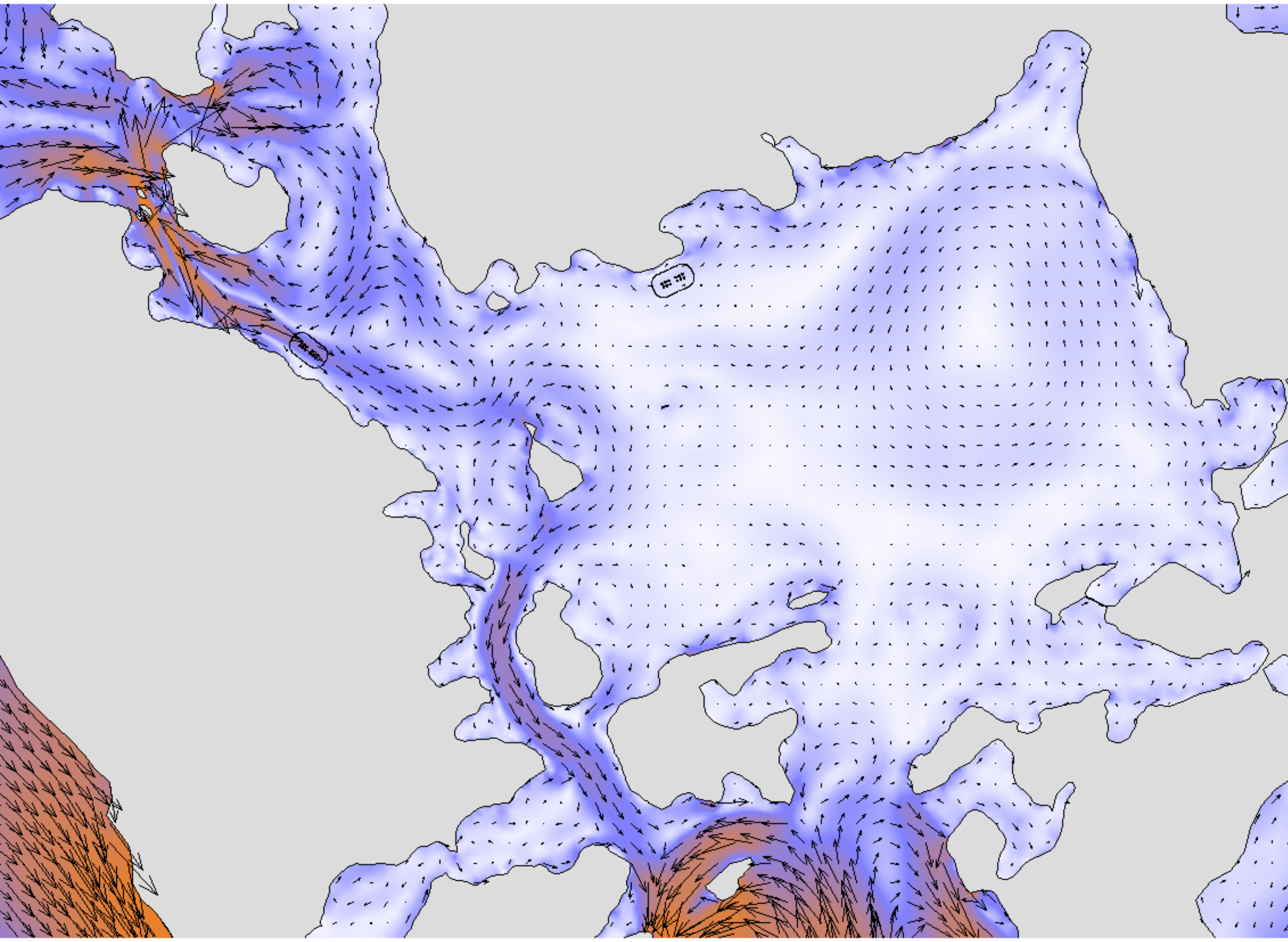
Orkney - Scapa Flow
Hydrodynamic Modelling Assessment
Bring Head and Toyness

Modelling &
Impact Assessment Report

Project No: 26801744-WP01

13th July 2022

Prepared for Scottish Sea Farms



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Prepared for: Scottish Sea Farms
Represented by [redacted]

Project Manager:	[redacted]	
Project No.:	26801744-WP01	
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Contents

Appendices

Figures

Tables

1 Introduction

Scottish Sea Farms (SSF) are seeking to develop two existing Marine Pen Fish Farms (MPFF's) in Scapa Flow, Orkney. The Bring Head and Toyness farms will be enlarged with a proposed peak biomass of 2,500 tonnes at each location. The regulator (SEPA) requires an assessment of the potential impact of these proposed developments on the key water quality aspects of interest. A Hydrodynamic Modelling Assessment is proposed that will provide the numerical basis for undertaking a series of Impact Assessments including waste solids and in-feed treatment.

1.1 Background to the study

The following services have been requested to support the development of two marine pen fin fish aquaculture sites in Scapa Flow, Orkney; one at Toyness and the other at Bring Head (see Figure 1.1).

1. Preparation of a local high-resolution 2D hydrodynamic model for Scapa Flow, forced by the Scottish Shelf Model (SSM) climatology for the production runs.
2. Model Resolution: to be 20 to 50m at farm sites, narrow straits and identified features of interest and 50 to 200m within Scapa Flow.
3. Undertake particle tracking assessment of discharges (waste solids and in-feed treatment) from the proposed sites, and up to 10 other active/proposed sites within Scapa Flow.

1.2 Aims and objectives

This study aims to develop a dedicated, high-resolution 2-dimensional hydrodynamic model that will form the basis for the subsequent impact assessments at Bring Head and Toyness MPFF's.

The calibration of the hydrodynamic model will be for a 45-day period during 2018. This will then be the basis for a production run of a one-year climatology driven by the Scottish Shelf Model which will form the basis for the period of assessment.

The impact assessment will then be undertaken for each aspect on this year of data against relevant environmental quality standards as defined by SEPA. Of particular interest is the potential for this to impact on areas containing Priority Marine Features as identified by SEPA as shown in Figure 1.1 and listed in Table 1.1.

1.3 Layout of the report

This report details the background data used in the study and the development and calibration of the MIKE 21 hydrodynamic model for Scapa Flow (Sections 2-4). Sections 5-6 detail the impact assessment methodology and results with Section 7 providing conclusions of the study.

Table 1.1 Features identified in each PMF within Western Scapa Flow.

PMF Number	Features identified
1	Flame shell beds
	Horse mussel beds
	Maerl beds
2	Horse mussel beds
	Fan mussel
3	Maerl beds
4	Seagrass Beds
	Maerl beds
5	Maerl or coarse shell gravel with burrowing sea cucumbers
6	Maerl beds

