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27 March 2014

Hawkesbury-Nepean Catchment Management Authority
10 Valentine Avenue
PARRAMATTA NSW 2124

Attention: Dr Peter Freewater

CC: Dr David van Senden (Cardno), David Taylor (Baird Australia), Sean Garber (Baird Australia)

Dear Peter,

SYDNEY HARBOUR ERM – SETUP AND CALIBRATION OF 3D MODEL OF PORT JACKSON AND THE PARRAMATTA RIVER

PREAMBLE

Following discussions between the Hawkesbury-Nepean Catchment Management Authority (CMA), Baird and Cardno, the following scope of work/model simulations is being undertaken by the study team (Cardno and Baird). The final details and specifications for a number of inputs and requirements of the model systems are still being finalised including:-

- Bayesian zone definition clarification with Rebecca Kelly (isNRM Pty Ltd) (in resolution);
- Catchment runoff information details from Joel Stewart (Catchment Research Pty Ltd - CRPL) (clarified 25 March 2014); and
- Water quality processes with Angus Ferguson (OEH) (meeting canceled, correspondence in preparation).

This letter summarises the construction and development and recalibration of a detailed 2D/3D hydrodynamic model of Port Jackson and the Parramatta River. The purpose of this hydrodynamic model is to provide spatial and temporal descriptions of tidal levels, currents and salinity that will be used to drive a detailed water quality and ecological response model for Port Jackson and the Parramatta River termed the Sydney Harbour Ecological Response Model - SHERM. Water temperatures will be handled by adopting monthly temperatures based on recorded 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 CMA 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 CMA. An additional set of spring-summer WQ data was collected over the period from October to December 2012.

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.

2D OPTIMISATION & CALIBRATION

Significant effort has been 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 time and minimise the impact on the calibrated model flows.

Figure 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 1 below summarizes the optimizing process by presenting the number of cells and minimum and maximum grid resolutions of the 9 model domains (pre and post stages):-

Table 1: Model Grid Counts and Dimension Ranges

Grid	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 3 in both the M and N grid directions. However, you will 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. The excessive details of the pre-optimization grid setup have been removed (grid resolution under 4m).

The 2D post-optimization model is now 25 times faster than the pre-optimization model due to the reduction in the number of grid cells that 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.

Furthermore, sub-grid weir structures were updated or introduced at:-

- Marsden Street
- Charles Street
- Lane Cove weir

These structures are critical for the management of important catchment flows coming from upstream and also control the water levels upstream of the weirs.

Figure 2 presents the overall model bathymetry overlaid by the location of the 9 cross section discharge measurement locations from Lawson and Treloar (1992).

Figures 3a and **3b** show the calibration results that compare the measured flow discharges with the pre and post-optimization model results. This figure demonstrates that the pre and post-optimization models both perform very well when compared to measurements at all cross-sections. The very good correlation between the measurements and the models can be linked to the intensive calibration of the pre-optimisation model (eddy viscosity, roughness maps, bathymetry, 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, which is being undertaken in this project, there is no appreciable differences in the hydrodynamic fluxes which are provided by either the original detailed model, or the computationally optimised model layout.

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 the turbulent exchange of oxygen, heat, salinity, suspended sediments and passive contaminants. 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: 3D-Z and 3D-Sigma layer models.

Both options have been tested to identify the most 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.

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 salinity and temperature.

The vertical grid system in the Z-model is based on horizontal layers with constant z co-ordinate 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 2 presents the horizontal layer configuration adopted for the Z-model.

Table 2: Z Model Vertical Grid Structure

Z-model		Depth Extent Levels		Maximum Width (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 4a 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 4b** that shows 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 3a and **3b** 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.

3D-SIGMA LAYER MODEL

For the vertical sigma-coordinate 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 is constant in this case.

The vertical sigma-grid is commonly used in Delft3D-FLOW. However, occasionally this grid may not be sufficient to solve 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 the physical space. However, this is not a common, persistent feature of the water column in Sydney Harbour, as demonstrated by the data collected by SIMS for the CMA as demonstrated in **Figure 5.** 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 indicates that for nearly 80% of site samples over that period, the observed salinity gradient is 0.25 ppt or less. A total of 10% of samples observed a salinity gradient 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 is considered to be appropriate for the 3D hydrodynamic model discretisation.

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 3a and **3b** 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 6a is a map of the depth averaged velocity from the sigma-model that covers the complete extent of the model. **Figure 6b** shows the vertical cross-section (transect) of the velocity with the sigma-model that can be compared with **Figure 4b** (Z-model). Velocity magnitude and directions are very comparable despite the important changes in the bathymetry. The sigma-model has the advantage to have a better representation of the flows near the seabed because the layer width adapts to bathymetric changes.

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

SALINITY & DISPERSION CALIBRATION

Cardno has undertaken an advanced 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 7** 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 Joel Stewart (March 2014). The catchment discharges were prepared by the study team and adjusted based on previously calibrated water quality model data (Baird Australia, 2013).

Eddy diffusivity has been set universally at $20m^2/s$.

CONCLUDING REMARKS

Cardno has successfully optimized the pre-existing Delft3D 2D hydrodynamic FLOW model by reducing the run time without compromising on the accuracy of the model. This was a key step before the conversion to a 3D model.

Cardno has setup and calibrated 3D hydrodynamic Z and sigma-layer models. Although the Z-layer model enables a better description of the vertical stratification, the sigma-layer model presents similar vertical and horizontal velocity magnitude and direction gradients. The sigma-layer model has been found to run about 5 times faster than the Z-model. The sigma-layer model (8 layers and salinity) requires 1 day of computational time for 1 day of real time.

The study team has decided to use the 3D hydrodynamic sigma-model to generate the hydrodynamic flow data required as input for the water quality modelling. However, the hydrodynamic sigma-model outputs will be converted into equivalent Z-layer data prior to be used with Delft3D-WAQ model because the stratification is critical to water quality processes.

