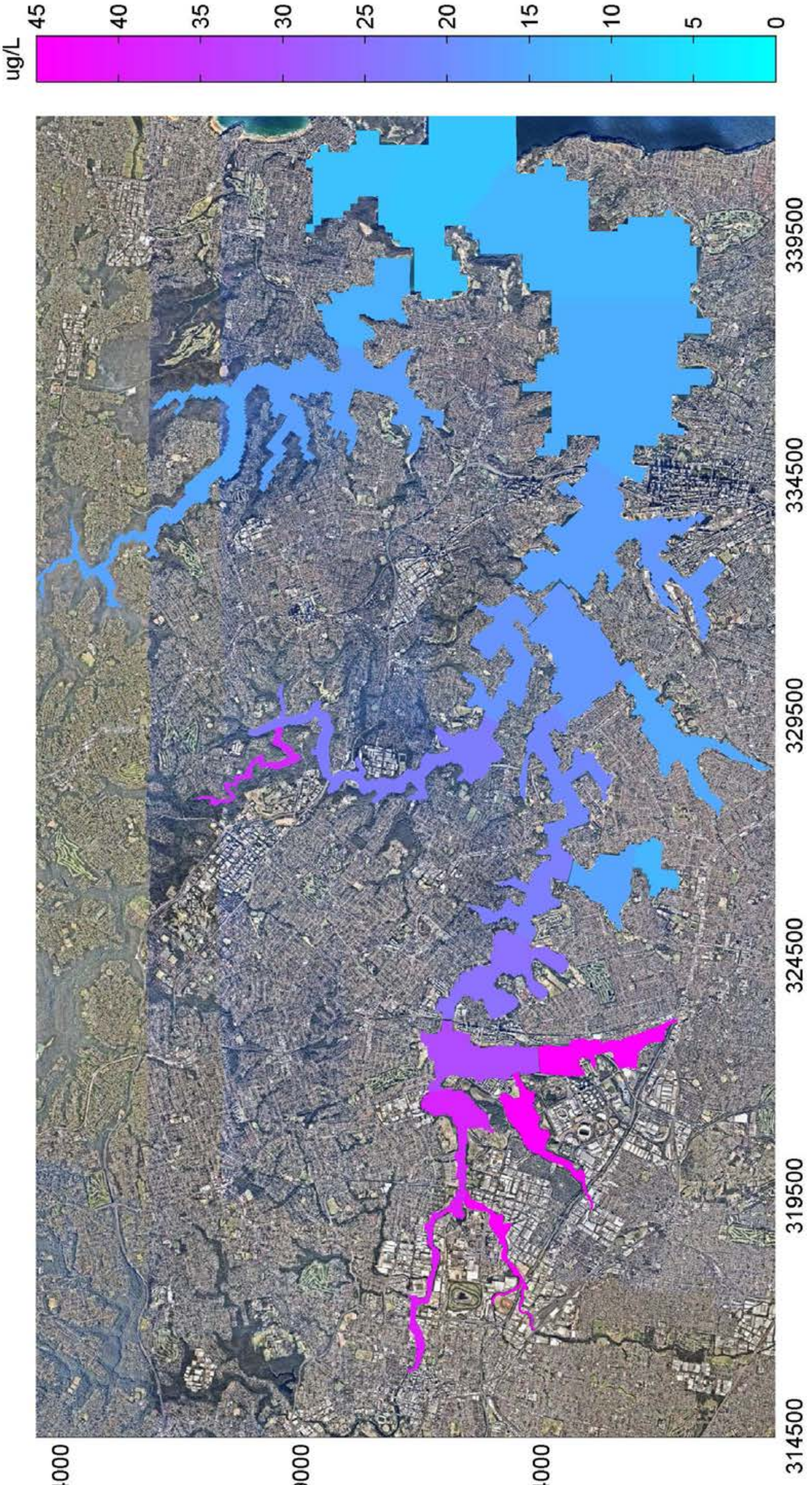
Water Quality 3D Box Model: Surface Layer 50% Chl−a Concentration (ug/L)
BLOOM Model − Wet Year (Apr 2011 − Mar 2012)

Figure 9.5a



Sydney Harbour Ecological Response Model
Water Quality 3D Box Model: Surface Layer 90% Chl−a Concentration (ug/L)
BLOOM Model − Wet Year (Apr 2011 − Mar 2012)

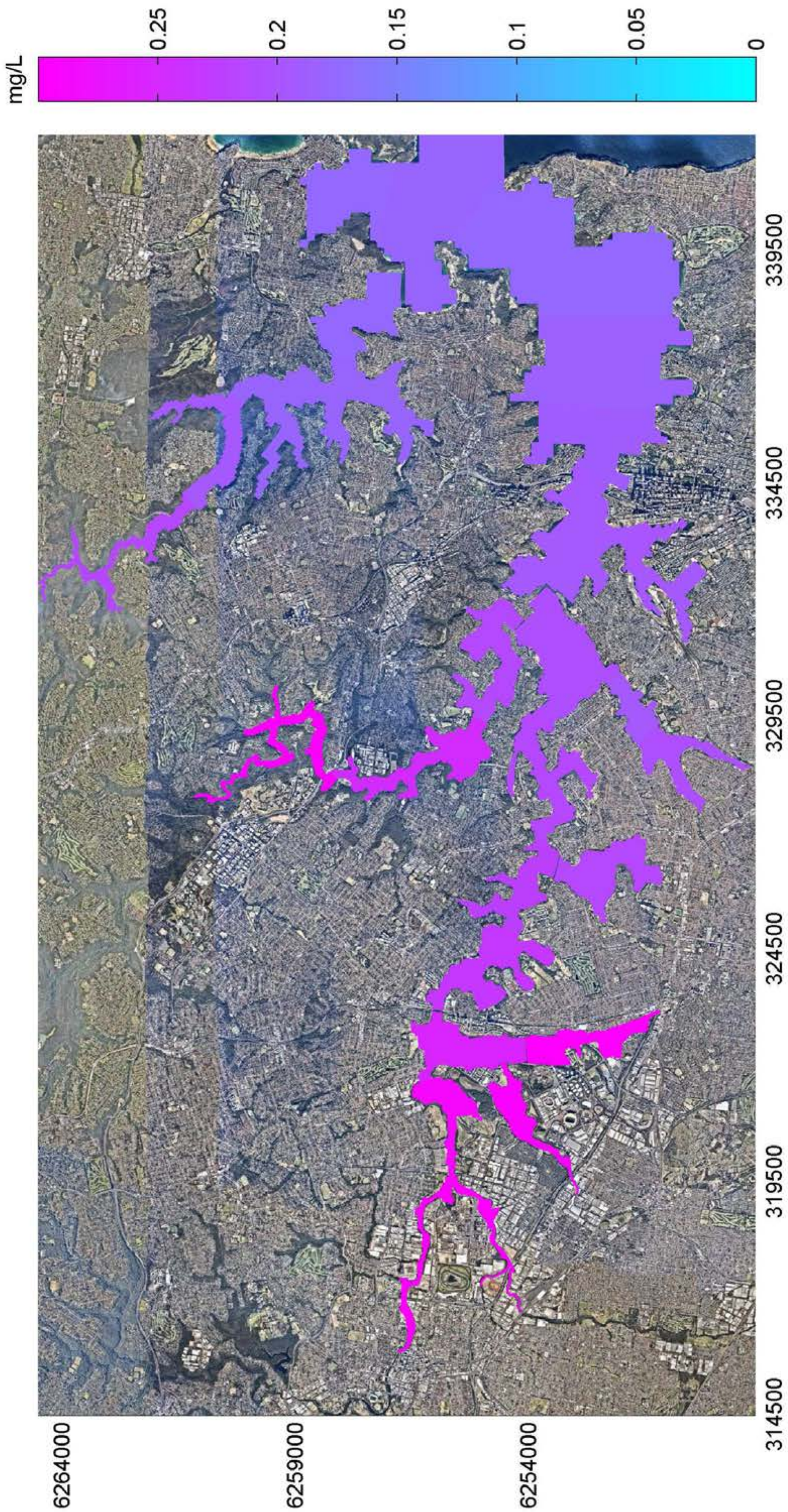
Figure 9.5b



Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 99% Chl−a Concentration (ug/L)
BLOOM Model − Wet Year (Apr 2011 − Mar 2012)

Figure 9.5c



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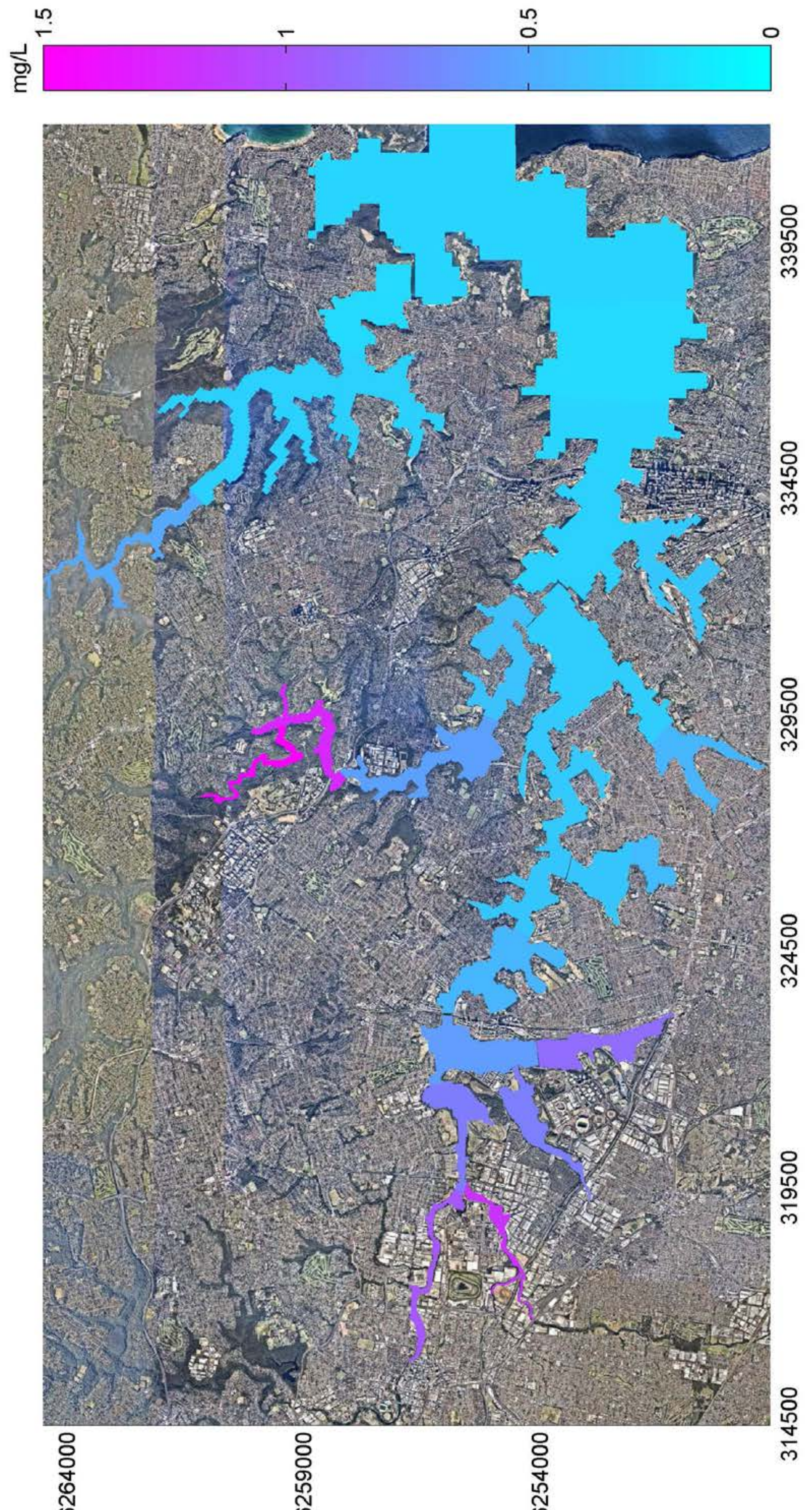
Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 50% Total Nitrogen (mg/L)
BLOOM Model − Wet Year (Apr 2011 − Mar 2012)

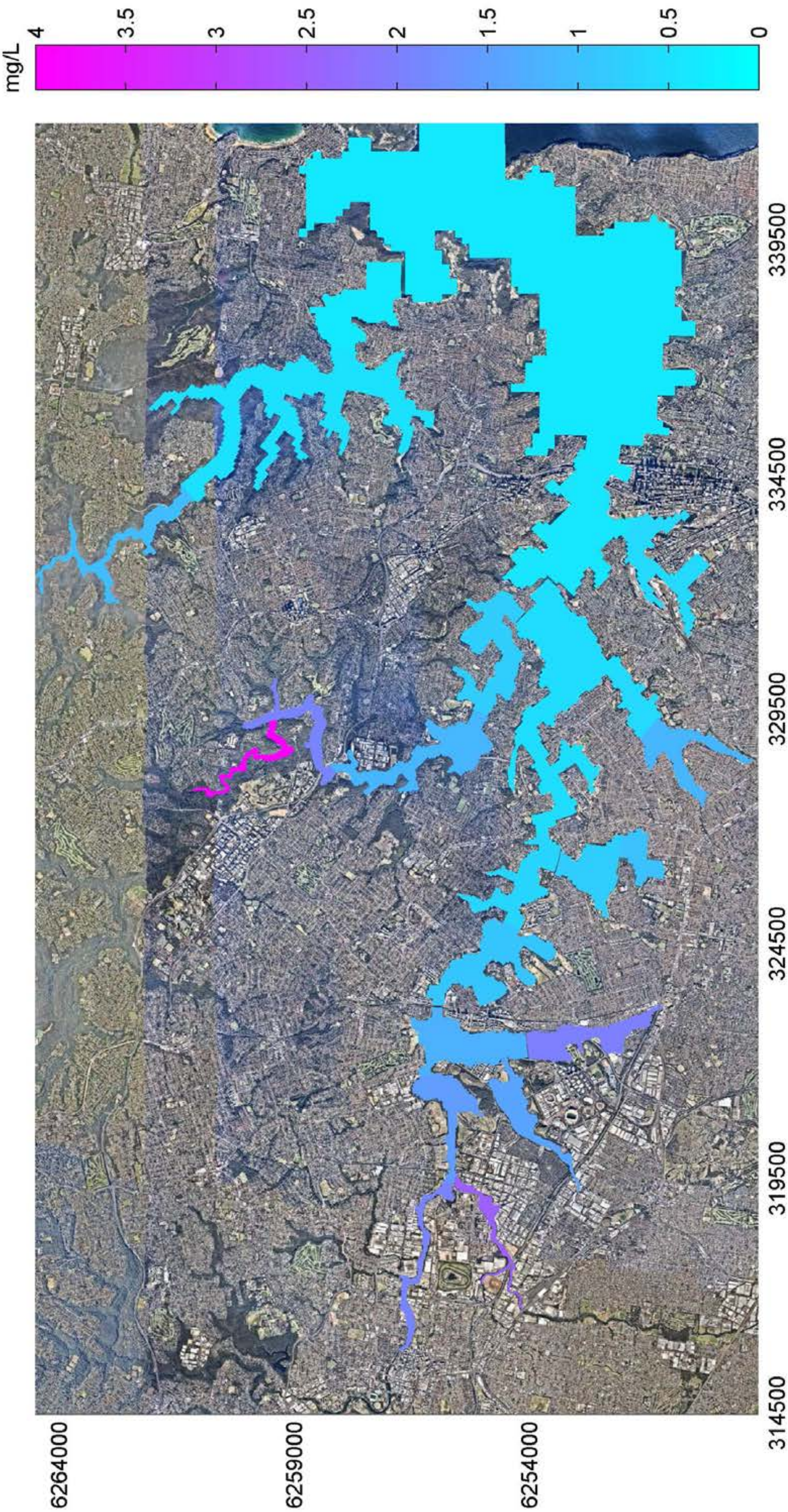
Figure 9.6a



Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 90% Total Nitrogen (mg/L)
BLOOM Model − Wet Year (Apr 2011 − Mar 2012)

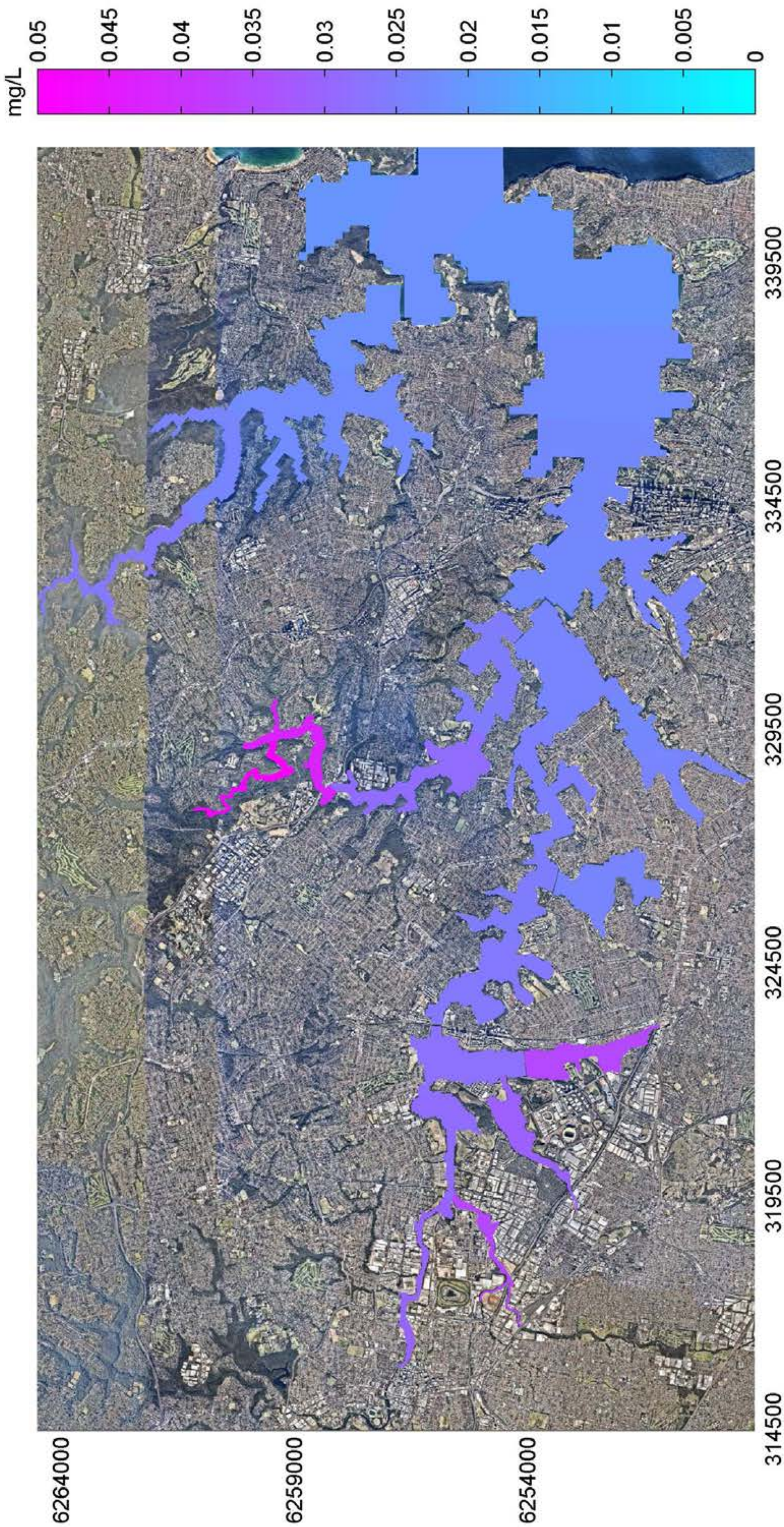
Figure 9.6b



Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 99% Total Nitrogen (mg/L)
BLOOM Model − Wet Year (Apr 2011 − Mar 2012)

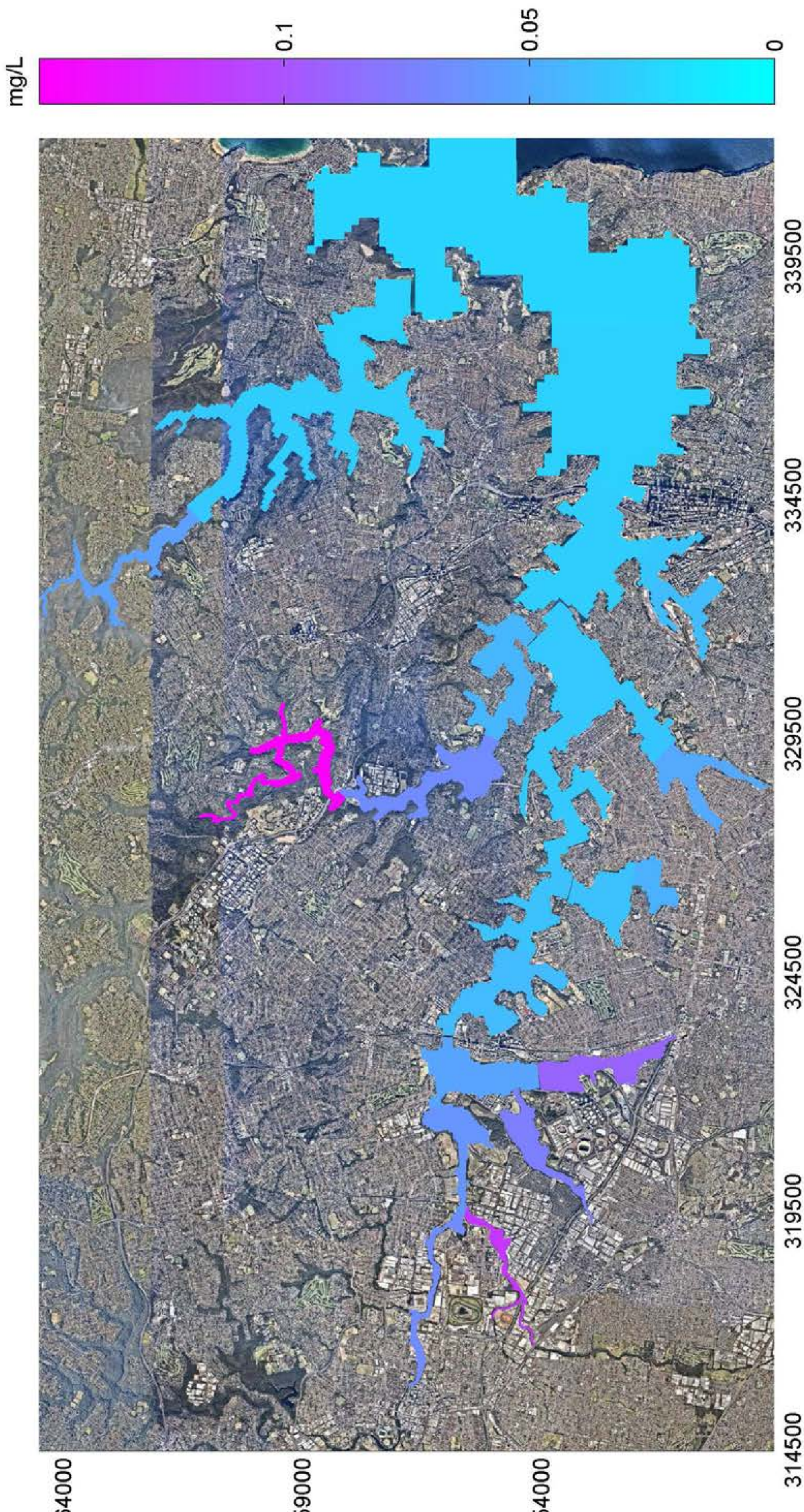
Figure 9.6c



Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 50% Total Phosphorus (mg/L)
BLOOM Model − Wet Year (Apr 2011 − Mar 2012)

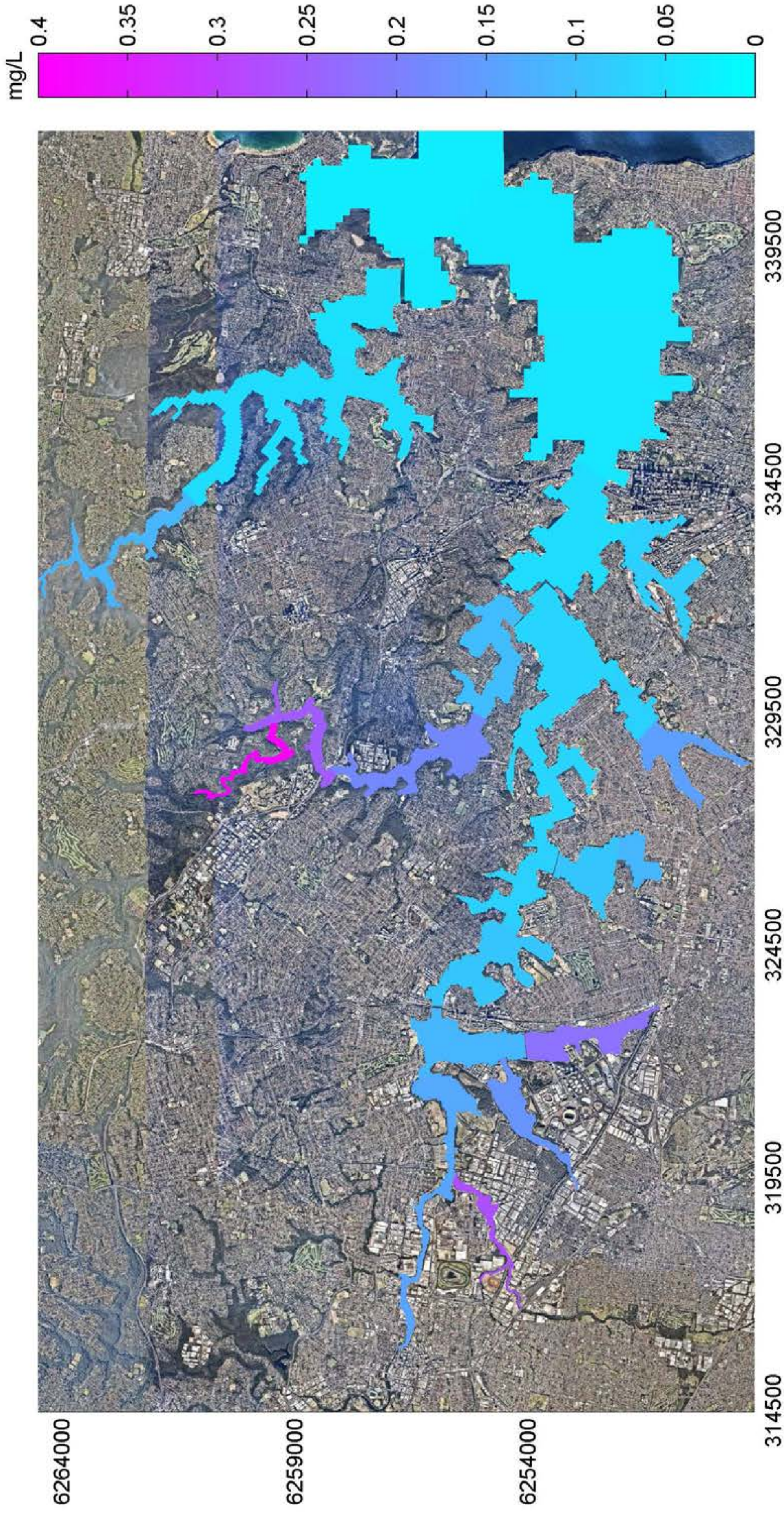
Figure 9.7a



Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 90% Total Phosphorus (mg/L)
BLOOM Model − Wet Year (Apr 2011 − Mar 2012)