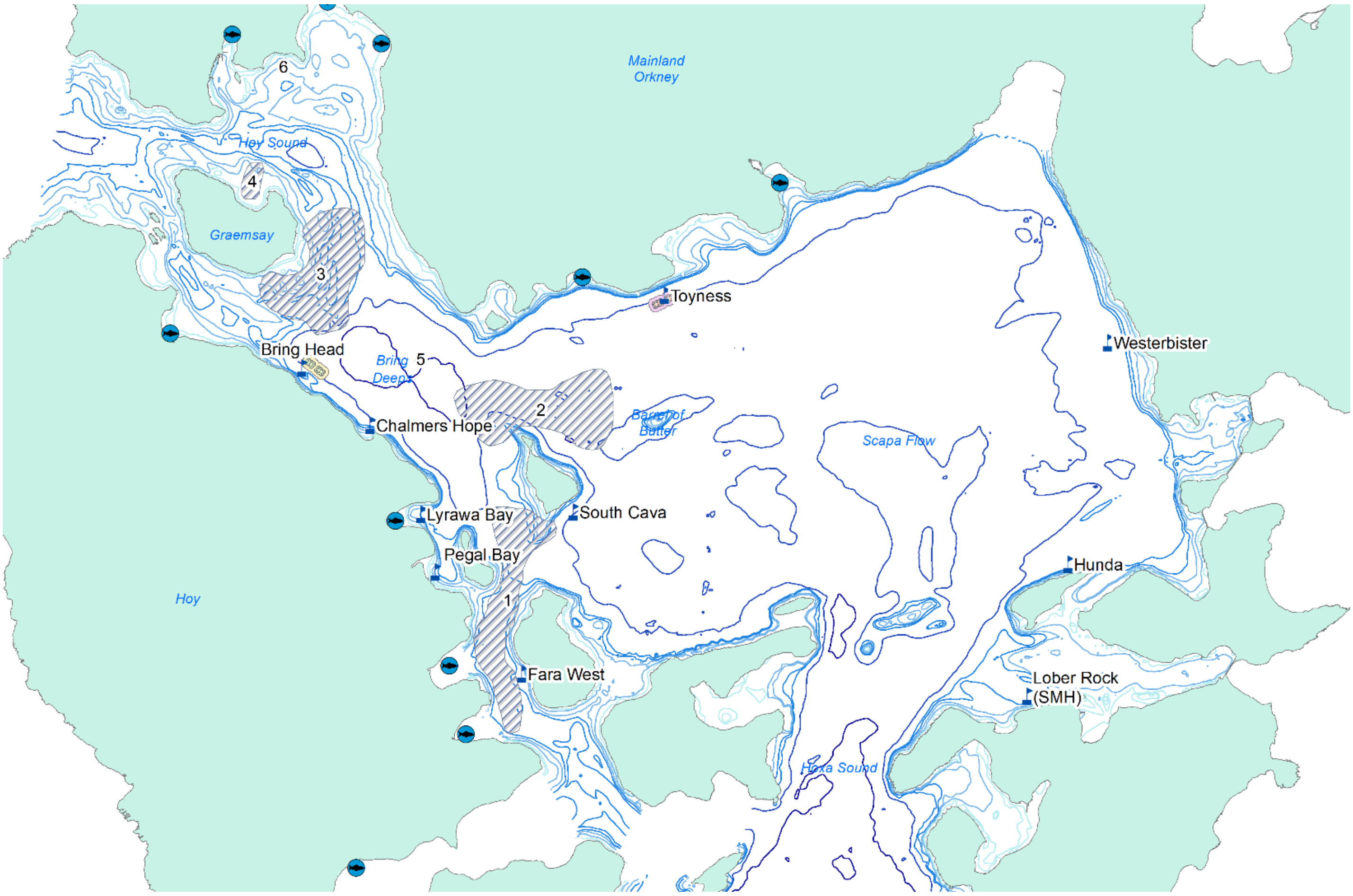

Figure 1.1 Location of Bring Head and Toyness MPFF's within Scapa Flow, Orkney. Other MPFF sites as listed by SEPA are shown as blue flag markers. Areas containing Priority Marine Features identified by SEPA are shown as hatched areas and numbered accordingly. Trout Burns are marked with a blue fish marker.

2 Data Basis

This section outlines the key data sets that are used in both the model development and in the calibration and validation process. This includes the bathymetry used in the model mesh, the current and water level measurements, and the input wind fields

2.1 Bathymetry and coastline

The bathymetry within the model is made up from several data sources, as described below.

2.1.1 Coastline

Ordnance Survey highwater shoreline data (OS HWS) was applied as the governing indicator of the separation between land and water. These data were obtained via OS OpenData[1] licensed under Open Government License[2].

2.1.2 Offshore

For offshore areas, beyond 2km that are not covered by the multibeam bathymetric data sets, bathymetric data from the Digital Terrain Model (DTM) data products have been adopted from the EMODnet Bathymetry portal (version, 24 September 2018). This portal was initiated by the European Commission as part of developing the European Marine Observation and Data Network (EMODnet). The EMODnet digital bathymetry has been produced from bathymetric survey data and aggregated bathymetry data sets collated from public and private organisations. The data are provided processed, and quality controlled at a grid resolution of 1/16 x 1/16 arc minutes (c. ~115 x 60 meters). The average water depth in mLAT for each cell is provided.

2.1.3 Nearshore

For the coastal regions within Orkney and Pentland Firth, high resolution data have been sourced from the UKHO Admiralty Marine Data Portal[3]. This consists of a range of gridded and non-gridded processed survey data sets at horizontal resolutions ranging from 2m to 15m. The coverage of the different survey data sets is shown in Figure 2.1. The highest resolution data has been used within Scapa flow to ensure an accurate as possible representation of the local bathymetry is achieved.

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[1] OpenData - Free GIS Data Download - Geospatial Data Sources for Mapping (ordnancesurvey.co.uk)

[2] Contains OS data © Crown copyright [and database right] (2021)

[3] Admiralty Marine Data Solution, Marine Data Portal (UKHO) accessed March 2021

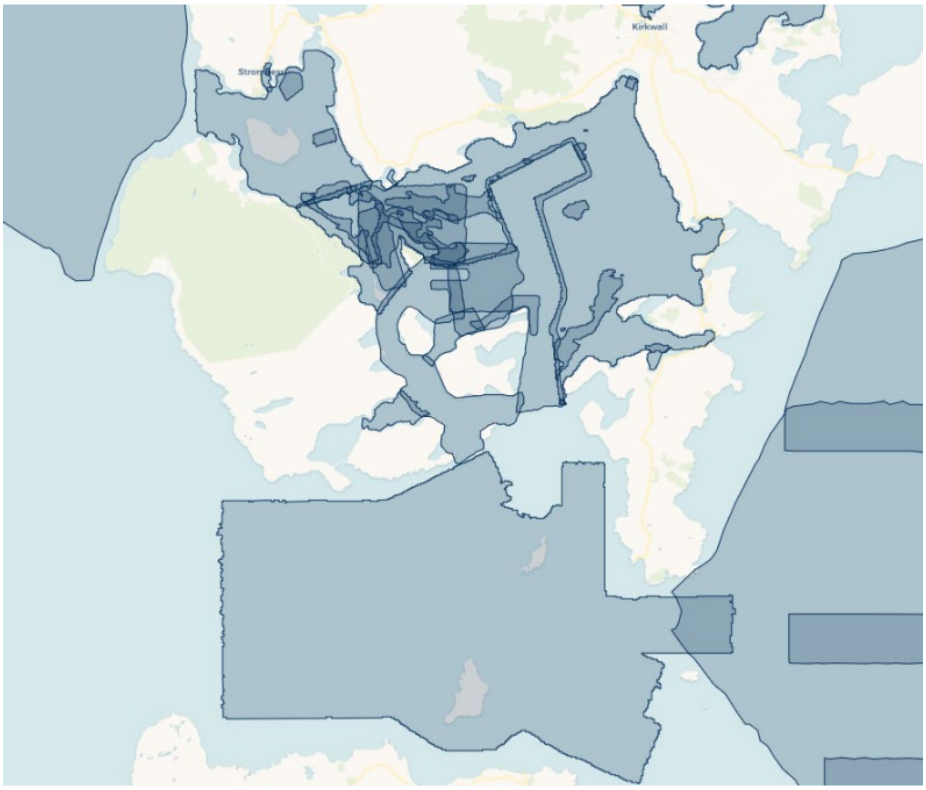


Figure 2.1 Coverage of data sets from UKHO Admiralty data portal

Remaining coastal areas not covered by either EMODNET or the UKHO have been filled from the CMAP digital bathymetry archive and from spot heights manually entered by cross referencing against UKHO chart data. This has typically been for the intertidal zones within Scapa Flow where the survey data does not extend.

Where necessary conversion from Chart Datum/LAT to MSL was achieved by a correction factor of -2.05m. Vertical datums within the model are all relative to mean-sea-level (MSL).

2.2 Boundary conditions applied to the modelling

2.2.1 Calibration period

Boundary conditions for the hindcast calibration period of the hydrodynamic model are based on 2D depth averaged current speed and surface level timeseries from the combined baroclinic and barotropic signals of the HYCOM[4] and global tidal model DTU10[5] solutions, respectively. Both source models are data assimilated in relevant quantities and have been extensively used and validated in various projects in the Northwest Shelf region. Testing of the boundary conditions was undertaken as part of the calibration process, further details of which are provided in the Technical Note in Appendix D.

[4] https://www.hycom.org/)

[5] https://www.space.dtu.dk/English/Research/Scientific_data_and_models/Global_Ocean_Tide_Model.aspx

2.2.2 Climatological production run

The climatology based hydrodynamic realisation is using boundary conditions from the Scottish Shelf Model (SSM) [1, 2]. The SSM is a one-year climatology model that represents average conditions with a 1993 tidal component. The model was implemented using an unstructured grid coastal ocean model, FVCOM (Finite-Volume Community Ocean Model) [3].

2.3 Currents & water level measurement data

2.3.1 Measurement data basis

SSF provided pre-processed ADCP survey data for a range of locations within Scapa Flow and adjacent Orkney waters. The data has undergone further inspection for errors, before deriving depth-averaged current direction and depth-averaged current speed.