Should you have any questions, please don't hesitate to contact me.

Yours faithfully,

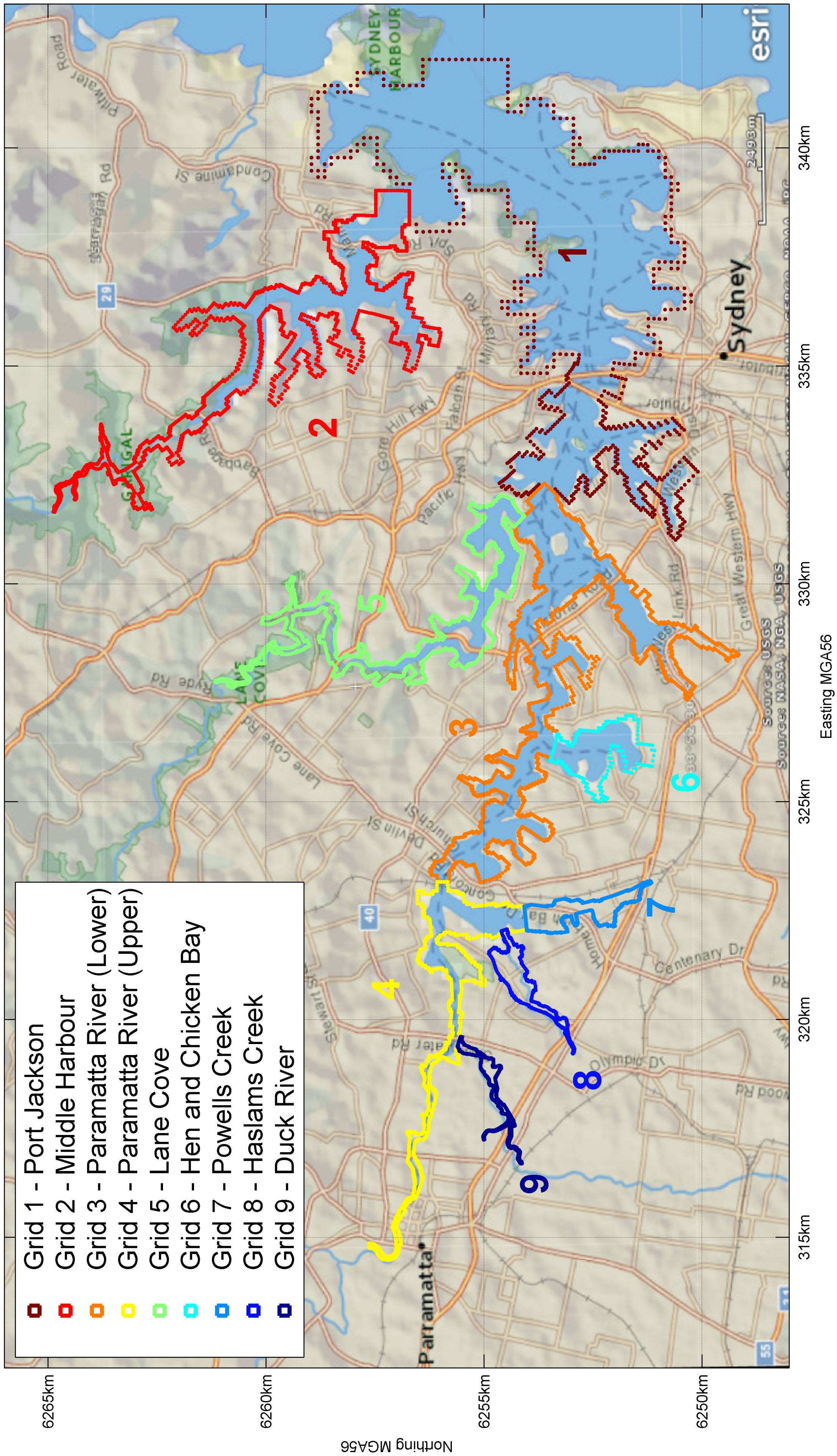
P.D. Treloar
Senior Principal
for **Cardno (NSW/ACT) Pty Ltd**

References

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

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

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 ERM – SETUP AND CALIBRATION OF 3D MODEL