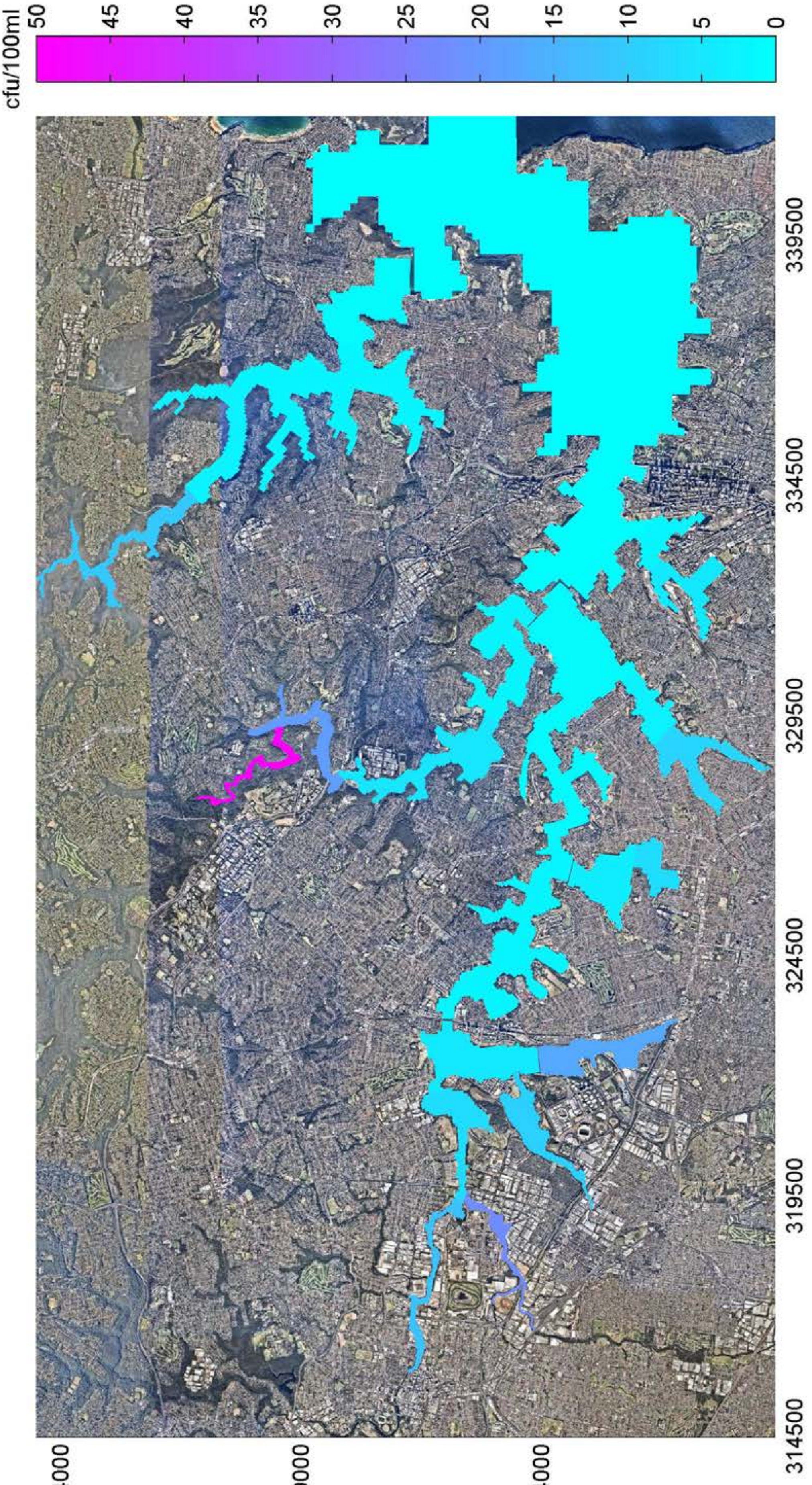
Figure 9.7b



Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 99% Total Phosphorus (mg/L)
BLOOM Model − Wet Year (Apr 2011 − Mar 2012)

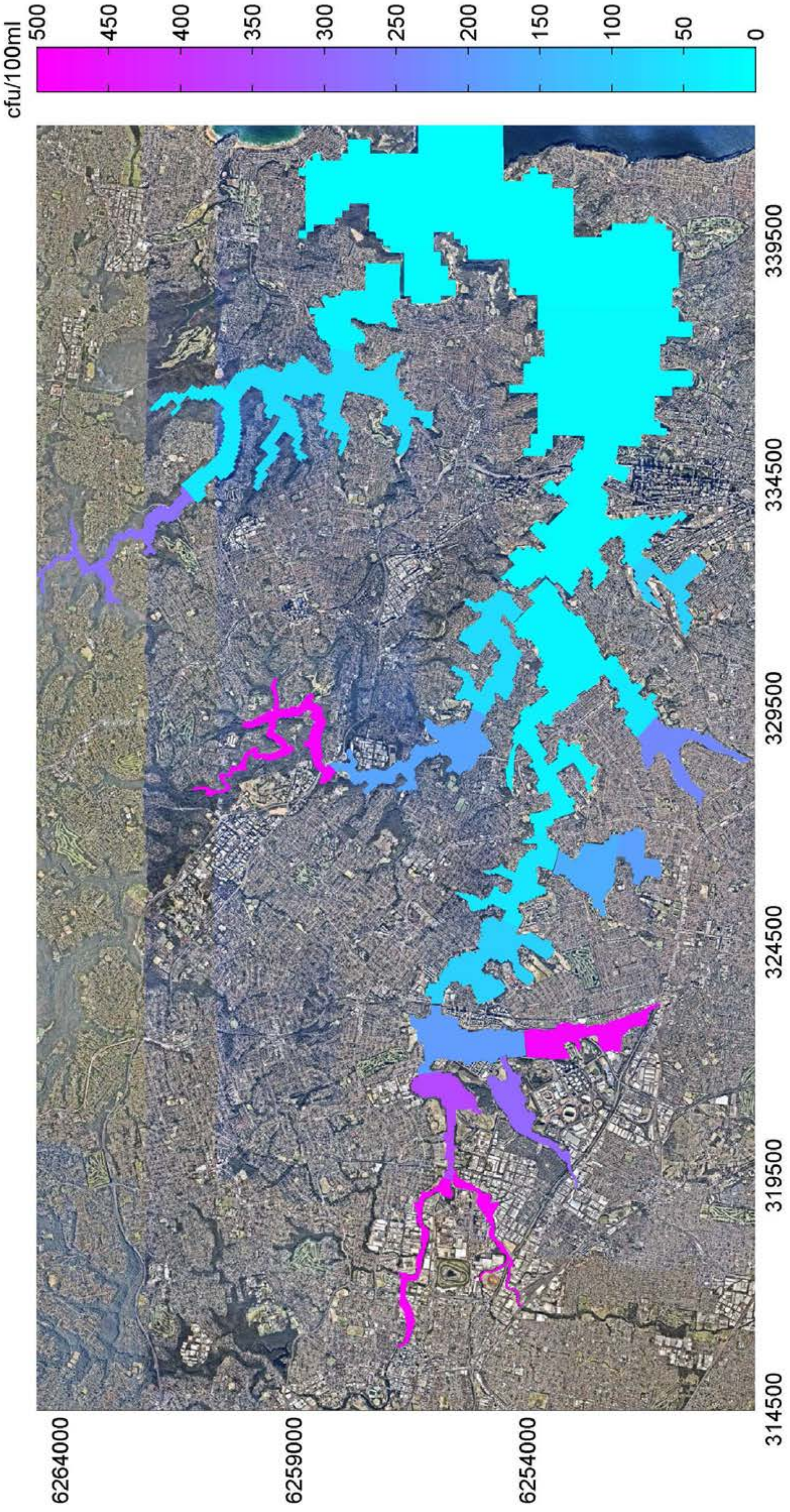
Figure 9.7c



Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 50% Enterococci (cfu/100ml)
BLOOM Model − Wet Year (Apr 2011 − Mar 2012)

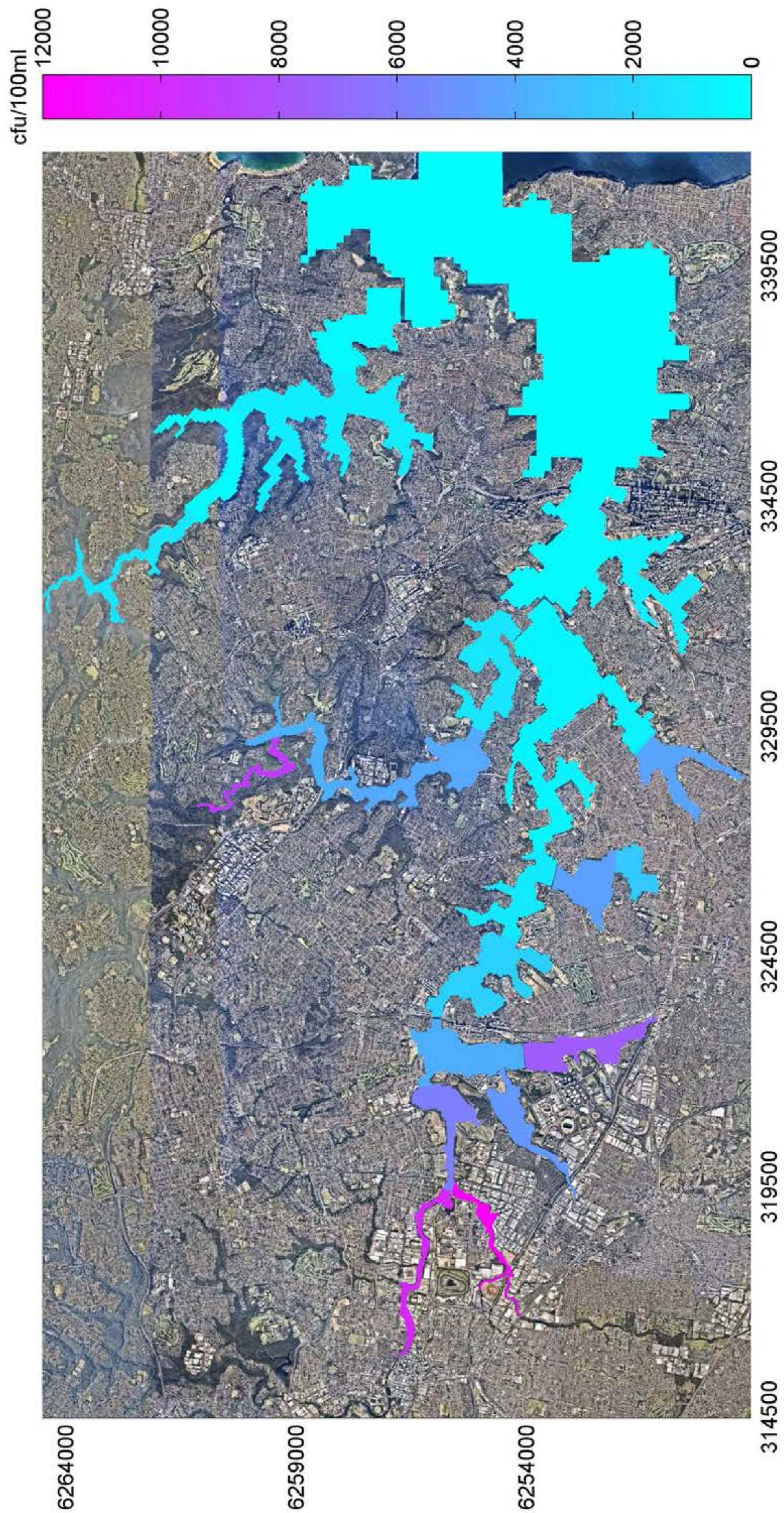
Figure 9.8a



Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 90% Enterococci (cfu/100ml)
BLOOM Model − Wet Year (Apr 2011 − Mar 2012)

Figure 9.8b



Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 99% Enterococci (cfu/100ml)
BLOOM Model − Wet Year (Apr 2011 − Mar 2012)

Figure 9.8c

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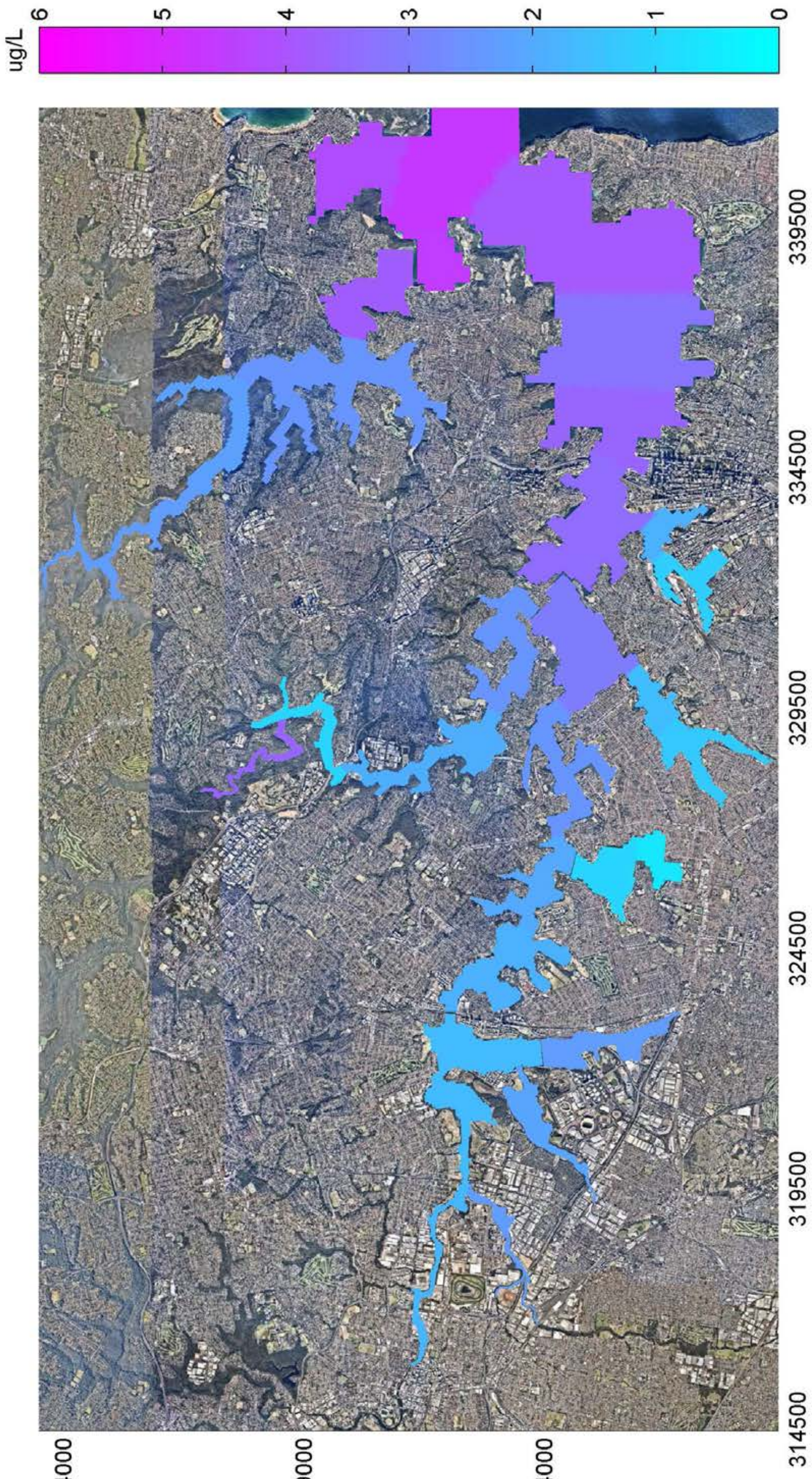

Sydney Harbour Ecological Response Model

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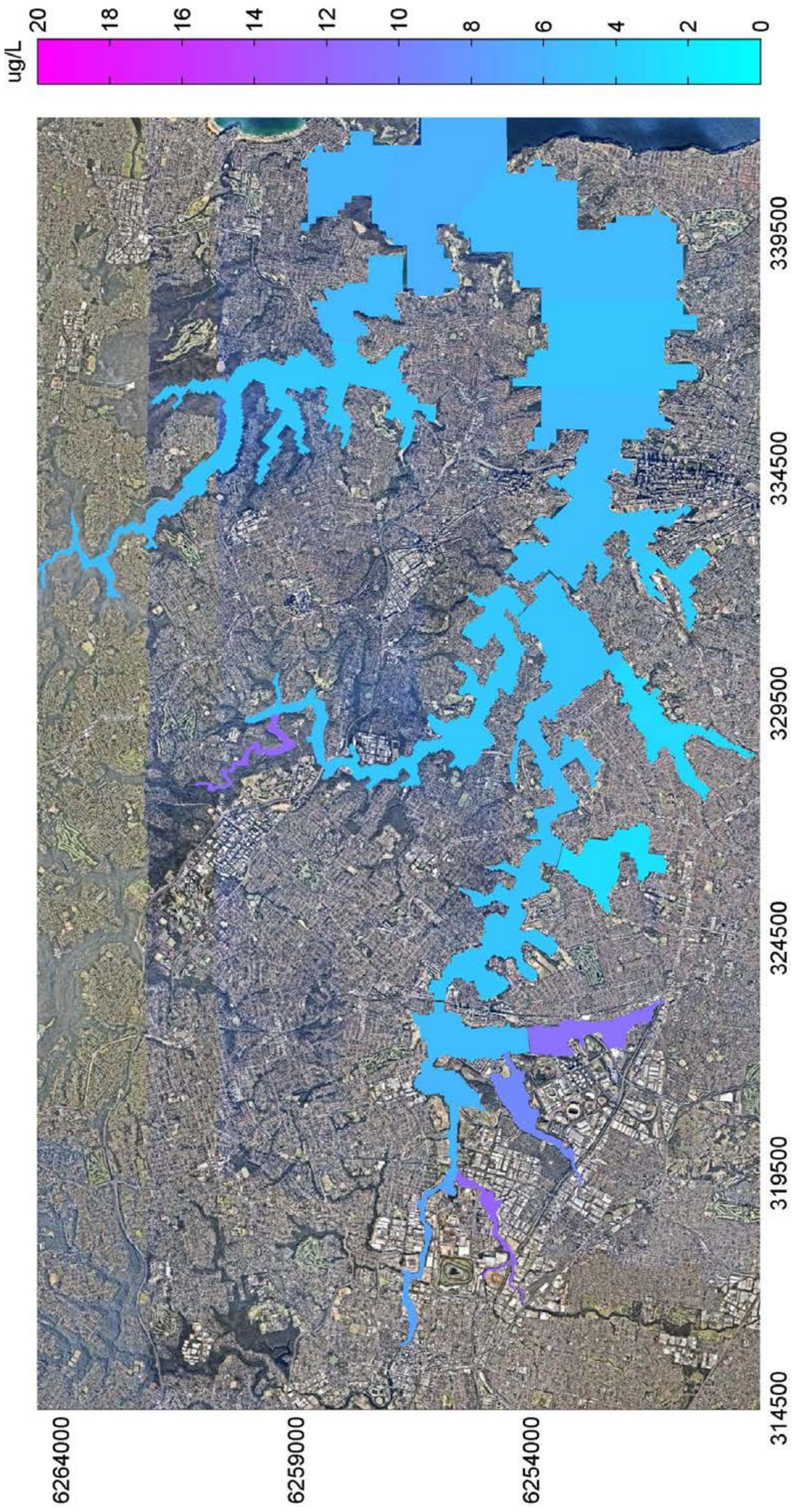
Water Quality 3D Box Model: Surface Layer 50% Chl−a Concentration (ug/L)
BLOOM Model − Dry Year (Apr 2002 − Mar 2003)

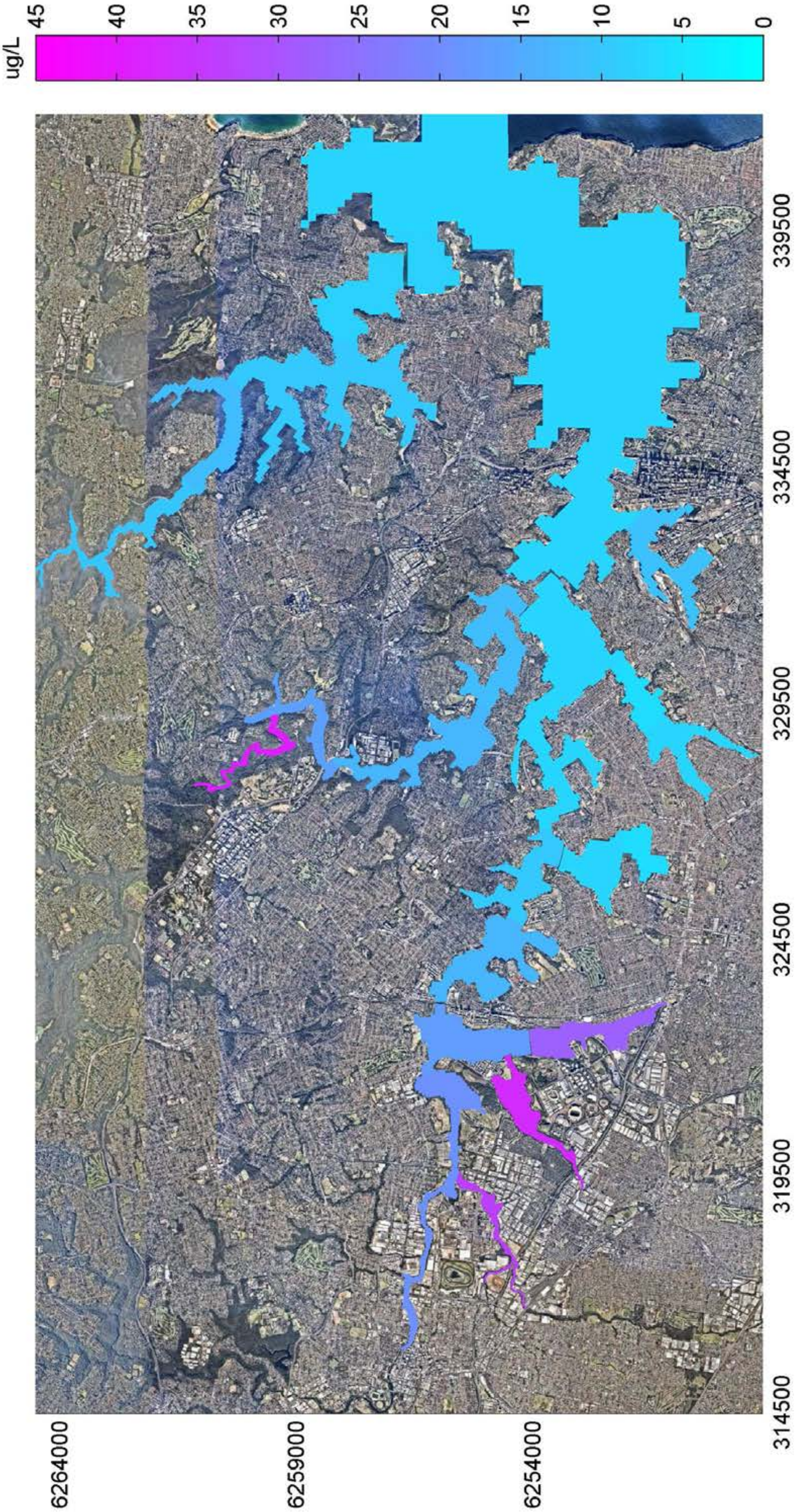
Figure 9.9a



Sydney Harbour Ecological Response Model

Cardno Water Quality 3D Box Model: Surface Layer 90% Chl−a Concentration (ug/L)
BLOOM Model − Dry Year (Apr 2002 − Mar 2003)

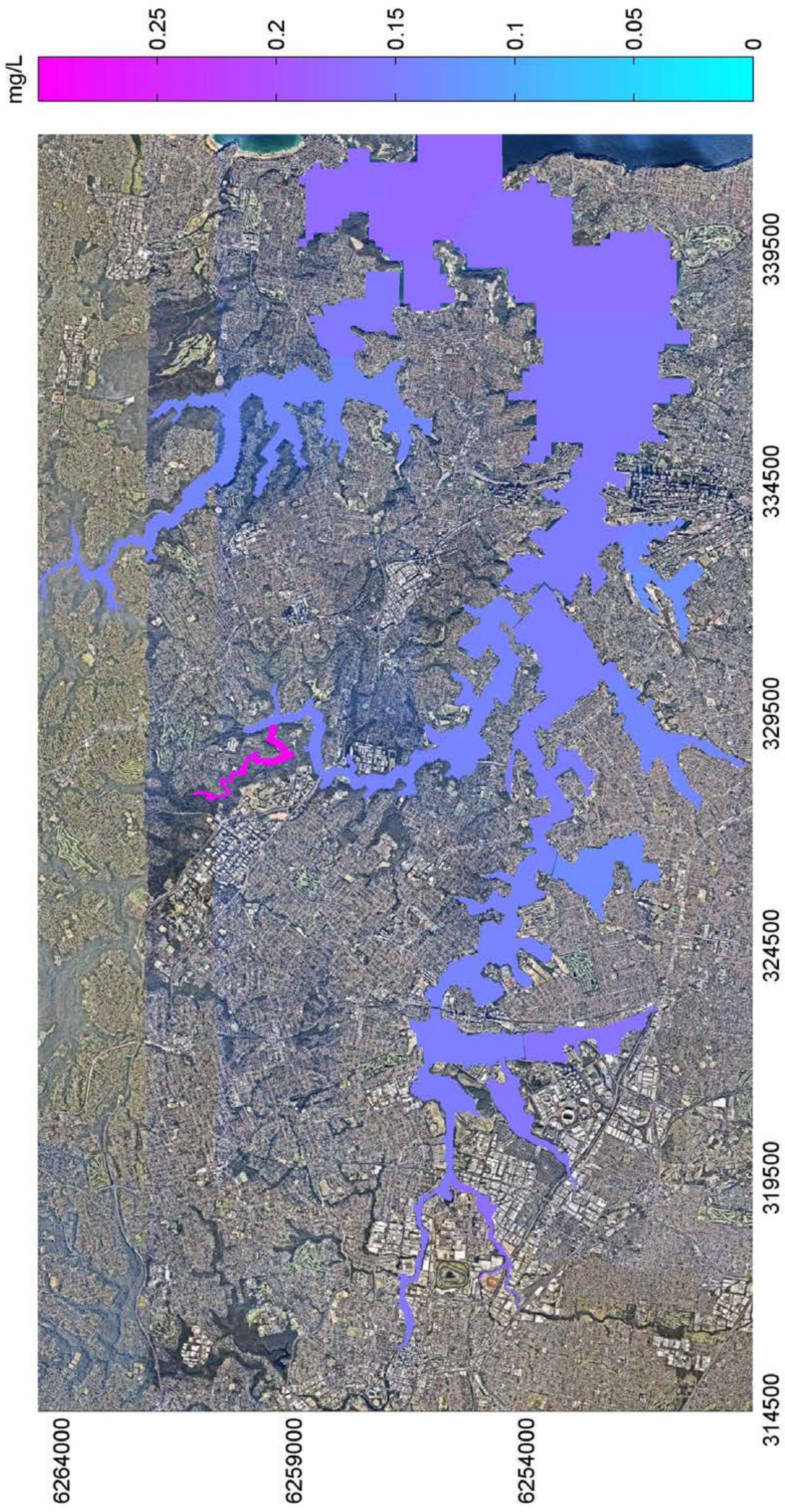
Figure 9.9b



Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 99% Chl−a Concentration (ug/L)
BLOOM Model − Dry Year (Apr 2002 − Mar 2003)