Data cleaning included removing any noise from the data set (defined as measurements in the top 10% of the water column, which can be influenced by reflections from the water surface). Depth averaged current direction and depth averaged current speed was determined from this processed record, whereby the current speed and direction was split into its u and v velocity components and averaged across all bins (ignoring NaN values). The average u and average v velocities were then recombined to give depth averaged current speed and depth averaged current direction.

Surface elevation for each site was determined by adding the frame height of the ADCP to the sensor depth record and then subtracting the MSL value for the ADCP deployment location from the data record.

Figure 2.2 shows the locations of each measurement location within Scapa Flow and Figure 2.3 presents the time coverage of each measurement data set. Measurement campaigns cover three distinct periods: January 2008, April 2011, and September to November 2018. With regards to the locations of interest in Scapa flow, the data sets that are most relevant are at Bring Head and Toyness. There is only a single period where the data from these locations overlap, which is from 26th September 2018 to 14th November 2018. This has been the primary period chosen for the model calibration.

The Westerbister data set for this primary calibration period did not pass SSF's internal screening process; hence, only the Bring Head and Toyness data sets are used for the model calibration period in 2018.

Further model validation has been carried out using the measurements in 2005 (Toyness), 2008 (Bring Head) and 2011 (Hunda, Roo Point, St Margaret's Hope and Westerbister for the earlier period).

Sections 2.3.2 and 2.3.3 provide a descriptive summary of the Bring Head and Toyness data sets used for the calibration period and Section 2.3.4 provides a summary of the remaining data sets used for validation.

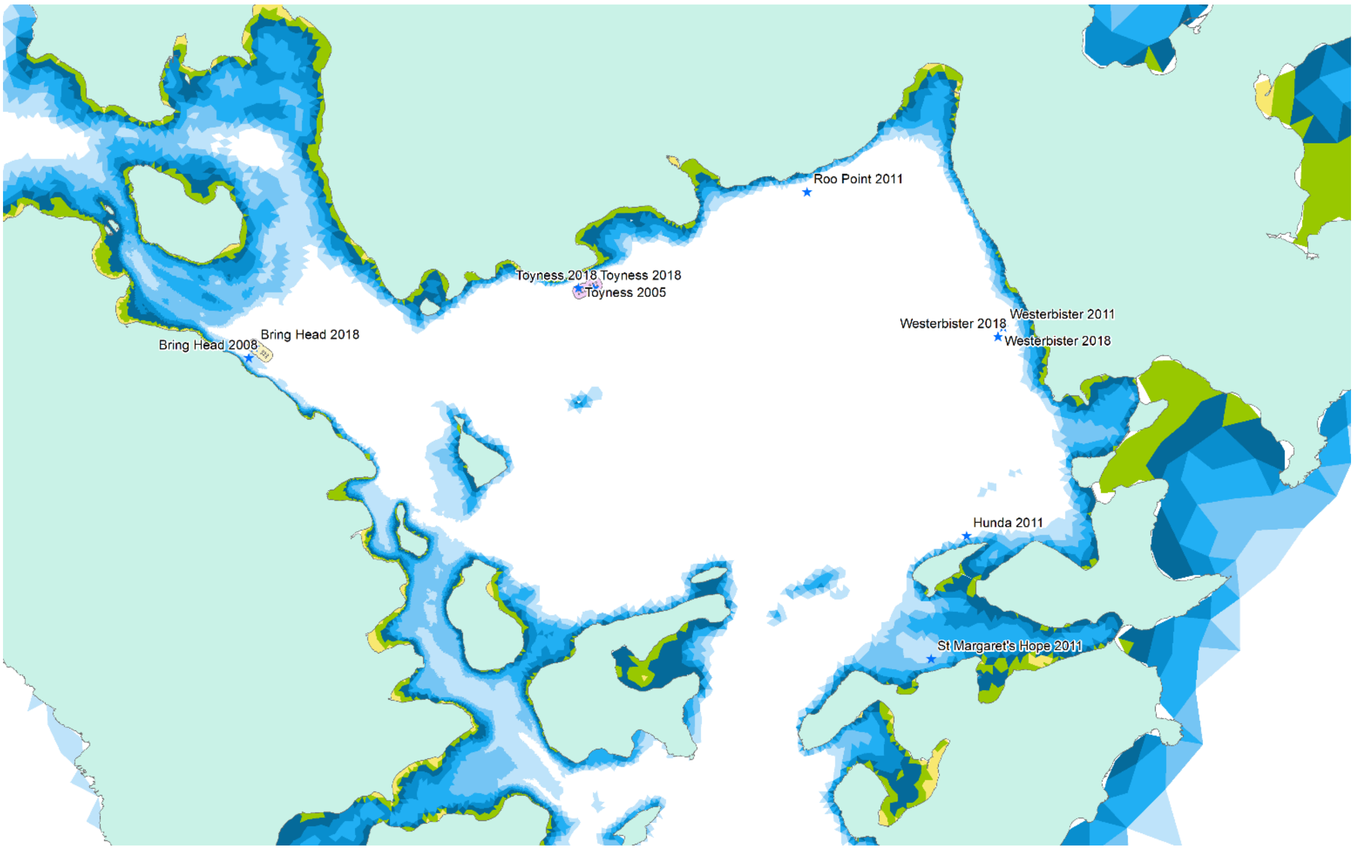


Figure 2.2 Figure showing measurement locations in Scapa Flow

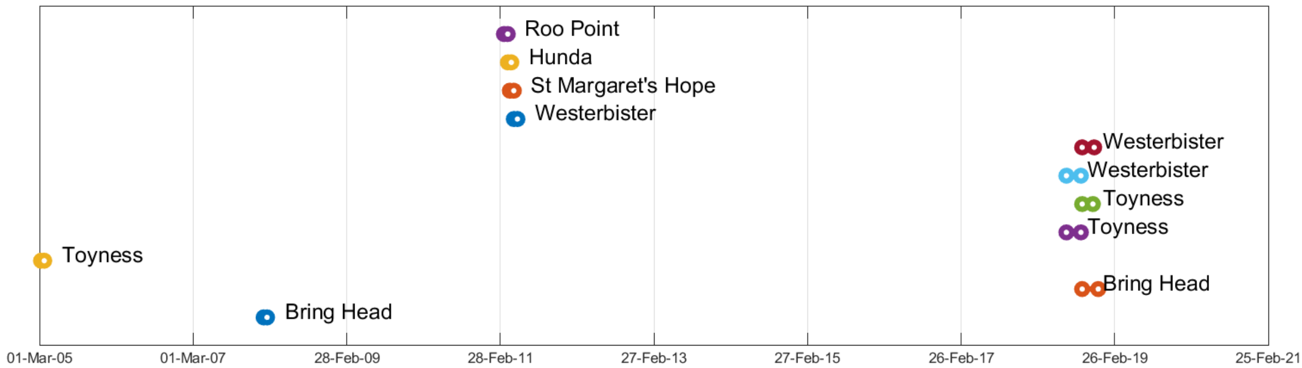


Figure 2.3 Temporal coverage of the observation data being used in this assessment

2.3.2 Bring Head Summary data

For Bring Head, the selected calibration data set was collected during the period from September to December 2018. The following figures provide a summary of the measured conditions.

From the vertical profiles in Figure 2.4, it is seen that generally the currents follow a typical vertical velocity profile. Directions do vary slightly with depth, particularly on the South-southeast directions (~120°), where at depth, the persistence of those currents can be seen to weaken slightly. Otherwise, currents are primarily bi-directional through the water column, with a residual current directed towards the northwest.

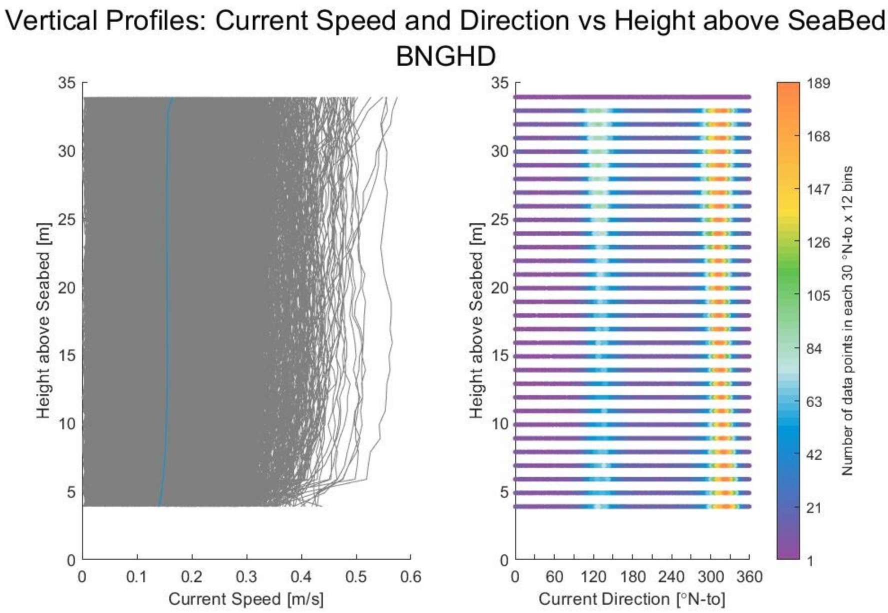


Figure 2.4 Vertical profile at Bring Head

The rose plot shows a similar directional pattern with depth-averaged current speeds that are typically between 0.1 m/s and 0.3 m/s, with a persistence of flow towards the northwest, though with an even spread of magnitudes in both primary directions.