Model Extent and Domain Decomposition

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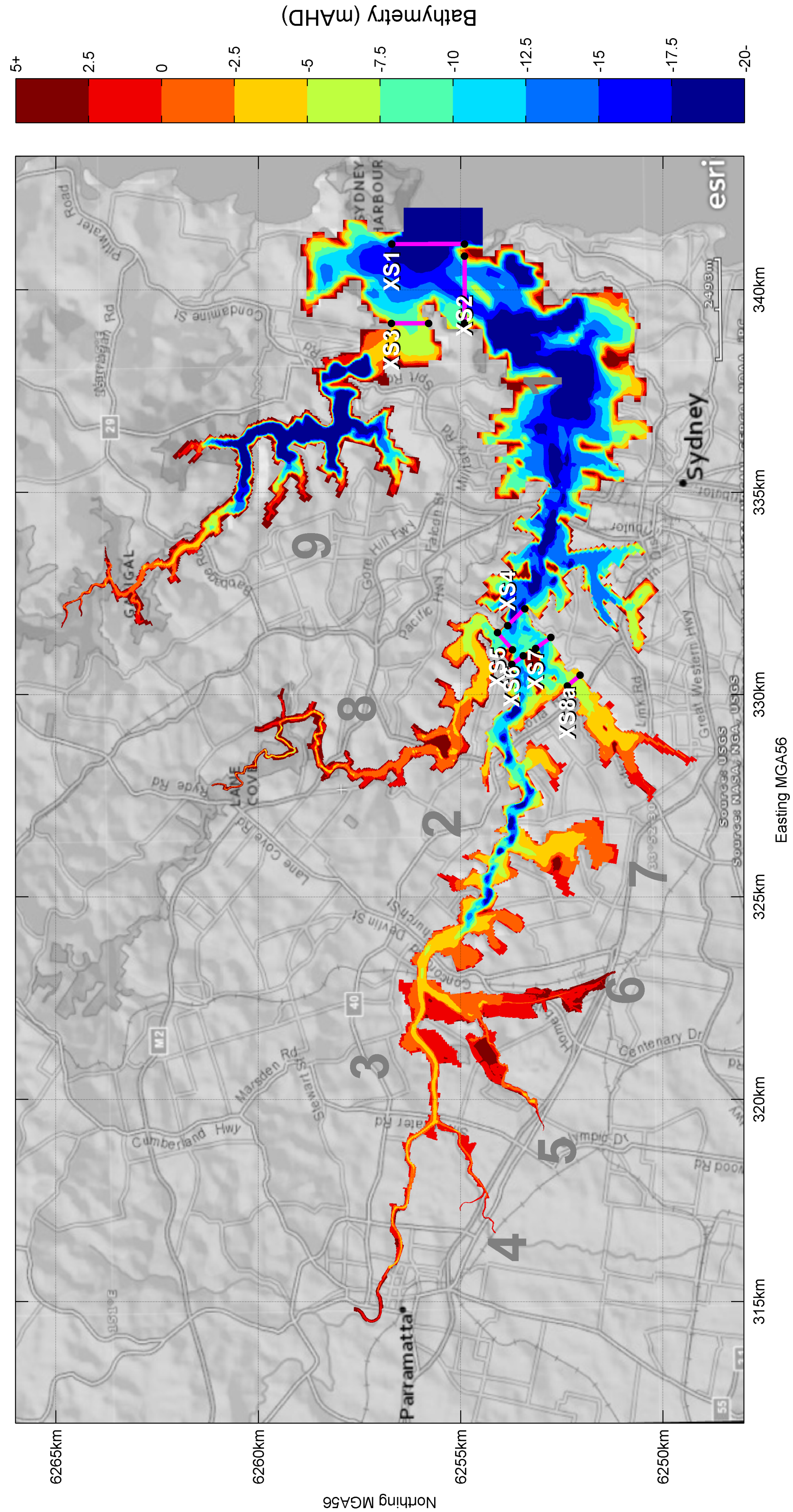
Figure 1



SYDNEY HARBOUR ERM – SETUP AND CALIBRATION OF 3D MODEL

Model Bathymetry
Discharge Calibration Cross−Section Locations

Figure 2

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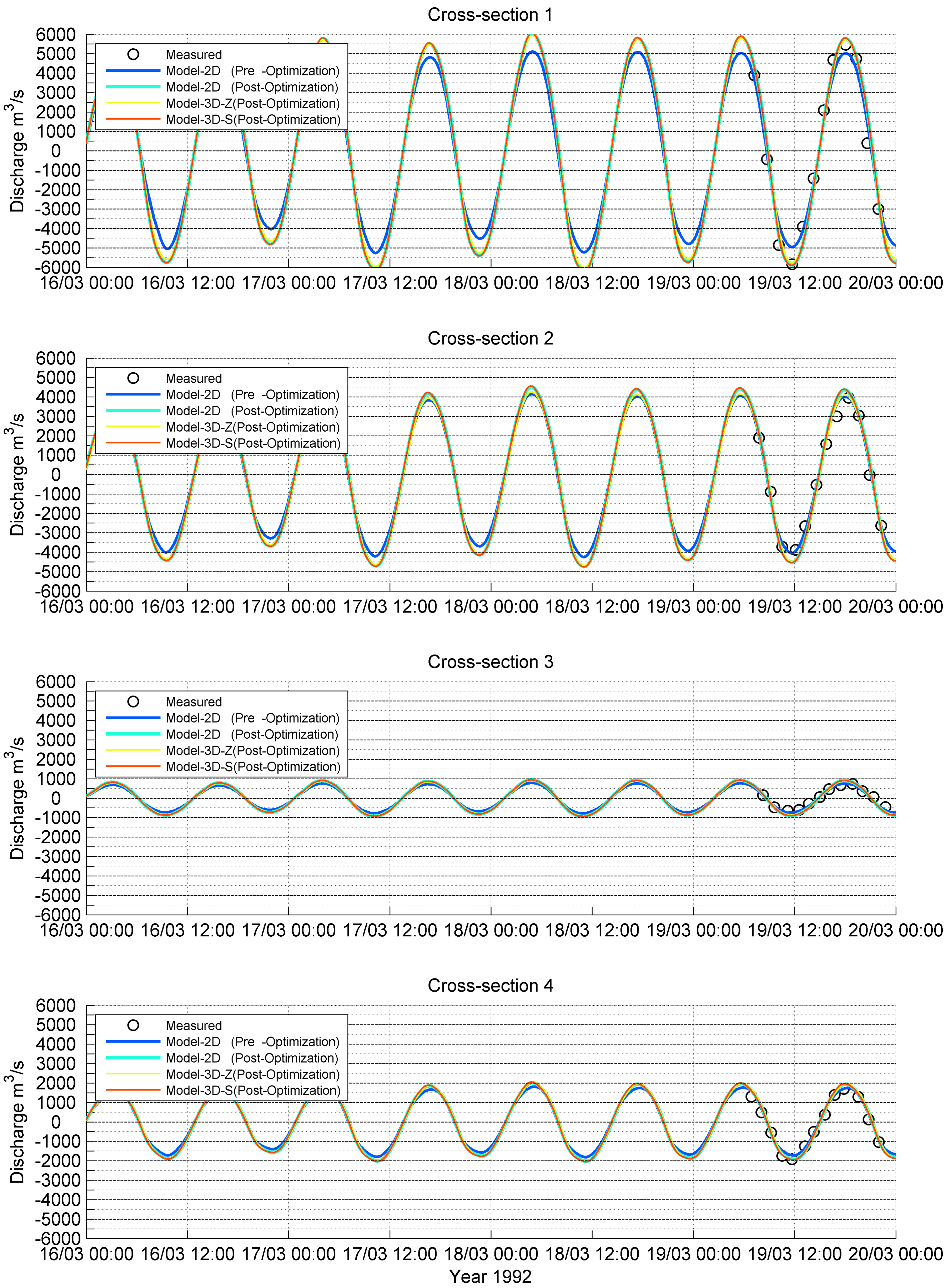

