ADS Environmental Services Sdn Bhd

Project South, Stewart Island New Zealand

Volume 2 – Hydrodynamic Modelling

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Report prepared by

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For

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The hydrodynamic model is arguably the core of the numerical modelling suite and is used to simulate water movement across the proposed farming area and across the entire model domain.

A 2D/3D MIKE flexible mesh model was constructed to cover the waters around Stewart Island and lower South Island with the 2D model acting as a test model (faster to run) for the 3D model.

The 3D model has a horizontal resolution of 80-120 meters in areas of interest and is comprised of 10 vertical layers. For the present study, regional drivers of wind, currents, and tide data (water level) are provided by high-quality, globally vetted models designed to be integrated into coastal hydrodynamic models.

The hydrodynamic model was calibrated and validated against ADCP data from 2010, 2017 and 2019. Each ADCP was deployed for a period of at least 14 days and collected current speed and direction information every 10 minutes at a vertical resolution of 1 meter. After this process was complete the hydrodynamic model was run for a period of one year (2017) to allow for full seasonal effects. Results of these simulations will be used to drive water movement within the water quality nutrient and depositional models whose results are presented in Volumes 3&4.

The model was calibrated/validated against 3 sets of ADCP current meter data as well as four additional tidal stations situated within the model domain and was found to be fit for purpose.

Results indicate that the main flow directions at the site are to the east, north east, south west and west. Flow is generally between 0.2-0.4 meters per second at the site with maximums of approximately 0.7 meters per second. Much stronger flows were observed to the west particularly near Ruapuke Island.

2 INTRODUCTION

This volume focuses on the description of the numerical modelling tools developed to address the hydrodynamic regime of the proposed farming area south of Ruapuke Island.

There are limited previous hydrodynamic studies of the proposed farming area. However, **Stevens *et al.* (2019)**, **Cullen (1967)**, and **Cranfield (1968)** report that currents can reach speeds of 1.2 m s^{-1} though generally at sites west of the proposed farming areas; with currents travelling between islands in Foveaux Strait potentially reaching greater speeds *e.g.* between Ruapuke and Green Islands. In the case of **Cullen (1967);** reported mean current flows on the western edge of the proposed expansion site are corroborated by ADS's hydrodynamic model outputs during the ebb tide (see ADS Hydrodynamic Report Volume 2). (**Cranfield (1968)** provides some surface current data, but these describe an area between Ruapuke and Green Islands situated well north of the proposed expansion area and situated between two closely spaced islands. **Heath (1973)** also describes current using drogues which indicate a NE SW tidal drift.

2.1 DESCRIPTION OF THE MODELLING PROCESS

The hydrodynamic model is arguably the core of the numerical modelling suite and is used to simulate water movement across the proposed farming area and across the entire model domain. The hydrodynamic model was run for a period of one year (2017) to allow for full seasonal effects. Results of these simulations were also used to drive water movement within the water quality module and depositional modelling scenarios.

Hydrodynamics were modelled using MIKE modelling software (see full description in section 1.2). A 2D regional model was constructed to cover the waters around Stewart Island and lower South Island. This 2D model was also used as a test model to check/test the, mesh, domain size, tidal and wind data inputs. This model included regional tidal, wind, and current information provided by international recognised global models (see Section 2.2 below). The same model domain was also used for a 3D model. The 3D model has a horizontal resolution of 80-120 meters in areas of interest and is comprised of 10 vertical layers, with higher vertical resolution at the surface. It should be noted that at the proposed farming area little 3D hydrodynamics processes were observed i.e. current speed and direction is relatively uniform down the entire water column and there were no sudden mid water column changes in direction observed (see Appendix 2).

The hydrodynamic model was calibrated/validated against current speed and direction collected at three sites.

1) Big Glory Bay February 2010
2) Port Adventure February/March 2017
3) South of Ruapuke Island August/September 2019

The model was also calibrated against water levels from several locations around Stewart Island and the lower part of the South Island (see Section 3 below).

While 3D effects i.e. stratification were not observed during the ADCP deployments a 3D model with 10 vertical layers has been constructed for this study.

A description of the modelling software, methodology, model calibration/validation and a presentation of the flow regime are presented in the following sections.

Impacts to the water column and seabed impacts are the primary components of any assessment dealing with open cage aquaculture. The fate of both soluble and solid wastes released by farming operations is determined by the flow conditions prevailing at the locations of the farms and their surroundings.

Predicting potential impacts requires not only knowledge about the current, or historic, flow conditions, but also the ability to predict future conditions or scenarios. Hydrodynamic models can simulate any period, provided there is sufficient bathymetry for the model extent as well as forcing's (tides, wind, *etc*.) are available for model use. Since the model is based on sets of physical equations it will compute results based on inputs and the quality of the output is a direct consequence of the quality and accuracy of the inputs used. To make sure that the model is accurately depicting *in-situ* conditions, a calibration/validation process is required.

Hydrodynamics govern the prevailing patterns of flow at the area of interest, however hydrodynamic results are not enough by themselves to define the potential impacts to the water column and seabed. The current flow fields need to be associated with additional numerical modelling modules in order to simulate the fate of waste generated by the farms. Water column and seabed impacts are both described in their relevant volumes.

2.2 Model Description

Numerical modelling using MIKE3DFM is utilised to predict and assess the potential impacts on the marine and coastal environment before and during the operational phases of farming activities. The modelling tools applied in this study were:

A hydrodynamic model providing information on water levels and current dynamics driven by the interaction of tides, wind (including a regional wind model), atmospheric pressure, waves, and the underlying bathymetry.

2.3 Modelling Software

The numerical modelling was undertaken using MIKE, more specifically MIKE3DFM.

MIKE3DFM is a suite of modelling tools that have undergone over 35 years of development. MIKE3DFM offers the flexibility to develop numerical models of different dimensions (2D, 3D) and has several modules to answer almost any water related question.

Mike is a fully integrated computer software suite suitable for multi-disciplinary studies, focusing on 2D or 3D computations of coastal, river and estuarine areas. It can carry out simulations of flow, sediment transport, waves, water quality, morphological development, and ecology. It has been designed for experts and non-experts alike. The MIKE3DFM suite is composed of several modules, grouped around a mutual interface, which allows for interaction between each module. The core module is the hydrodynamic module.

MIKE3DFM is a multi-dimensional (2D or 3D) hydrodynamic (and transport) simulation program which calculates non-steady flow and transport phenomena that result from tidal and meteorological data on a flexible mesh grid. The grid itself can be altered to any size across the model domain with smaller mesh sizes being used in areas of most interest such as within the proposed farming area.

MIKE3DFM (https://www.mikepoweredbydhi.com/) is routinely used for the following applications:

- Tide and wind-driven flows (*i.e*. storm surges).
- Stratified and density driven flows.
- River flow simulations.
- Simulations in deep lakes and reservoirs.
- Simulation of Tsunamis, hydraulic jumps, bores and flood waves.
- Freshwater river discharges in bays.
- Salt intrusion.
- Thermal stratification in lakes, seas and reservoirs.
- Cooling water intakes and wastewater outlets.
- Transport of dissolved material and pollutants including nutrients.
- Online sediment transport and morphology.
- Wave-driven currents.
- Non-hydrostatic flows.

Thanks to its modular structure MIKE3DFM can also be used to assess water quality, ecological impacts, and littoral transport.

2.4 Development of Regional and Local Hydrodynamics

As stated in Section 1.3, given the size of the proposed area under consideration a flexible mesh model grid was created. A flexible mesh model focuses its resolutions on areas of interest *i.e.* the farms and ADCP locations rather than areas 10's if not 100's of Km away from the proposed farming areas, but still within the model domain (**Figure 1** & **Figure 2**). The finest mesh size utilised in the proposed farm areas was 80-120m (with 10 vertical layers to capture any possible 3D effects). Further from areas of interest intermediate mesh sizes of 120m, 300m, 720m, 900m, 1440m and coarsest 2000m were utilised.

A large model domain was utilised to capture regional tidal, current and wind impacts (**Figure 1**). The model (production runs for impact assessment and to highlight the flow conditions at the site) was run for a period of one year from January 2017 to December 2017. The hydrodynamic model was calibrated and validated against ADCP data from 2010, 2017 and 2019. Each ADCP was deployed for a period of at least 14 days and collected current speed and direction information every 10 minutes at a vertical resolution of 1 meter.

Boundary conditions (water level, wind, pressure, current speed and direction) for the model are described in Section 2.5 below.

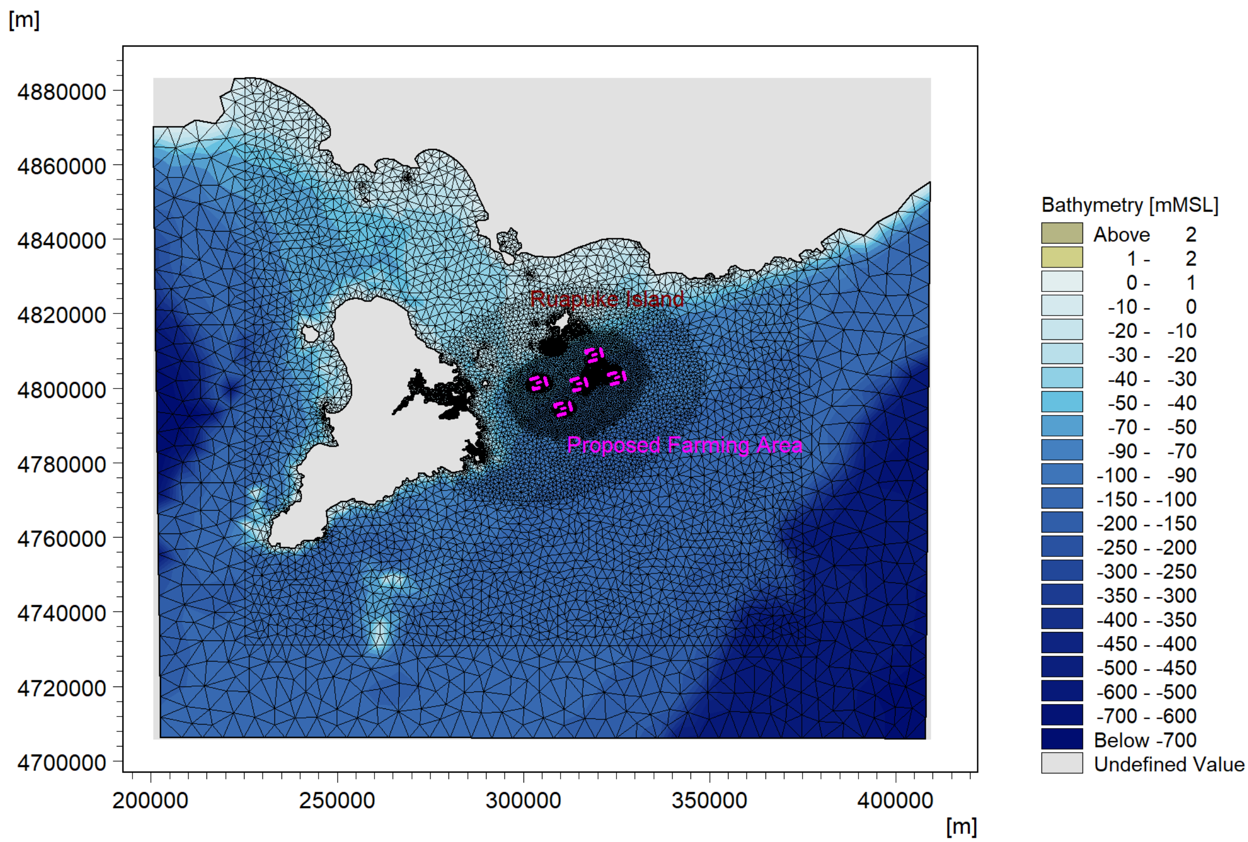

Figure 1 - Extent of regional model flexible mesh.

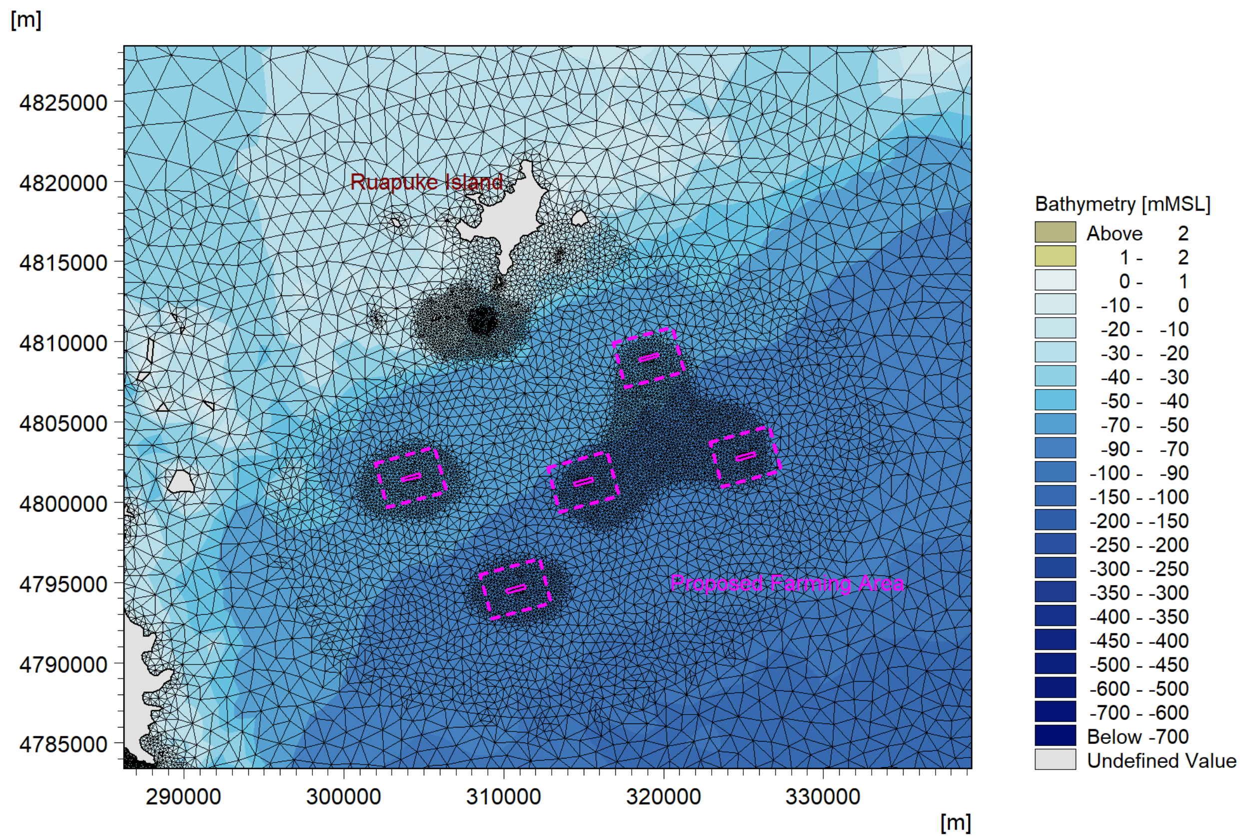

Figure 2 - Extent of local flexible mesh for the proposed farming locations.

2.5 Boundary and Climatic Conditions

For the present study, regional drivers of wind, currents, and tide data (water level) are provided by high-quality, globally vetted models designed to be integrated into coastal hydrodynamic models. The data extraction period matches the production model (used to provide information on currents at the site for other modelling modules i.e. deposition and water column nutrients) run length of 1 year. The model was run for 2017 as all global data sets were available during this time period without interruption. 2017 was also one of the warmest years on record with the summer of 2017/2018 the warmest on record. Thus, representing the physical forcing i.e. wind/pressure during and leading up to these extreme warming periods is a good representation of the likely future climatic conditions.

These data sets were also used during the calibration and validation modelling periods.

Regional and model boundary tide data (water level data) were provided by the Oregon State University's TOPEX/Poseidon Global Inverse Solution (TPXO, Egbert 1997; Egbert and Erofeeva 2002), a global oceanic tidal model (Figure 3**Figure 3**). The model provides amplitudes of 8 primary harmonic constituents, 2 long-period constituents, and 3 non-linear constituents on a ¼ degree resolution global grid (total of 13 constituents). Additional descriptions and detailed information concerning the TPXO model can be found at http://volkov.oce.orst.edu/tides/global.html. For the purpose of this study, no Admiralty tide was utilised due to the lack of correction coefficients (usually only 2-4 unlike TPXO which has 13). This results in an improved water level calibration.