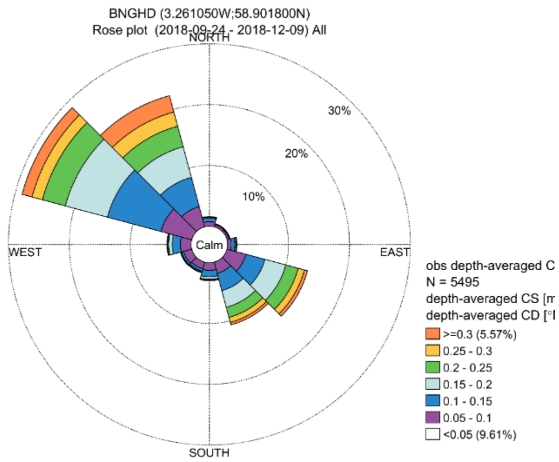


Figure 2.5 Observed depth averaged total current rose plot at Bring Head

2.3.3 Toyness Summary Data

For Toyness, Figure 2.6 and Figure 2.7 provide a representation of the current conditions. It is noted that the current speeds are much lower than at Bring Head, with a slight 3D profile seen with a bulge in the current profile from 5-15m above the seabed and a more pronounced surface increase, particularly for the higher current speeds.

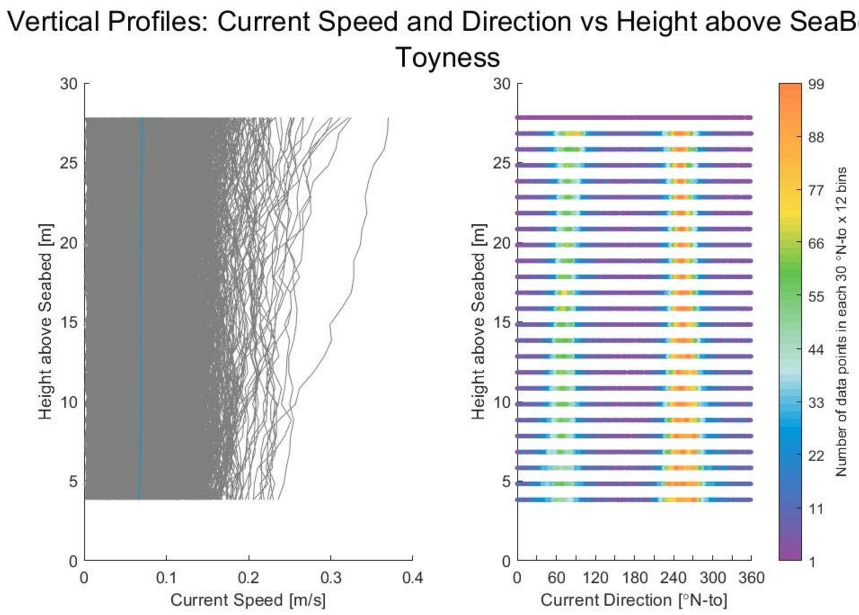


Figure 2.6 Vertical profile at Toyness

Directionally the currents are aligned in a broadly East-West direction, with a slight offset NNE and SSW to some of the currents. From a frequency basis, it is apparent that the depth average currents are more often seen to be in a SW direction, with a residual current towards the southwest.

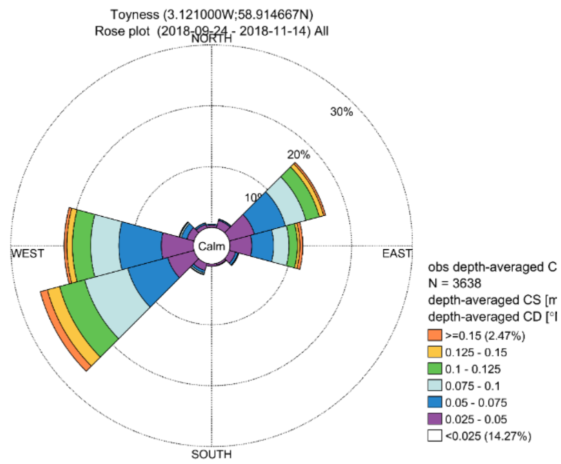


Figure 2.7 Observed depth averaged total current rose plot at Toyness

2.3.4 Additional sites in Scapa Flow

Further measurements across Scapa Flow have been processed for use in the validation phase (Roo Point, Westerbister, Hunda and St. Margaret's Hope). Rose plots of the total, depth-averaged current speed for these sites, along with the measurement data at Bring Head and Toyness, are presented in

Figure 2.8 and show the geographical variability of current speeds within Scapa Flow.

It can be clearly seen that currents on the eastern side of Scapa Flow are weak, typically less than 0.1m/s, and suggest an overall anti-clockwise circulation pattern in the depth averaged values. It should be noted that the 2011 data sets are only for 15-days and so may not be representative of the overall current regime.

Additionally, it is seen that there is seasonal variability in the flows, which is considered most likely to be caused by non-tidal effects potentially including the wind or other 3D driven effects of the flow through Scapa. The 3D nature of the flow is more noticeable in the eastern parts of Scapa Flow (see Figure 2.9), where the tidal currents are seen to be less dominant and current speeds at the surface are noticeably different to those further down the water column.

Further details of the validation results are presented in Section 3.6.