Figure 9.9c



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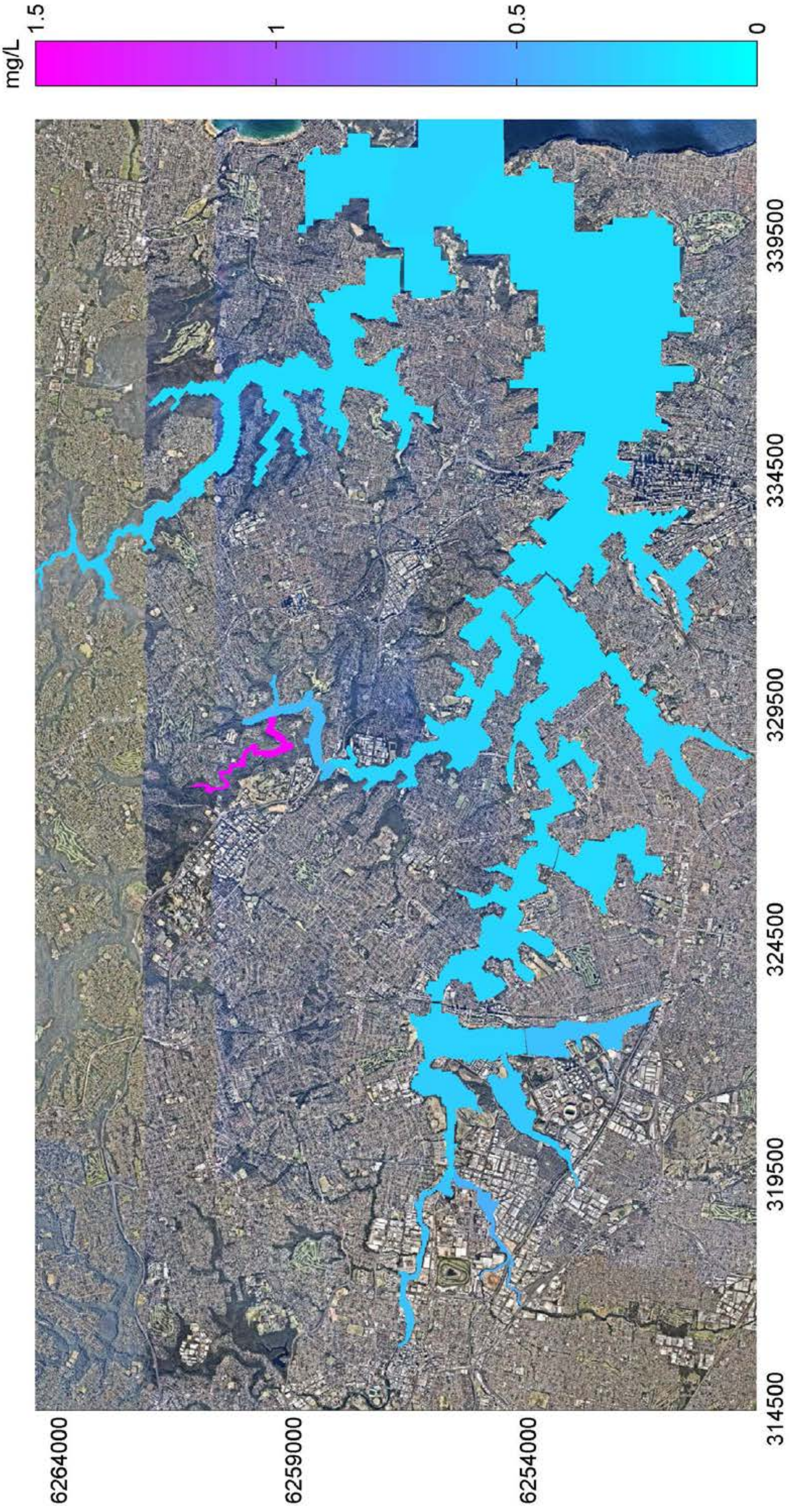
Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 50% Total Nitrogen (mg/L)
BLOOM Model − Dry Year (Apr 2002 − Mar 2003)

Figure 9.10a



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Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 90% Total Nitrogen (mg/L)
BLOOM Model − Dry Year (Apr 2002 − Mar 2003)

Figure 9.10b

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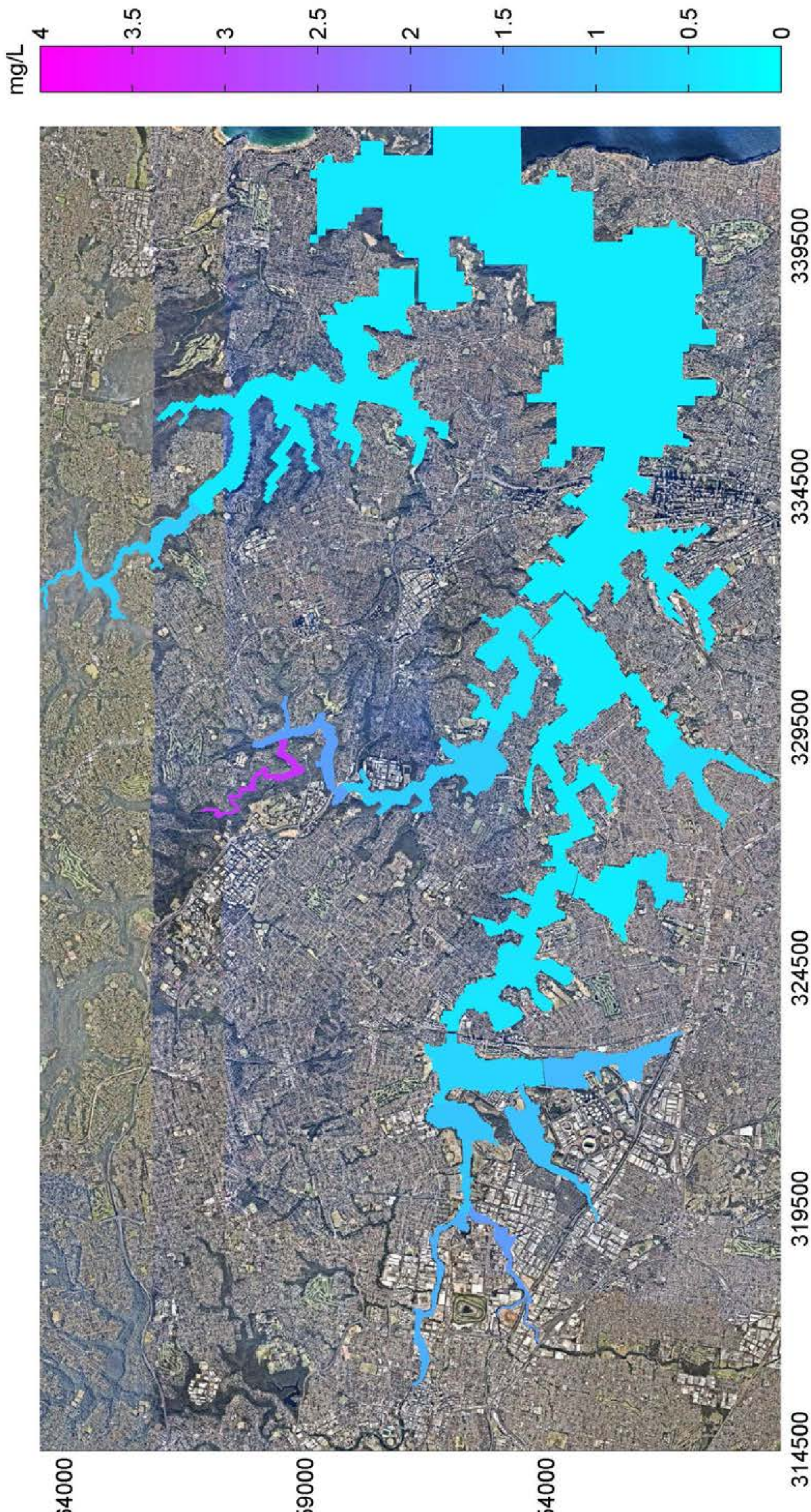
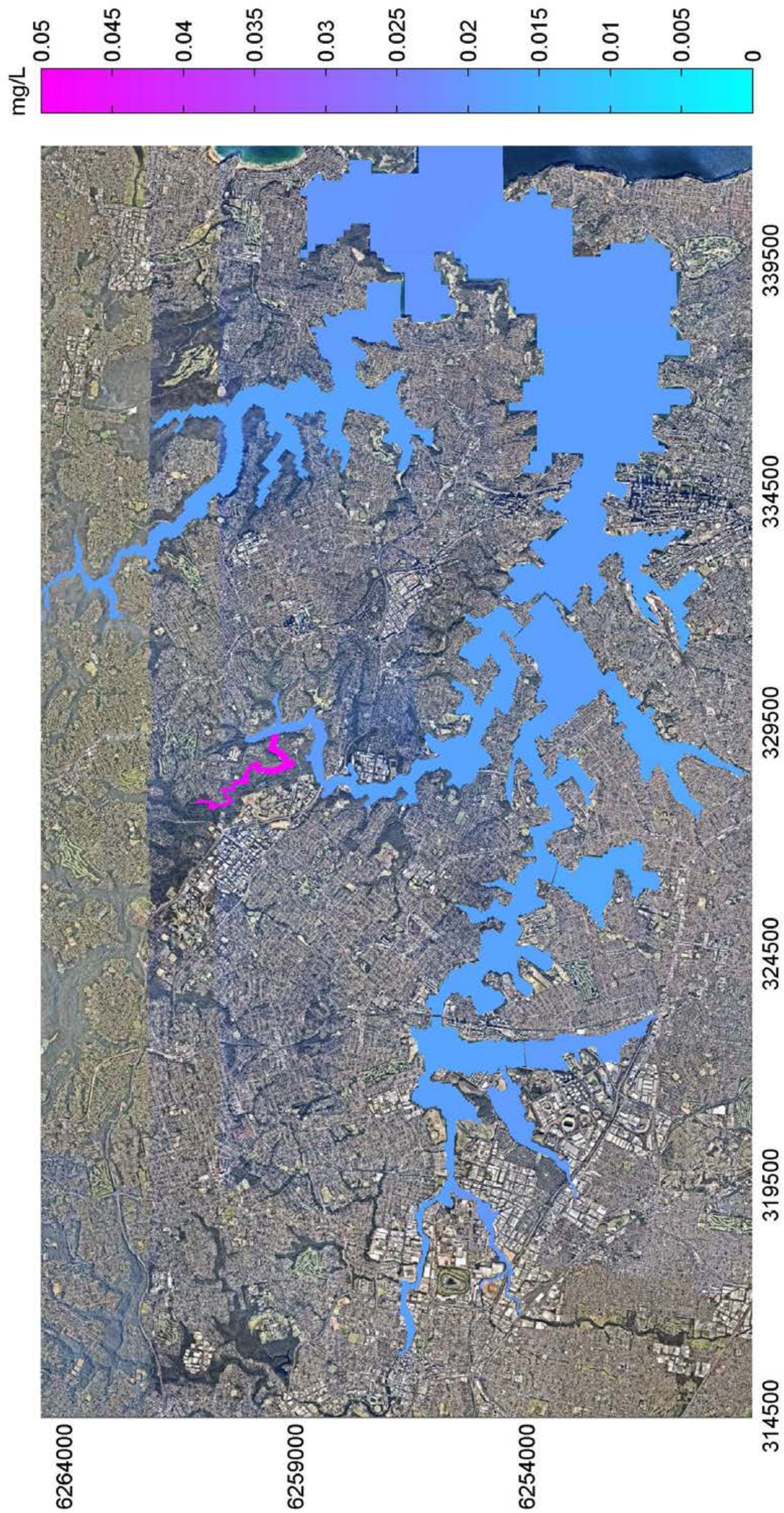


Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 99% Total Nitrogen (mg/L)
BLOOM Model − Dry Year (Apr 2002 − Mar 2003)

Figure 9.10c



Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 50% Total Phosphorus (mg/L)
BLOOM Model − Dry Year (Apr 2002 − Mar 2003)

Figure 9.11a

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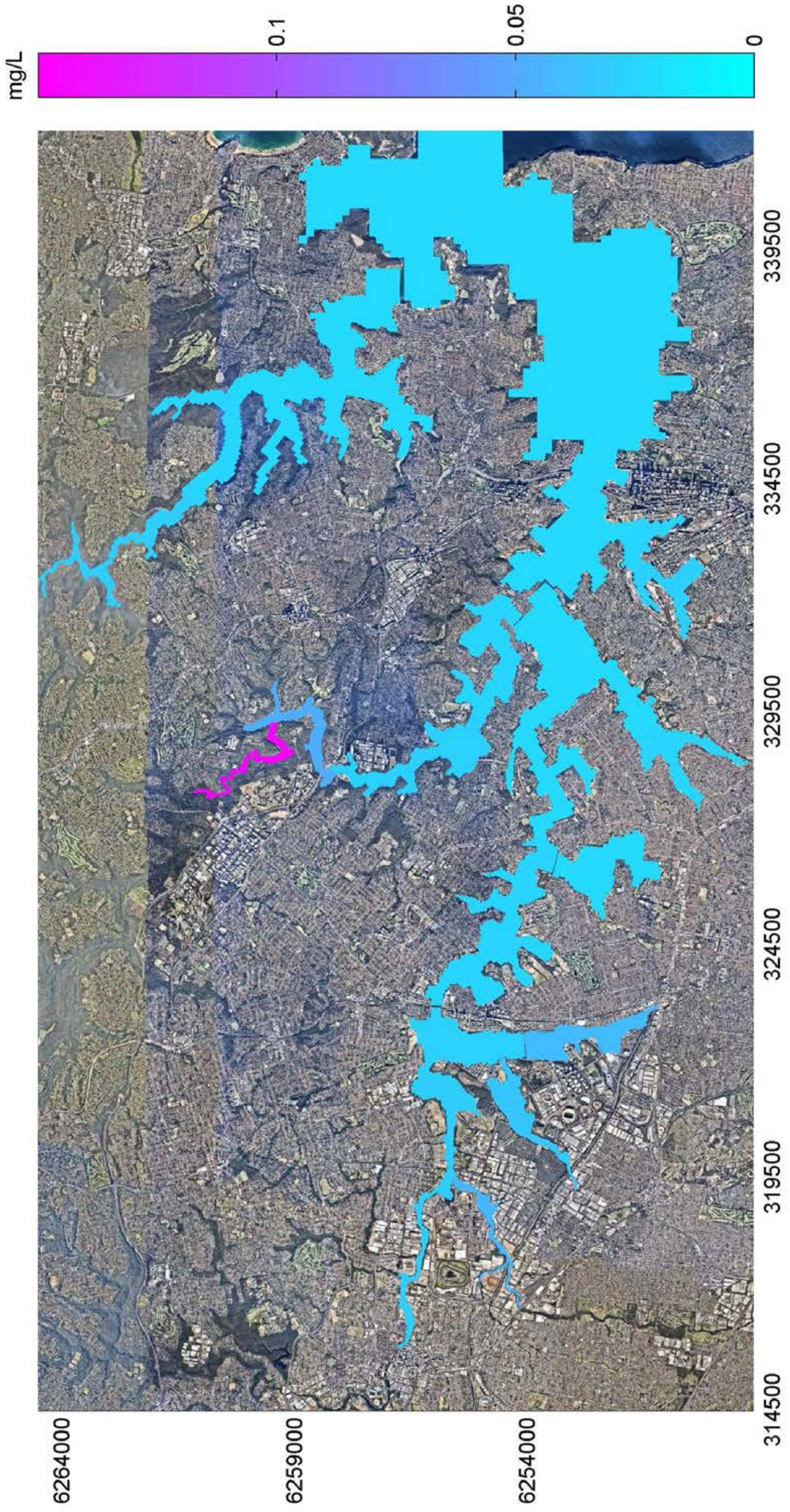
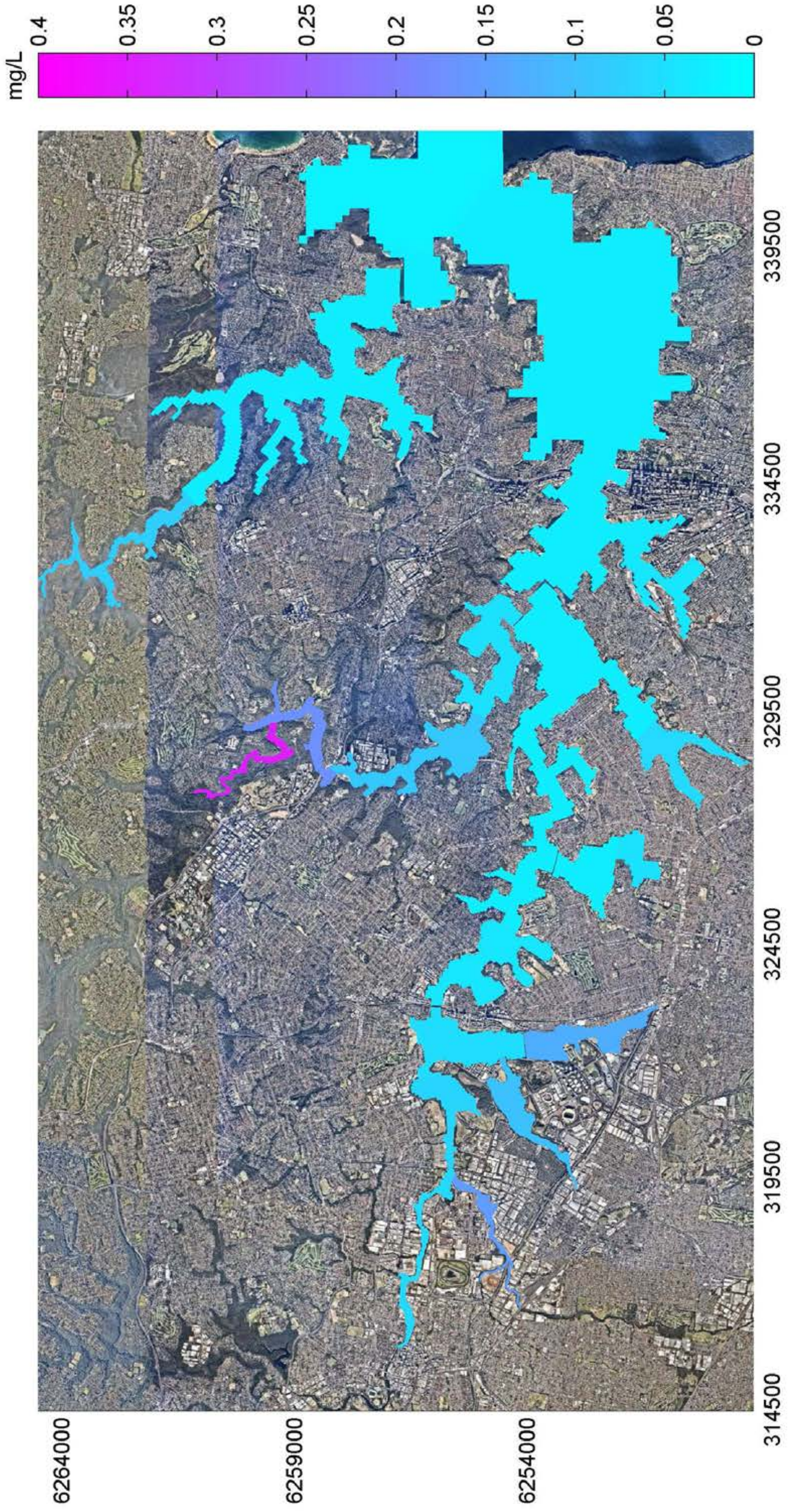


Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 90% Total Phosphorus (mg/L)
BLOOM Model − Dry Year (Apr 2002 − Mar 2003)

Figure 9.11b



Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 99% Total Phosphorus (mg/L)
BLOOM Model − Dry Year (Apr 2002 − Mar 2003)

Figure 9.11c

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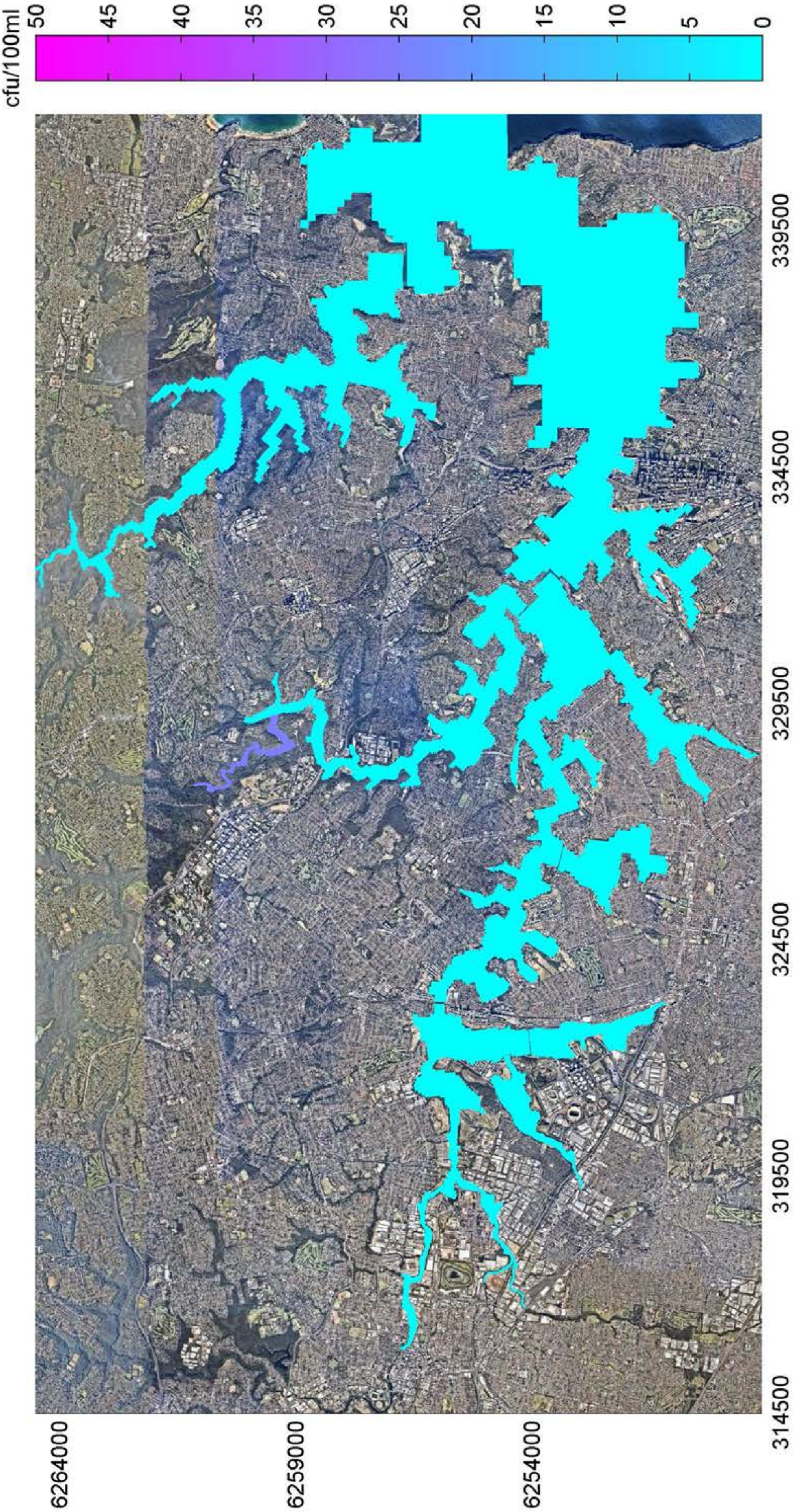
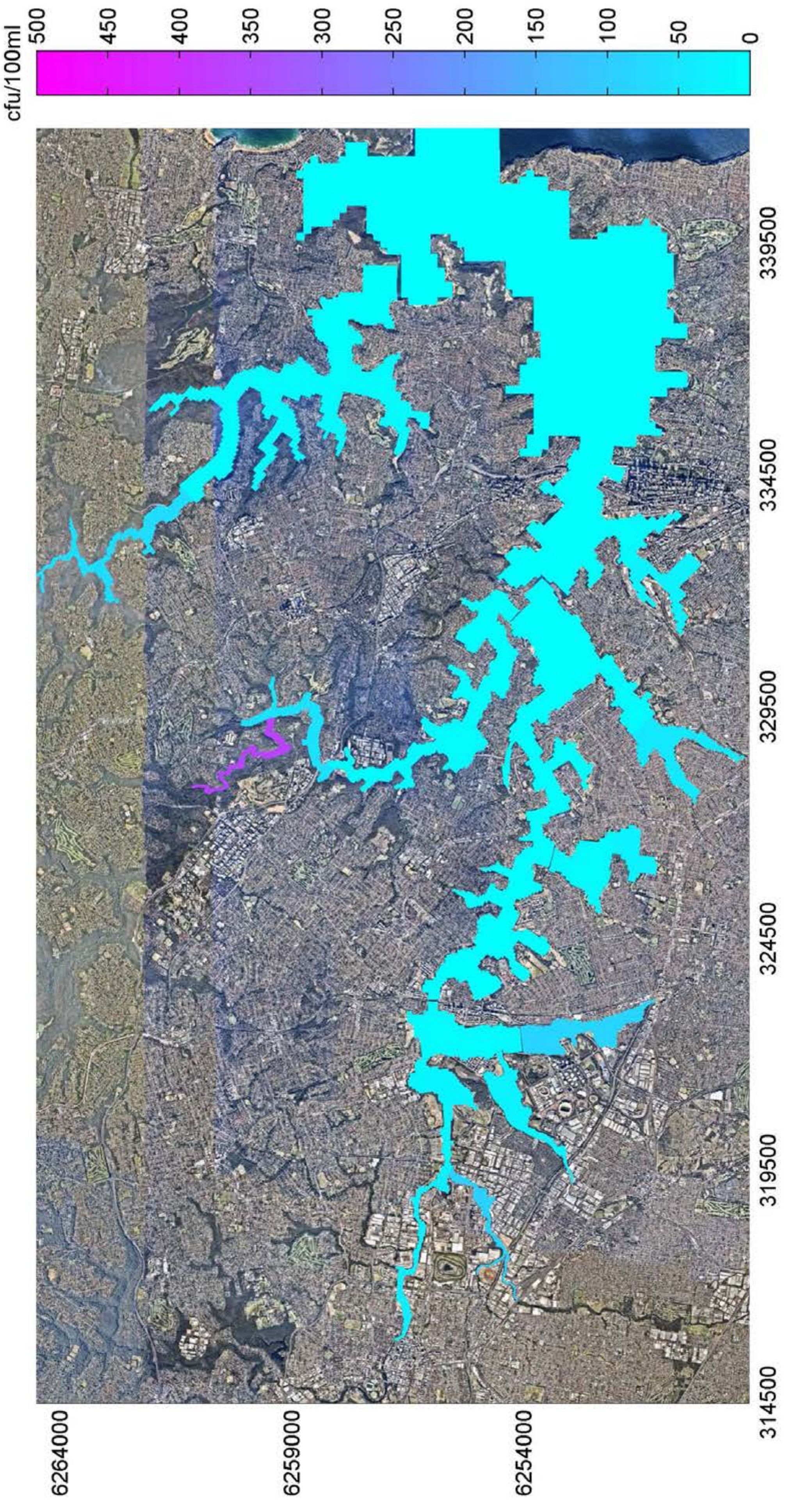


Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 50% Enterococci (cfu/100ml)
BLOOM Model − Dry Year (Apr 2002 − Mar 2003)

Figure 9.12a



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Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 90% Enterococci (cfu/100ml)
BLOOM Model − Dry Year (Apr 2002 − Mar 2003)

Figure 9.12b

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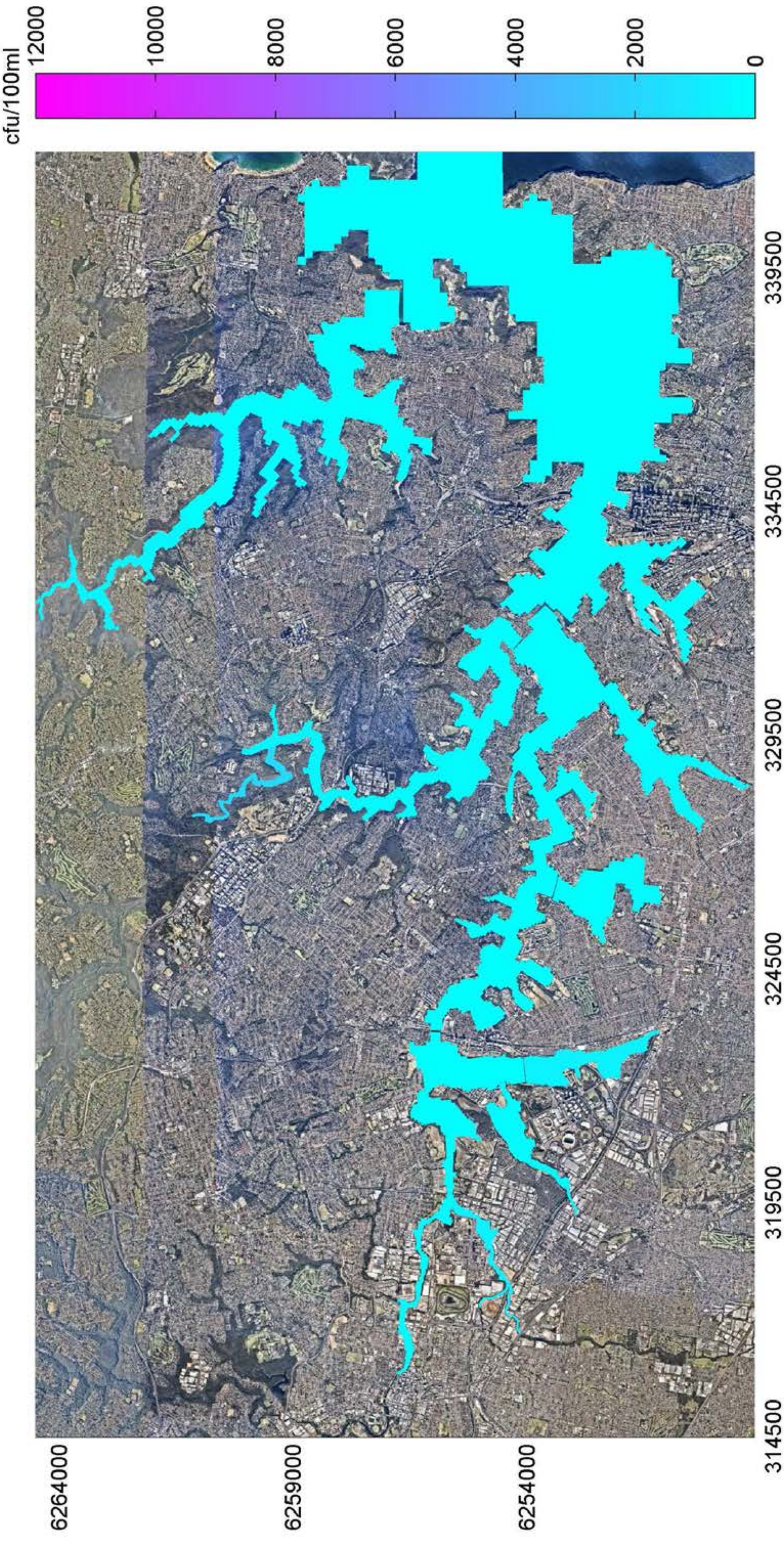

Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 99% Enterococci (cfu/100ml)
BLOOM Model − Dry Year (Apr 2002 − Mar 2003)

Figure 9.12c

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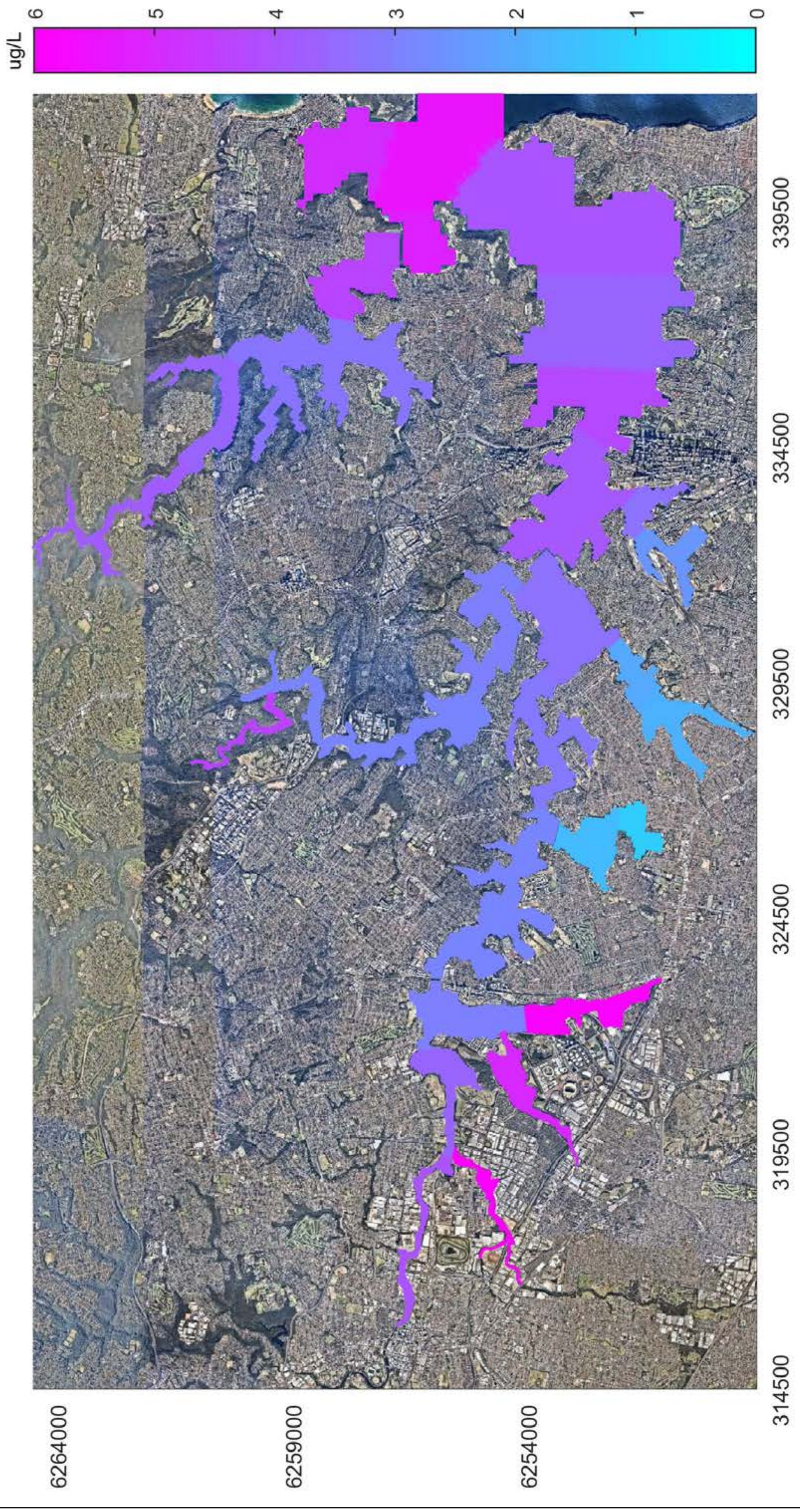

Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 50% Chl−a Concentration (ug/L)
BLOOM Model − Wet Year, 20% Reduced TN/TP Catchment Loads

Figure 9.13a

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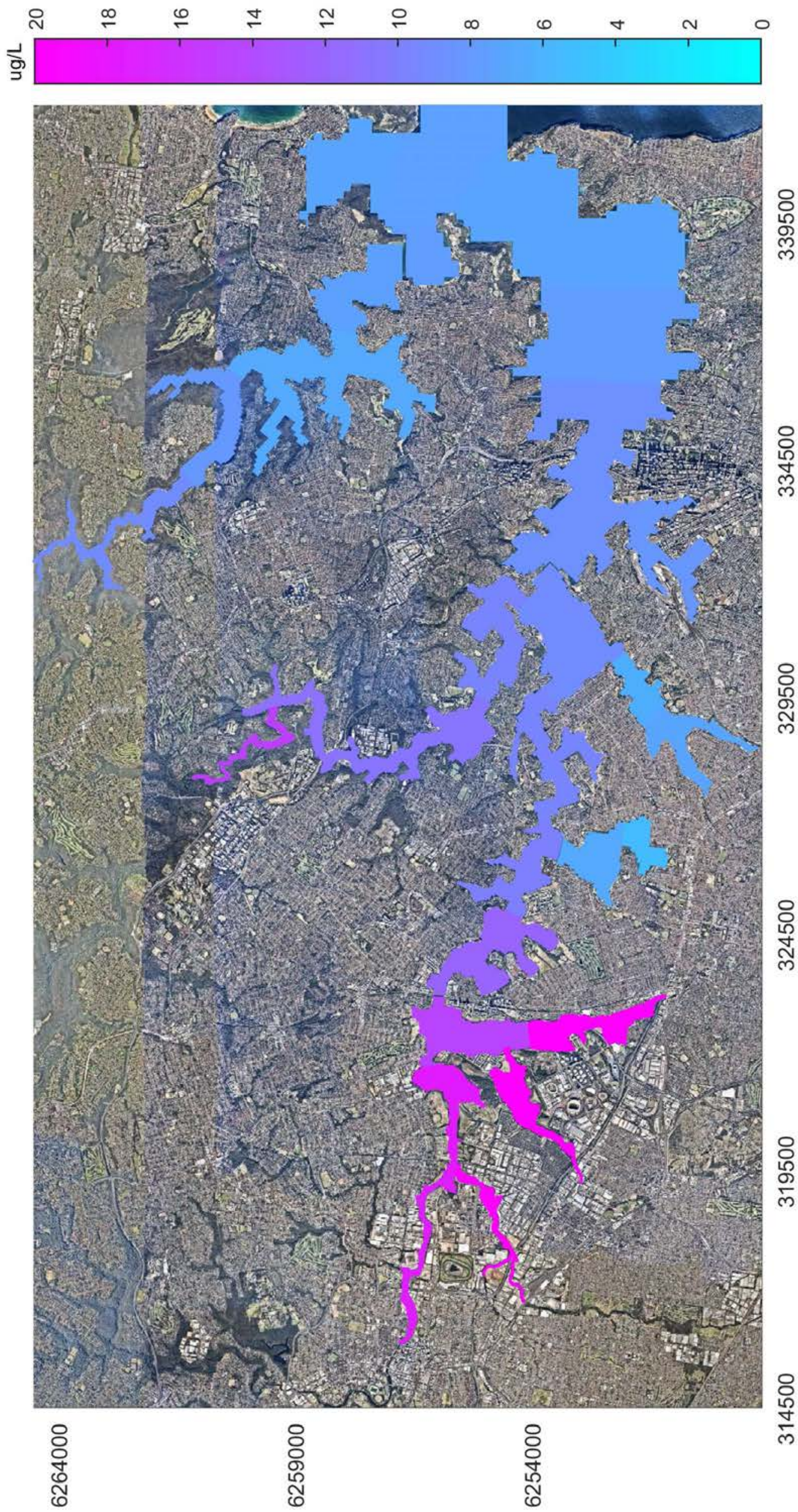

Sydney Harbour Ecological Response Model

Cardno Water Quality 3D Box Model: Surface Layer 90% Chl−a Concentration (ug/L)

BLOOM Model − Wet Year, 20% Reduced TN/TP Catchment Loads

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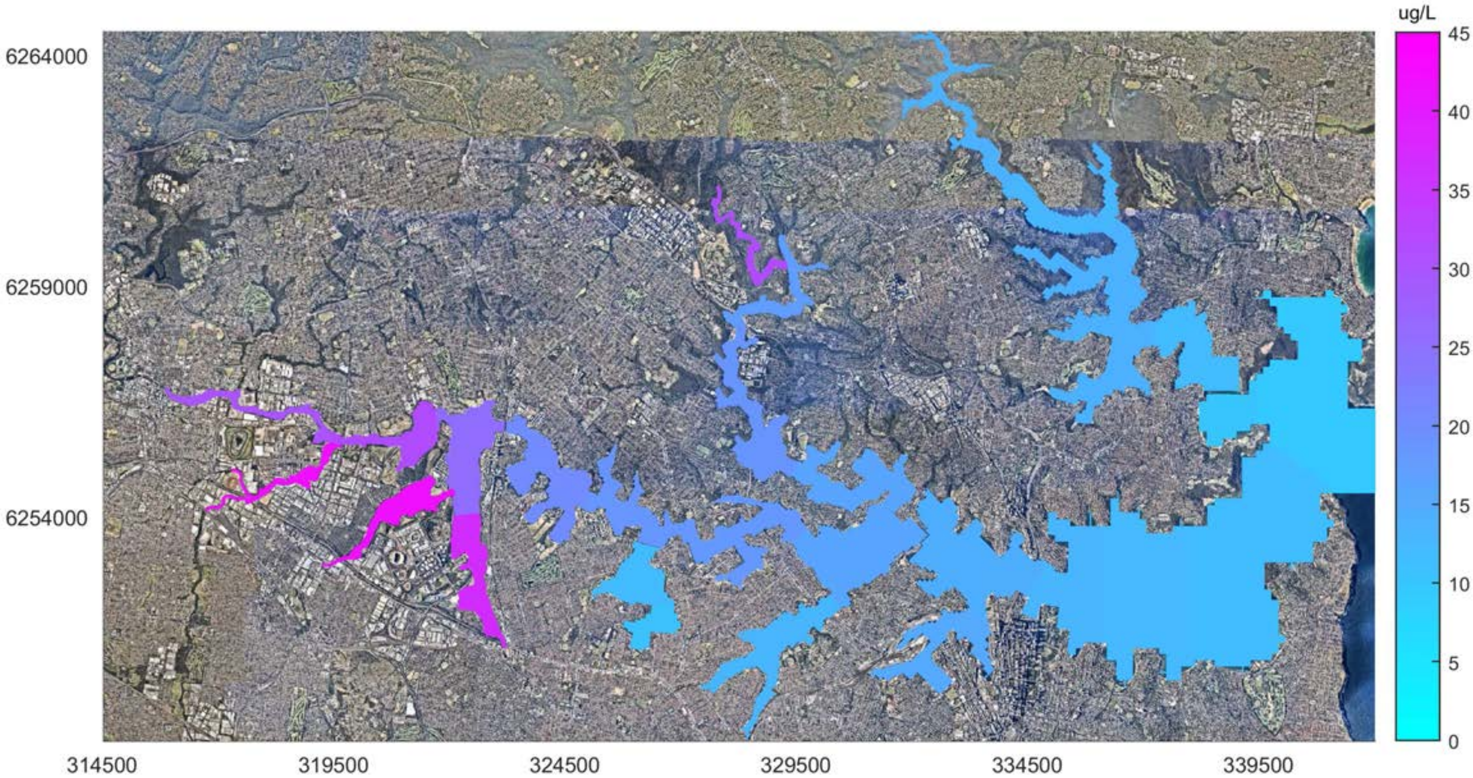
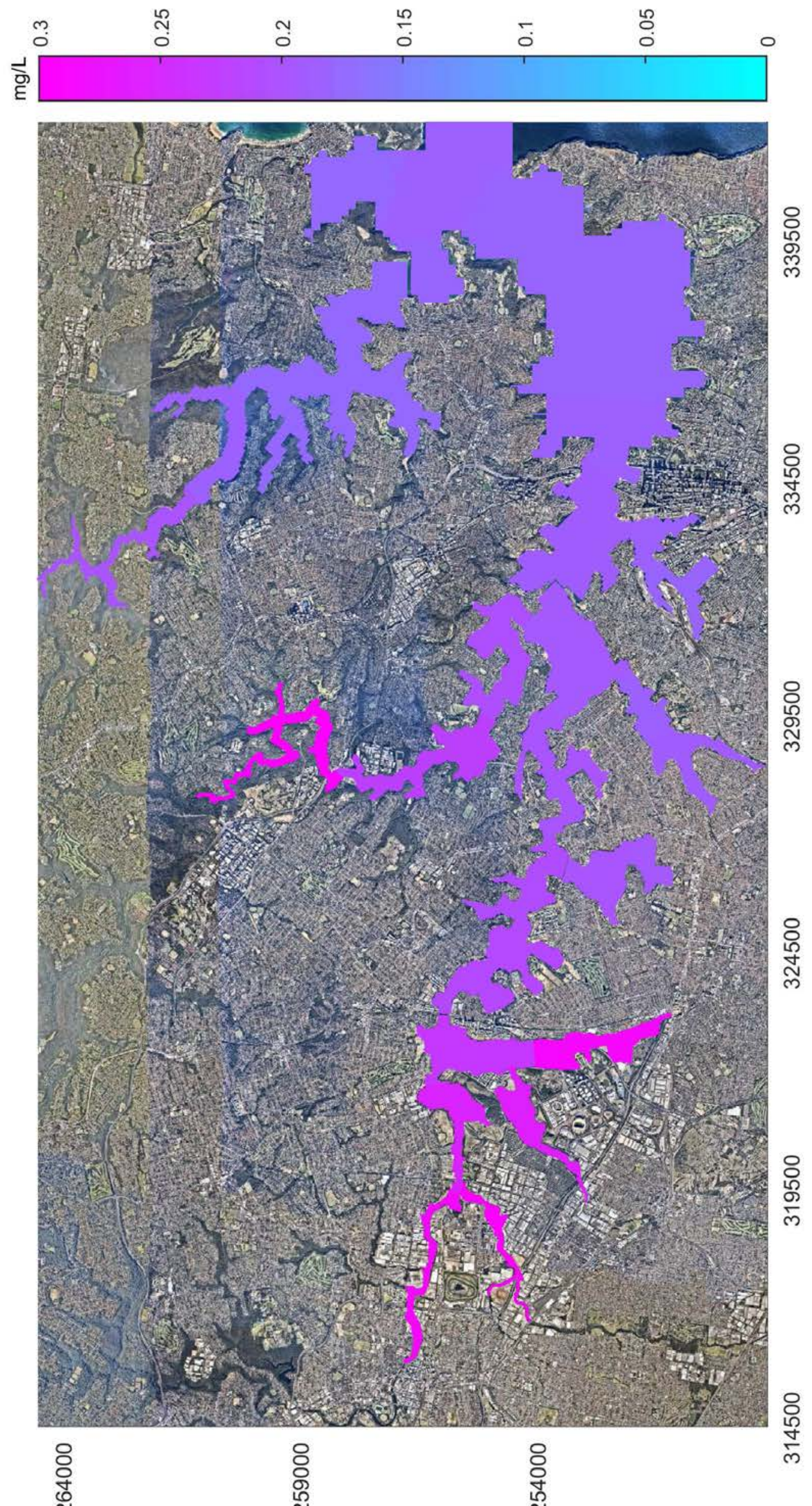
Figure 9.13b



Water Quality 3D Box Model: Surface Layer 99% Chl−a Concentration (ug/L)
BLOOM Model − Wet Year, 20% Reduced TN/TP Catchment Loads

Figure 9.13c



Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 50% Total Nitrogen (mg/L)
BLOOM Model − Wet Year, 20% Reduced TN/TP Catchment Loads

Figure 9.14a

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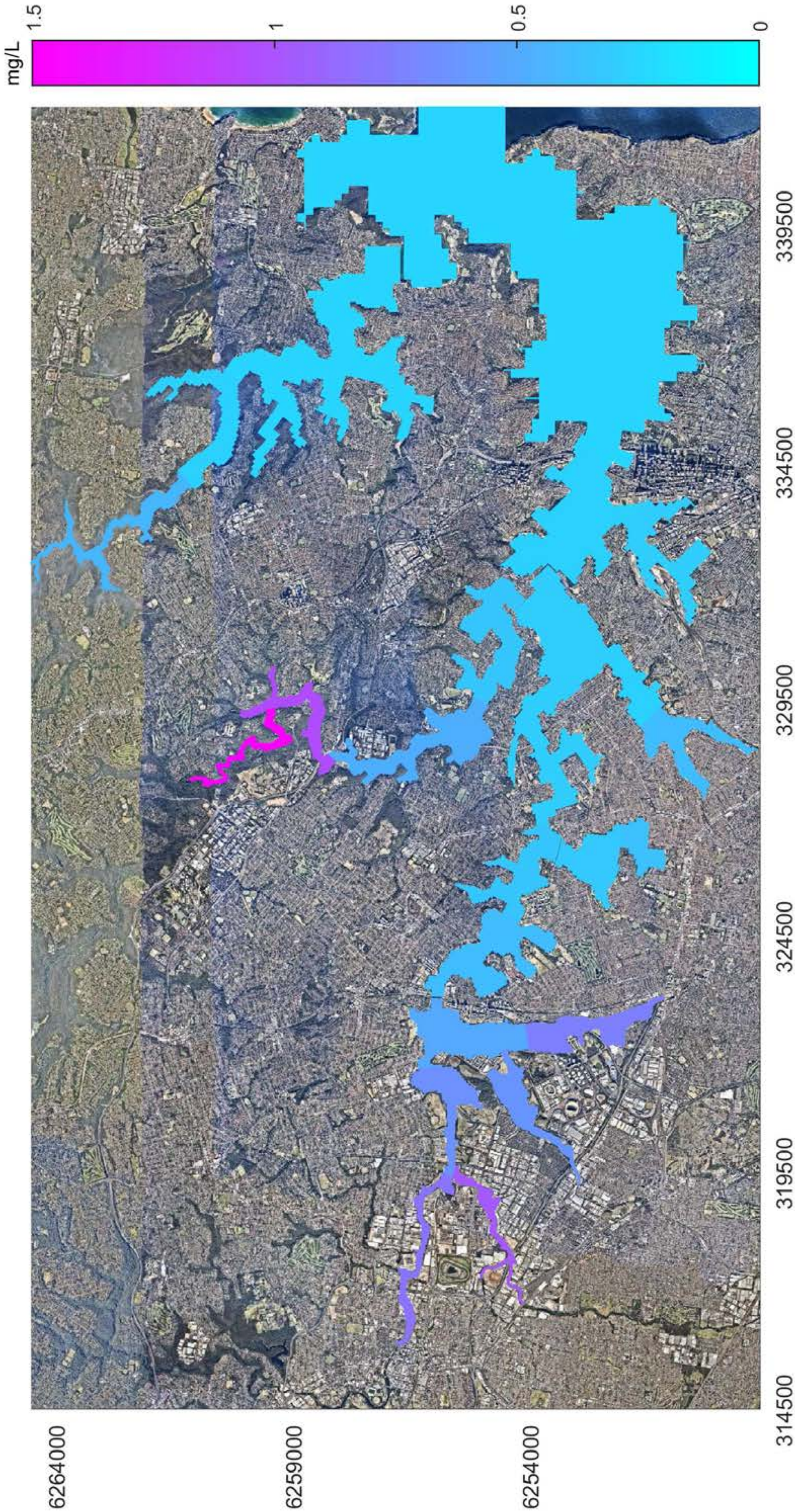
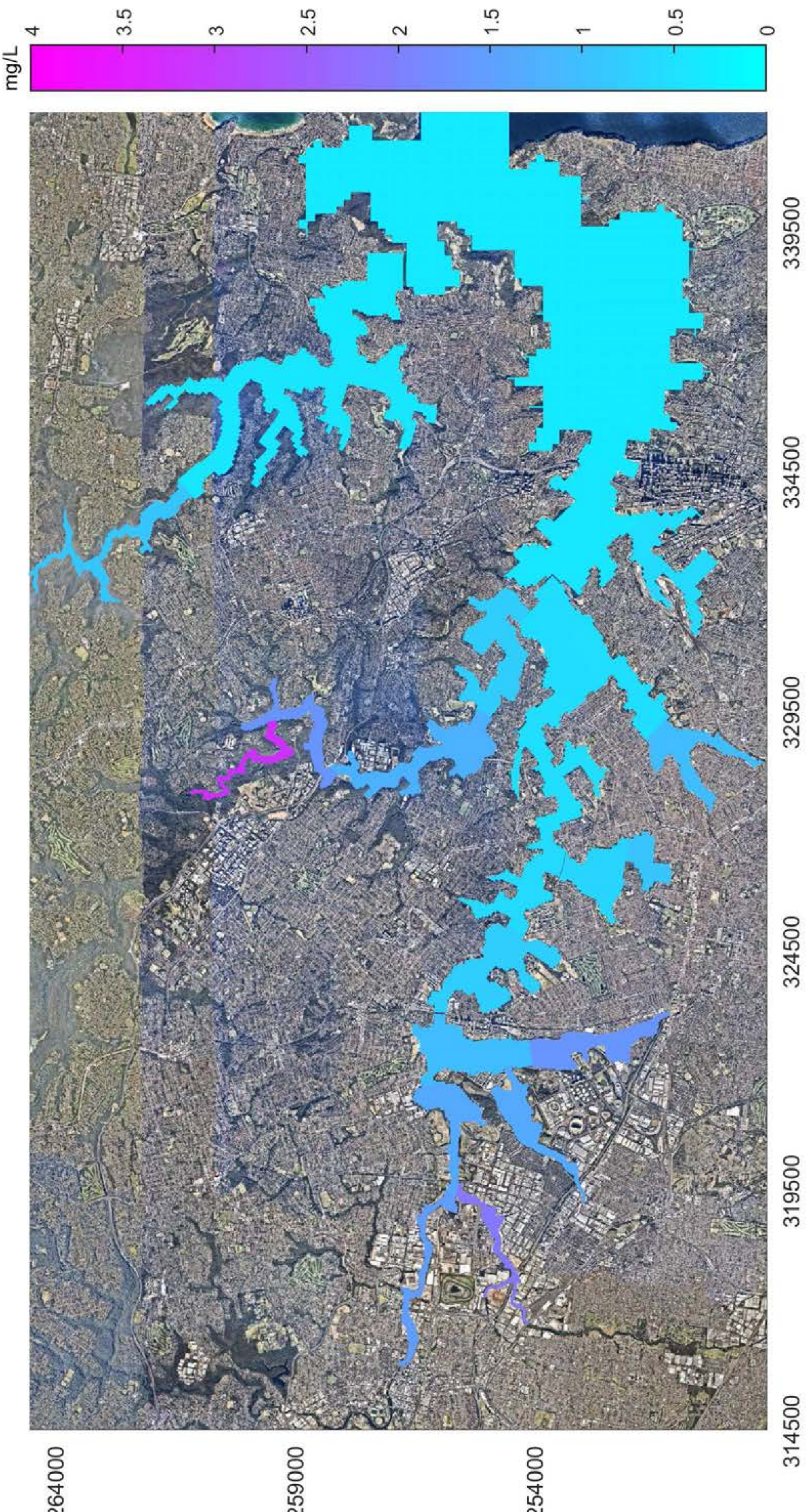


Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 90% Total Nitrogen (mg/L)
BLOOM Model − Wet Year, 20% Reduced TN/TP Catchment Loads

Figure 9.14b



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Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 99% Total Nitrogen (mg/L)
BLOOM Model – Wet Year, 20% Reduced TN/TP Catchment Loads