Regional 3D current data are provided by the National Ocean Partnership Program's (NOPP) HYbrid Coordinate Ocean Model (HYCOM), a real-time global fine resolution model (*e.g.* Bleck and Boudra 1981, Bleck 2002) designed to provide boundary conditions for coastal and regional models like the hydrodynamic model developed for this study. Several academic, governmental, and commercial entities involved in the Global Ocean Data Assimilation Experiment (GODAE) are responsible for this model. Additional descriptions and detailed information concerning the HYCOM model can be found at http://hycom.org/about. MATLAB Scrips were utilized to convert HYCOM data into a format readily readable by the MIKE software.

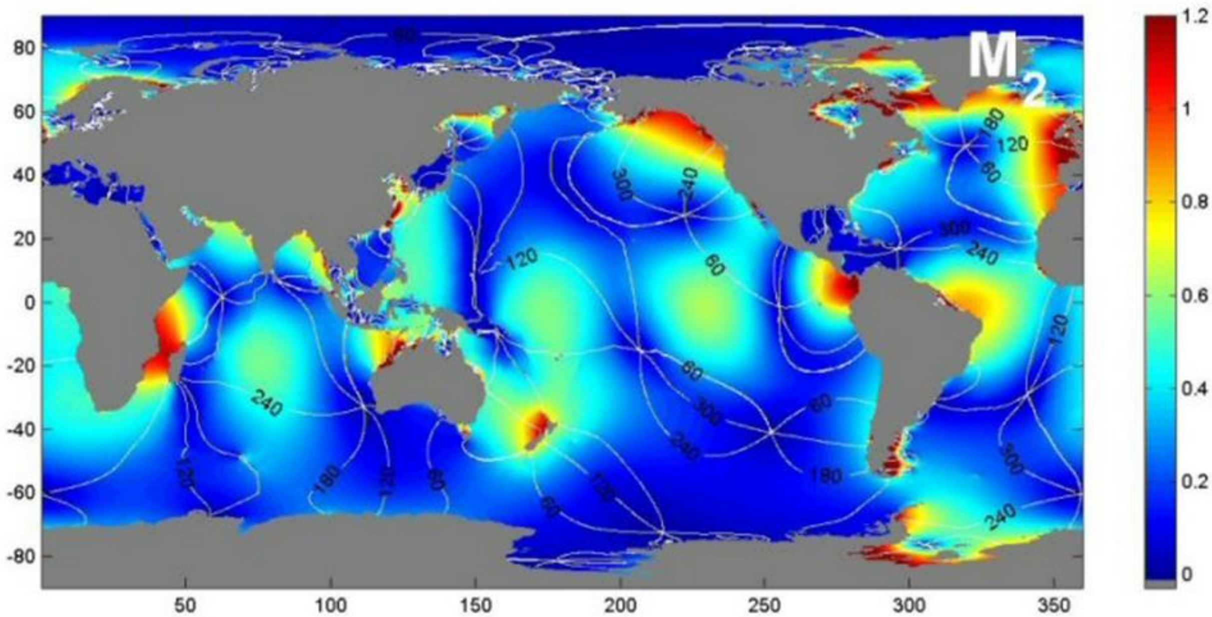

Figure 3 - Image depicting a sample output from the TPXO model.

Offshore wind forcings for the regional model are provided by the National Oceanic and Atmospheric Administration (NOAA) National Centre for Environmental Information (NCEI) Global Forecast System (GFS) model (**Figure 4**). The GFS is a weather forecast model that covers the entire globe at a base resolution of ~28 km (though a finer resolution of 16km was ustilised in this study area) and is used worldwide for weather predictions (*e.g*. Sela 1980; Kanamitsu 1989; Kalnay et al. 1990). The GFS model is composed of 4 separate models (atmospheric, oceanic, land/soil, and sea-ice models) that provide an accurate depiction of weather conditions and is constantly updated to improve its performance and accuracy. Additional descriptions and detailed information concerning the GFS data sets can be found at https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/global-forcast-system-gfs. The GFS model provided both wind (see **Figure 5**) and speed and direction data used in this particular model and atmospheric pressure data for the regional model domain in 3 hour intervals.

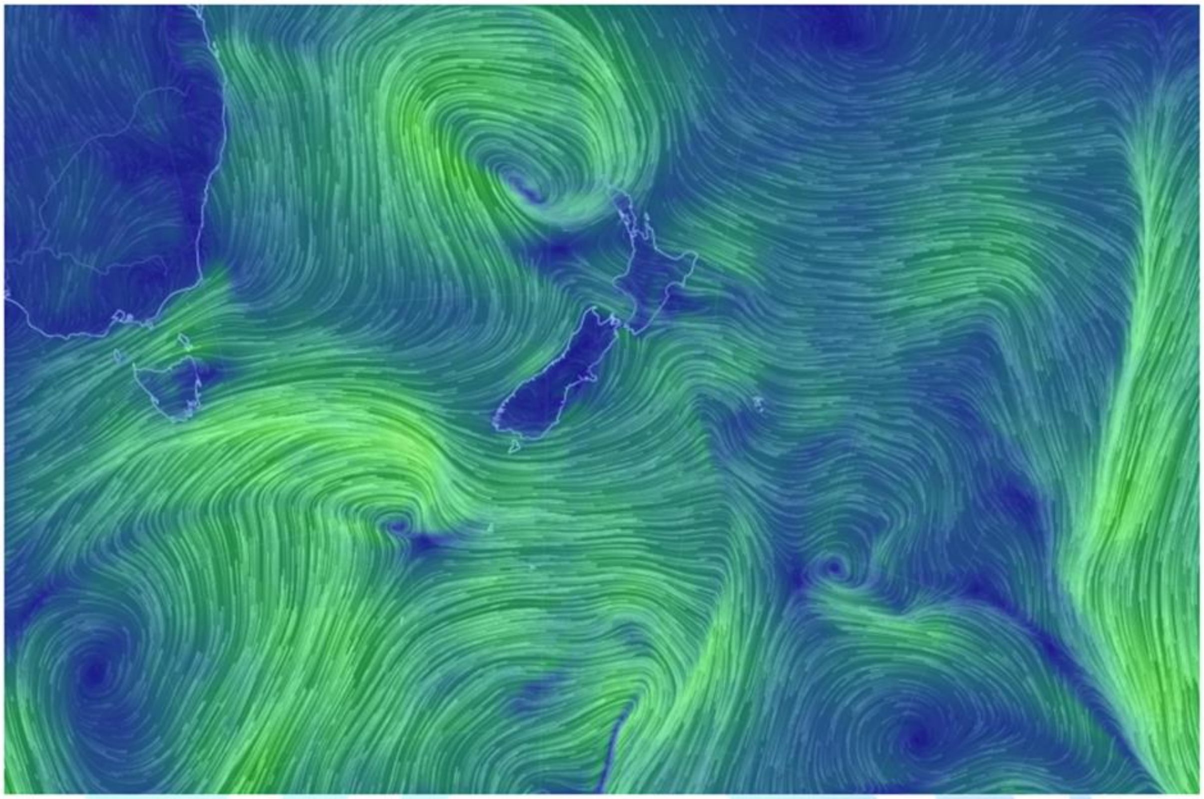

Figure 4 - Example of GFS wind data centered on New Zealand at 2015-09-04 at 0600 GMT (source: http://earth.nullschool.net/).

In addition, wind data collected from 4 locations within the vicinity of the study area were also utilized in the model (**Figure 5**). These data replaced the GFS wind model data sets at the four locations across the model domain. These local wind data sets were averaged every 3 hours to coincide with the GFS wind information.

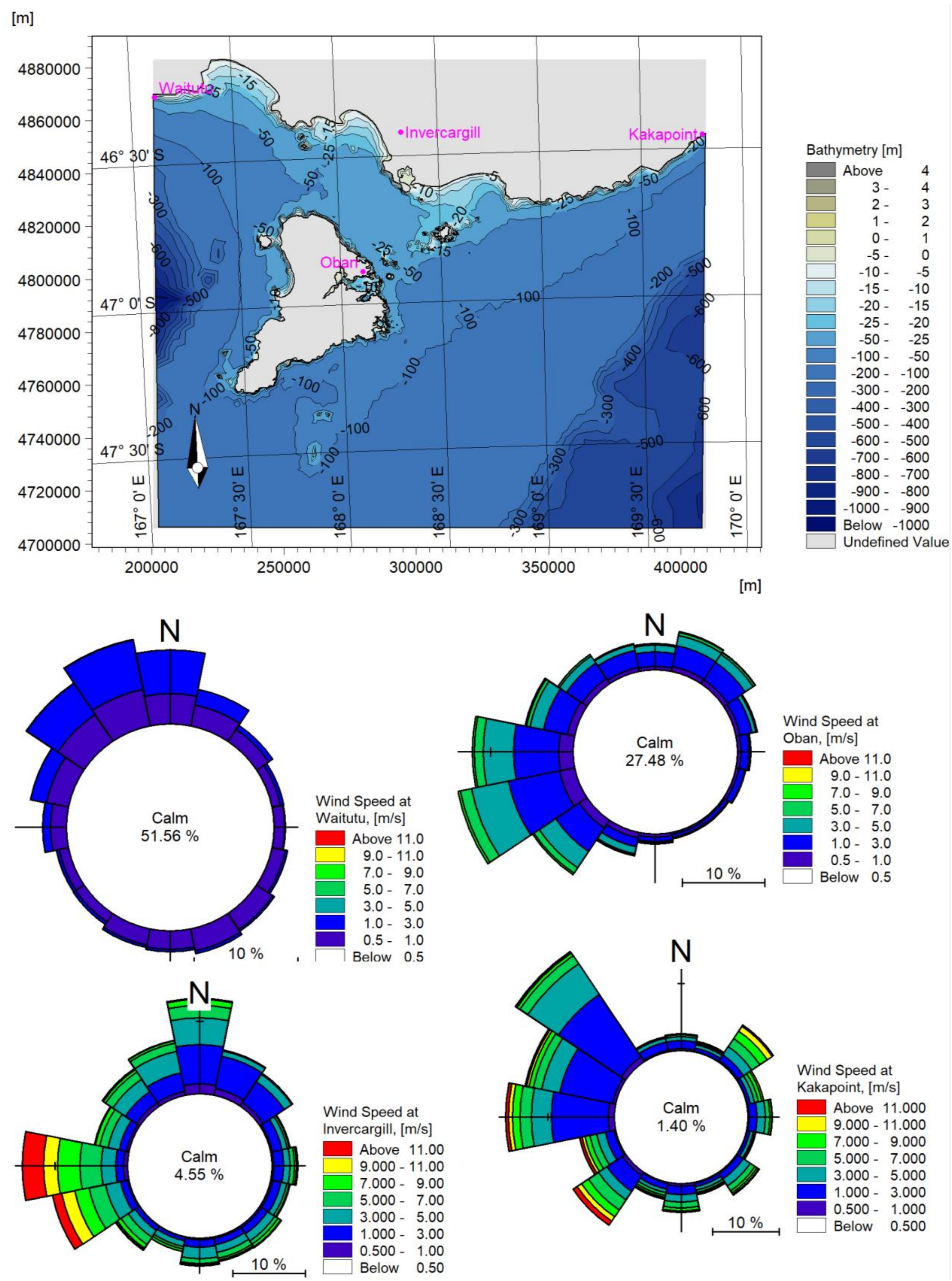

Figure 5 – Wind speed and direction data from four locations adjacent to the proposed aquaculture production area (Calm is wind speed below 0.5 meters per second while wind speed information represents wind conditions from 2017-2019.

Bathymetry data were obtained across the model domain from data collected by Land Information New Zealand and Sanford. A summary of the main data sources used to build both the regional and local hydrodynamic models is provided in **Table 1** below.

Table 1 - Summary of main data sources used to build the Hydrodynamic model.

Data Type	Sources
Predicted Tidal Elevation	TPXO Global Tidal Solution and WX tidal data
Current (ADCP) Calibration and Validation periods	ADCP1 (at BGB): 168.119°E, 46.986°S 06/09/2010 - 06/10/2010, data collected by Cawthron. ADCP2 (at Port Adventure): 168.192°E , 47.064°S 20/02/2017 - 24/03/2017 ADCP3 (South of Ruapuke Island): 168.491 °E, 46.823°S 21/08/2019 - 04/09/2019
Wind	Global Forecast System by National Oceanic and Atmospheric Administration (GFS), Local in-situ wind stations (4).
Regional Current data	HYCOM
Bathymetry	Chart data from Land Information New Zealand and previous Sanford and ADS bathymetry surveys.

In summary the model has used regional/global wind models, a global current model (HYCOM) to drive 3D water column boundary conditions and global tide model. In addition to these global models the model has incorporated wind forcing's from 4 locations within the model domain.

3 HYDRODYNAMIC MODEL CALIBRATION/VALIDATION

3.1 INTRODUCTION TO CALIBRATION AND VALIDATION

An accurate calibration is vital to ensuring the accuracy of the hydrodynamic model and its ability to simulate real world conditions across the proposed study. The calibration is an iterative process in which model parameters such as wind drag and seabed roughness are adjusted until comparison between simulated results and measurements (currents and water level) result in a suitable fit. To assist in the calibration process other information such as wind pressure, wind, tide and regional currents also play a role in obtaining a robust calibration.

The calibration/validation process in this study included comparing model results with predicted water levels, and against Acoustic Doppler Current Profiler (ADCP) data (depth averaged current speed and direction data).

Three sets of ADCP data were used for the calibration/validation process (**Figure 6**). Each ADCP data set was collected at a different location across the model domain. The main focus of the calibration/validation process was to determine if the model could replicate conditions (currents and water level) at different locations across the domain during other periods of time without changing the model set up. RMSE calculations are presented in **Appendix 3** to highlight the robustness of the model.

In addition, 4 water level stations were also utilised to assist in both the calibration and validation process (**Figure 7**). ADCP 1 was used for calibration.

- ADCP1 (at BGB): 168.119°E, 46.986°S 06/09/2010 - 06/10/2010

As described above GFS wind, Hycom and TXPO tidal forcing's were also extracted for these periods and used to drive the model during the validation periods. These global models help to represent regional ocean patterns within the study area.

In addition to the calibration process, the model was also validated against current meter and water level data collected at two other locations and during other time periods. To test the robustness of the model two validation locations were used to compare current velocity in addition to four water level stations.

- ADCP2 (at Port Adventure): 168.192°E, 47.064°S 20/02/2017 - 24/03/2017
- ADCP3 (South): 168.491 °E, 46.823°S 21/08/2019 - 04/09/2019

Model calibration and validation plots can be found below in Sections 3.2 and 3.3.