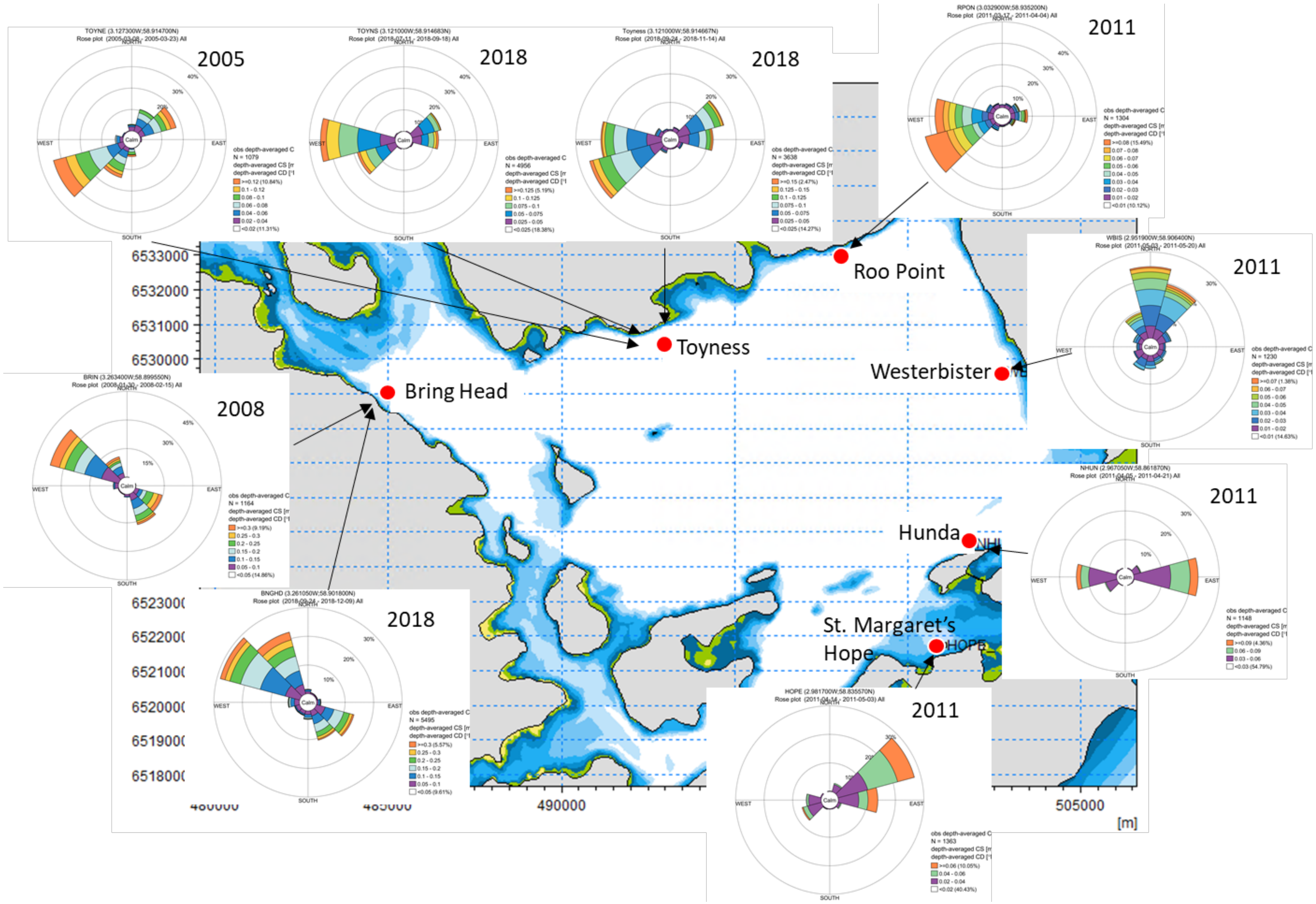


Figure 2.8 Rose plots of observed current speeds data sets used in study calibration and validation

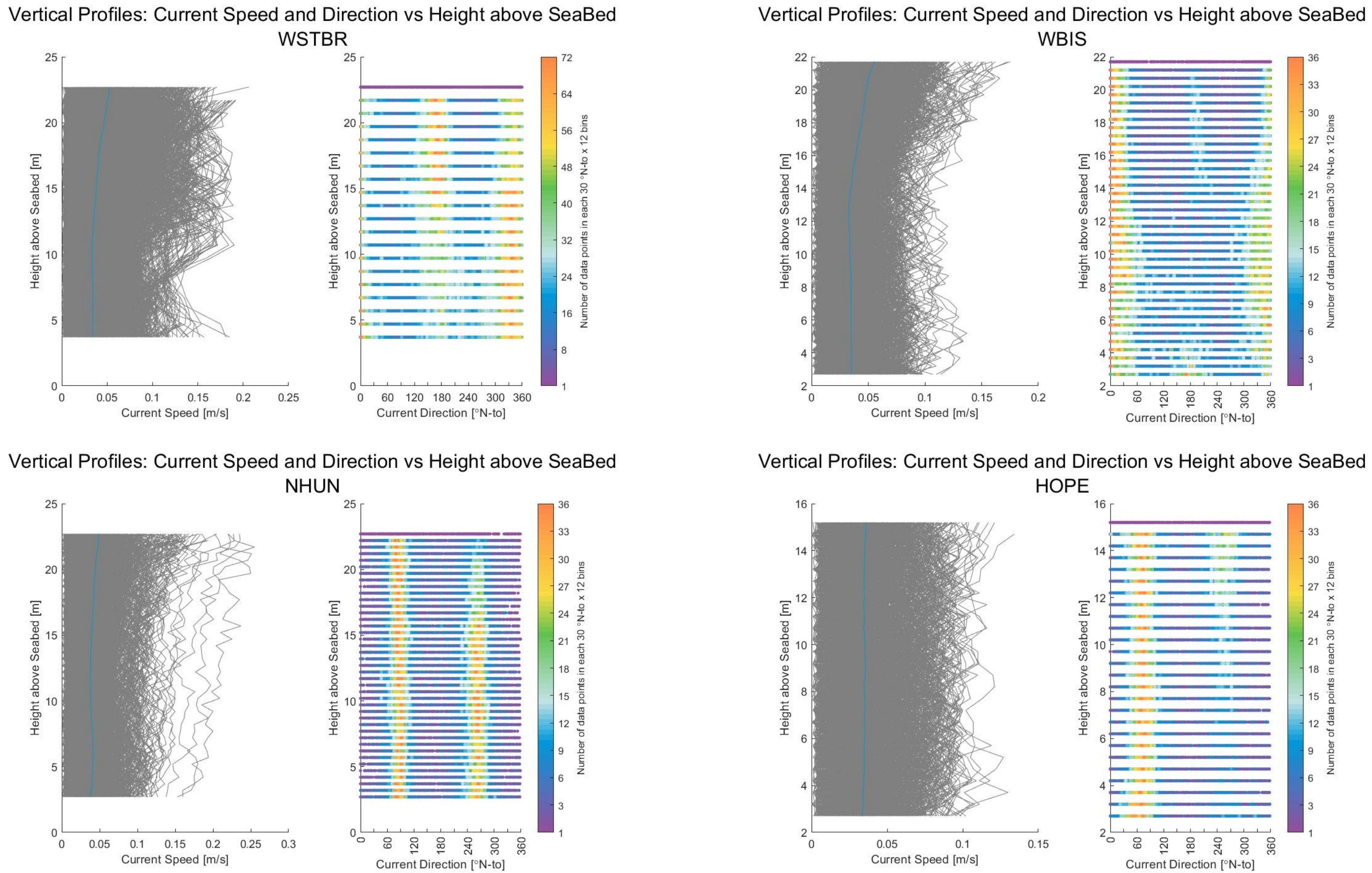


Figure 2.9 From top left in a clockwise direction - Vertical profiles at Westerbister (2018 first period), Westerbister (2011), St Margaret's Hope (2011) and North Hunda (2011)

2.4 Wind data

2.4.1 Calibration period

Meteorological conditions for the calibration period in the hydrodynamic modelling are based on the ERA-5 re-analysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) [4]. The meteorological forcing includes wind conditions (wind speed and direction) and atmospheric pressure. Figure 2.10 shows the gridded wind field from a single time step in the model to illustrate the grid resolution. Heat exchange in the hydrodynamic modelling has been excluded given the hydrodynamic modelling approach herein is constrained to a 2D representation of the flow neglecting density driven flows both through the atmosphere/water surface interface and open boundaries.

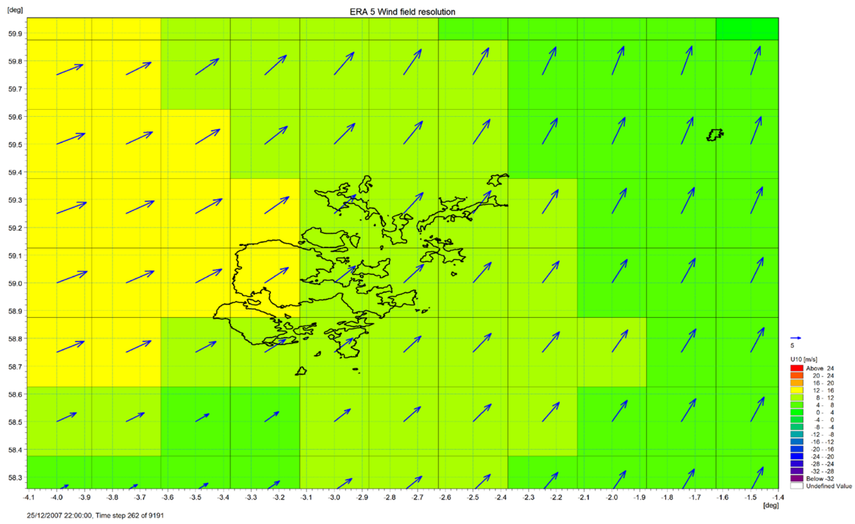


Figure 2.10 Example wind field from ERA-5 reanalysis data set

Limited measurement data were made available; however, some short time periods of wind data were available from the Barrel of Butter from previous studies in the area. These are discussed further in the context of application to the modelling study in Section 3.4.1.

2.4.2 Climatological production run

The climatology based hydrodynamic model is forced by climatologically averaged meteorological conditions used to force the Scottish Shelf Model (SSM). These are derived from the ERA-40 and ERA-Interim re-analysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). The climatology met forcing is based on centred monthly means at the respective calendar months. A linear interpolation between these centred monthly averages is then performed to complete the forcing timeseries and produce smoothed forcing data at 6-hourly intervals, i.e. mean February data were applied at the middle of February; then mean March data were applied mid-March etc., with time-interpolation between the two (see Section 5.3 of [2]).

3 Hydrodynamic Model Development

3.1 Model selection

The approach taken for this study has been to develop a single 2D numerical hydrodynamic model of Orkney encompassing all Scottish Sea Farms sites with a focus on the representation and interaction via tidal currents of the ten fin fish aquaculture sites within Scapa Flow.