Figure 9.14c

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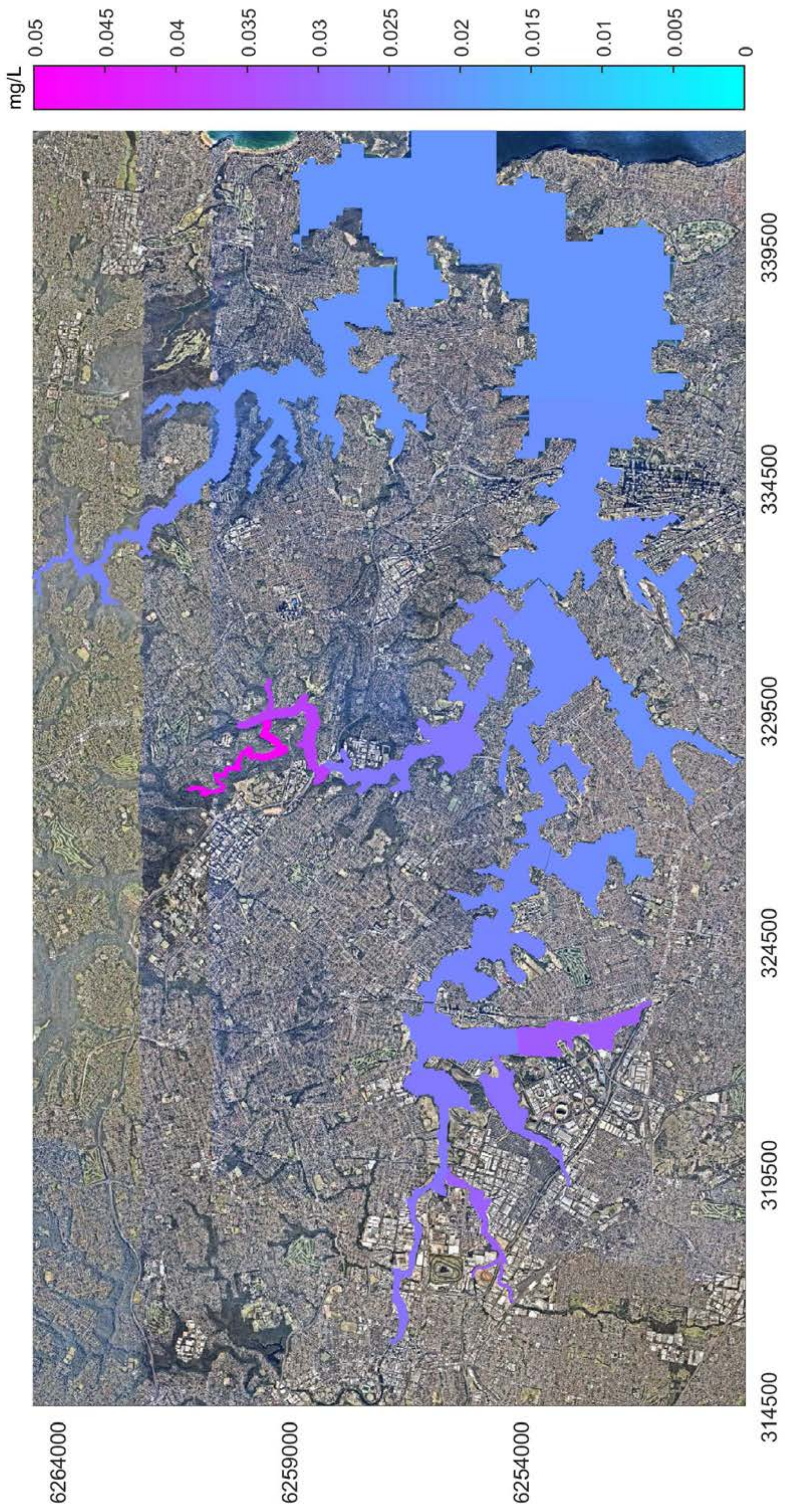
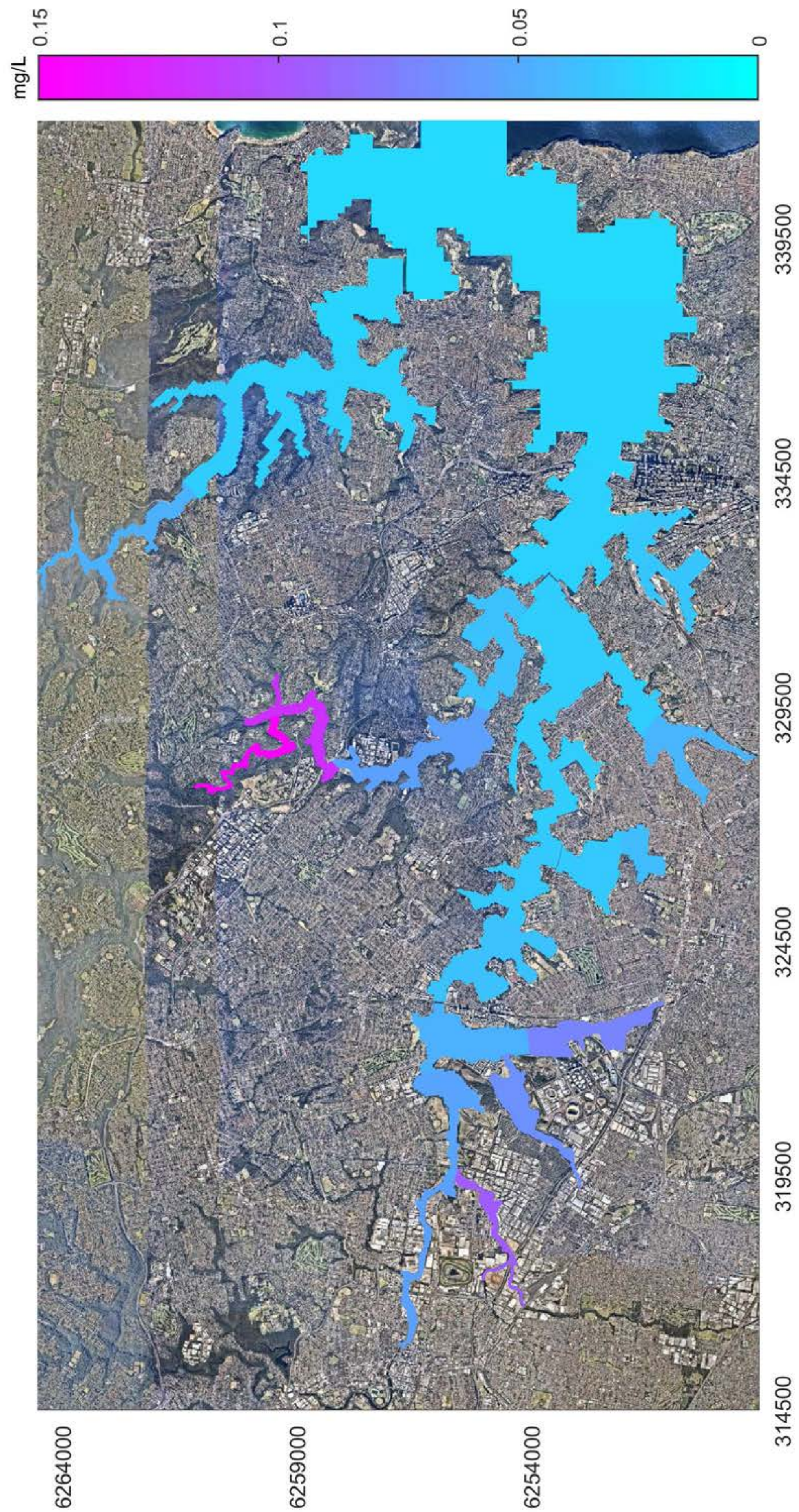


Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 50% Total Phosphorus (mg/L)
BLOOM Model − Wet Year, 20% Reduced TN/TP Catchment Loads

Figure 9.15a



Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 90% Total Phosphorus (mg/L)
BLOOM Model − Wet Year, 20% Reduced TN/TP Catchment Loads

Figure 9.15b

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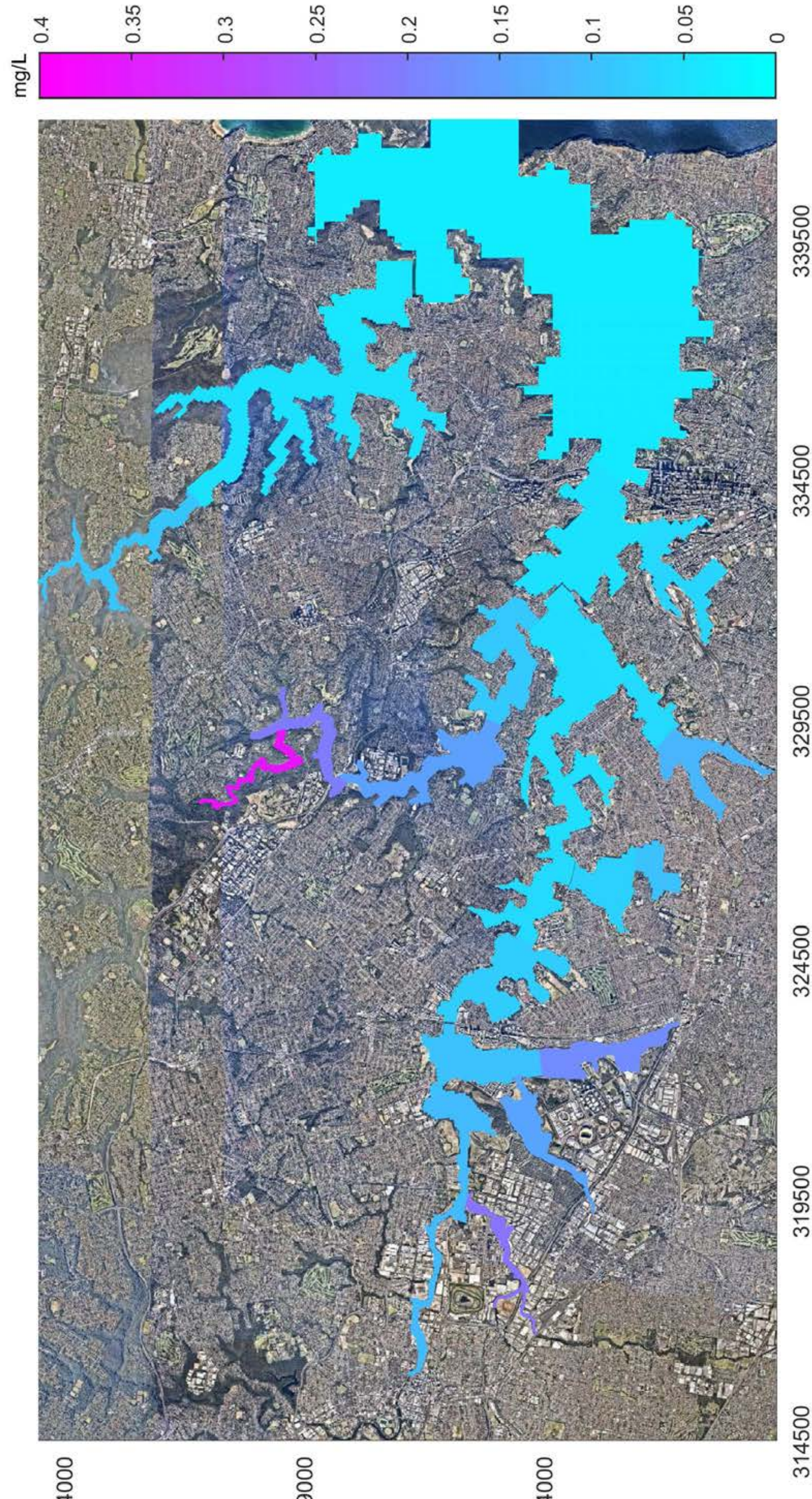
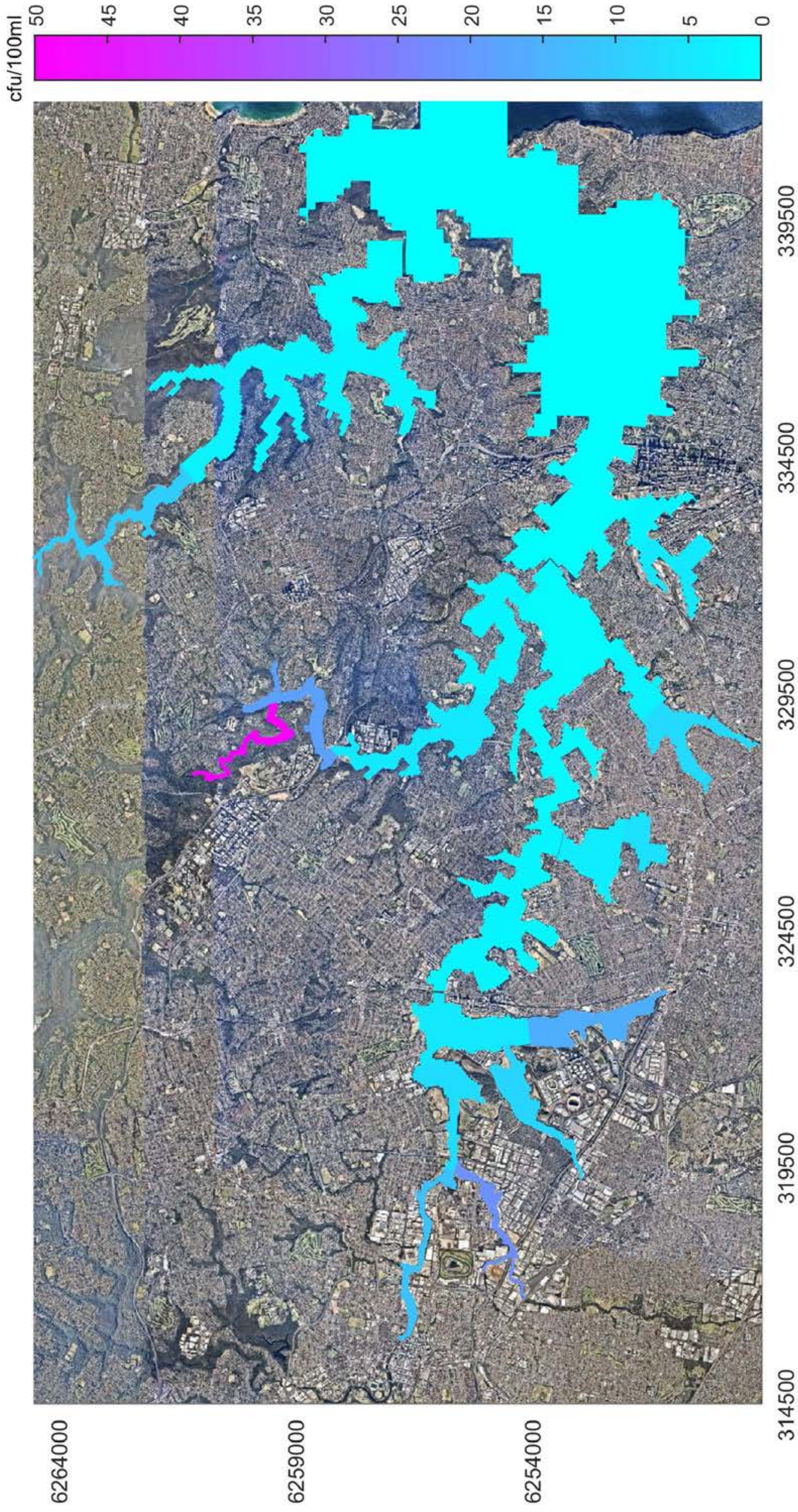


Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 99% Total Phosphorus (mg/L)
BLOOM Model − Wet Year, 20% Reduced TN/TP Catchment Loads

Figure 9.15c



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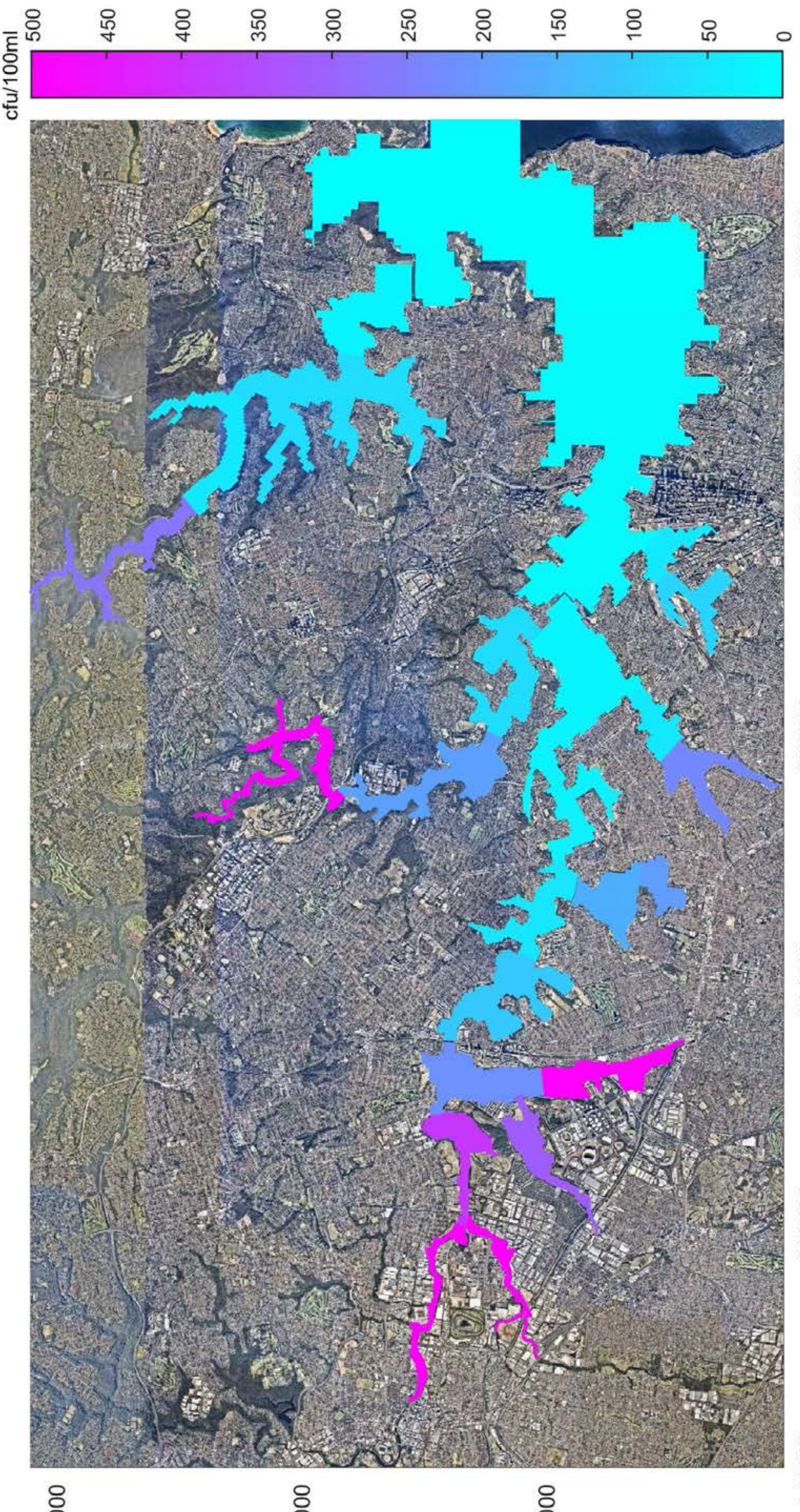
Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 50% Enterococci (cfu/100ml)
BLOOM Model – Wet Year, 20% Reduced TN/TP Catchment Loads

Figure 9.16a



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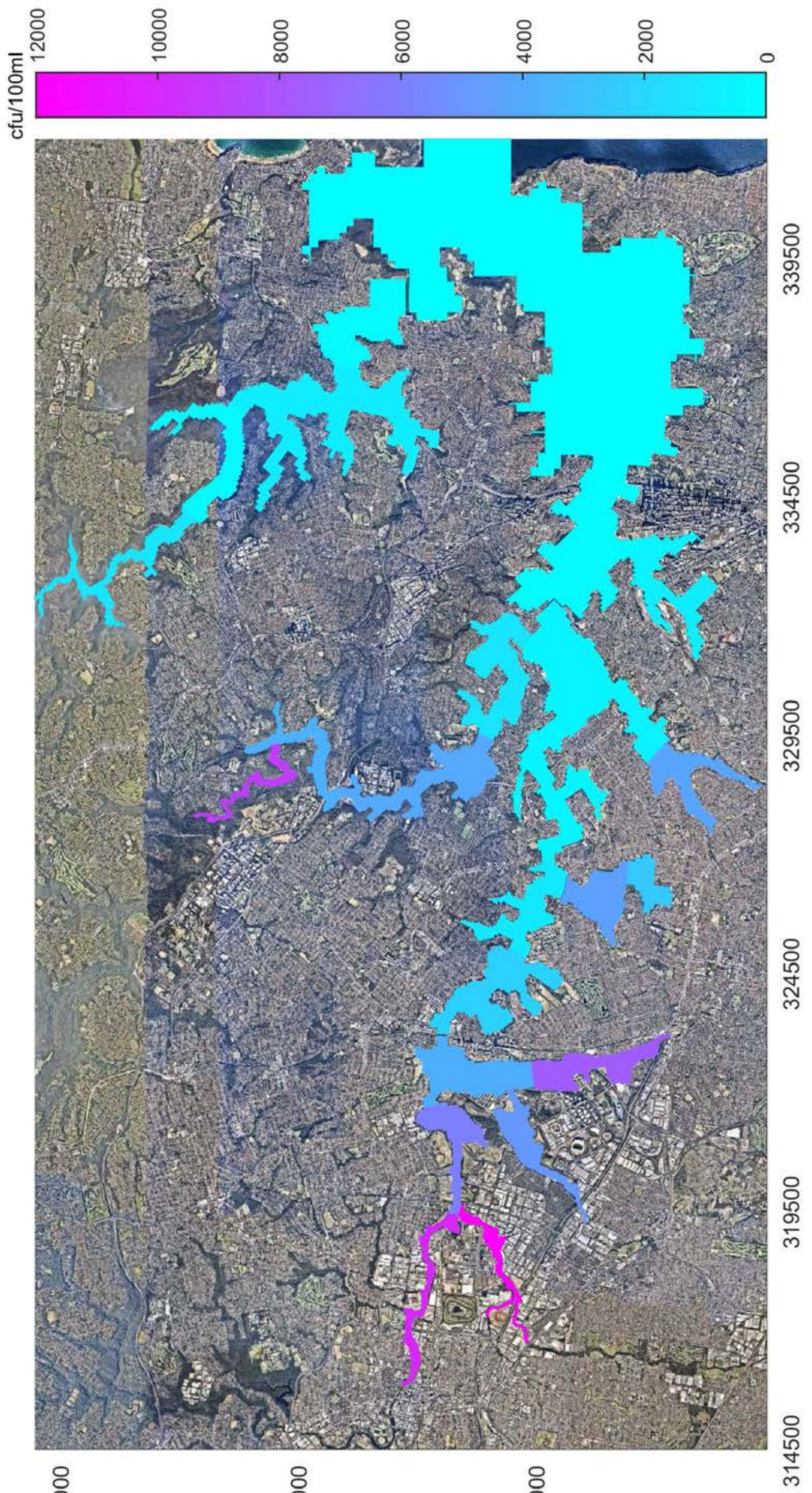
Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 90% Enterococci (cfu/100ml)
BLOOM Model − Wet Year, 20% Reduced TN/TP Catchment Loads

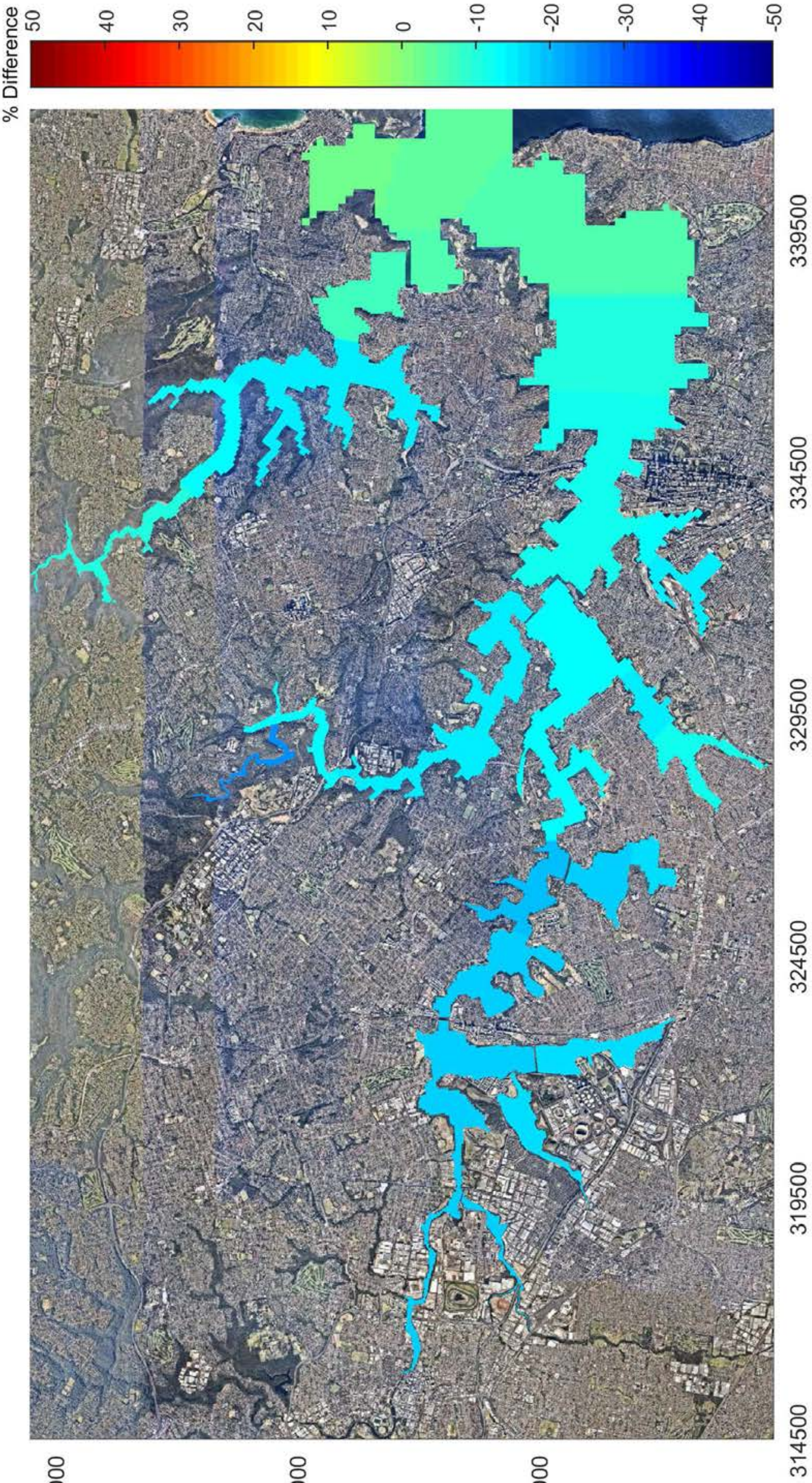
Figure 9.16b



Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 99% Enterococci (cfu/100ml)
BLOOM Model − Wet Year, 20% Reduced TN/TP Catchment Loads

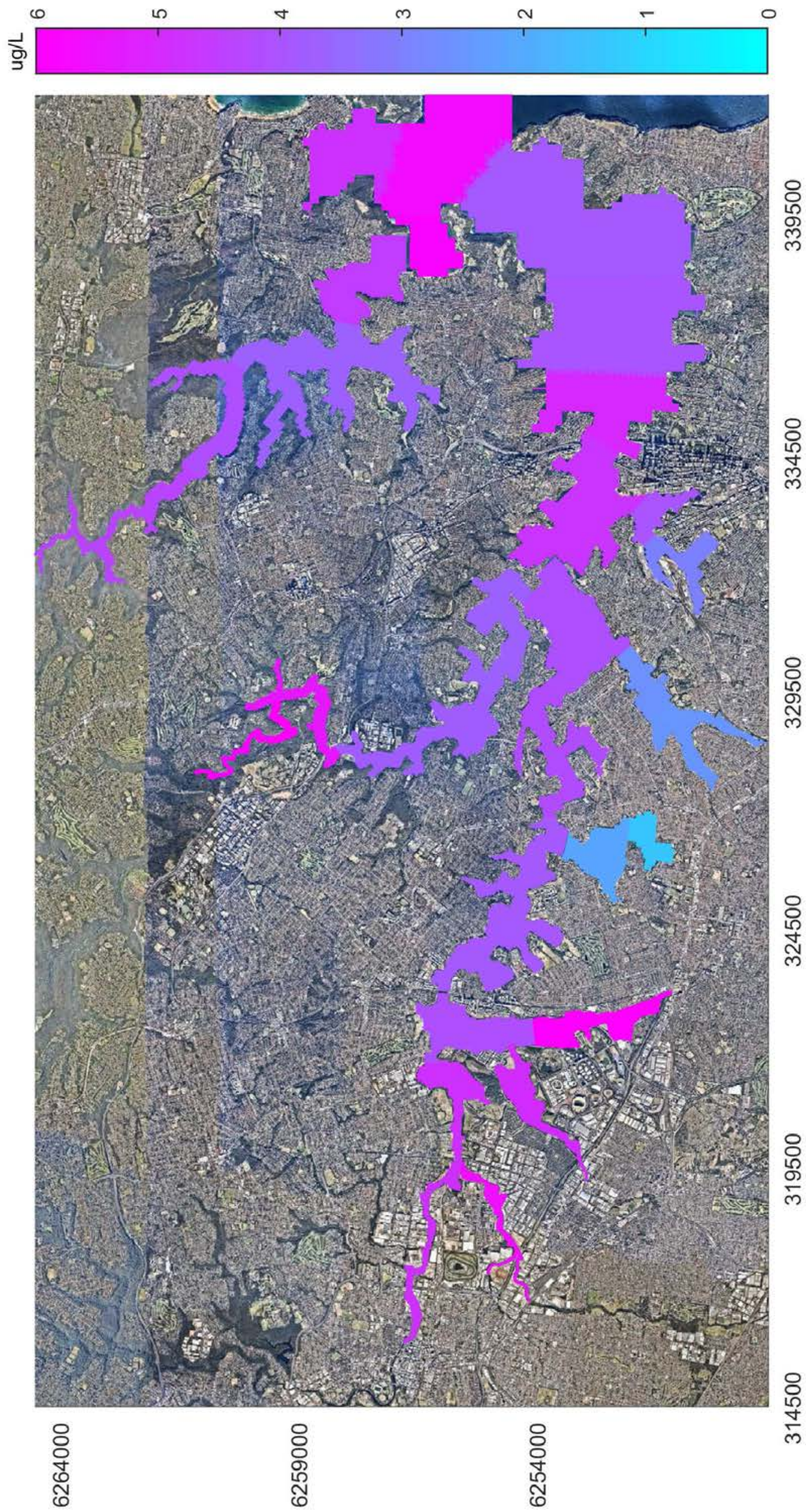
Figure 9.16c



Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer Change in 90% Chl−a
BLOOM Model − Wet Year, 20% Reduced TN/TP Catchment Loads

Figure 9.17



Sydney Harbour Ecological Response Model

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Water Quality 3D Box Model: Surface Layer 50% Chl−a Concentration (ug/L)
BLOOM Model − Wet Year, +0.9m SLR Scenario