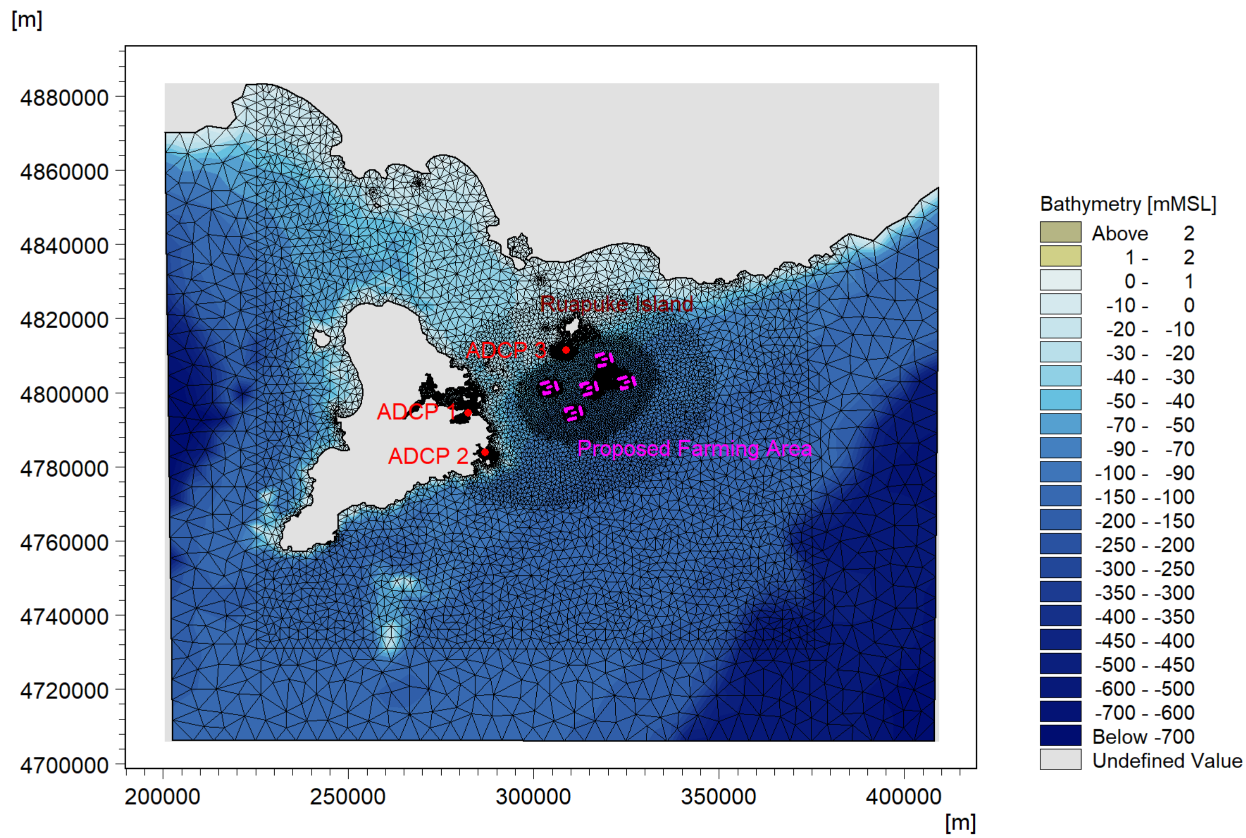

Figure 6 - Location of the ADCP deployments utilised for calibration and validation.

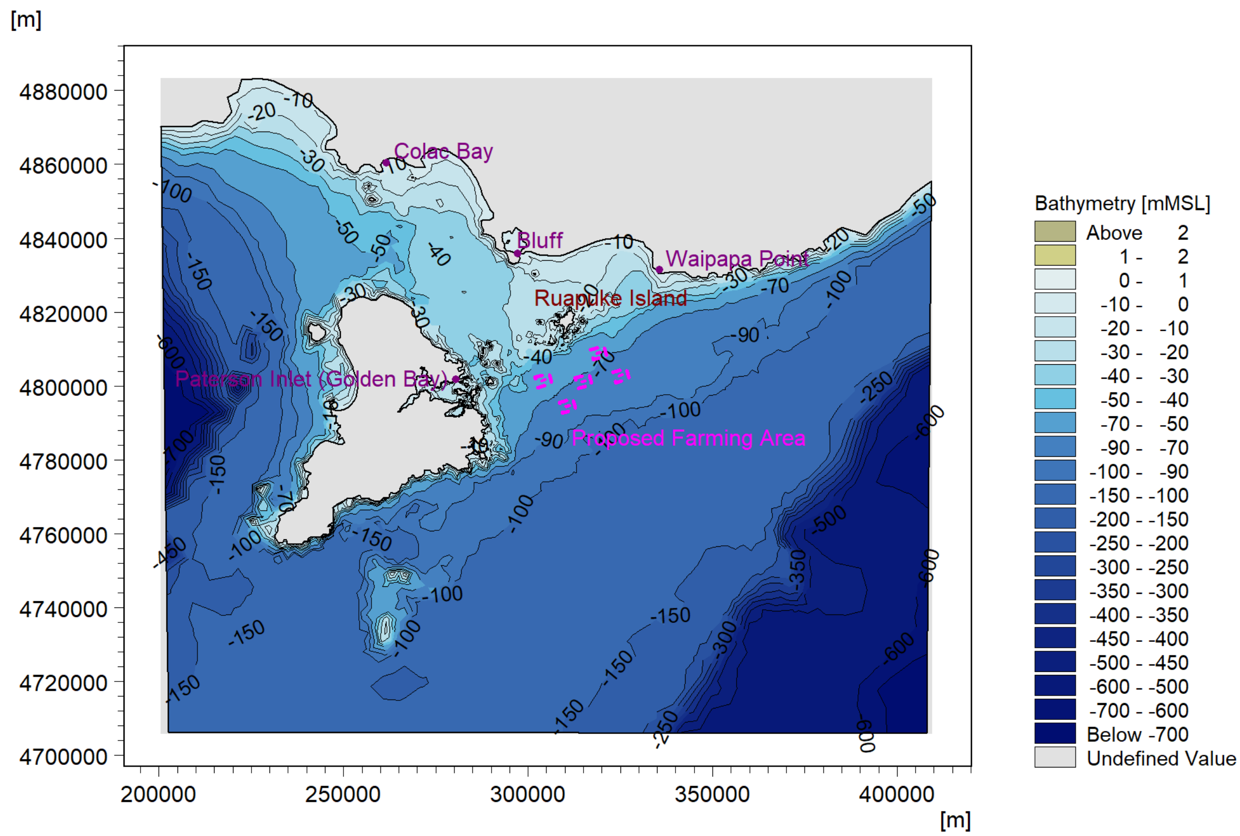

Figure 7 - Location of tidal stations utilised as part of the hydrodynamic model calibration process.

A number of calibration parameters were utilised in this study, key parameters are listed in **Table 2** below. As part of the calibration process one calibration parameter i.e. wind drag is generally altered each model run until the model passes RMSE model sensitivity calculations (see Appendix 3) vs collected ADCP and water level data. Once the calibration is complete no changes to the model set up are made. The model is then run during other time periods and compared against additional ADCP and water level data (often collected from other locations within the model domain). If the model passes these RMSE tests (again see Appendix 3) it is deemed to be validated.

Table 2 - 2D model calibration parameters

Calibration Parameter	Value(s)
Calibration Period	06/09/2010 - 06/10/2010
Time step	10 minutes
Initial Conditions	0 m for water level.
Boundaries	TXPO, HYCOM.
Wind Drag Coefficient	0.00063 at 0 m/s
	0.00723 at 100 m/s
Bed Resistance	Manning Map ranging from 32-50 m^(1/3)/s
Horizontal Eddy Viscosity	0.28 m^2/s
Turbulent kinetic energy	10^{-6} m^2/s^2
Dissipation of Turbulent Kinetic energy	5e-010 m^2/s^3

3.2 Model Calibration

At ADCP 1 the model passes RMSE model sensitivity calculations for current speed (see Appendix 3) during the calibration period (two weeks including a full spring neap cycle). It does slightly over estimate the flow during neap tide and slightly under estimate during spring tidal periods (**Figure 8)** though within RMSE values. When comparing the model current direction with the ADCP the model compares well and is considered to simulate both the neap and ebb tidal directions well.

The model utilised for this study replicates water level data collected from Paterson Inlet in terms of both amplitude and phase during spring and neap tidal periods (**Figure 9 & Appendix 3**). Additional water level information was also processed from Bluff, Colac Bay, Paterson Inlet and Waipapa Point and compared against the model output at each location. Overall the model matches the phase and amplitude at the Bluff, Paterson Inlet and Waipapa Point water level stations. The amplitude is not as well represented at Colic Point which we suspect may have to do with poor quality bathymetric data in this area.

Overall, the model is well calibrated and passes all RMSE model sensitivity calculations for water level, current direction and current speed (see Appendix 3).

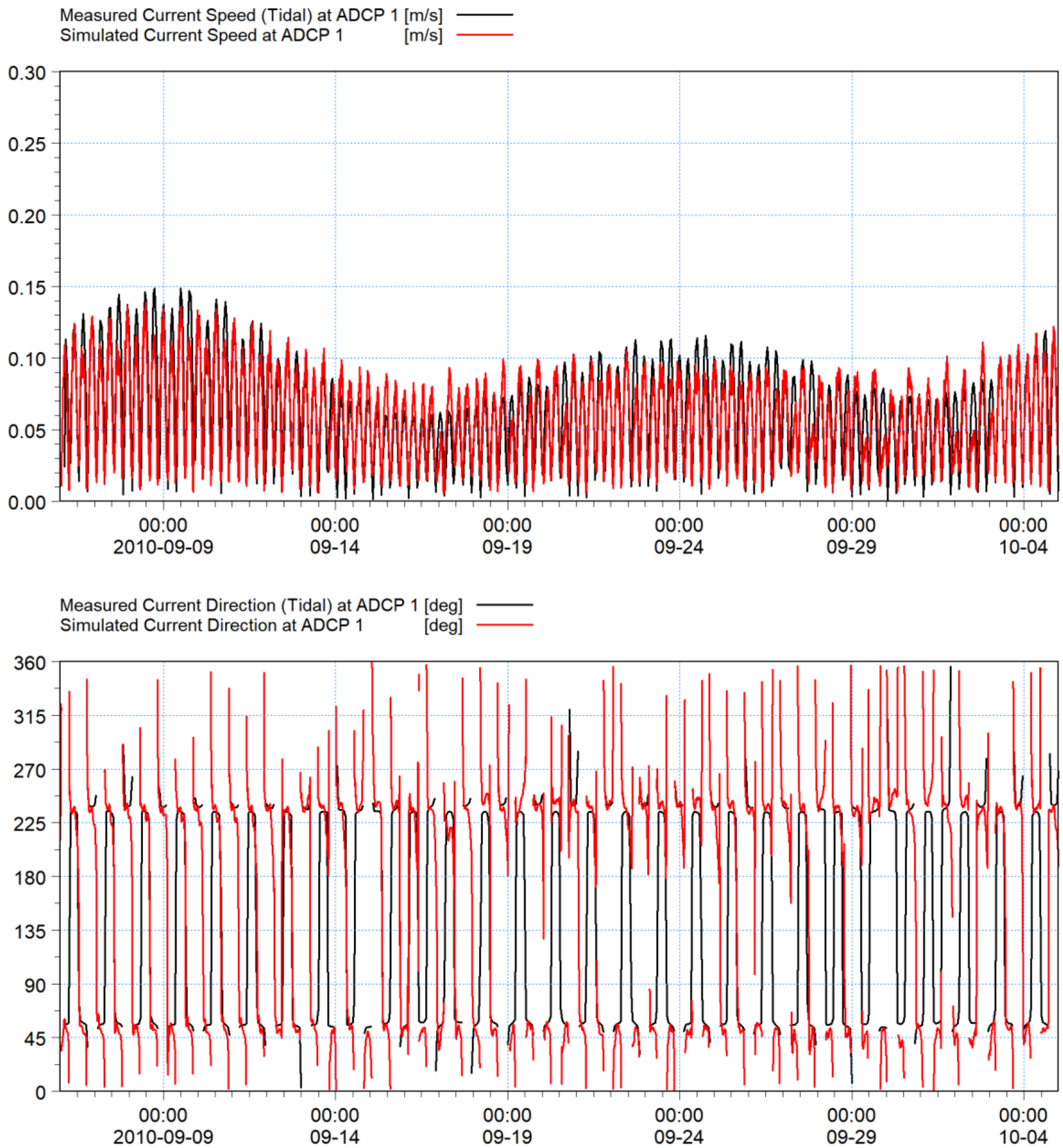

Figure 8 - Current speed and direction data comparison at ADCP1 (Big Glory Bay) between depth averaged measured data and modelled results.

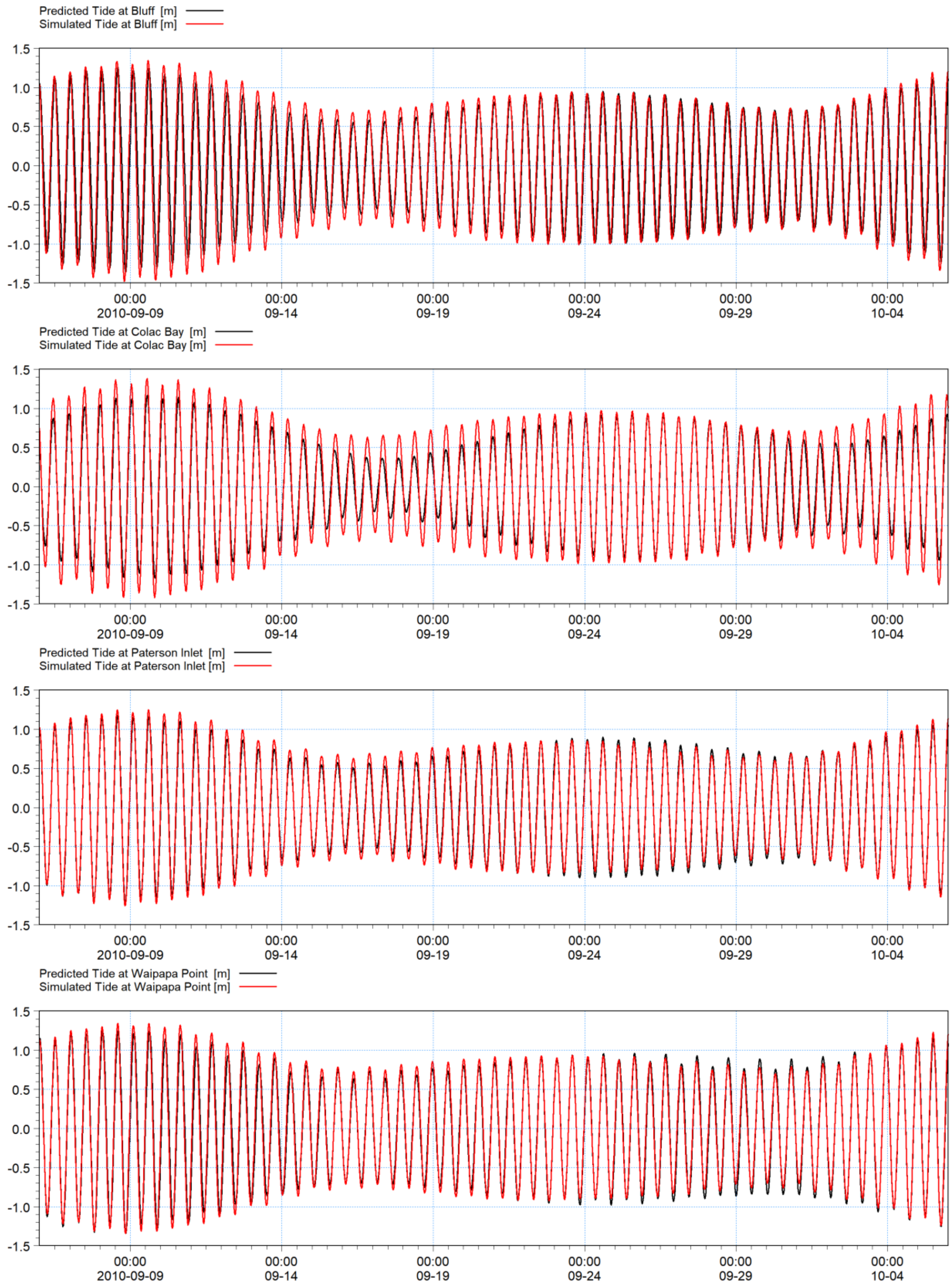

Figure 9 – Water level data vs model predictions at 4 locations within the model domain.

3.3 Model Validation

The model was validated against two sets of ADCP data each approximately two weeks in length and containing a full spring neap cycle:

The first set of validation data collected at Port Adventure (ADCP2) in 2017 indicates the model compares well (see Appendix 3 for RMSE calculations) against water level, current speed and current direction (**Figure 10**). Regarding current speed the model tends to underestimate a few of the high flow observations though generally it does match the magnitude. Helpfully, from an effects assessment perspective, this means the model may slightly over estimate the concentrations of farm deposition and under estimate the area over which deposition is expected to occur. The model was also compared against tidal data from 4 locations utilised in the model calibrate. As during the calibration period, the model matches the phase and amplitude at Bluff, Paterson Inlet and Waipapa Point. The amplitude is not as well represented at Colic Point though it still within the acceptable RMSE threshold of less than 10% variation (See Appendix 3).