DHI has significant experience in modelling of the Pentland Firth and Orkney waters. An existing model of the region has formed the basis for this study, with appropriate alterations and refinements made to the local bathymetry and grid resolution to capture the flow around Orkney and through Scapa Flow.

The 2D model approach is considered adequate to assess the impacts likely from the proposed farm development at Bring Head and Toyness due to the perceived dominance of the tide in the transport of material away from the sites.

3.2 MIKE 21 Hydrodynamic model

The hydrodynamic model for this study was established using the MIKE 21 Flow Model FM that is developed and maintained by DHI [5].

MIKE 21 Flow Model FM is a modelling system based on a flexible mesh approach and has been developed for applications within oceanographic, coastal, and estuarine environments (wherever stratification can be neglected). The Hydrodynamic (HD) Module is the basic computational component of the entire MIKE 21 Flow Model FM modelling system and provided the hydrodynamic basis for other components such as the Transport Module, and the Particle Tracking Module.

The HD module based on the numerical solution of the 2-dimensional incompressible Reynolds averaged Navier-Stokes (RANS) equations, subject to the assumptions of Boussinesq and hydrostatic pressure. The model can be used to simulate a wide range of hydraulic and related items, including tidal exchange, currents, and storm surges. The spatial discretization of the primitive equations is performed using a cell centered finite volume method. The spatial domain is discretized by sub-division of the continuum into non-overlapping element/cells. In the horizontal plane DHI's flexible Mesh (FM) approach is used comprising of triangles and/or quadrilateral mesh elements.

The MIKE 21 Model used for the present study was version 2021. For more information on the technical specifications of MIKE 21 Flow model FM the reader is directed to the description in [6].

3.3 Domain and Mesh

The model domain selected encompasses the northwest Scottish mainland coast, the Orkney Archipelago and up to the edge of Shetland (Figure 3.2). The large boundary limits have been chosen to ensure that the tidal wave propagation around Scotland and through the Orkneys and Fair Isle Gap is suitably captured.

The mesh generation has focused on achieving an accurate representation of the bathymetry combined with an appropriate model grid resolution. This is a balance between ensuring that a high enough resolution is achieved at the sites of interest that phases to a coarser resolution offshore whilst still maintaining a model runtime that does not inhibit the ability to make model calibration and production runs.

Of particular importance is accurately modelling the flow through the channels to the north and south of the island of Graemsay. The south eastwards flood flow from these channels directly impacts the conditions at both Bring Head and Toyness. Through the mesh iteration process, it was evident that features such as the Hoy Skerries, Sands of Klebreck, Bay of Quoys and The Fleshes (highlighted in Figure 3.1) needed careful consideration.

There is an additional focus on the need for accurate flow in the regions of the Bring Head and Toyness release locations. Further details of the mesh refinement work is covered in the Technical Note in Appendix D.

The final, entire model domain and mesh is illustrated in Figure 3.2 and a focus on Scapa Flow in Figure 3.3. Five different grid resolution zones are identified by the notations A to E. The approximate horizontal resolution for each zone is presented in Table 3.1, showing a phased increase from 5000m to 25m-50m.

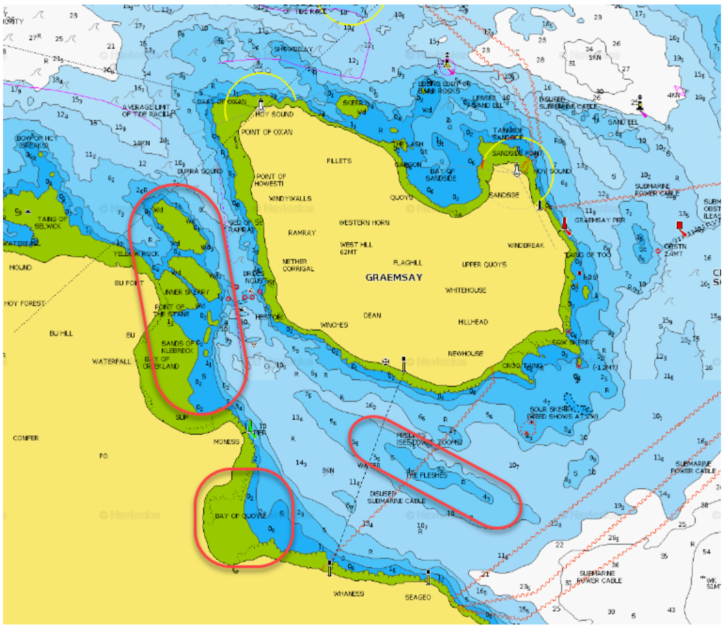


Figure 3.1 Bathymetry around Graemsay, highlighting features important in model mesh generation.