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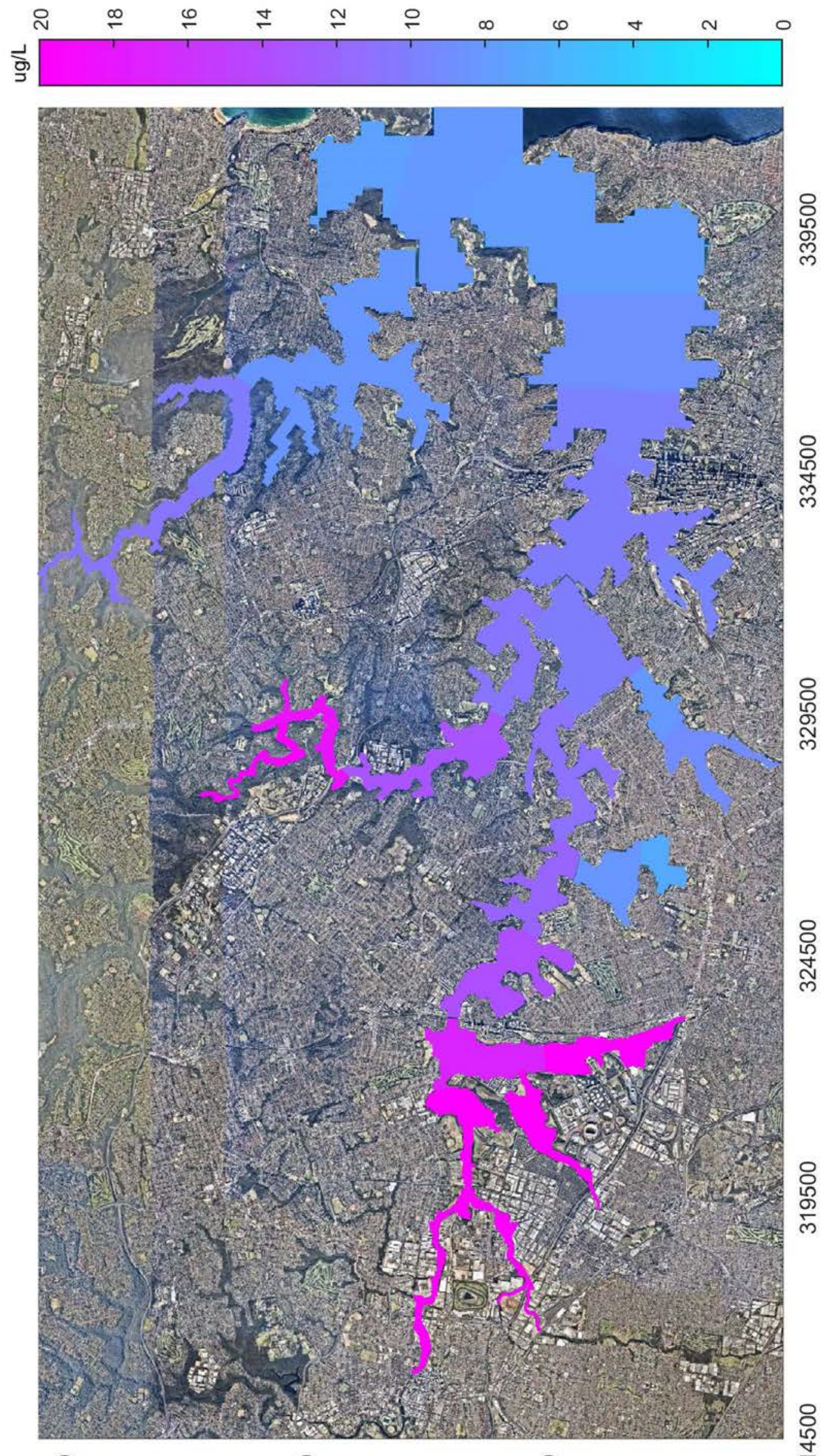
Figure 9.18a



Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 90% Chl−a Concentration (ug/L)

BLOOM Model − Wet Year, +0.9m SLR Scenario

Figure 9.18b

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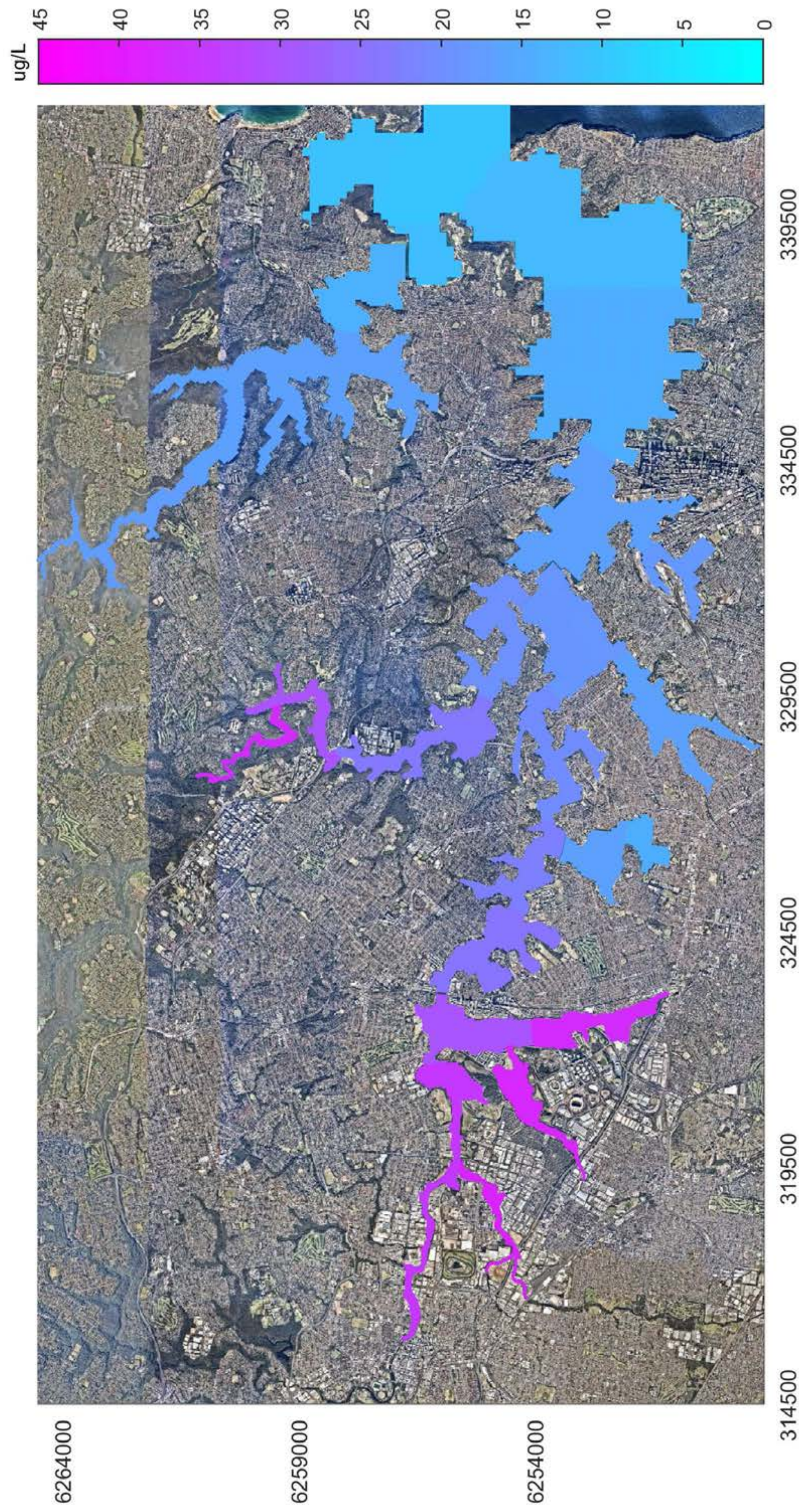
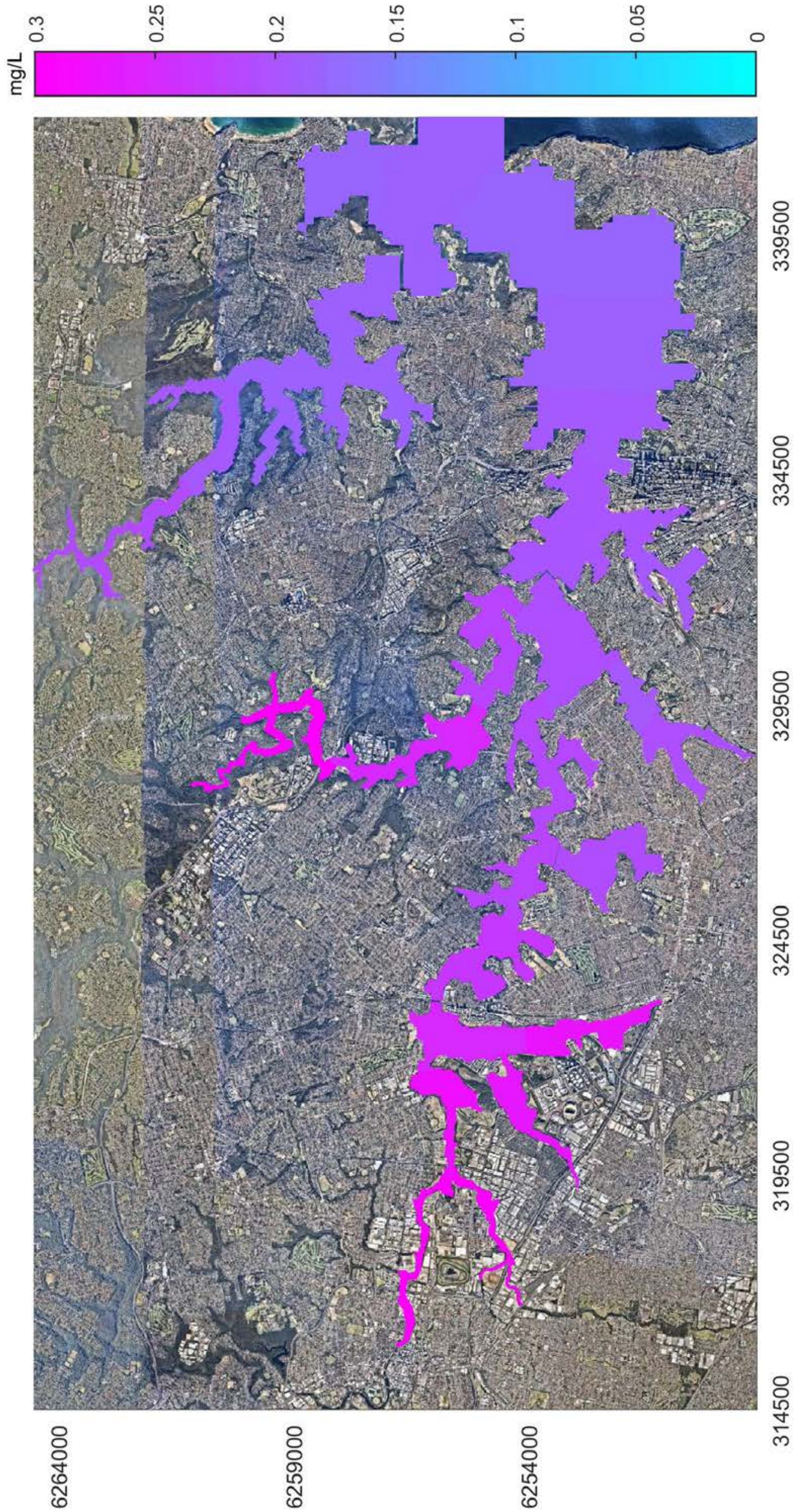


Sydney Harbour Ecological Response Model

Cardno Water Quality 3D Box Model: Surface Layer 99% Chl−a Concentration (ug/L)

BLOOM Model − Wet Year, +0.9m SLR Scenario

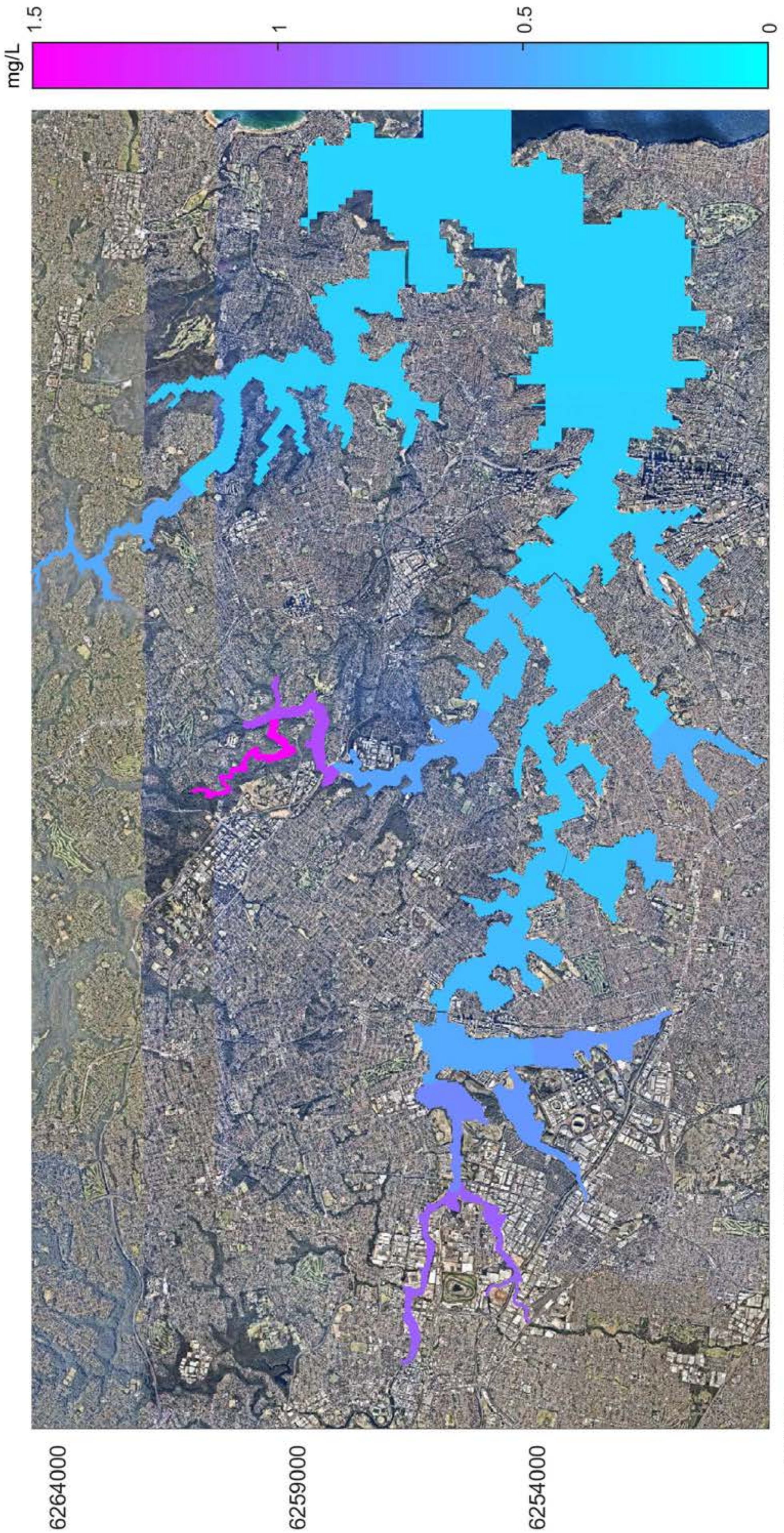
Figure 9.18c



Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 50% Total Nitrogen (mg/L)
BLOOM Model − Wet Year, +0.9m SLR Scenario

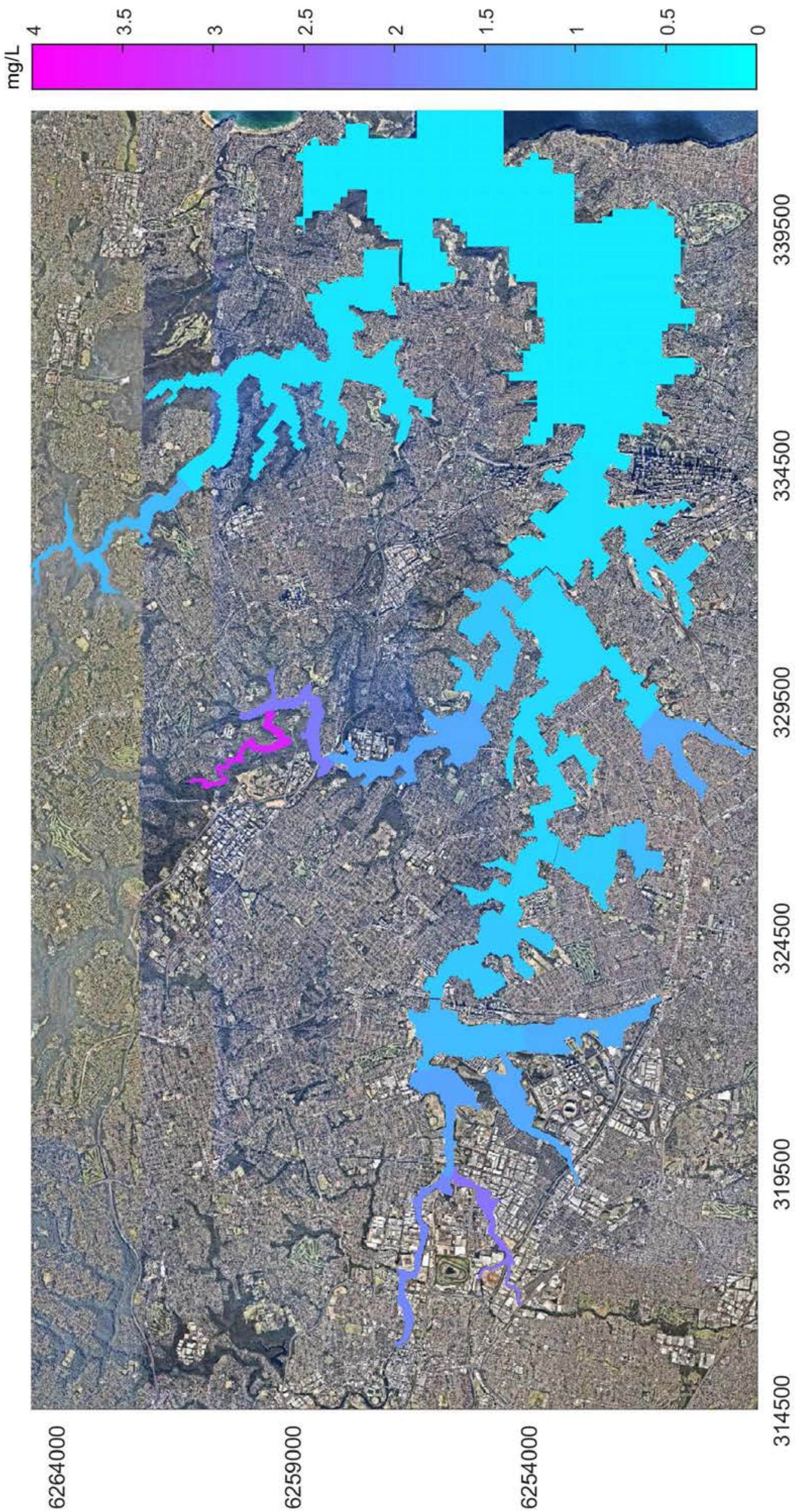
Figure 9.19a



Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 90% Total Nitrogen (mg/L)
BLOOM Model − Wet Year, +0.9m SLR Scenario

Figure 9.19b



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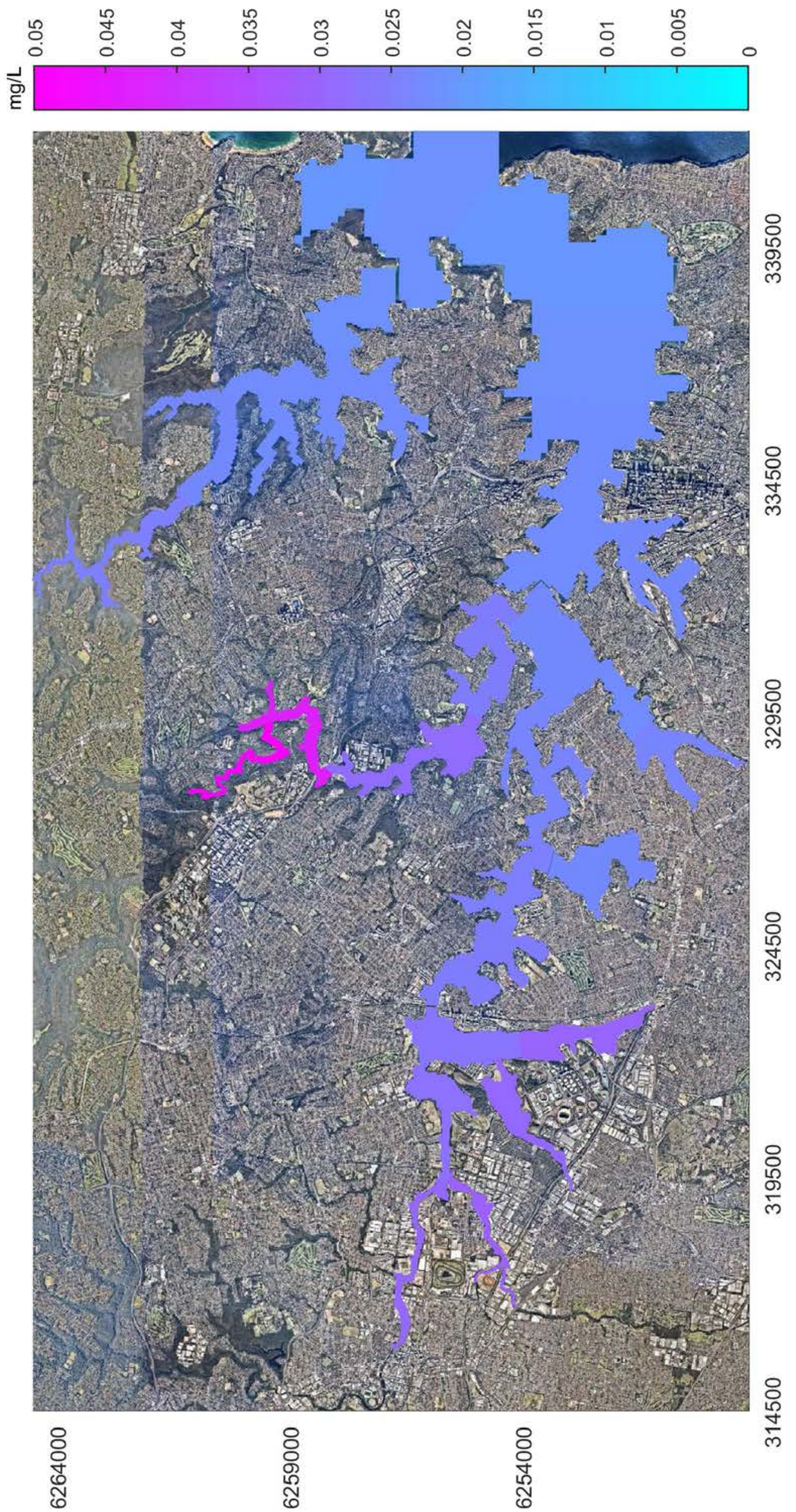
Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 99% Total Nitrogen (mg/L)
BLOOM Model − Wet Year, +0.9m SLR Scenario

Figure 9.19c



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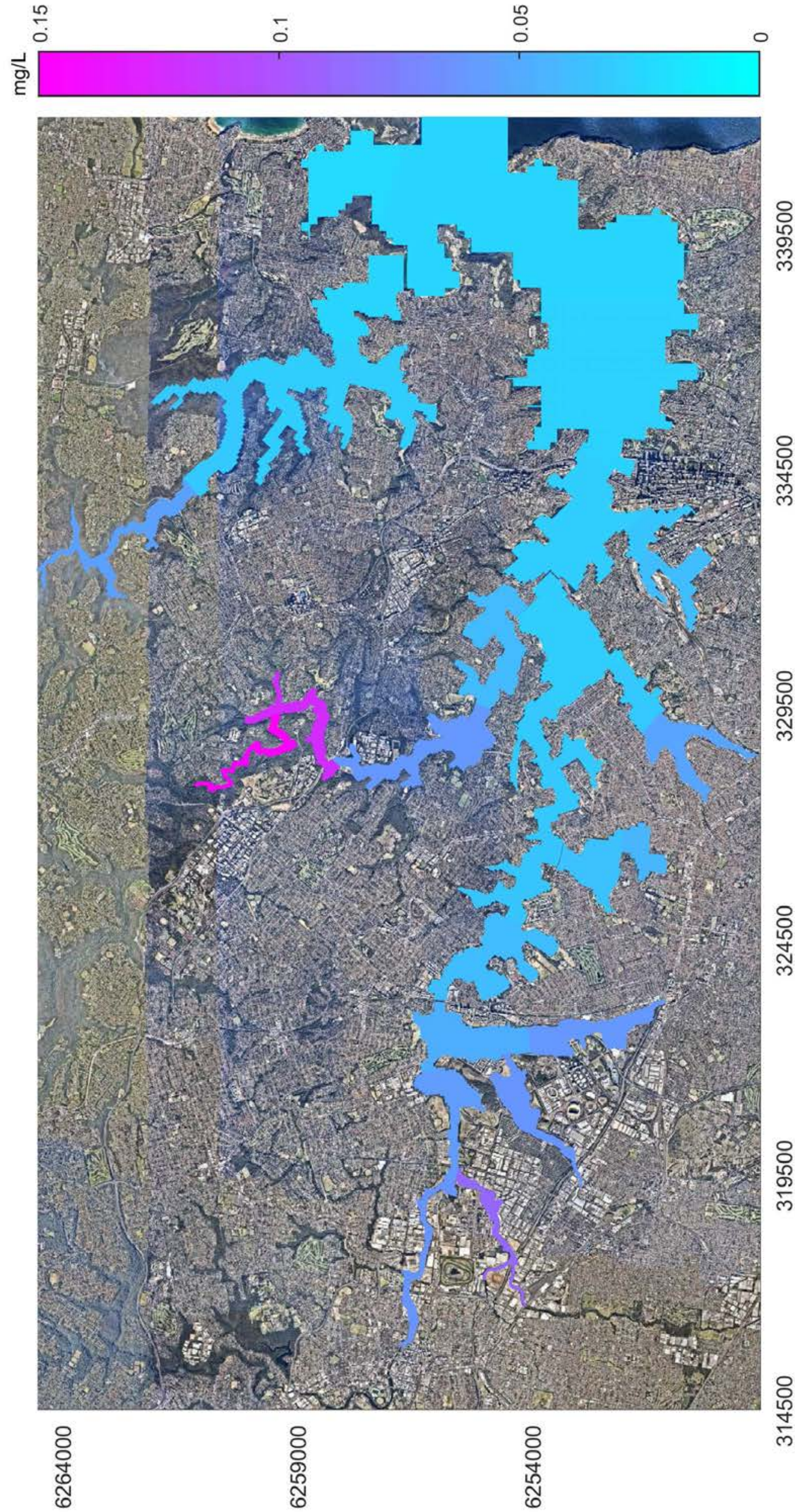
Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 50% Total Phosphorus (mg/L)
BLOOM Model − Wet Year, +0.9m SLR Scenario

Figure 9.20a



Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 90% Total Phosphorus (mg/L)
BLOOM Model − Wet Year, +0.9m SLR Scenario