The second set of validation data was collected south of Ruapuke Island for a period of approximately 14 days during August/September 2019. The ADCP indicates at times strong flow of up to 1.2 m/s. Though it should be noted that the ADCP location is in a shallow area between a series of small islands and the flow through this area is known to be strong (Stevens *et al.* 2019). No current direction data were collected at this location due to an issue with the instruments internal compass. Water level at this site matches the ADCP3 while the model underestimates the current speeds during both the neap and spring periods (on average about 20%). This is likely due to the lack of local bathymetry data for the area and that the site is complex being in behind a large island and surrounded by several smaller islands.

The model was compared against the same tidal data from 4 locations utilised in the model calibration. As during the calibration period and the 2017 validation period, the model matches the phase and amplitude at both Bluff, Paterson Inlet and Waipapa Point. The amplitude is not as well represented at Colic Point.

Overall the model is fit for purpose as it has been successfully calibrated and validated against current and water level data collected from three separate ADCP deployments. In addition, modelled water level was also compared against 4 additional tidal gauges across the model domain and obtained a good comparison.

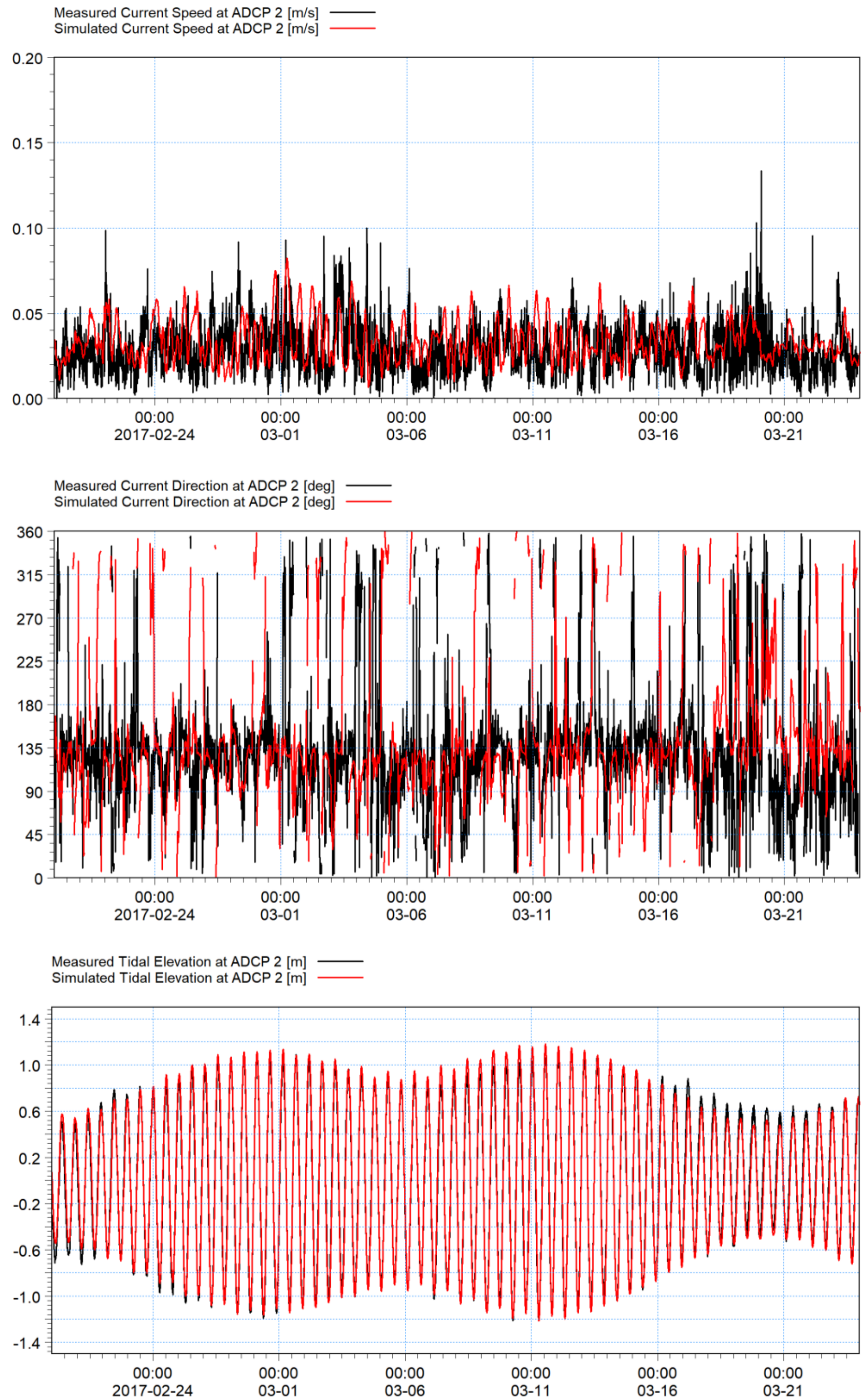

Figure 10 - Current speed and direction comparison at ADCP2 (Port Adventure) between depth averaged measured data and modelled results.

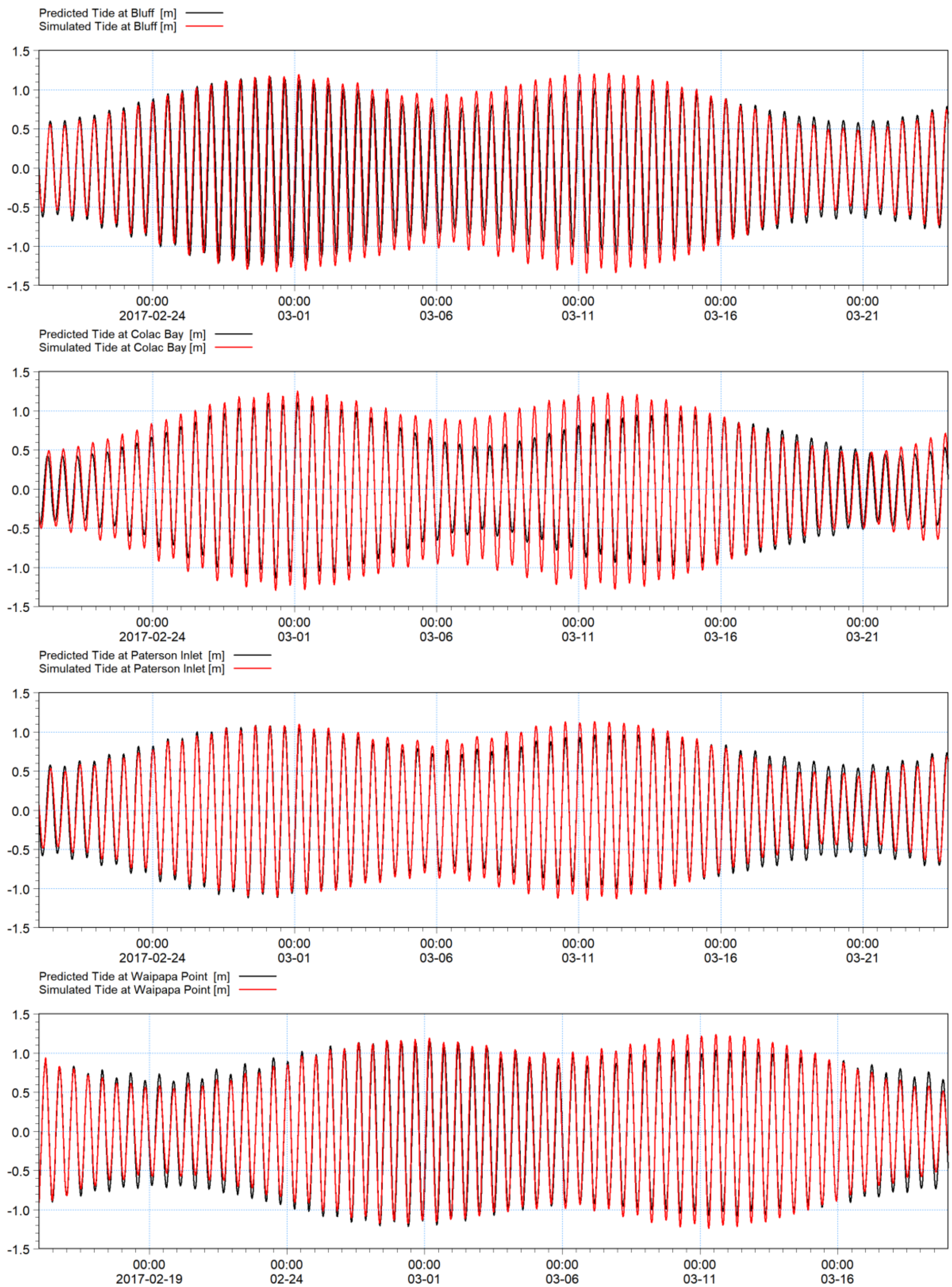

Figure 11 – Water level data vs model predictions at 4 validation locations within the model domain during the ADCP2 validation period.

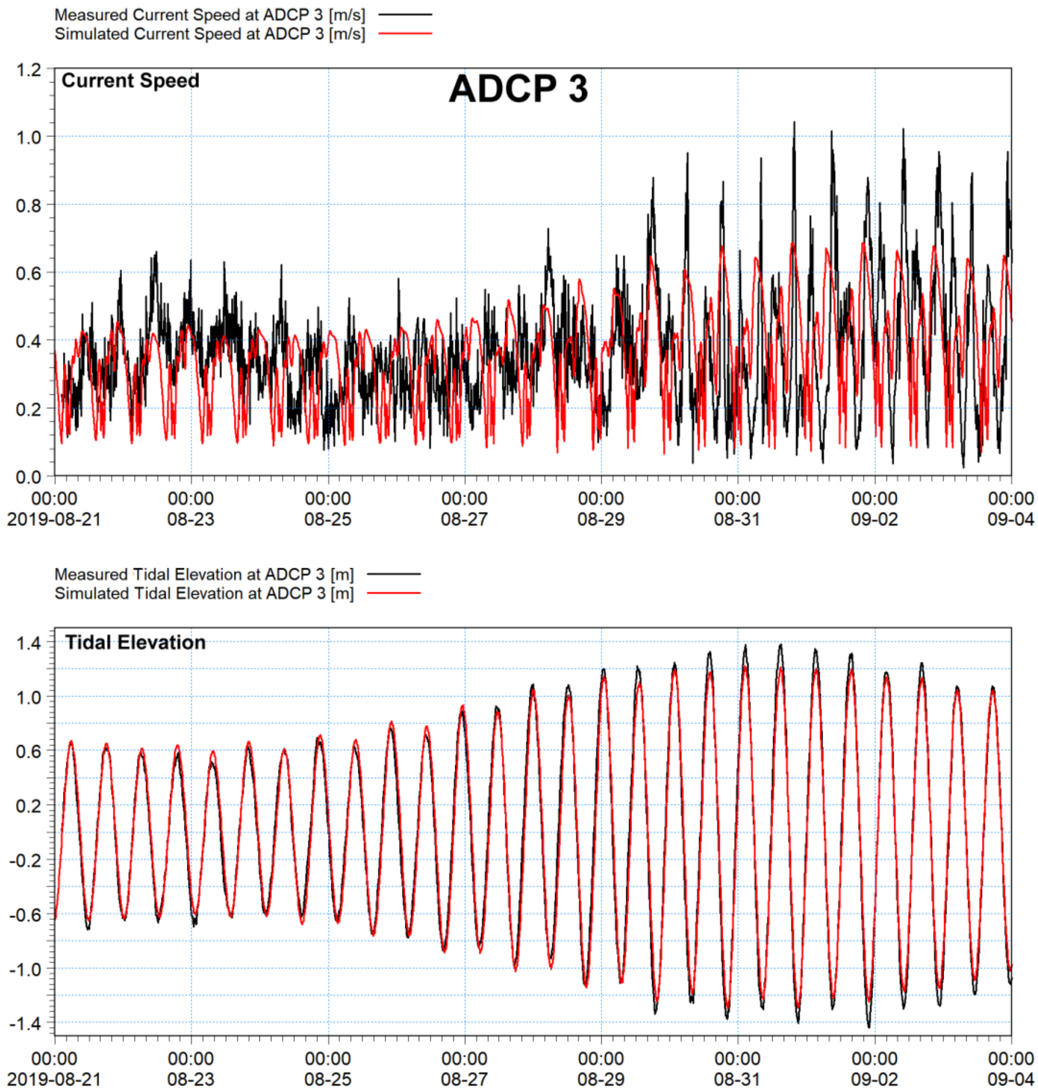

Figure 12 – Current speed and water level comparison at ADCP3 (South of Ruapuke Island) between depth averaged measured data and modelled results. Note no current directions are presented due to an issue with the instruments internal compass.

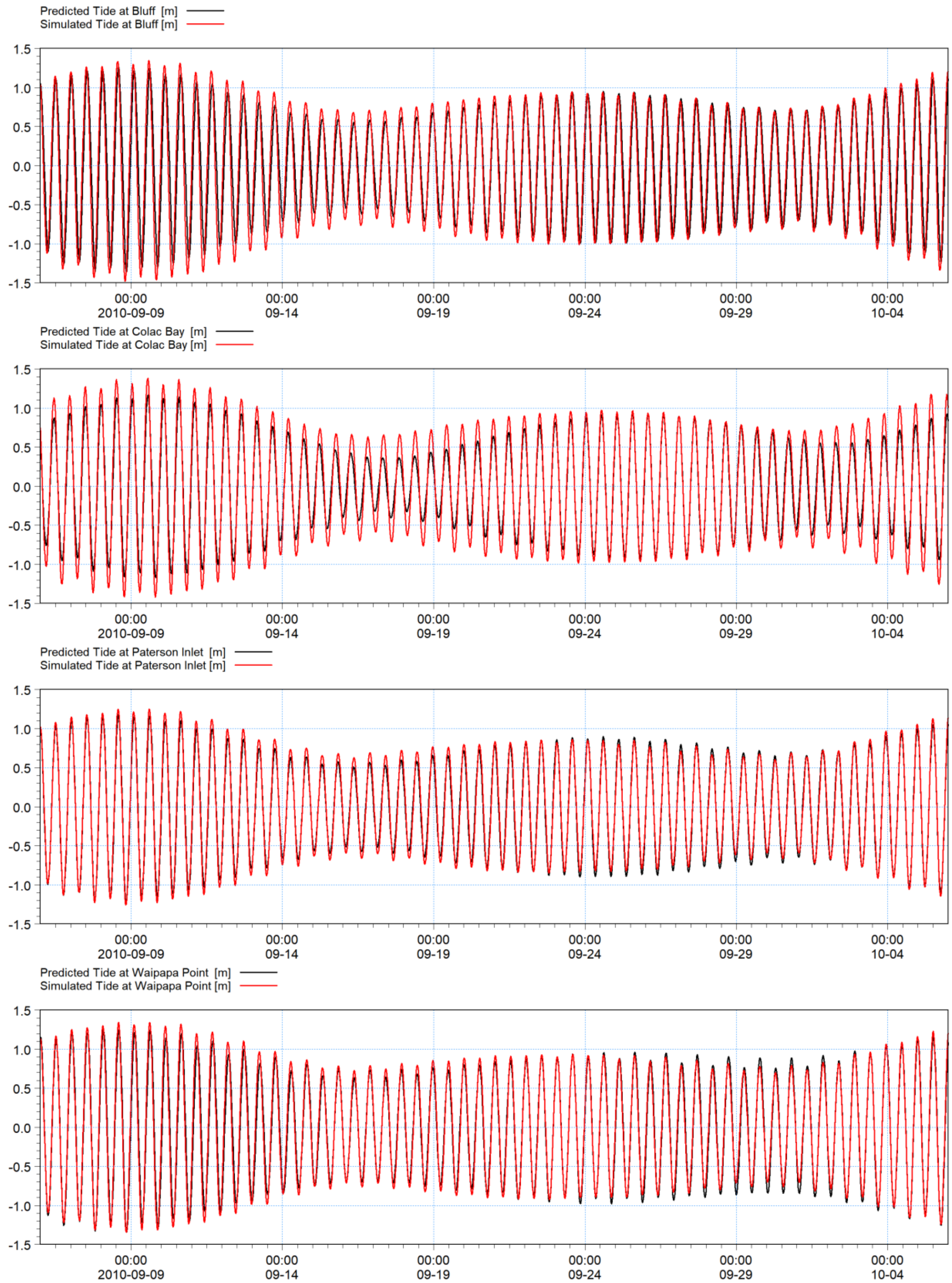

Figure 13 – Water level data vs model predictions at 4 validation locations within the model domain during the ADCP3 validation period.