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SYDNEY HARBOUR ERM – SETUP AND CALIBRATION OF 3D MODEL

Discharge Calibration Time Series
Cross−section 1 to 4

Figure 3a

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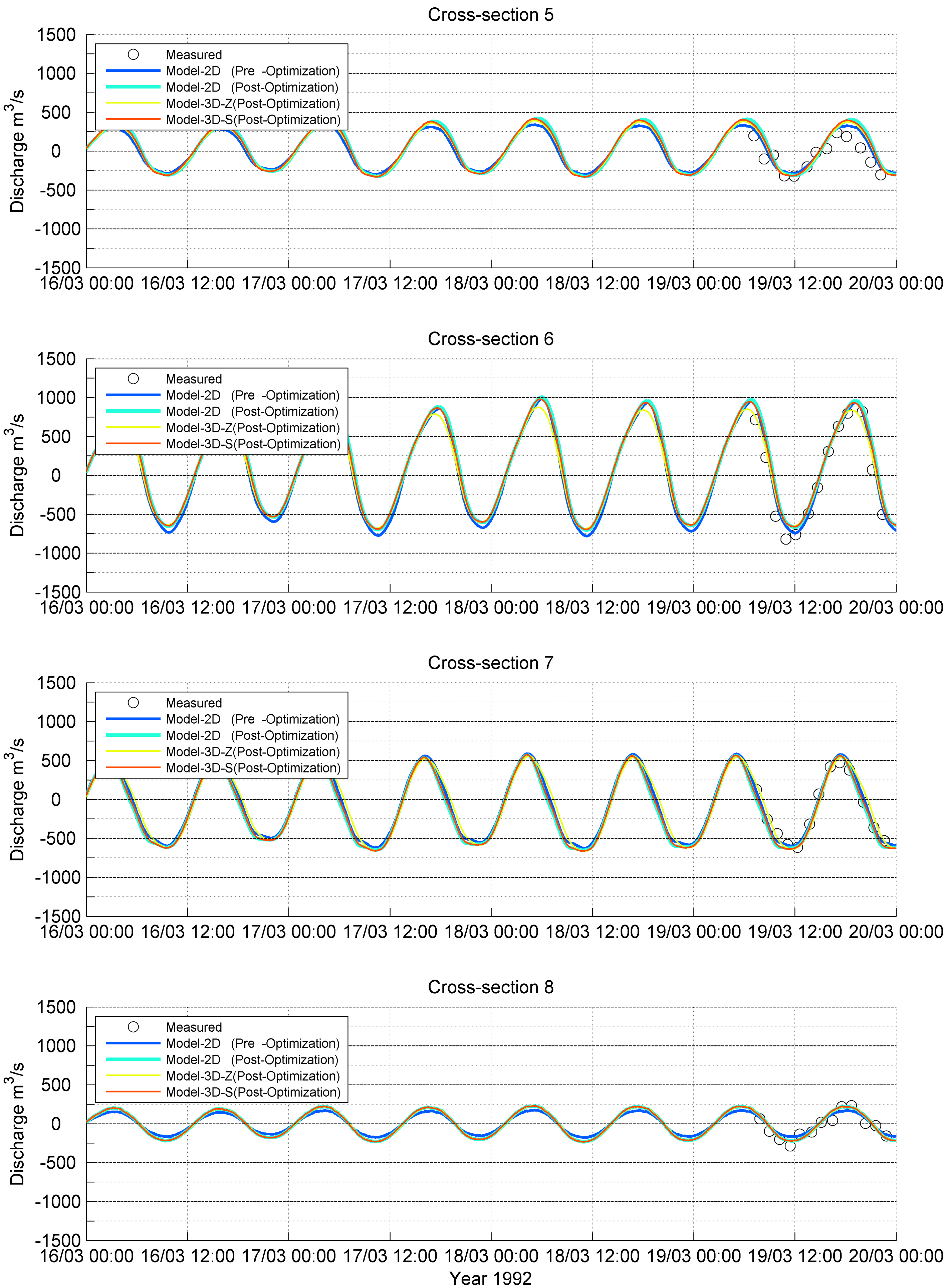