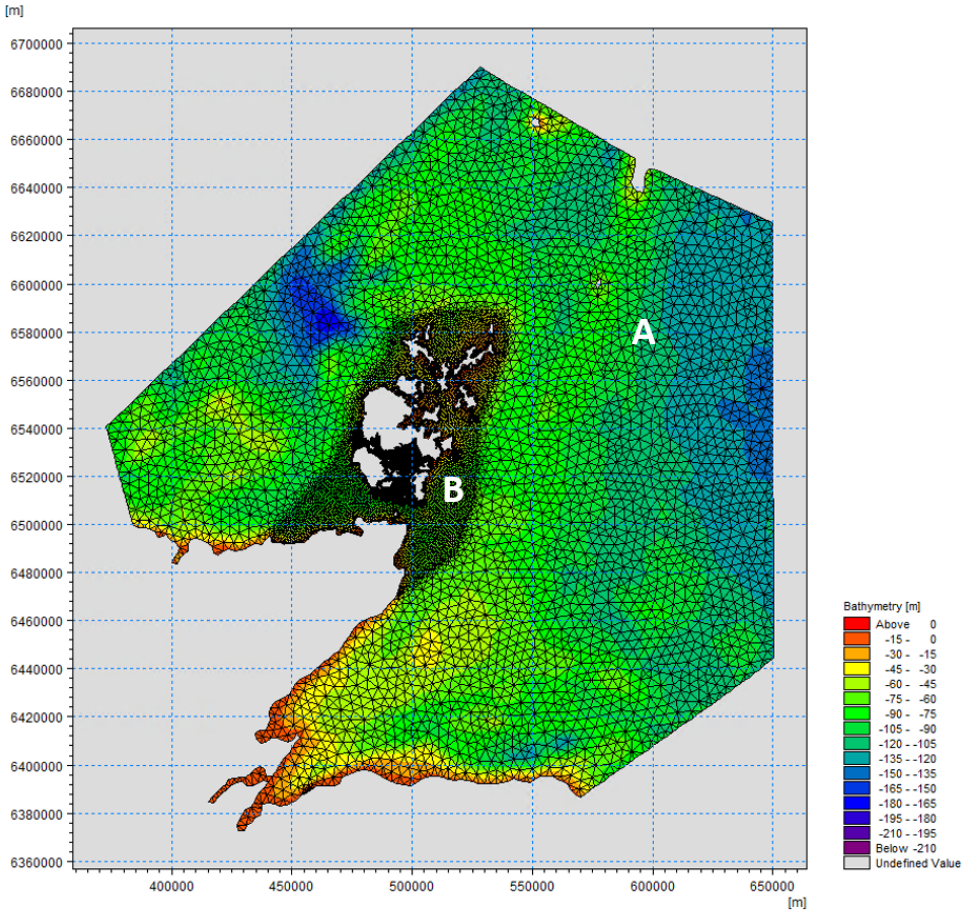


Figure 3.2 Orkney model domain, bathymetry, and mesh

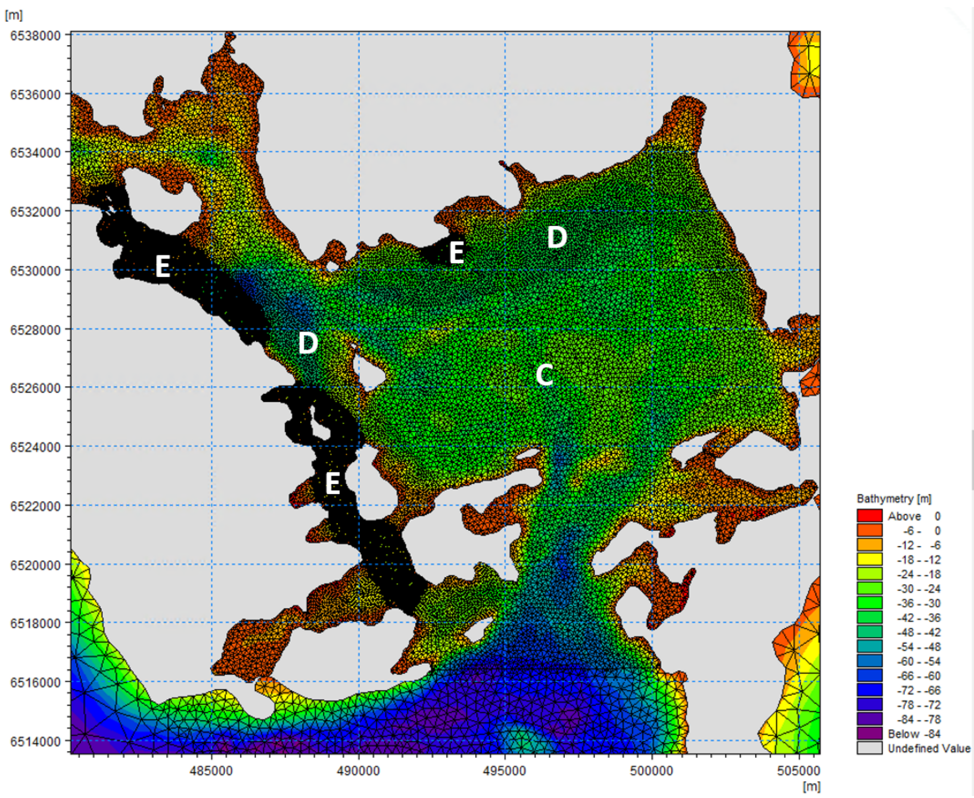


Figure 3.3 Close up of the model domain within Scapa Flow

Table 3.1 Details of horizontal mesh resolutions within the domain

Region	Approximate horizontal grid resolution (m)
A - Outer grid	5000
B - Approaches to Orkney, north of Mainland Orkney and Pentland Firth	1500
C - Main body of Scapa Flow	200
D – Intermediate high resolution	150
E – High resolution at farm sites and narrow channels	25-50

3.4 Hydrodynamic model calibration

The calibration phase has followed the standard approach [7] of adjusting the wind field, wind drag coefficients, and the bed roughness parameters to assess what impact these make and the sensitivity of the model. Further details on the standards applied for this modelling approach are provided in Appendix B.

The calibration model runs covers the period where there is overlapping measured data at Bring Head and Toyness, between 26th September 2018 and 14th November 2018 (as discussed in Section 2.3). Details of the wind field and bed roughness adjustments are provided in Section 3.4.1 and 3.4.2.

3.4.1 Wind field adjustments

To determine the impact of wind on the hydrodynamic model predictions, simulations were performed both with and without wind field forcing as described in Section 2.4.1. In addition, the surface drag coefficient has been increased to see how this impacts the model. Confirmation of the suitability of this wind data source has been provided by comparisons to a short period of measurements at the Barrel of Butter met station (see Figure 3.4) which shows a generally good comparison, with some slight directional deviations.

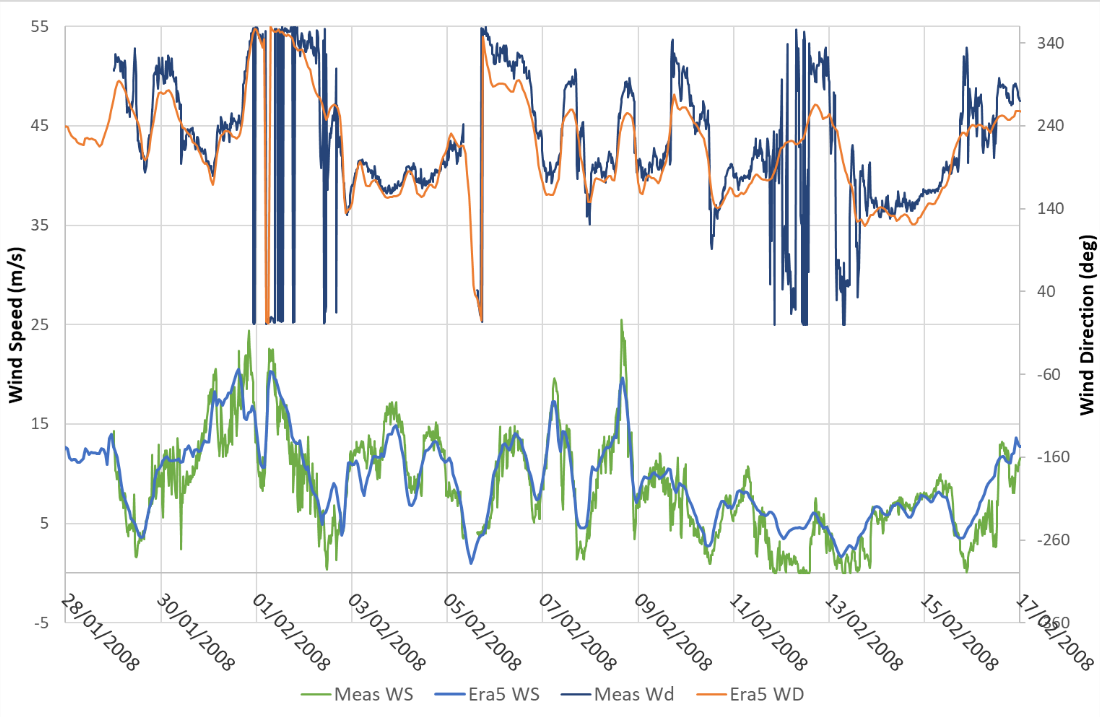


Figure 3.4 Comparison of measured and modelled wind speeds at Barrel of Butter met station

By default, in the model, wind friction is parameterized as a linear variation with a friction of 0.001255 at 7m/s and 0.002425 at 25m/s. Within the calibration process the friction parameters have been increased to 0.001355 and 0.02525 respectively.

The results of these adjustments showed marginal impact of the wind field and so the final model set up uses the described wind fields and the default wind friction.

3.4.2 Bed Roughness adjustments

Varying the Bed Roughness within the calibration process is a standard approach and can have the impact of slowing or speeding up the flow accordingly. Several adjustments have been made to the Bed Roughness parameter (Mannings Number M) to test for sensitivity and to tune the model closer to the observations.

By default, the model is run with a Mannings number M of $32 m^{1/3}s^{-1}$ across the whole model domain. Further model runs were conducted with M both increased and decreased within the range of $24\ m^{1/3}s^{-1}$ to $40\ m^{1/3}s^{-1}$. Variable bed roughness grids were also tested with different values of M assigned to different areas to assess the impact on current speeds within Scapa Flow.

The final mesh used has an M value of $32\ m^{1/3}s^{-1}$ for most of the domain with a region along the south coast of the mainland set at $24\ m^{1/3}s^{-1}$, as shown in Figure 3.5.

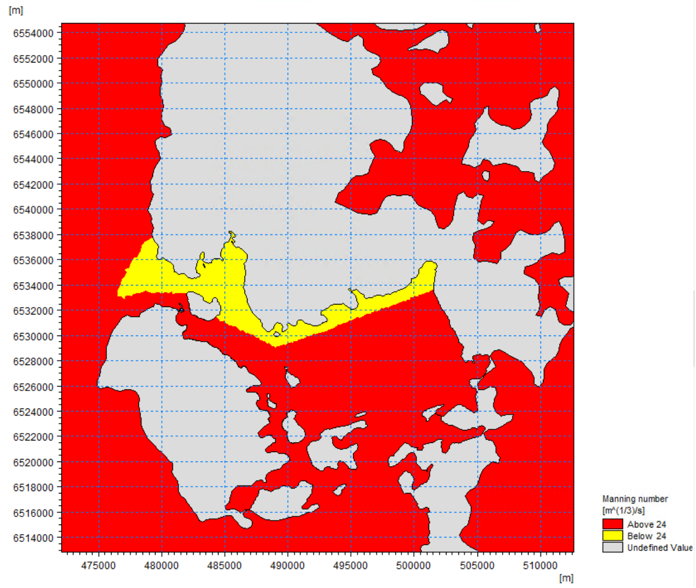


Figure 3.5 Variable Bed Roughness grid used in final model set-up

3.5 Calibration Results

Calibration of the hydrodynamic model has focused on quantitative comparisons with observation data sets of depth average water level and current speed at Bring Head and Toyness in 2018 (as described in Section 2.3). In addition, a validation process is described in Section 3.6 and qualitative assessments have been made on the overall flow regime within Scapa Flow to help put spot location assessments into context (see Section 3.7).

3.5.1 Around Orkney

To confirm that the model boundaries being used were suitable, the initial calibration stages included a confirmation that the boundaries are being propagated from offshore to nearshore were suitable.