4 HYDRODYNAMIC MODEL RESULTS

Representative depth averaged tidal patterns (without wind forcing's) are presented for spring neap ebb and flood tidal periods across the model domain (**Figure 14** & **Figure 15**). Model results indicate that tidal flow within the study area is generally between 0.1-0.2 m/s with much stronger flows to the west of Ruapuke Island and south of Stewart Island. Tidal flow direction is variable and to the NW, SW and the NE.

The 3D model was also run to calculate the impact of both regional winds and pressure for a period of one year. Seasonal depth averaged current speed and direction results from the center of the proposed farming area are presented in the following current rose plots (**Figure 16** to **Figure 20**). Depth averaged plots were presented as little difference in current speed and direction was observed in different vertical model layers. The model confirms that the main current flow is to the NNE, east, west and WSW directions which is similar to previously reported studies. Flow is predominately between 0.2-0.4 m/s across all 4 seasons with maximum flows of 0.7 m/s. ***Further details of the current speed and direction at each of the 5 farming sites are presented in Volume 3.***

Additional seasonal depth averaged current speed and direction instantaneous plots are presented in Appendix 1.

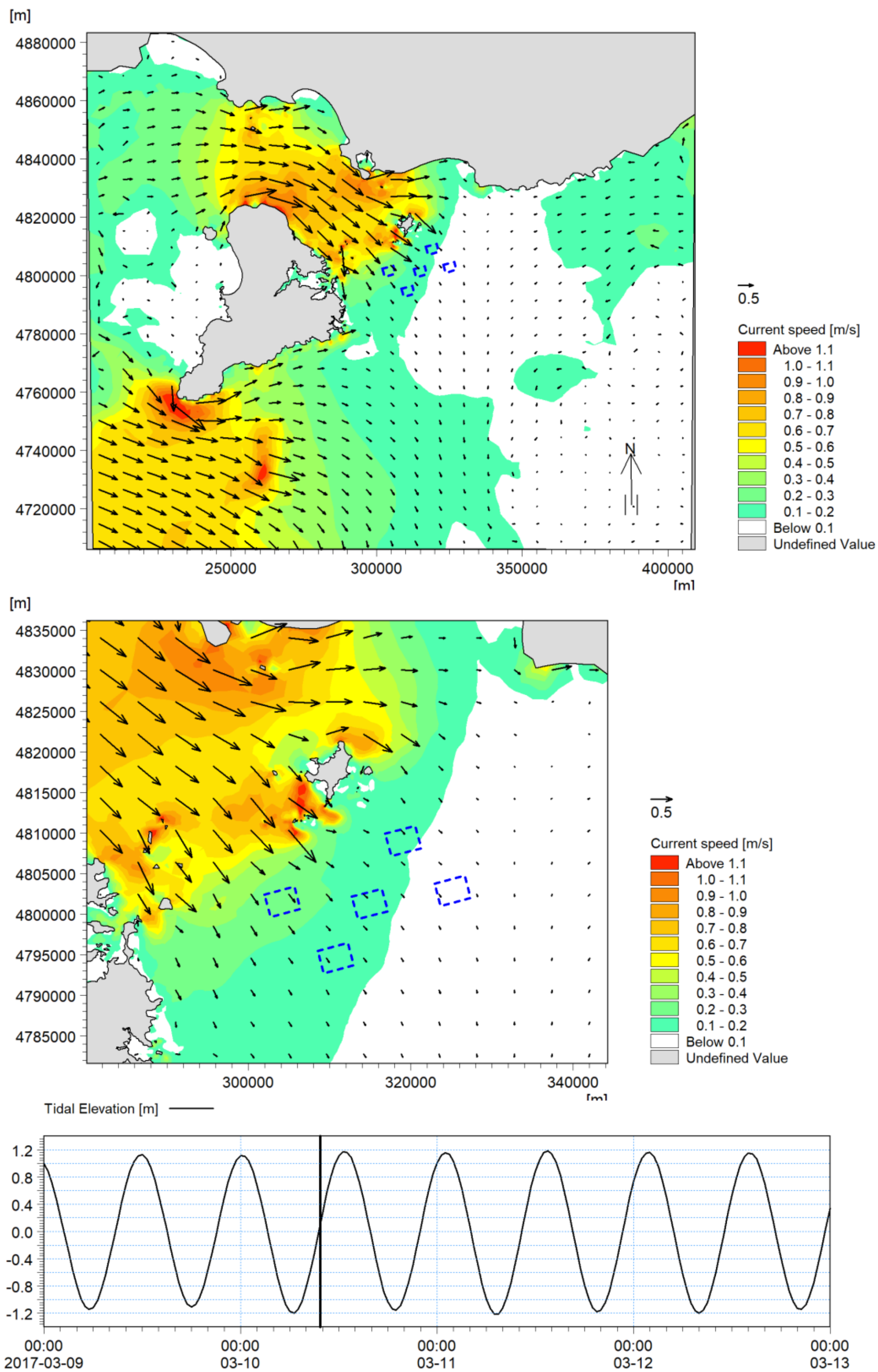

Figure 14 -An example of depth averaged flood driven tidal flow. Flow is to the south-east at the proposed site

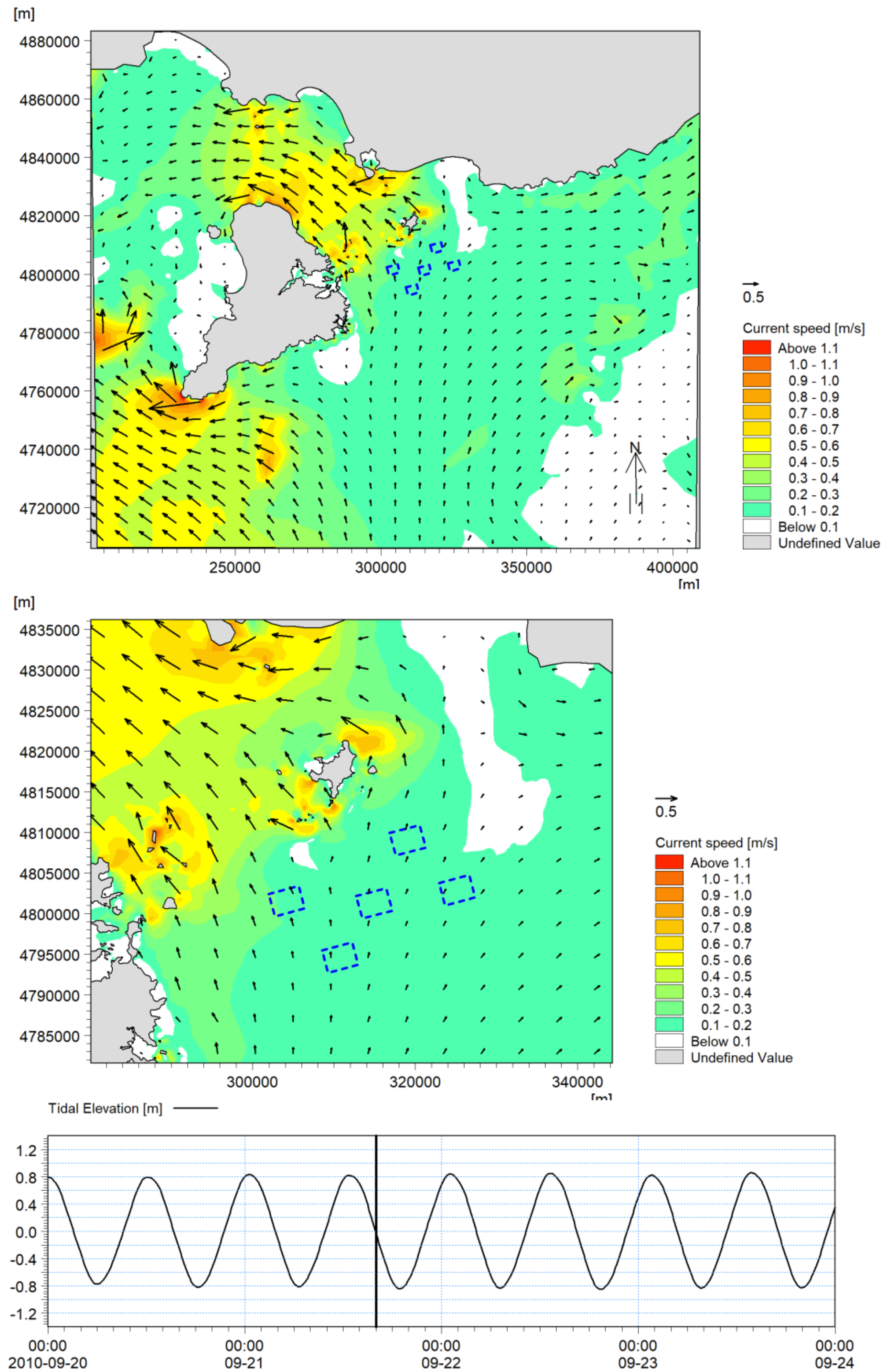

Figure 15 -An example of depth averaged ebb driven tidal flow. Flow is generally to the north east at the proposed site. The western side of the lease has a slight north westerly flow. Note: these plots represent tide only without wind/pressure forcing.

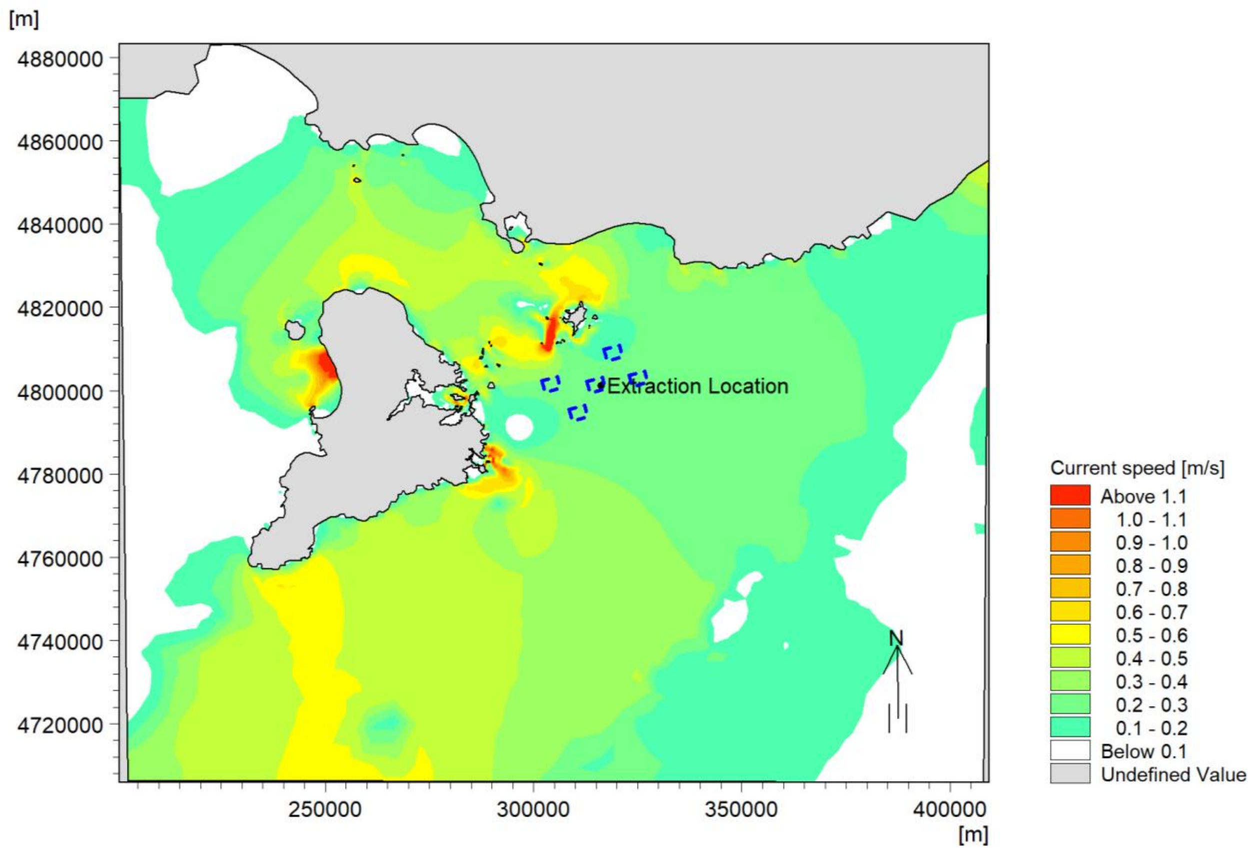

Figure 16 -Extraction location for wind rose plots highlighting seasonal current speed and direction.

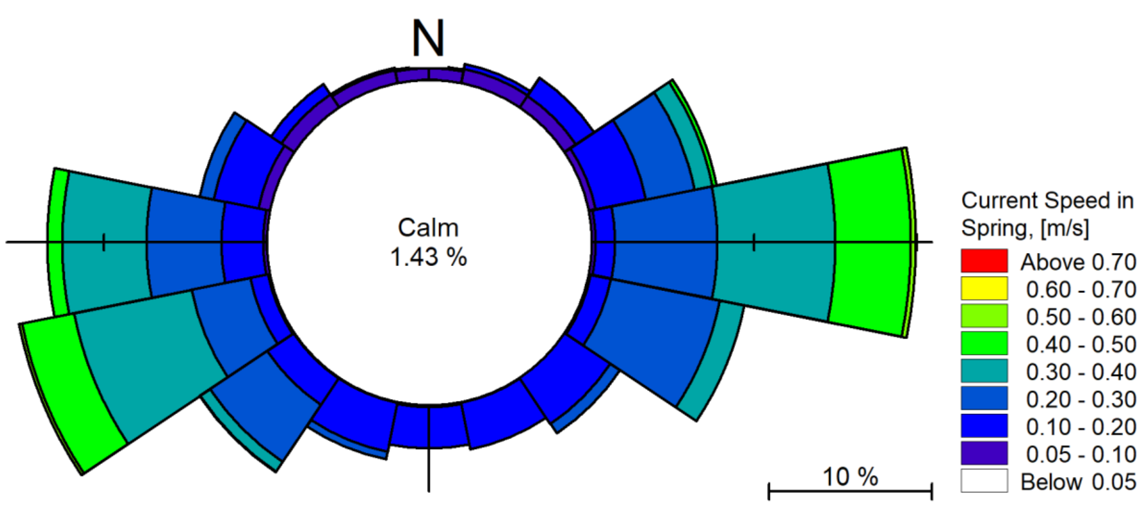

Figure 17 -Spring current speed and direction from the middle of the proposed farming area

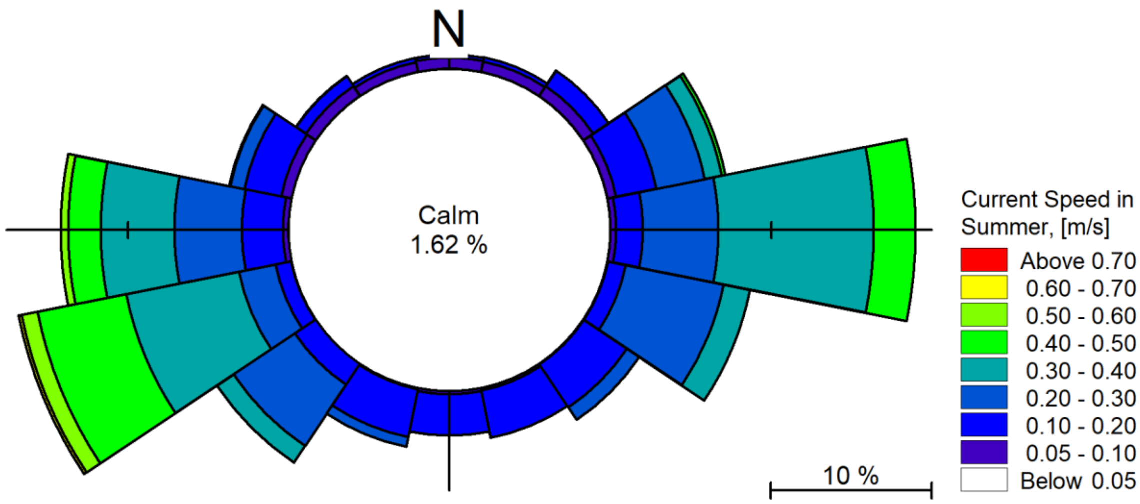

Figure 18 - Summer current speed and direction from the middle of the proposed farming area