SYDNEY HARBOUR ERM – SETUP AND CALIBRATION OF 3D MODEL

Discharge Calibration Time Series
Cross−section 5 to 8

Figure 3b

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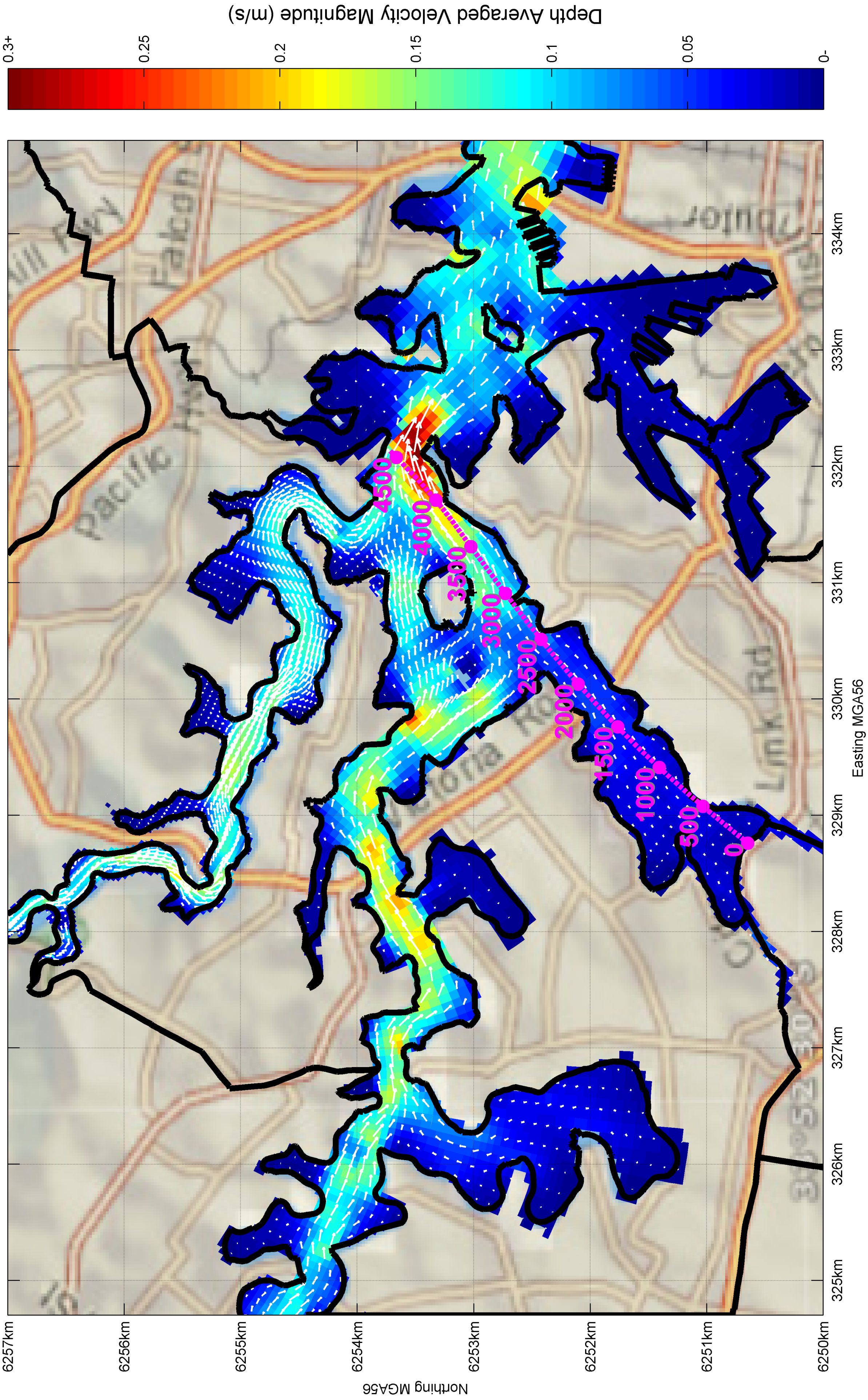