Figure 9.20b

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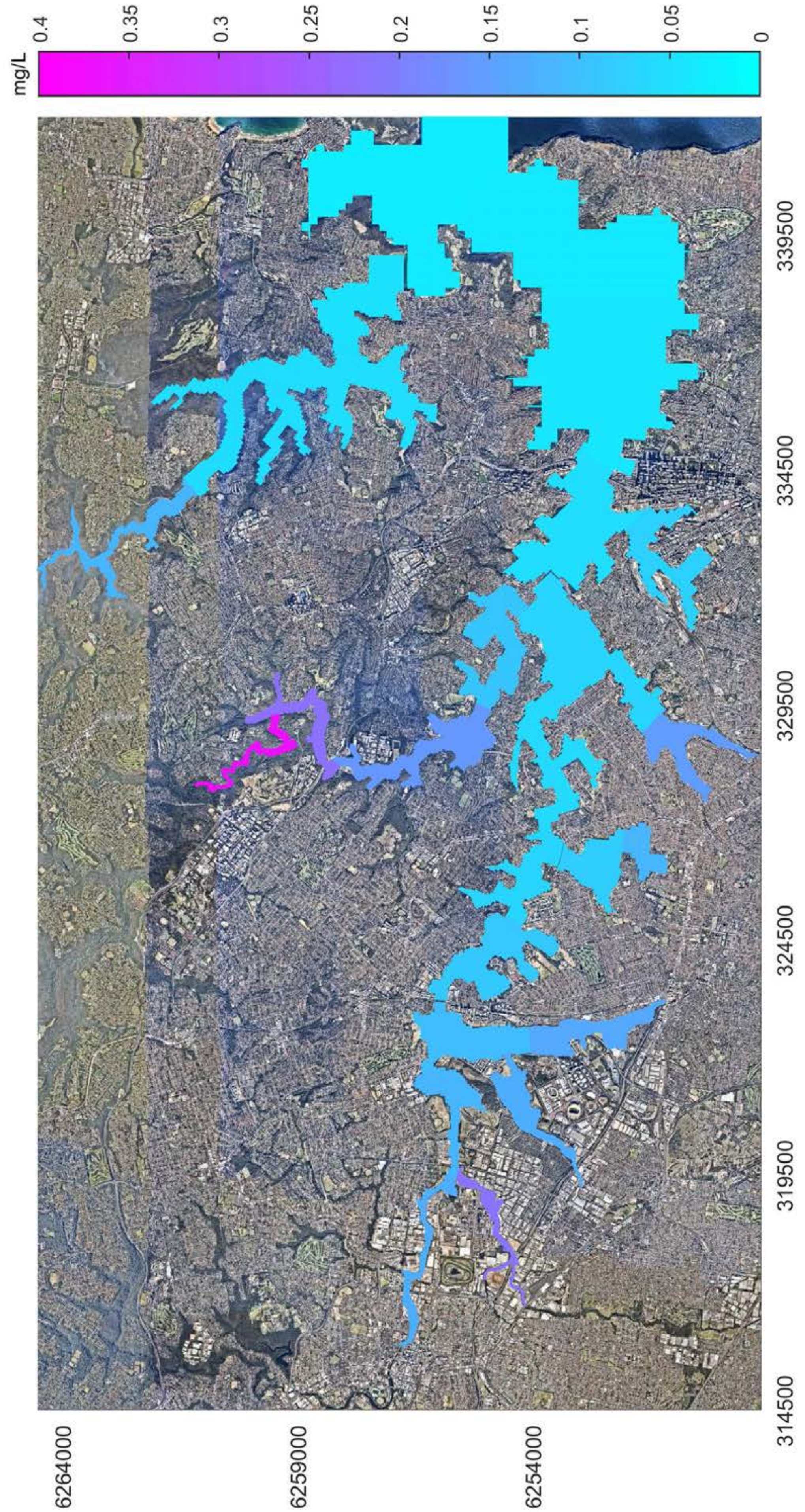

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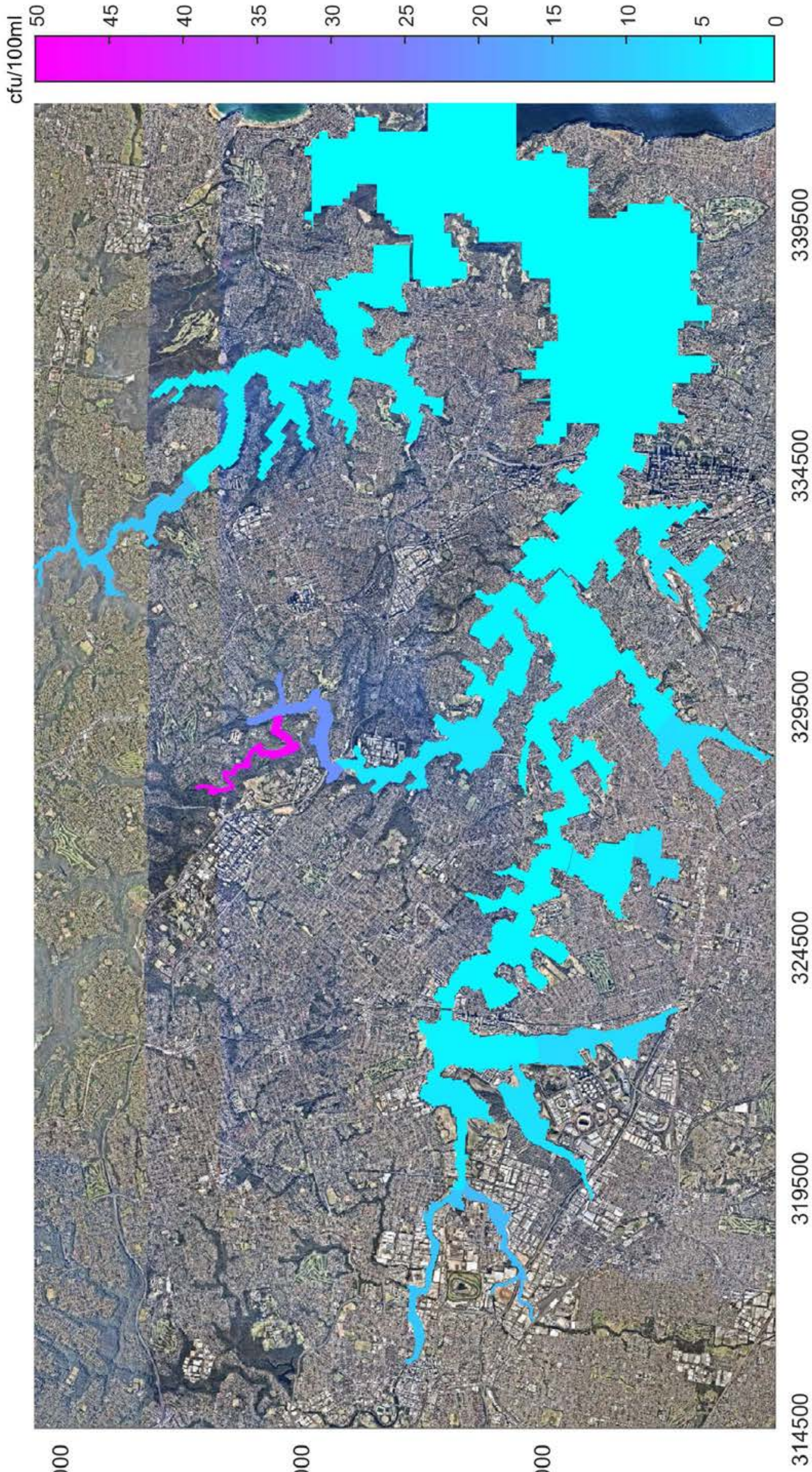
Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 99% Total Phosphorus (mg/L)
BLOOM Model − Wet Year, +0.9m SLR Scenario

Figure 9.20c



Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 50% Enterococci (cfu/100ml)
BLOOM Model − Wet Year, +0.9m SLR Scenario

Figure 9.21a

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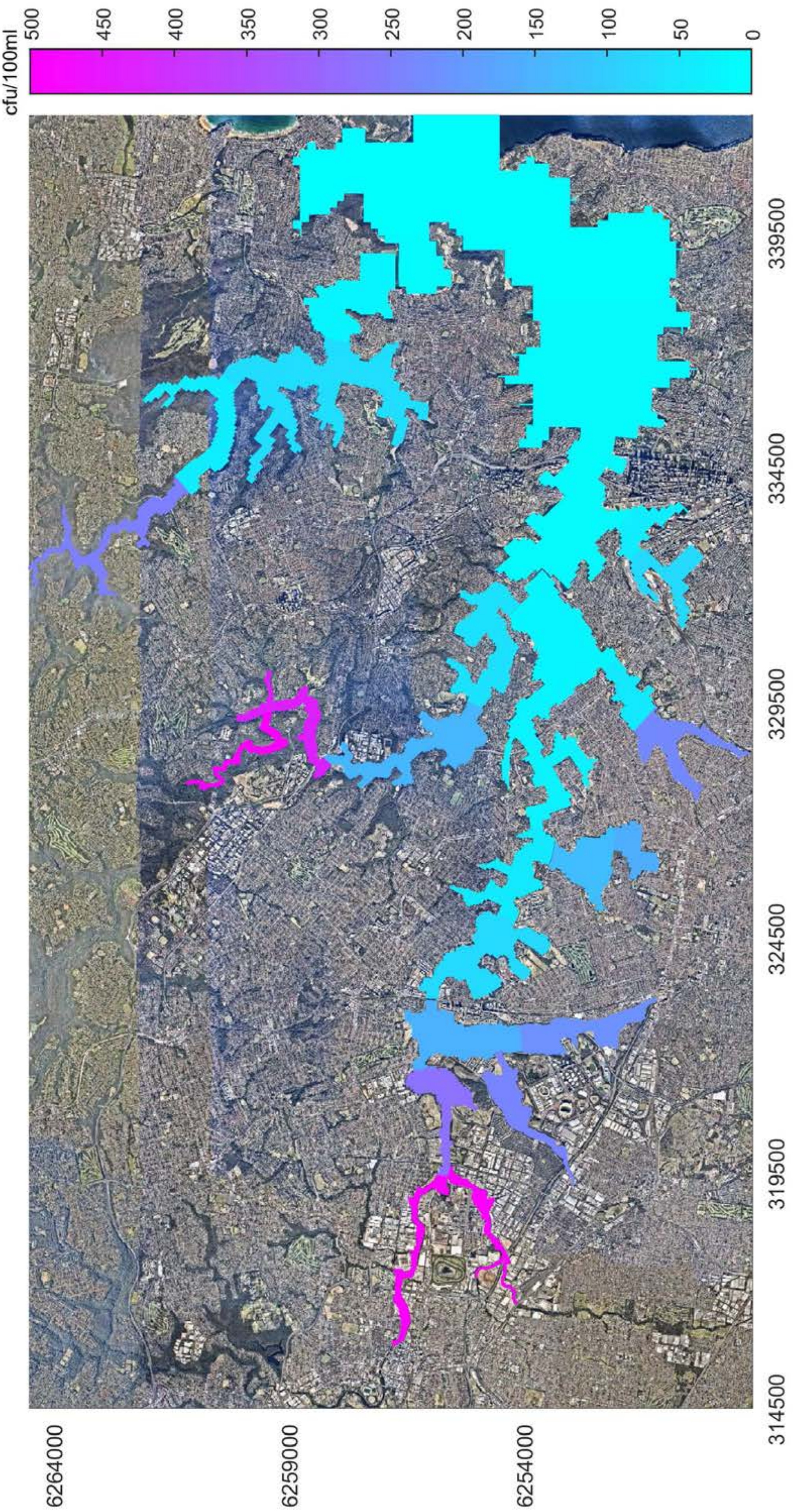

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Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 90% Enterococci (cfu/100ml)
BLOOM Model − Wet Year, +0.9m SLR Scenario

Figure 9.21b

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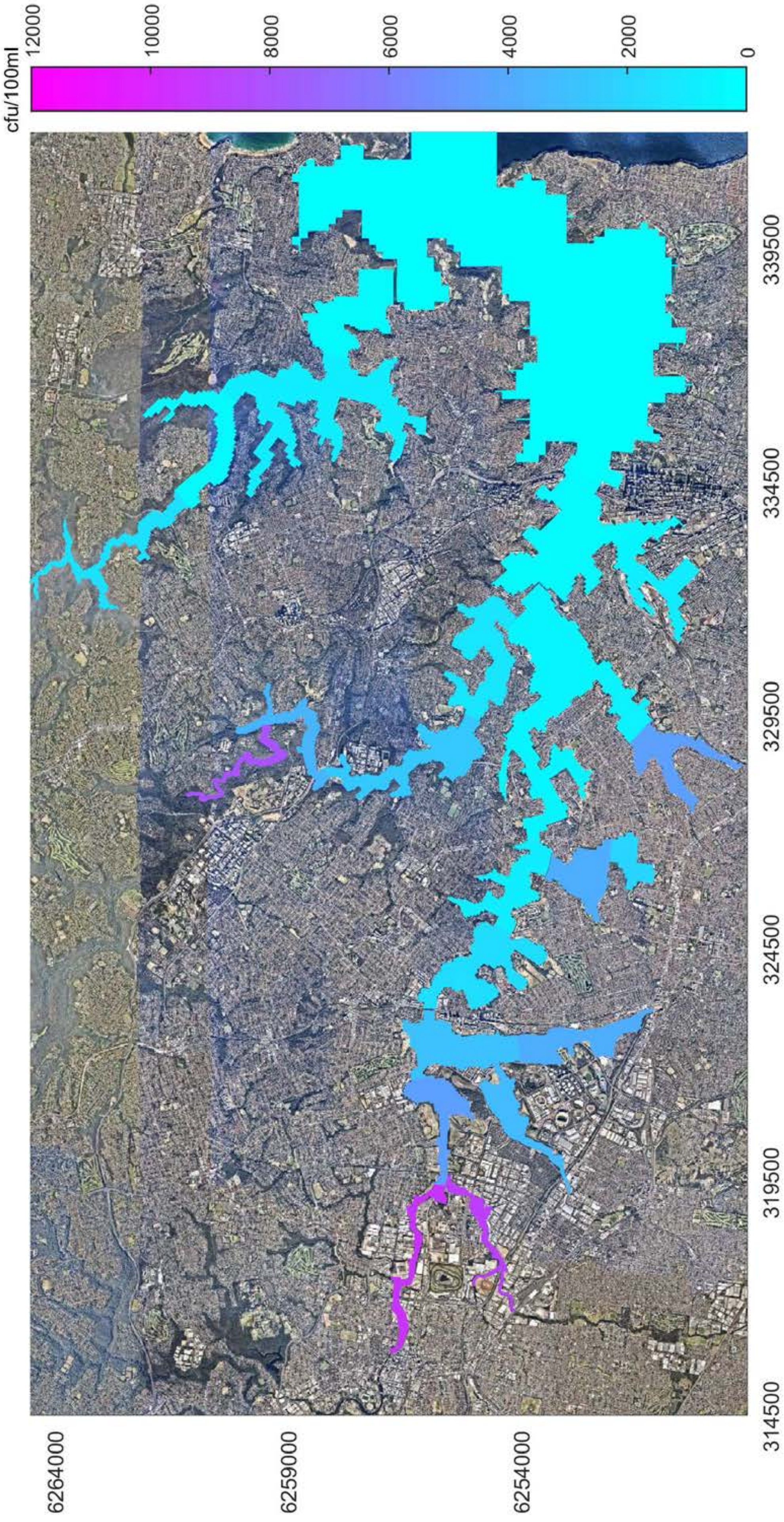

Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer 99% Enterococci (cfu/100ml)
BLOOM Model − Wet Year, +0.9m SLR Scenario

Figure 9.21c

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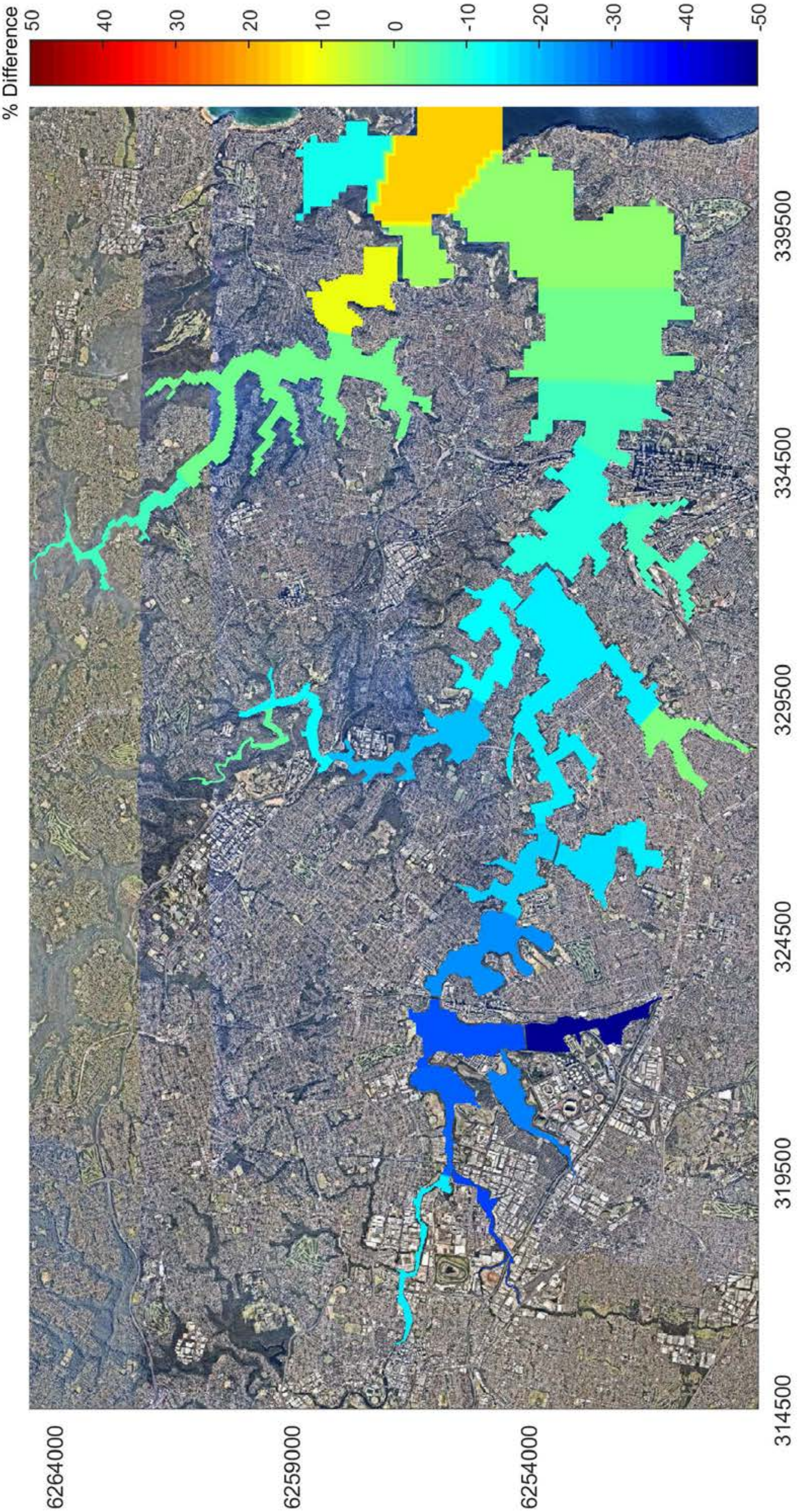
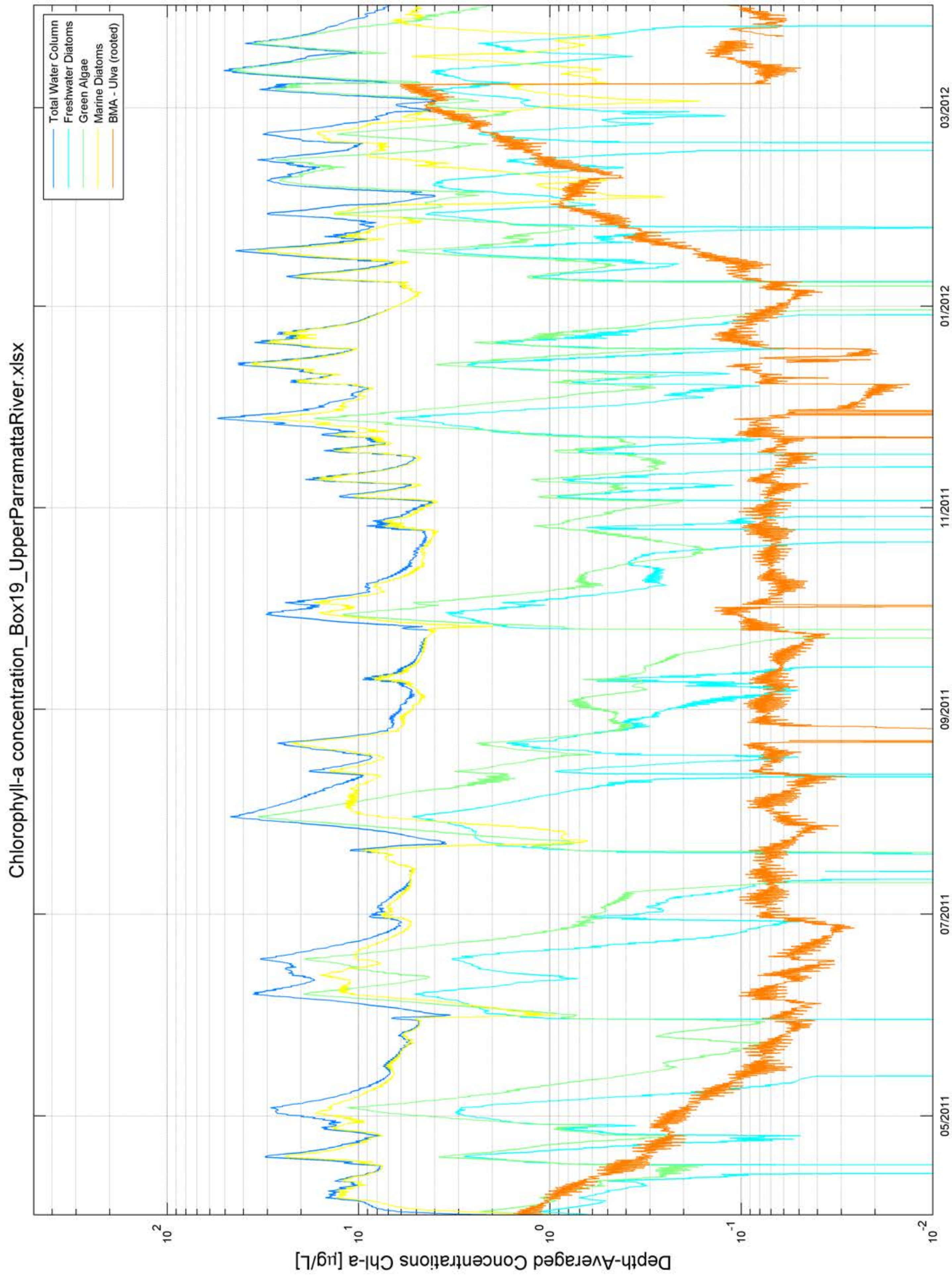


Sydney Harbour Ecological Response Model

Water Quality 3D Box Model: Surface Layer Change in 90% Enterococci
BLOOM Model − Wet Year, +0.9m SLR Scenario

Figure 9.22



Sydney Harbour Ecological Response Model

Time Series of Modelled Algal Concentrations
Detailed WAQ – Upper Parramatta River

Figure 9.23

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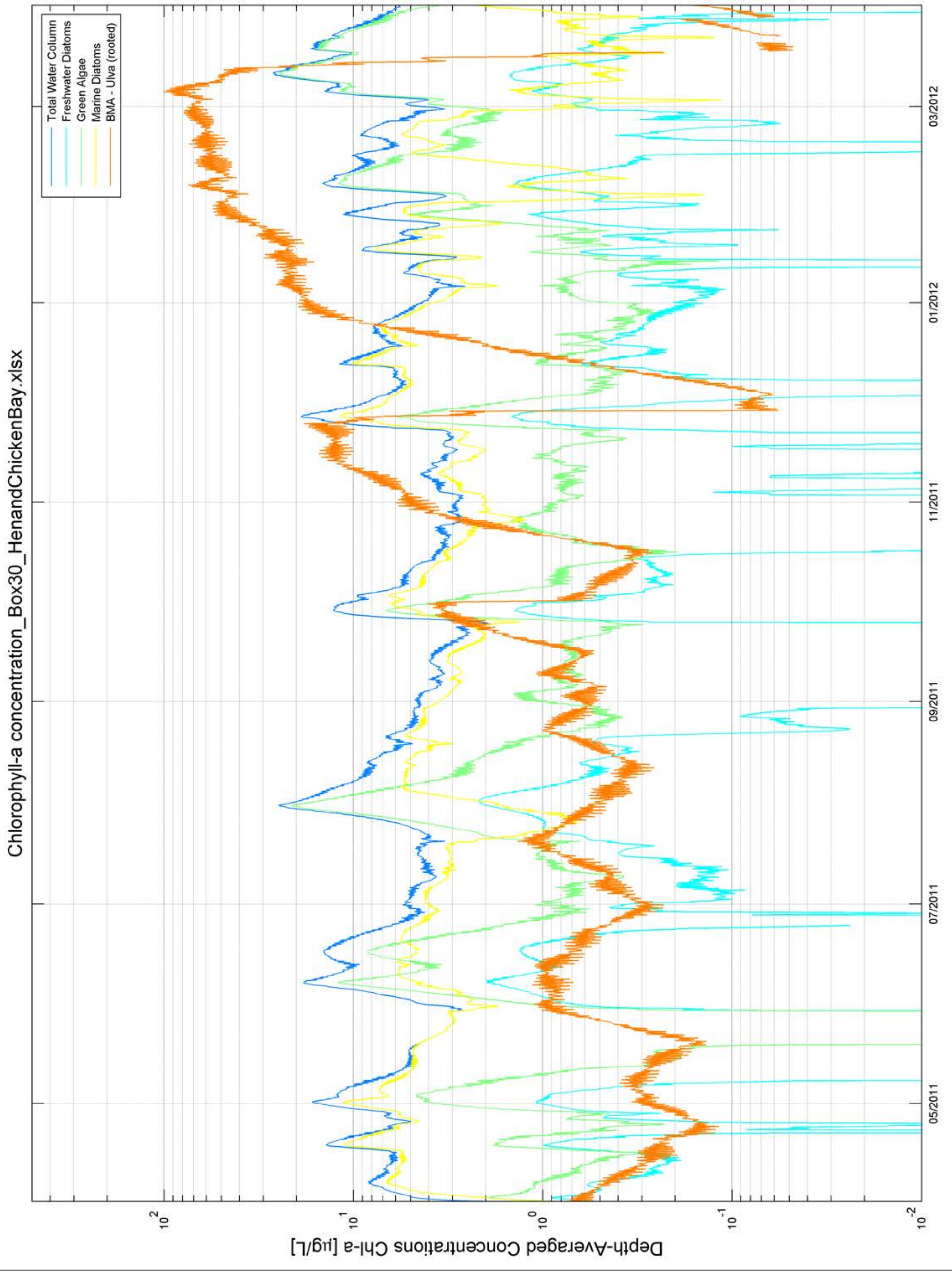
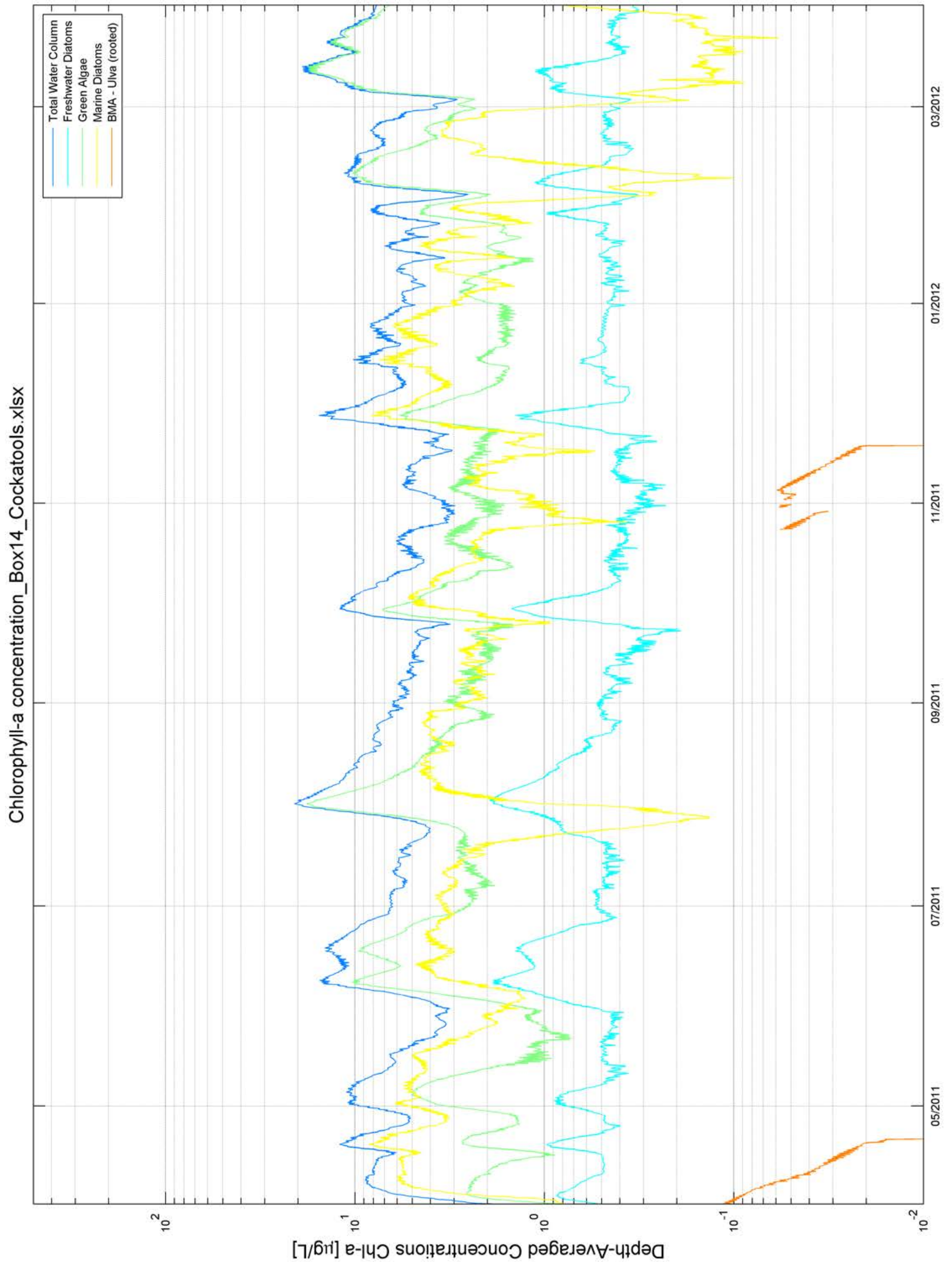