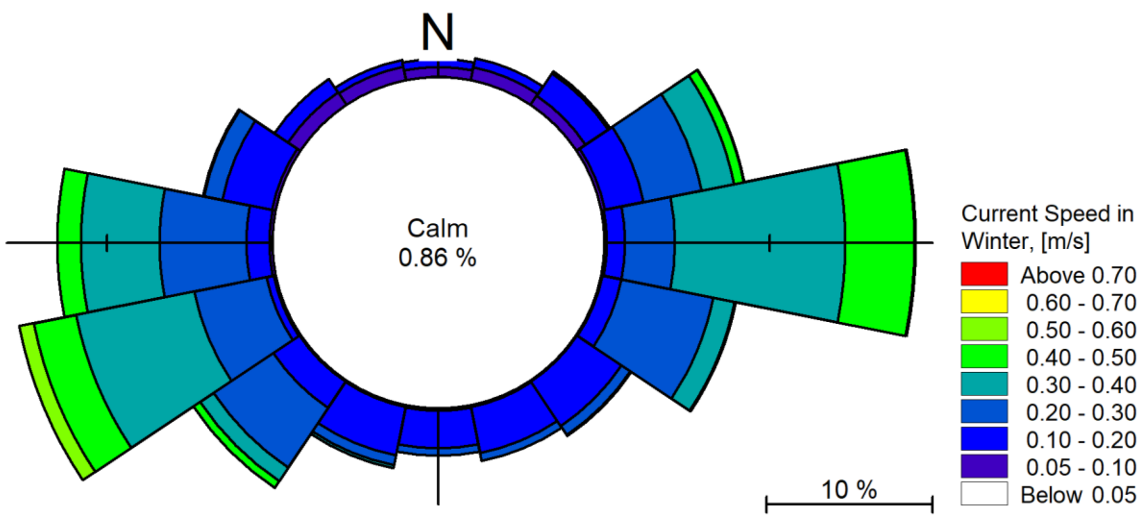

Figure 19 - Autumn current speed and direction from the middle of the proposed farming area

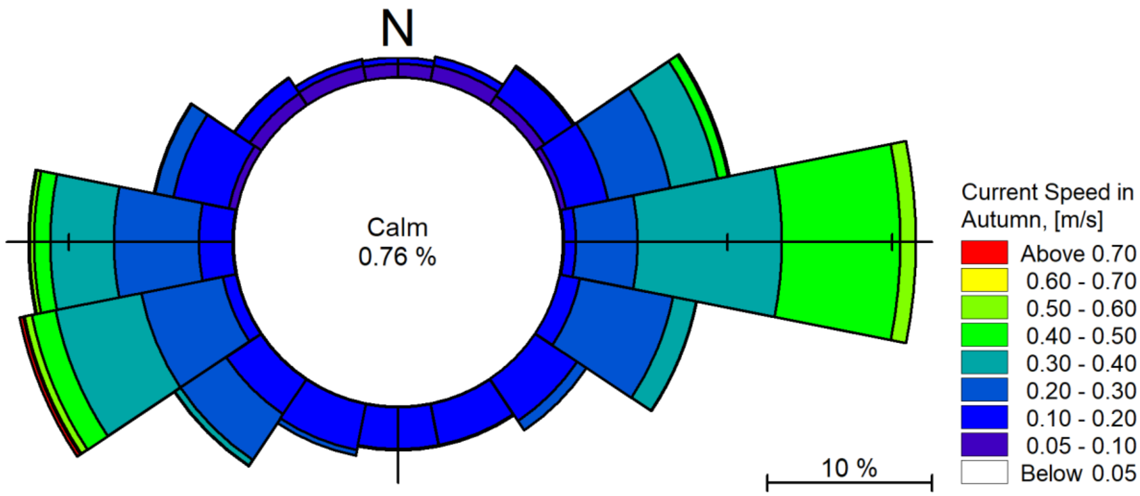

Figure 20 - Winter current speed and direction from the middle of the proposed farming area

5 CONCLUSIONS

Hydrodynamics were modelled using MIKE modelling software. A 3D model was constructed to cover the waters around Stewart Island. This model included regional tidal, wind and current information provided by internationally recognised global models. The model consists of 10 vertical layers and has a horizontal resolution of between approximately 80-2000 meters depending on the location.

The hydrodynamic model was successfully calibrated and validated against current and water level data collected from three separate ADCP deployments. In addition, modelled water level was also compared against 4 additional tidal gauges across the model domain and obtained a good comparison. Overall the hydrodynamic model is fit for purpose and there is a good match between the model and ADCP current and water level data. This hydrodynamic model will be used to drive the water quality and depositional modules (see Volumes 3 & 4).

Tidal flows at the proposed farming area are moderate between 0.1-0.2 m/s. Predominate wind/ocean circulation driven flow is to the ENE and WSE, W and E. Though there were notable stronger NE, SW components at times (see Volume 3).

The model was run for a period of 1 year using GFS and local wind data which generated stronger flows across the study area of between 0.2-0.4 m/s and a maximum flow of approximately 0.7 m/s. Strong flows of up to 1.2 m/s were predicted to the west of the proposed site near Ruapuke Island. Predominate current directions are to the west, southwest, east and northeast. Such directions and magnitudes are similar to those reported in previous studies conducted in the 1960's and by Stevens et al 2019.

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APPENDIX 1 EXAMPLES OF CURRENT FLOW AND DIRECTION SEASONAL PLOTS

6.1 SPRING

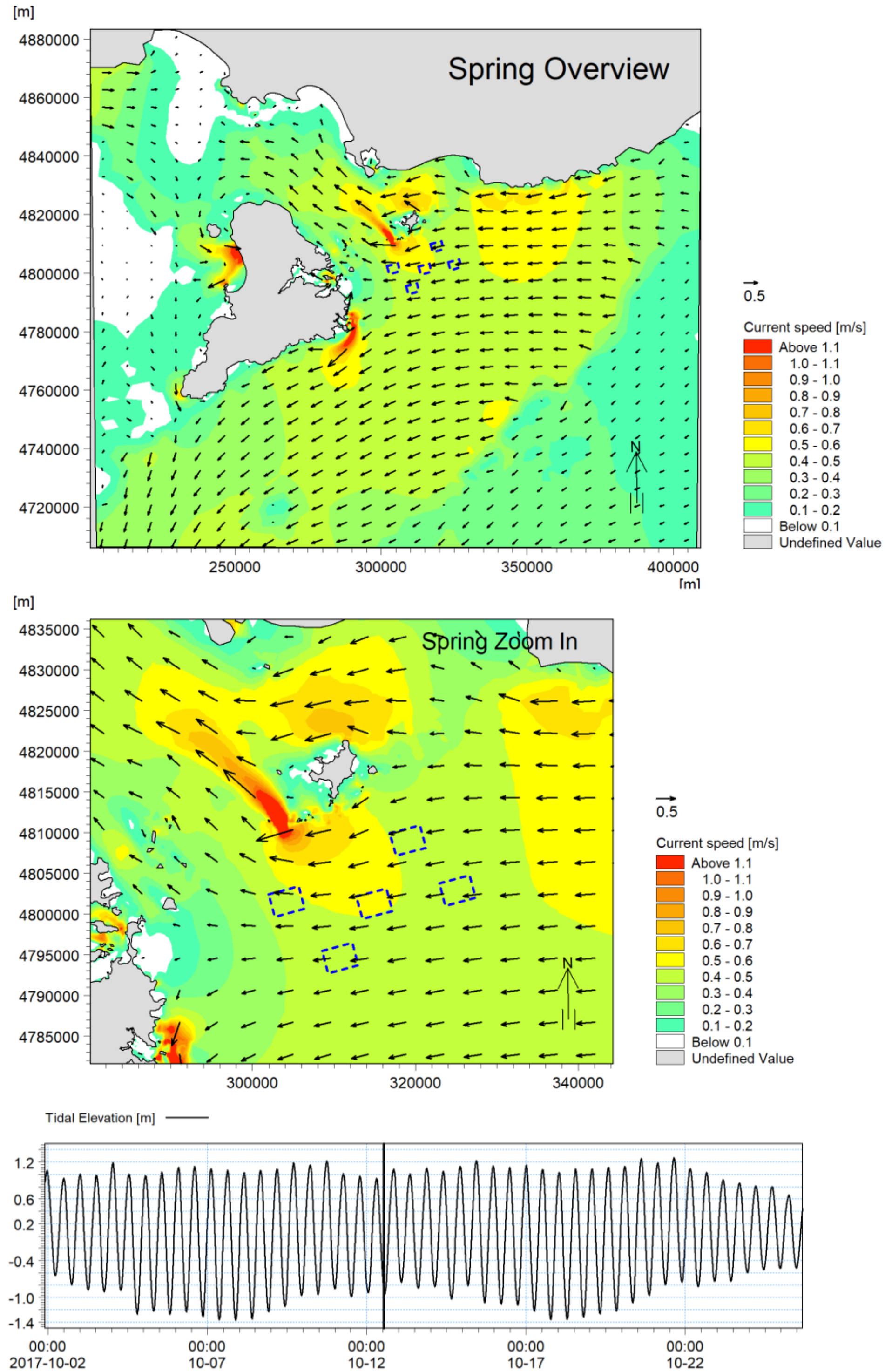


Figure 21 -An example of Ebb driven flow during spring.

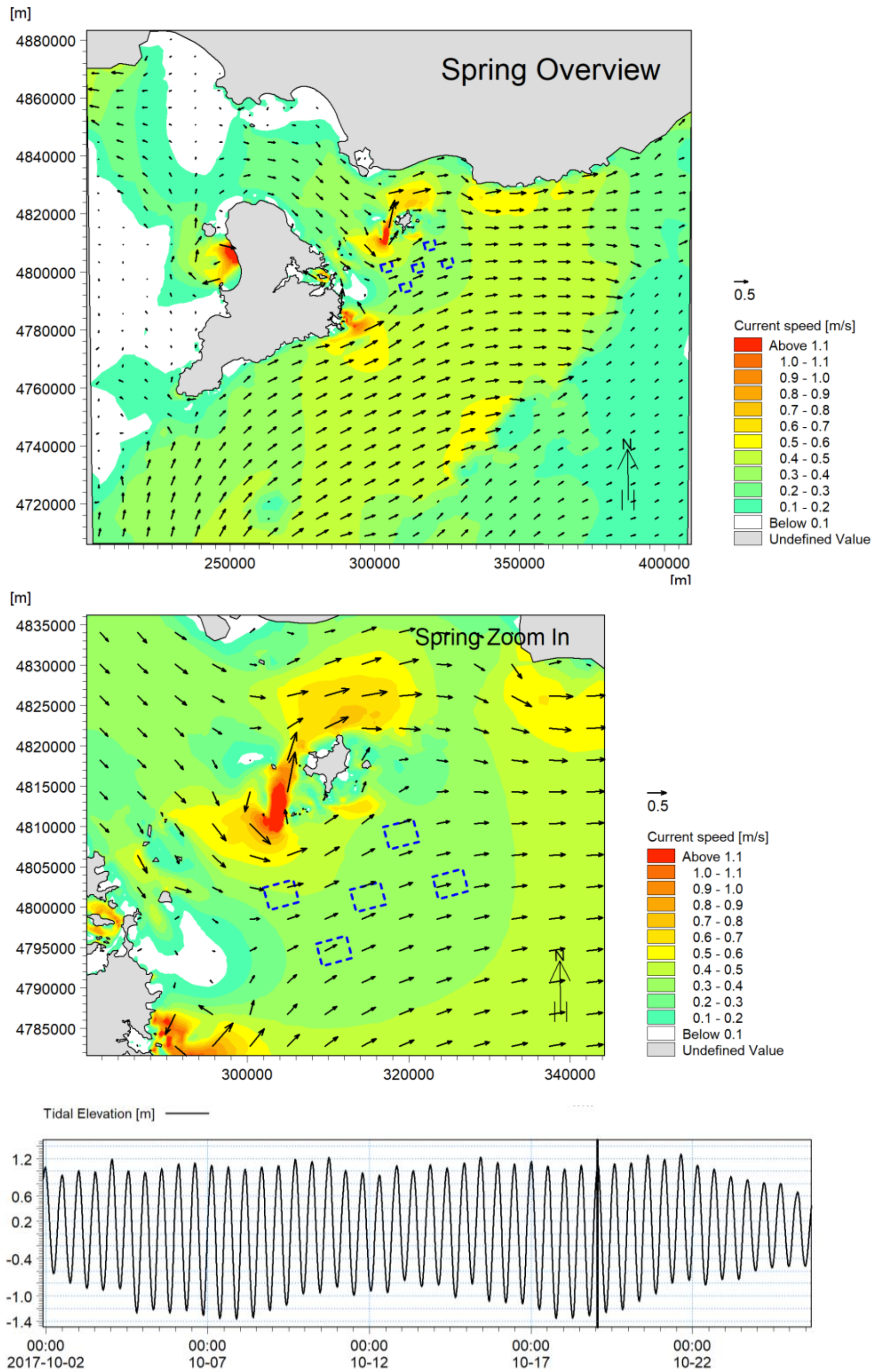


Figure 22 -An example of flood driven flow during spring.

6.2 Summer

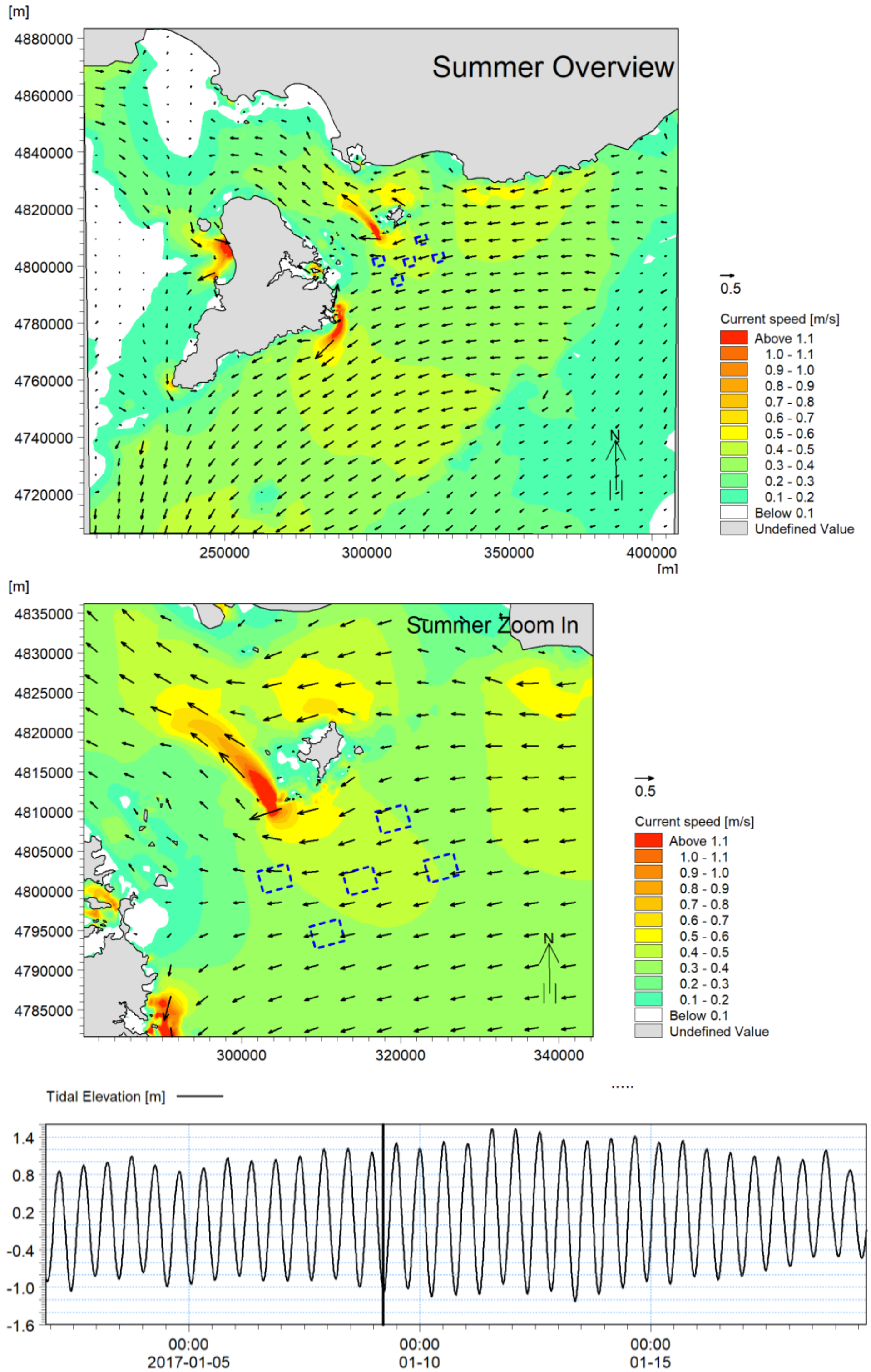


Figure 23 -An example of ebb driven flow during summer.