SYDNEY HARBOUR ERM – SETUP AND CALIBRATION OF 3D MODEL

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

Figure 4a

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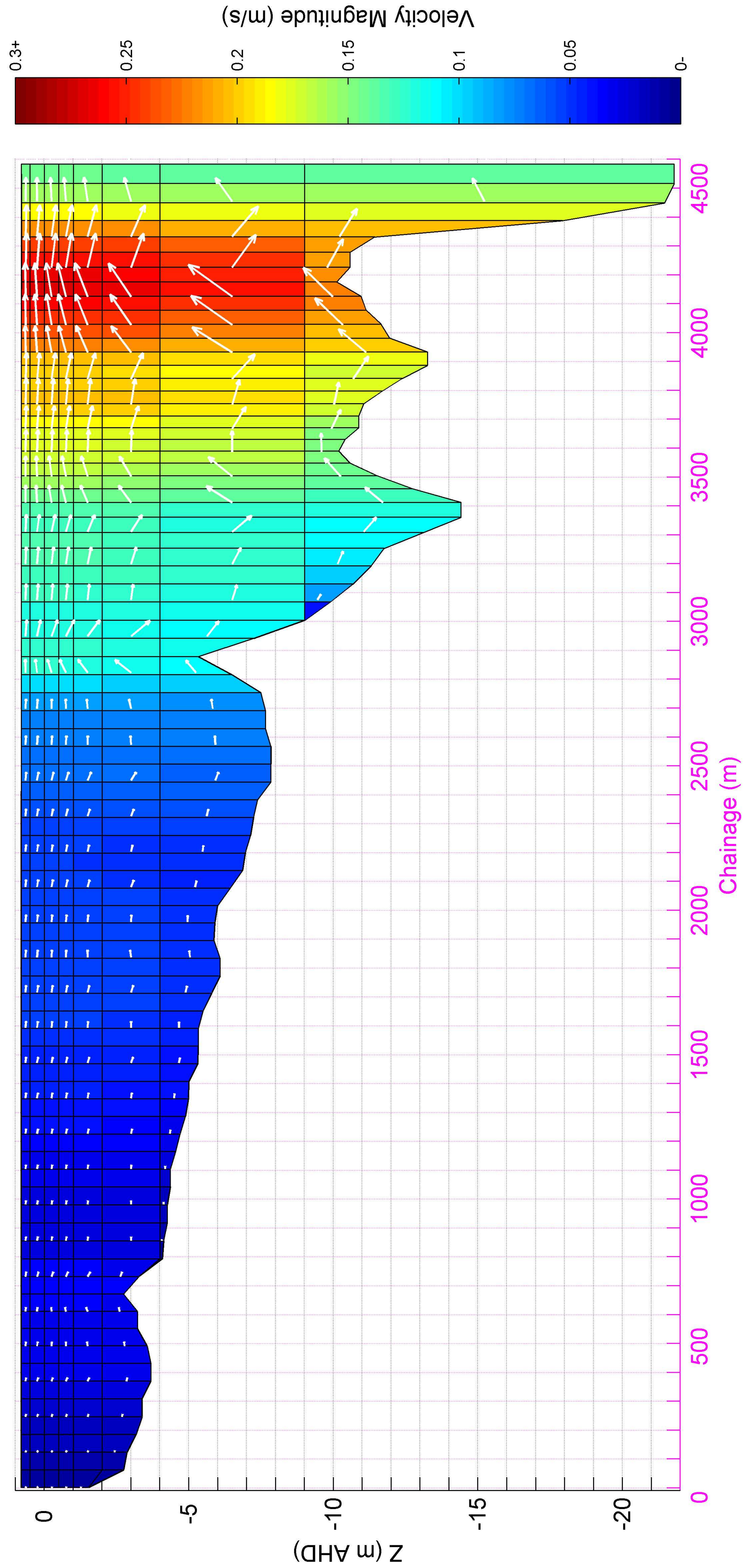
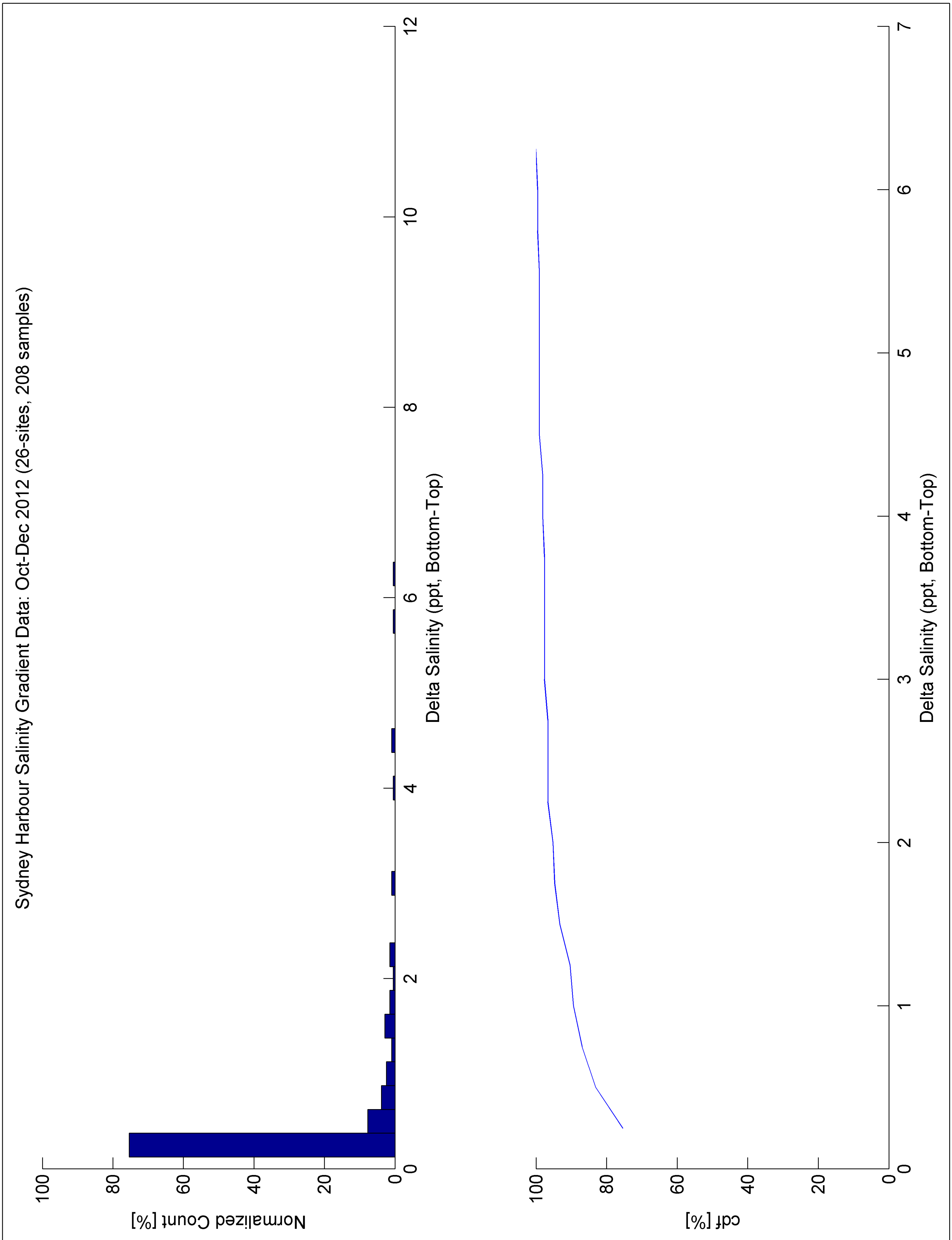