Sydney Harbour Ecological Response Model

Time Series of Modelled Algal Concentrations
Detailed WAQ − Hen and Chicken Bay

Figure 9.24



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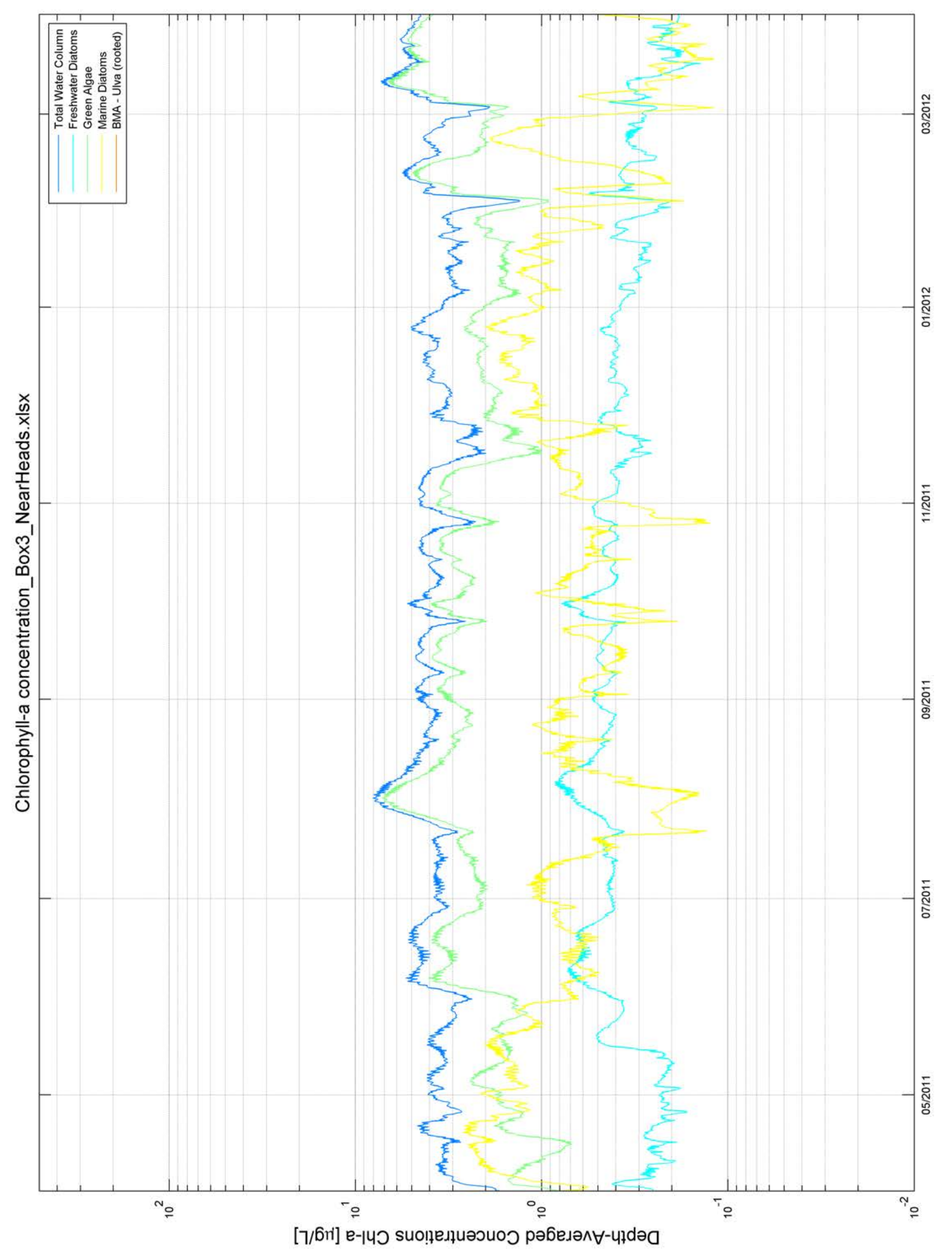
Sydney Harbour Ecological Response Model

Time Series of Modelled Algal Concentrations
Detailed WAQ – Cockatoo Island

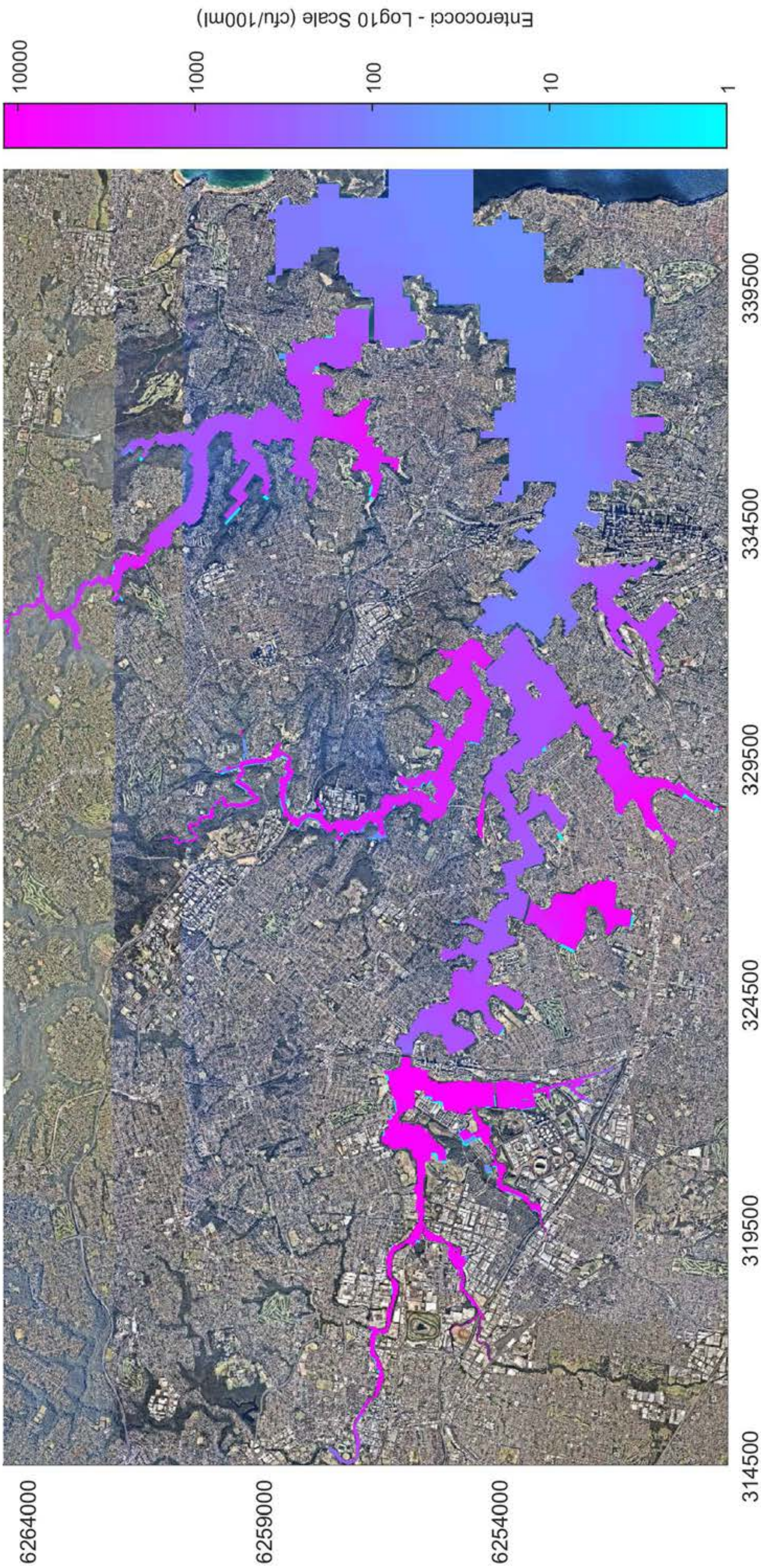
Figure 9.25



Sydney Harbour Ecological Response Model

Time Series of Modelled Algal Concentrations
Detailed WAQ − Near Heads

Figure 9.26



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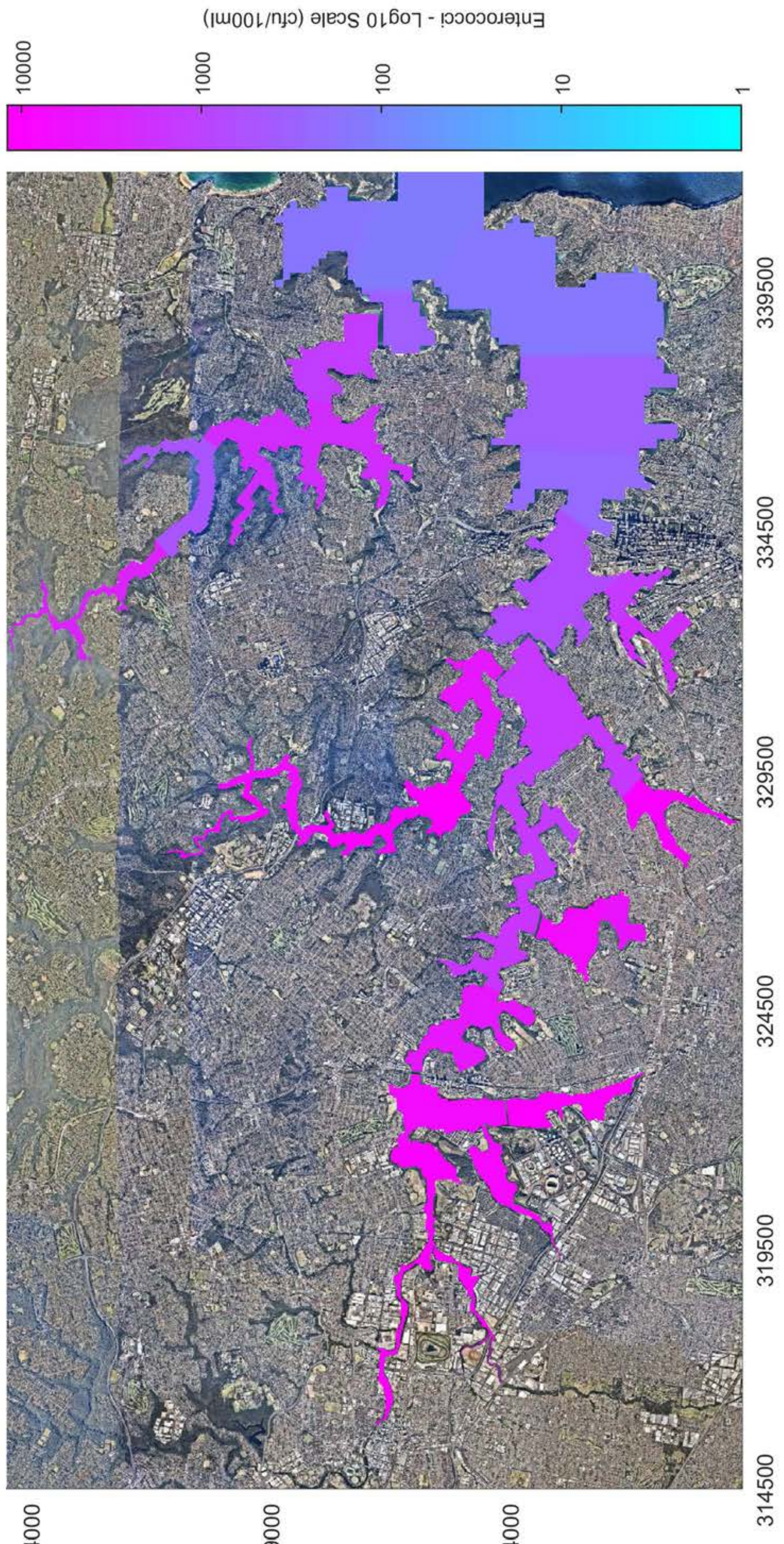
Sydney Harbour Ecological Response Model

Map of Enterococci in Surface Layer
Detailed WAQ

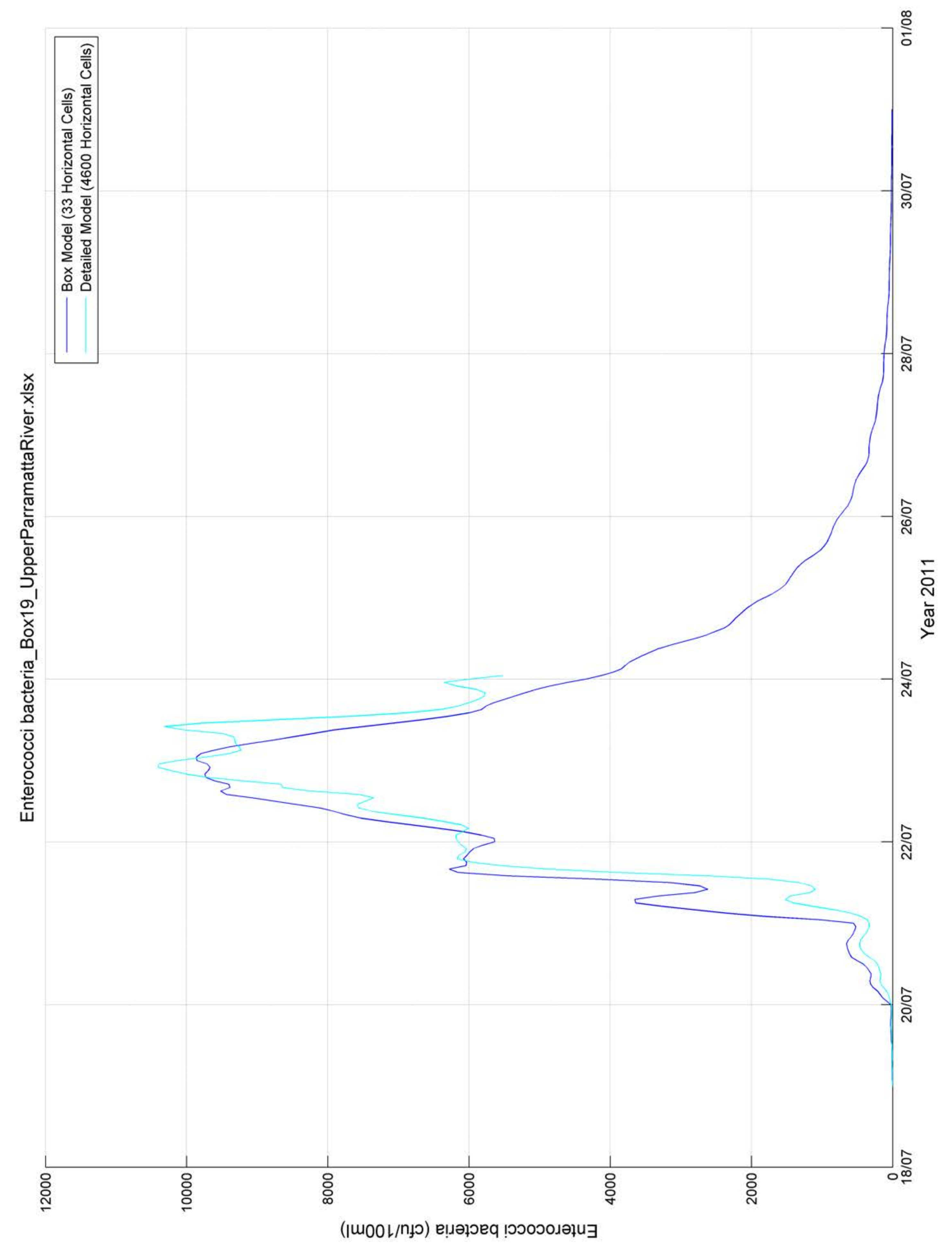
Figure 9.27



Sydney Harbour Ecological Response Model

Map of Enterococci in Surface Layer
Box WAQ

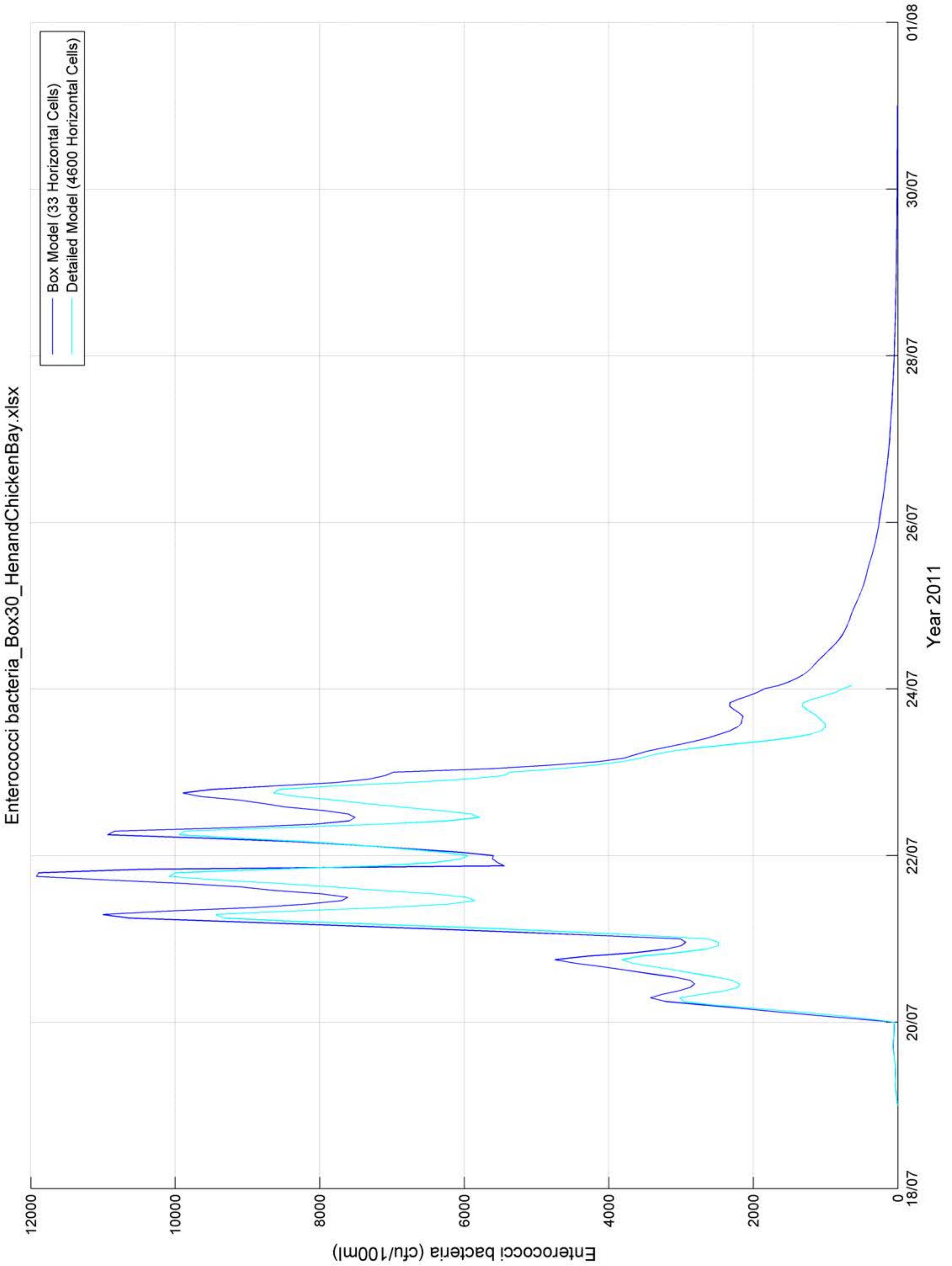
Figure 9.28



Sydney Harbour Ecological Response Model

Time Series of Enterococci
Detailed vs Box WAQ − Upper Parramatta River

Figure 9.29



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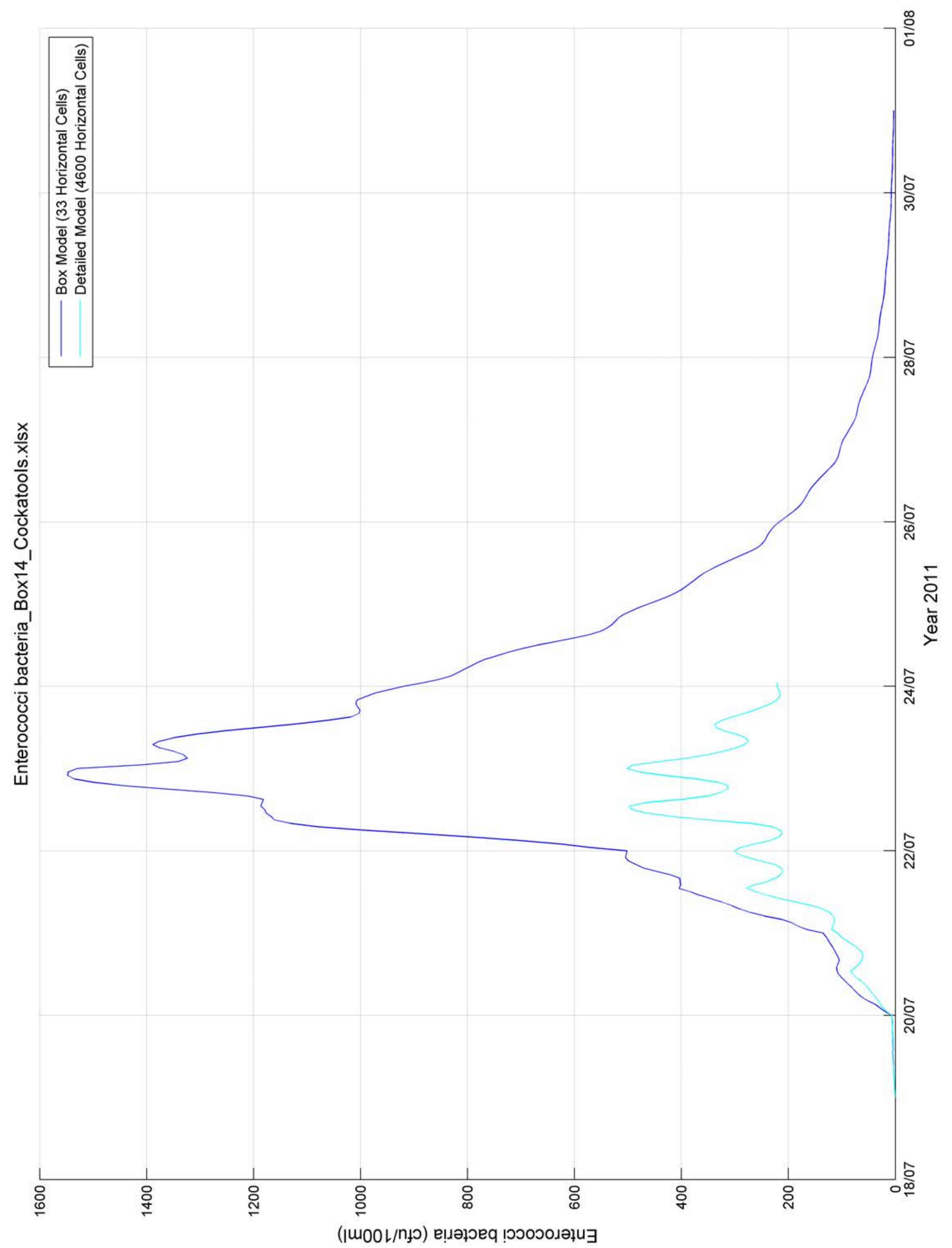
Sydney Harbour Ecological Response Model

Time Series of Enterococci
Detailed vs Box WAQ − Hen and Chicken Bay

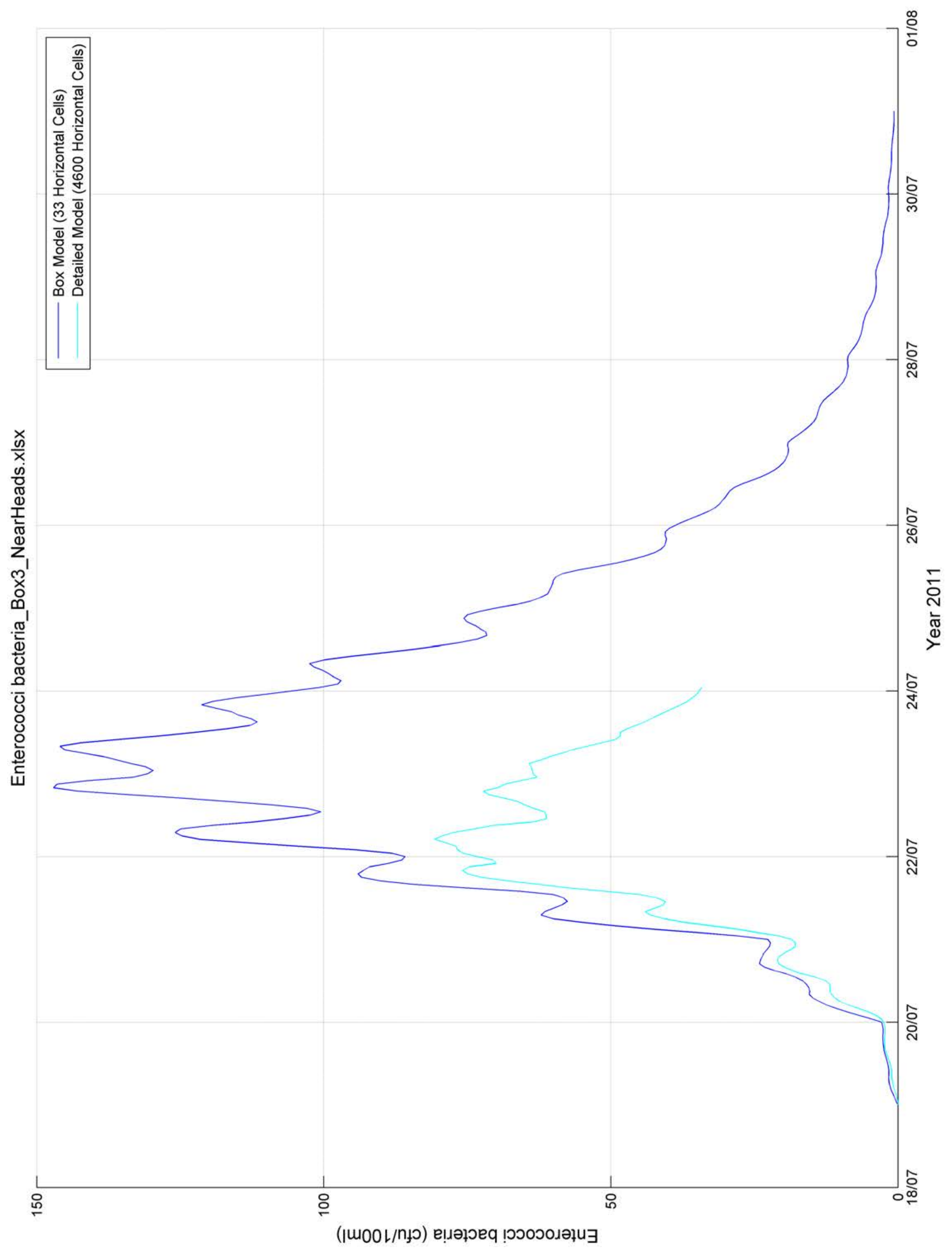
Figure 9.30



Sydney Harbour Ecological Response Model

Time Series of Enterococci
Detailed vs Box WAQ − Cockatoo Island

Figure 9.31



Sydney Harbour Ecological Response Model

Time Series of Enterococci
Detailed vs Box WAQ − Near Heads

Figure 9.32