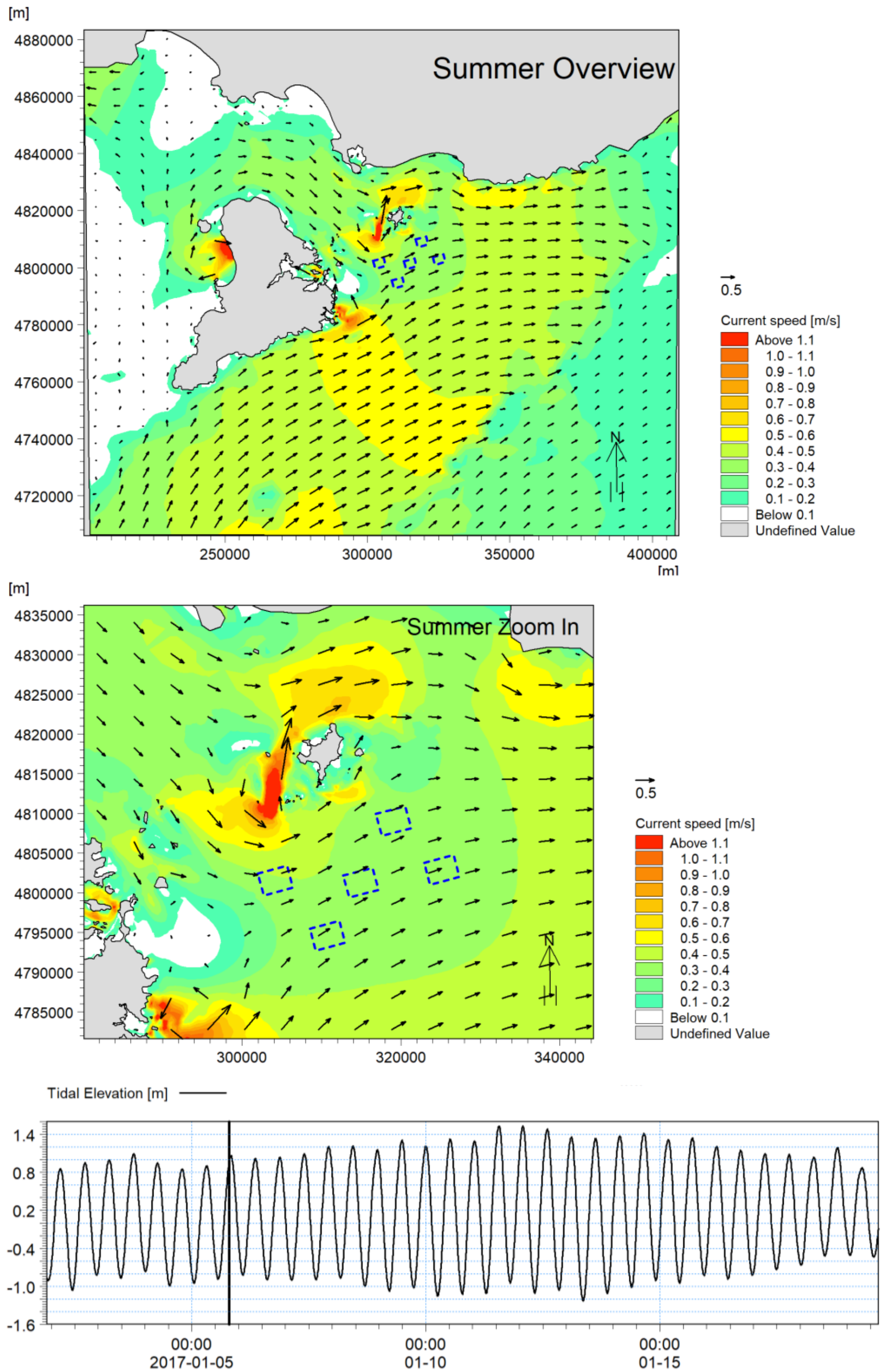


Figure 24 -An example of flood driven flow during summer.

6.3 AUTUMN

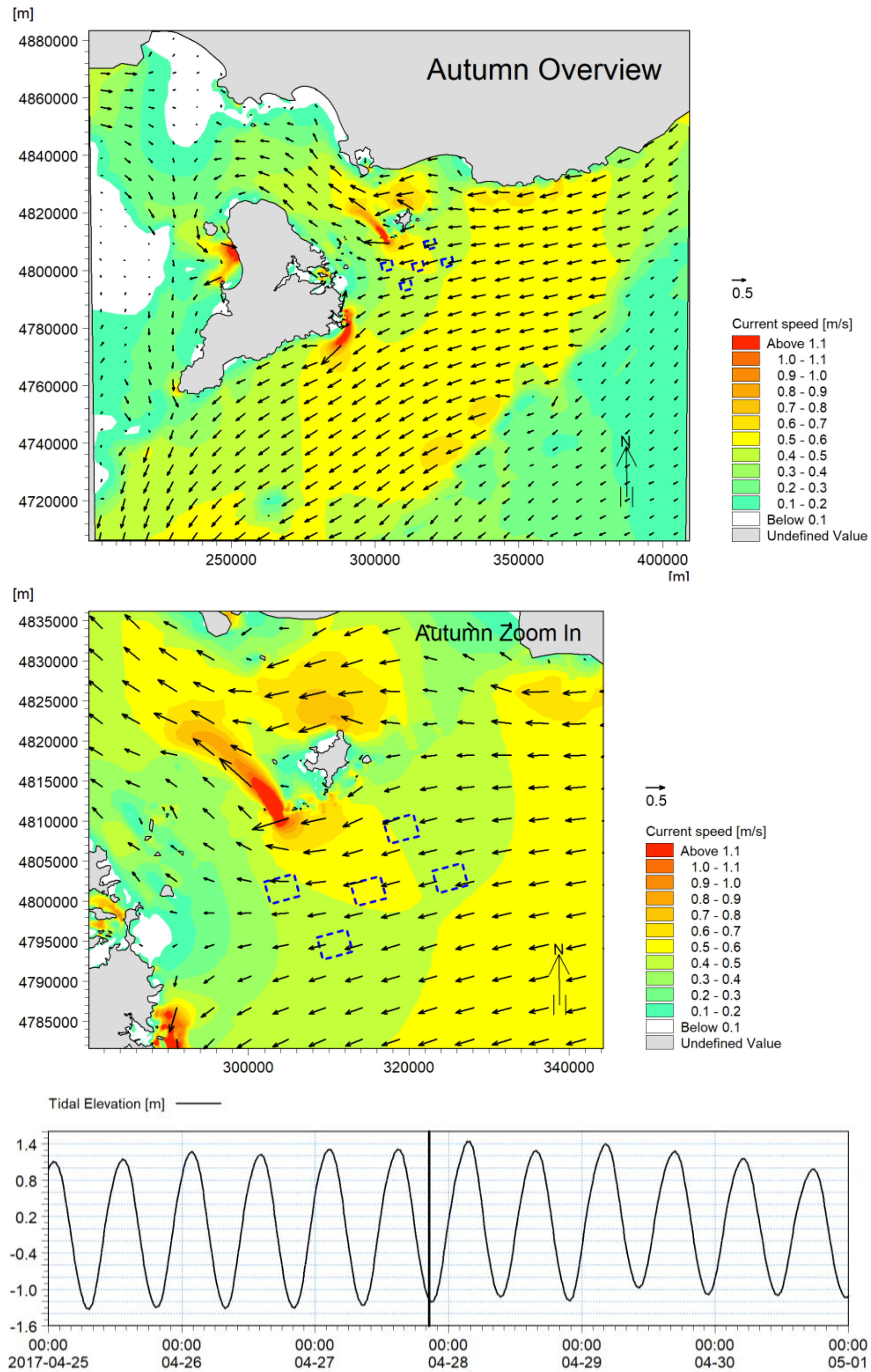


Figure 25 -An example of ebb driven flow during Autumn.

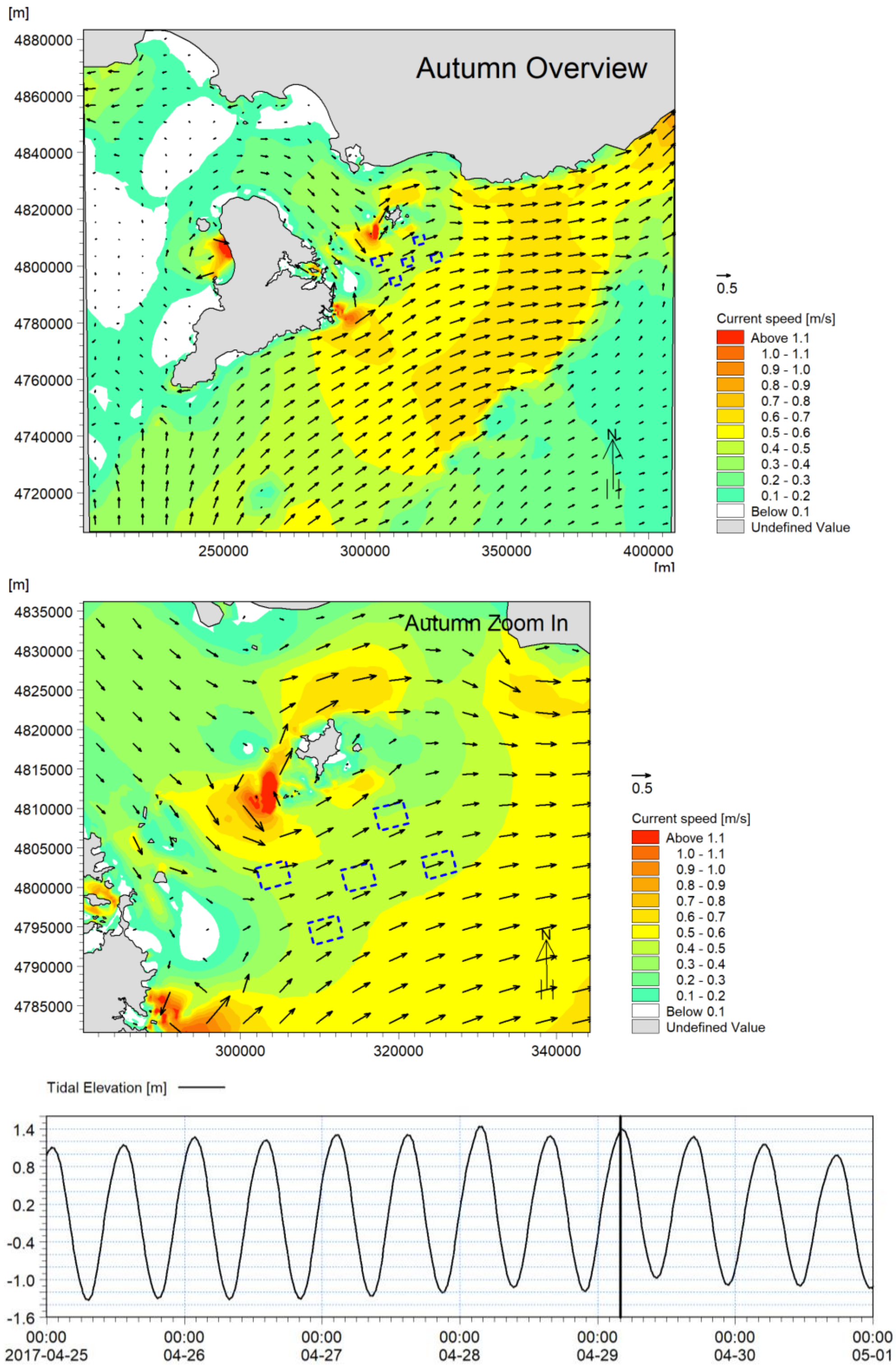


Figure 26 -An example of flood driven flow during Autumn.