SYDNEY HARBOUR ERM – SETUP AND CALIBRATION OF 3D MODEL

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

Figure 4b



SYDNEY HARBOUR ERM – SETUP AND CALIBRATION OF 3D MODEL

Salinity Gradient Distributions at Measurement Sites

Figure 5

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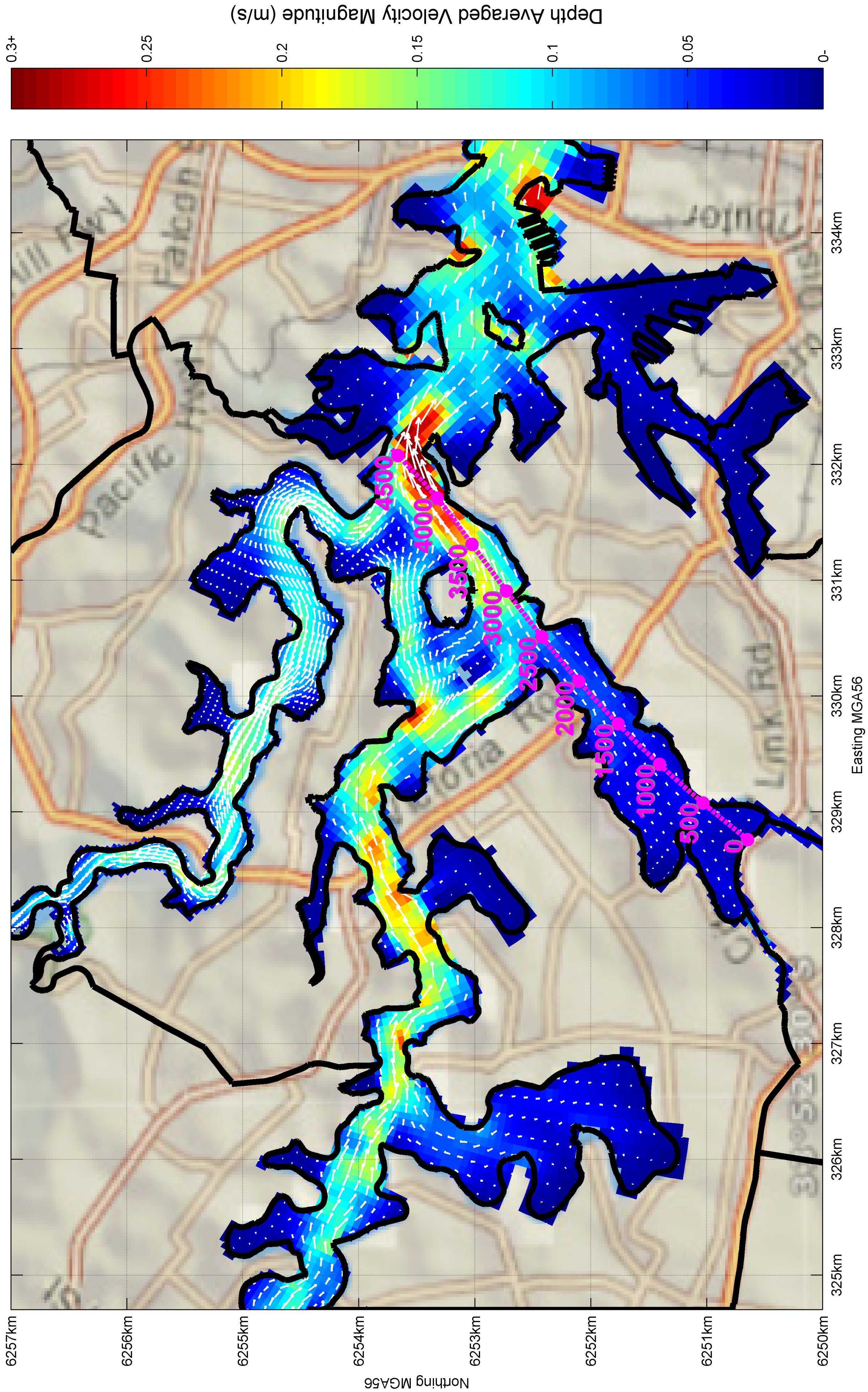

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SYDNEY HARBOUR ERM – SETUP AND CALIBRATION OF 3D MODEL

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

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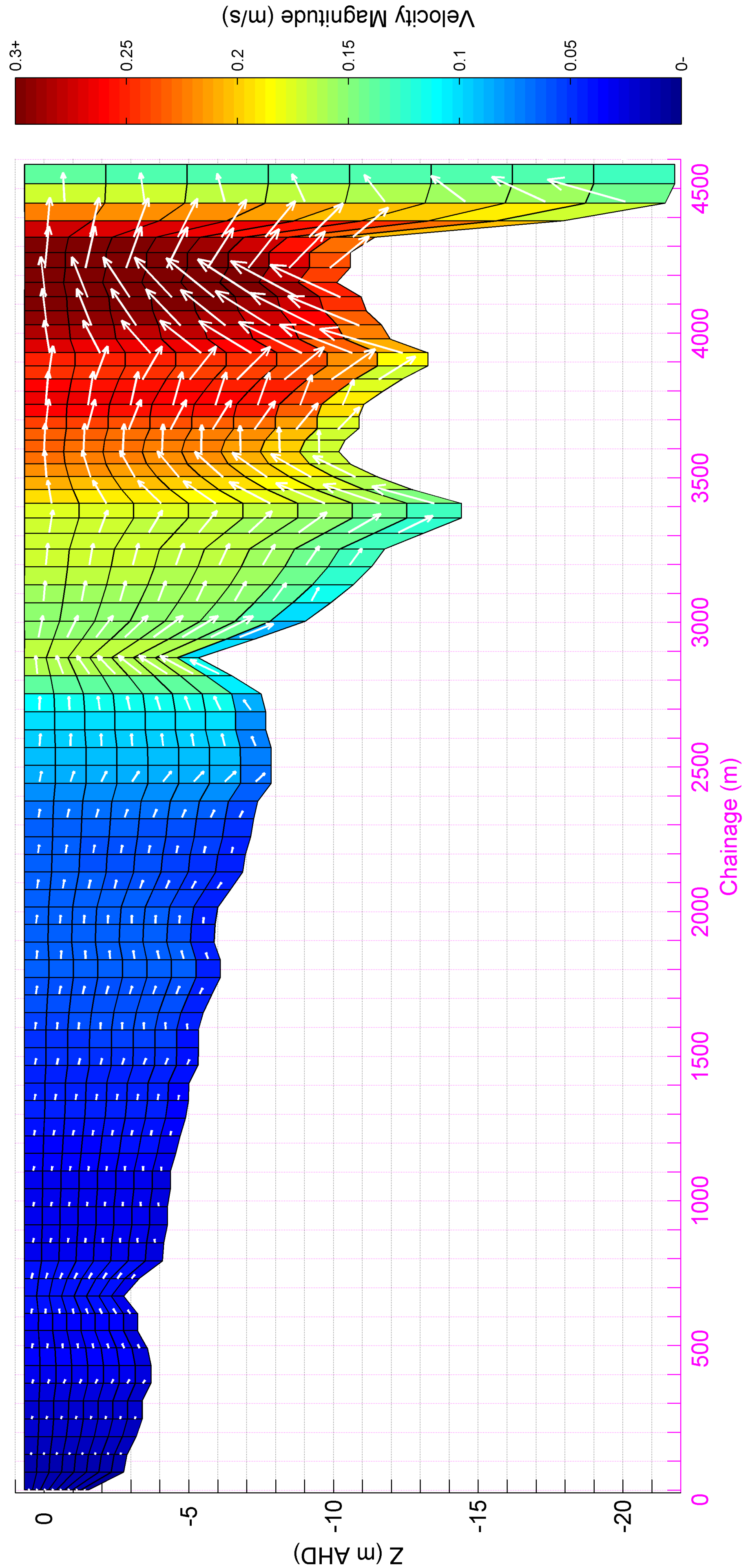
Figure 6a