6.4 WINTER

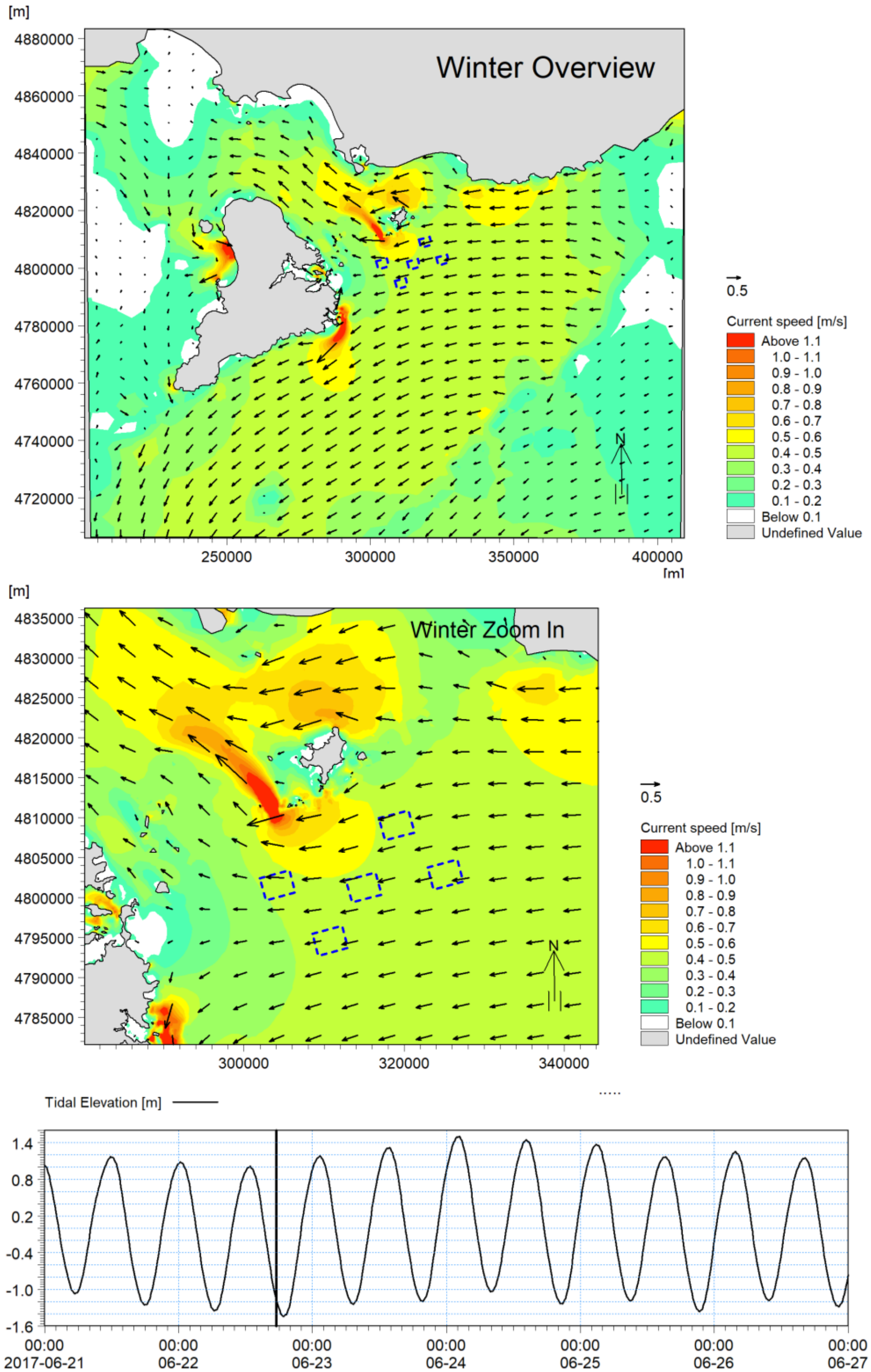


Figure 27 -An example of ebb driven flow during winter

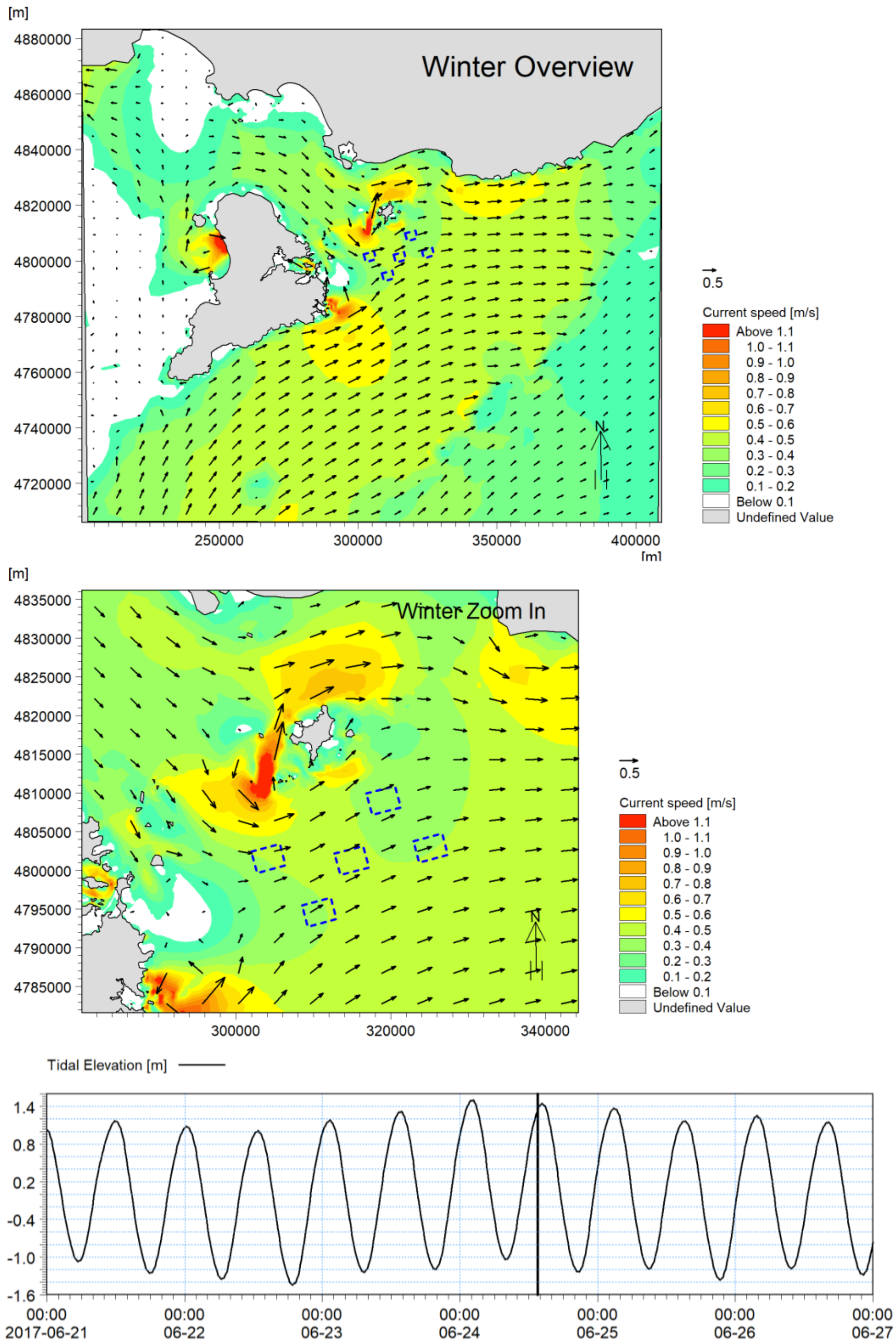
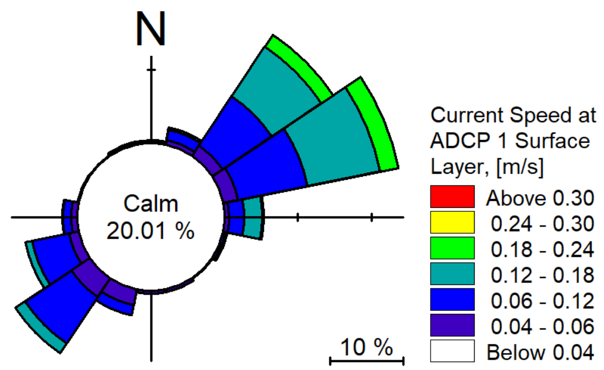
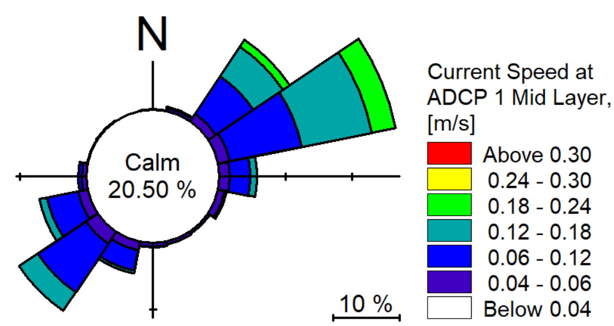


Figure 28 -An example of flood driven flow during winter.

APPENDIX 2 ADCP ROSE PLOTS





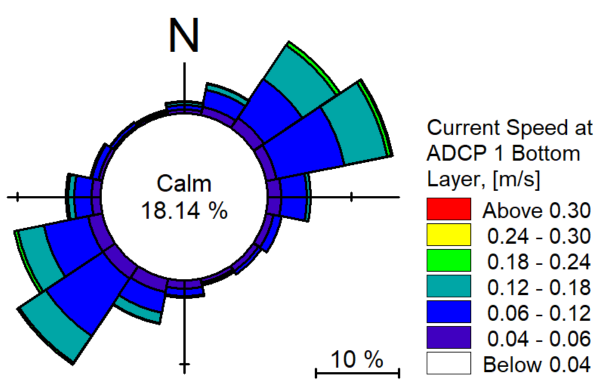


Figure 29 -ADCP1 current speed and direction rose plot. Note calm is flows below 0.04m/s.

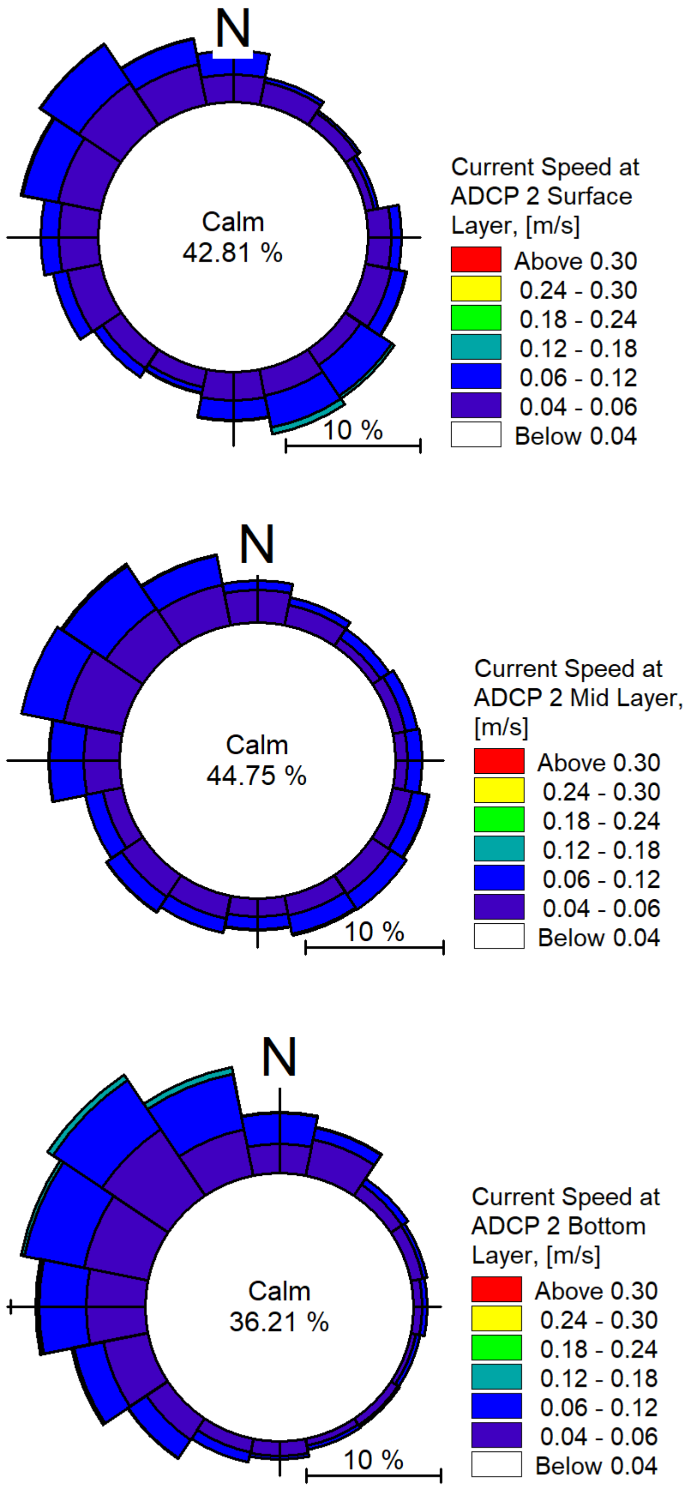


Figure 30 -ADCP2 current speed and direction rose plot. Note calm is flows below 0.04m/s.

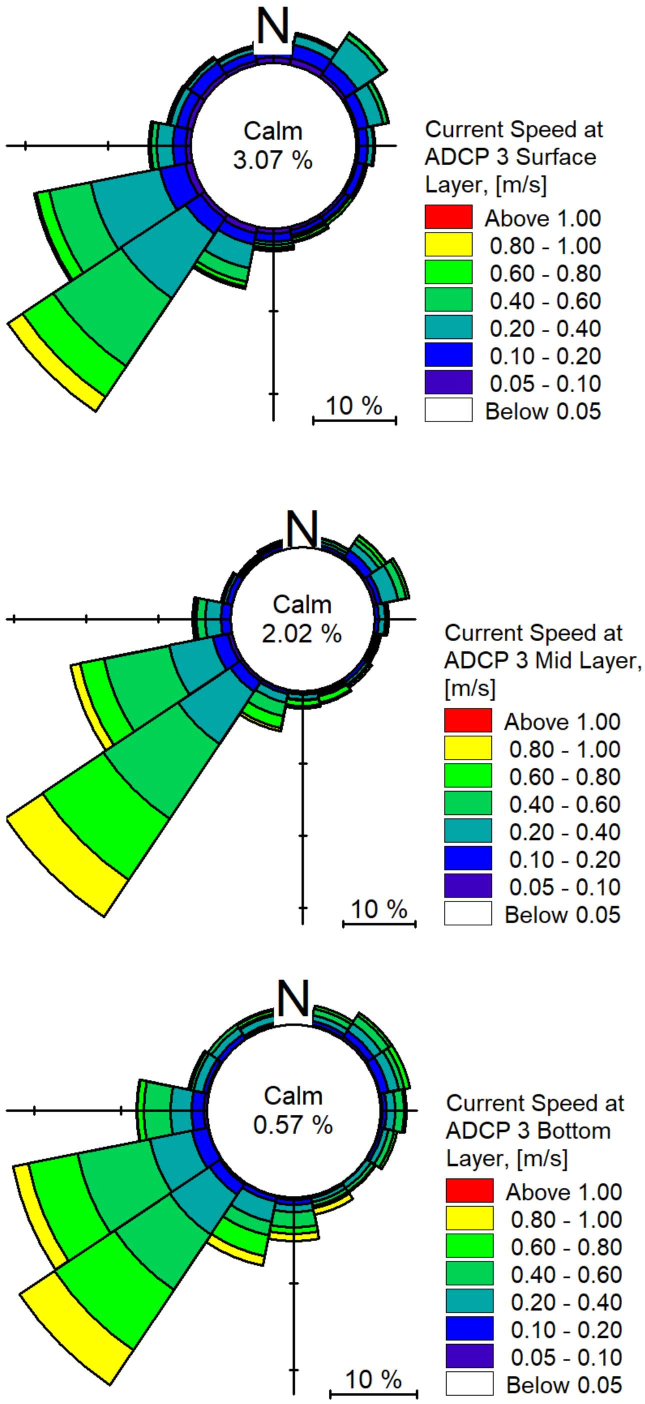


Figure 31 -ADCP3 current speed and direction rose plot. Note calm is flows below 0.05m/s.

Appendix 3 Root Mean Square Error Calculation

To test the suitability of the calibration/validation a RMSE calculation was undertaken. The RMSE value provides a quantitative measure of how good the model fits the data based on the mean of the data (Williams and Esteves 2017). RMSE is one of the commonly used error index statistics and historically, the RMSE and MSE have been popular, largely because of their theoretical relevance in statistical modelling (Hyndman & Koehler 2006, Moriasi 2007).

We have defined the RMSE calculation as the difference between a measured parameter and its associated predictor for the same timestamp (Each calculation is based over 3 days of spring and neap tidal periods). Since positive and negative errors might compensate one another and result in much lower estimates of the error than occurs, a square of the error is used. A mean of the squared errors is computed before a final square root operator returns the final RMSE as an error in the same units as the data the function is used on.

From a statistical perspective, if the estimator has a zero bias (unbiased), then the RMSE is effectively the square root of the variance.

The formula associated with the calculation of the RMSE is:

$$RMSE = \sqrt{\frac{\sum_{t=1}^{n}(y_{measured} - y_{predicted})^2}{n}}$$

We have provided RMSE calculations for current direction (when available), water level and current speed. While there is no standard method for normalized RMSE, mean (average) and range are most often applied and he results presented as percentages for current speed and water level (Williams and Esteves 2017).

Water levels oscillate around Mean Sea Level and as a result using the average would not result in any meaningful results. Therefore, the range was used instead, which also makes sense as this corresponds to the amplitude or tidal range.

Current speeds are always positive and therefore the same issue does not apply, hence the mean of the speed values was used to normalize the results presented.

RMSE calculation results are expressed in the Tables Below. We consider acceptable RMSE calibration/validation values of 10% for water level, 20% for current speed and 20-25 degrees for current direction, though granted these values can be subjective in nature.

Table 3 - RMSE for the modelled water level at the ADCP locations where data is available.

Water Level RMSE	Spring Tide	Neap Tide
ADCP1	N.A	N.A
ADCP2	2.41%	3.27%
ADCP3	5.82%	4.7%

Table 4 - RMSE for the modelled water level vs Tidal stations

	RMSE for Water Level (%)		
Tidal Stations	2010	2017	2019
Bluff	6.4%	7.1%	6.9%
Colac Bay	9.3%	10.1%	8.9%
Waipapa Point	5.1%	5.9%	5.2%
Paterson Inlet	6.6%	7.7%	6.6%

Table 5 - RMSE for the modelled current speeds.

Current Speed RMSE	Spring Tide	Neap Tide
ADCP1	15.93%	18.32%
ADCP2	9.68%	18.45%
ADCP3	21.34%	19.42%

Table 6 - RMSE for the modelled current directions.

Current Direction RMSE	Spring Tide	Neap Tide
ADCP1	17.98 °	19.74 °
ADCP2	20.1 °	19.833 °
ADCP3	N.A	N.A