SYDNEY HARBOUR ERM – SETUP AND CALIBRATION OF 3D MODEL

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

Figure 6b

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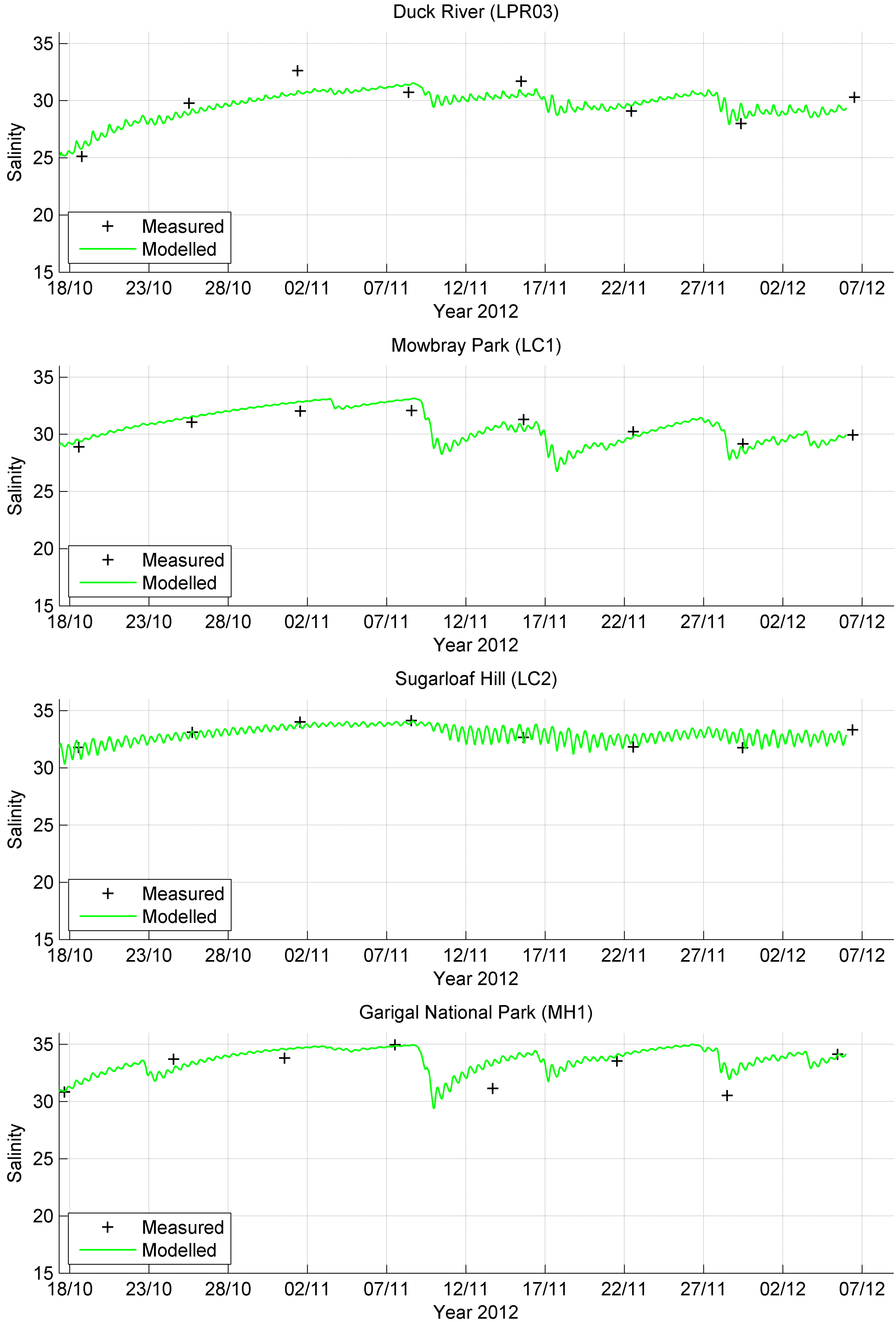

SYDNEY HARBOUR ERM – SETUP AND CALIBRATION OF 3D MODEL

Depth Averaged Salinity Calibration Time Series

Figure 7

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