Figure 3.6 shows a check of the modelled current speeds against predicted tidal currents (from Admiralty tidal diamonds) at four points around the Orkneys. This plot shows that the propagation of the boundary conditions within the model towards the islands is being handled correctly.

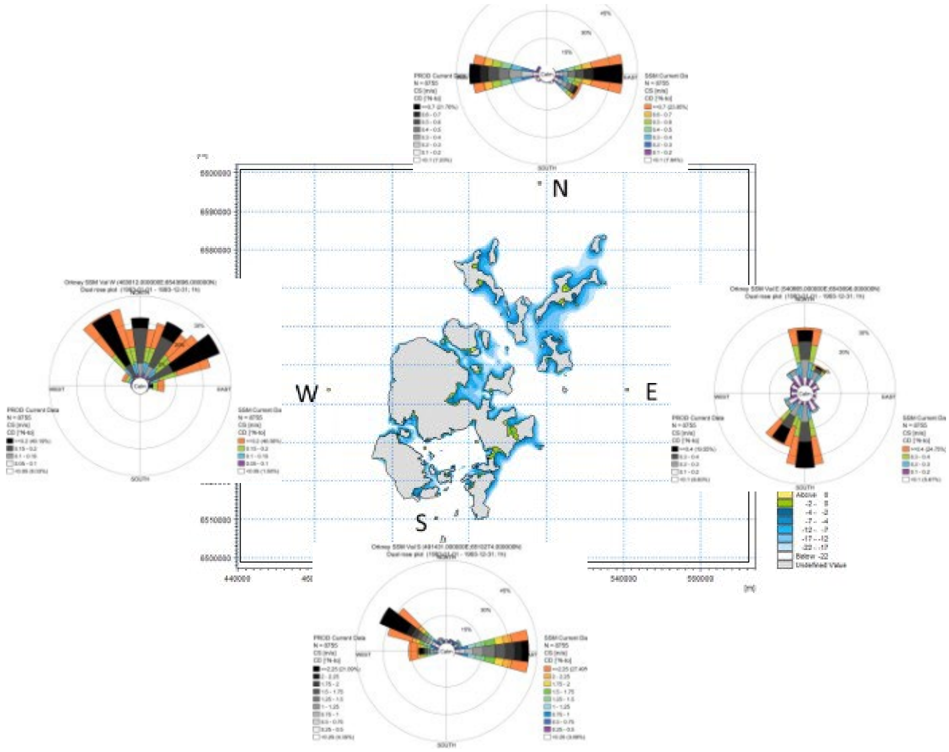


Figure 3.6 Comparison of predicted (Admiralty Tidal Diamonds) and modelled tidal currents around the Orkneys to confirm the validity of the boundaries applied (HYCOM and DTU 10)

3.5.2 Bring Head

The full set of calibration plots for water level and current speed for Bring Head are presented in Appendix A.1.1.

Inspection of the calibration plots show that for total water level there is a good overall fit between the observations and the model output especially with respect to the timing of high and low water. It is noted that the observations do show a slighter larger range between high water and low water values across both spring and neap tides, resulting in an RMS error of 0.19m (Figure A.8.1).

Regarding current speed, Bring Head is heavily influenced by a strong flood current that flows south-eastwards from the channel between Graemsay and Hoy. The location of this current varies through the flood tide and its interaction with the Hoy coast and the current coming from the north of Graemsay causes eddies to shed and persist in the region of Bring Head.

Figure 3.7 presents a 4-hour period during a strong flood tide event that illustrates how the elevated current speeds propagate south-eastwards and directly impacts the site. Through the exhaustive testing of many hydrodynamic model set-ups, it is apparent that the location of this jet of strong current speed and its associated eddies are time varying. Subtle variations in its location can cause noticeable differences in the current speed and direction distributions at single point locations.

The result of this is that the calibration results (Figure A.8.3 to Figure A.8.6) show that at the location of the 2018 observation data set the model is showing a strong southeast – north west flow orientation. A noticeable bias in the directions towards the southeast and higher current speeds during the flood tide was also observed.

Because of the highly dynamic nature of the current speeds at this location, it is not particularly useful to use only single spot location comparisons. Figure 3.8 shows a close-up of the Bring Head site showing the peak current flow with a well-defined eddy on its southern flank. The overlaid rose plots show the results from the 2018 calibration run and from a location closer towards the shore, out of the zone of stronger flow from 2008 which was used for model validation (see also Section 3.6).

It is important to also consider that there is difference between the two measurement locations (as seen in Figure 3.8, with the nearshore point showing a more dominant single northwest transport for the depth average period.

The results from the 2008 model validation run shows that the model represents this north-westwards flow more closely suggesting a rapid spatial variability in the currents experienced in this area.

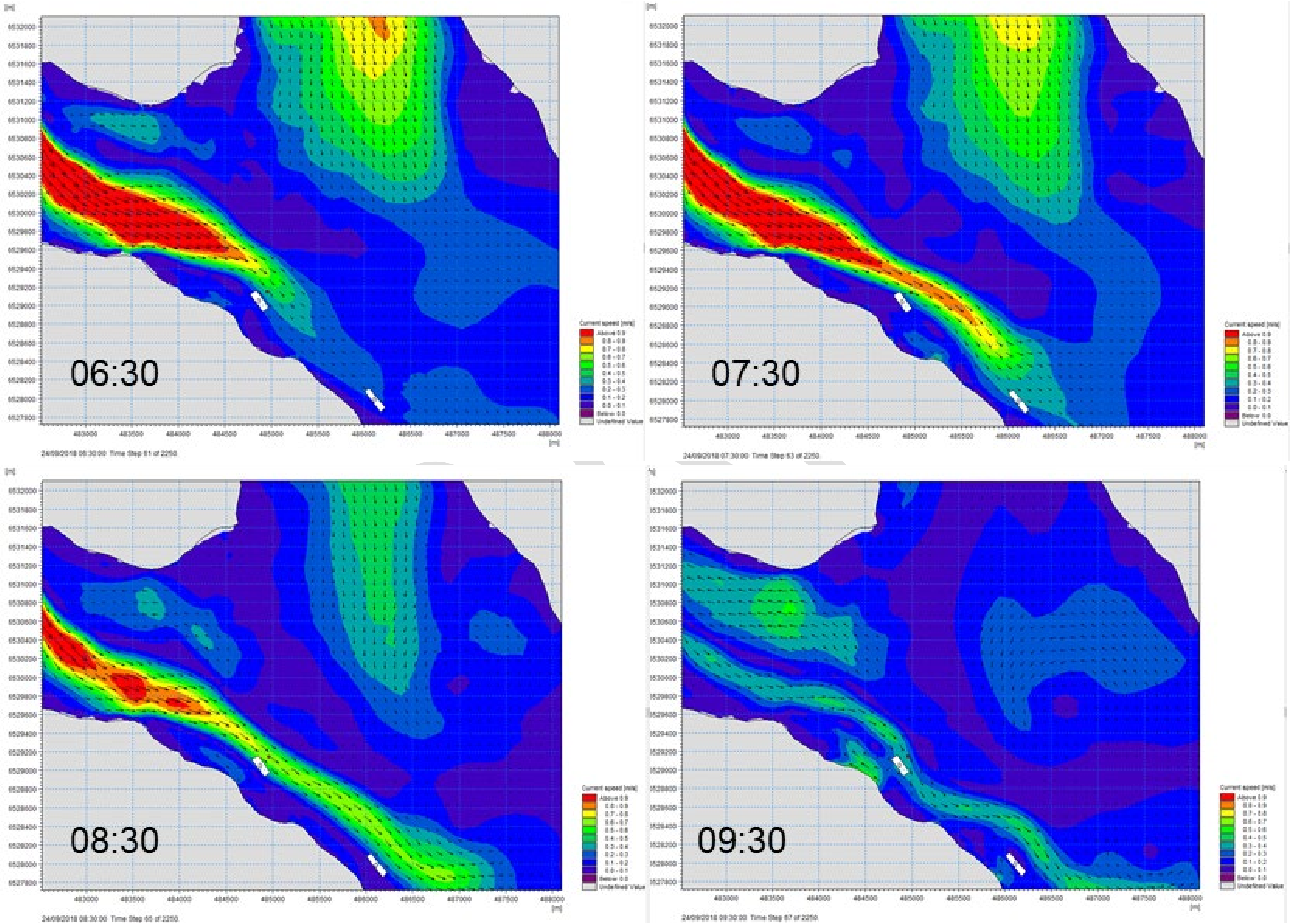


Figure 3.7 Illustration of current speed in region of Bring Head during a flood tide

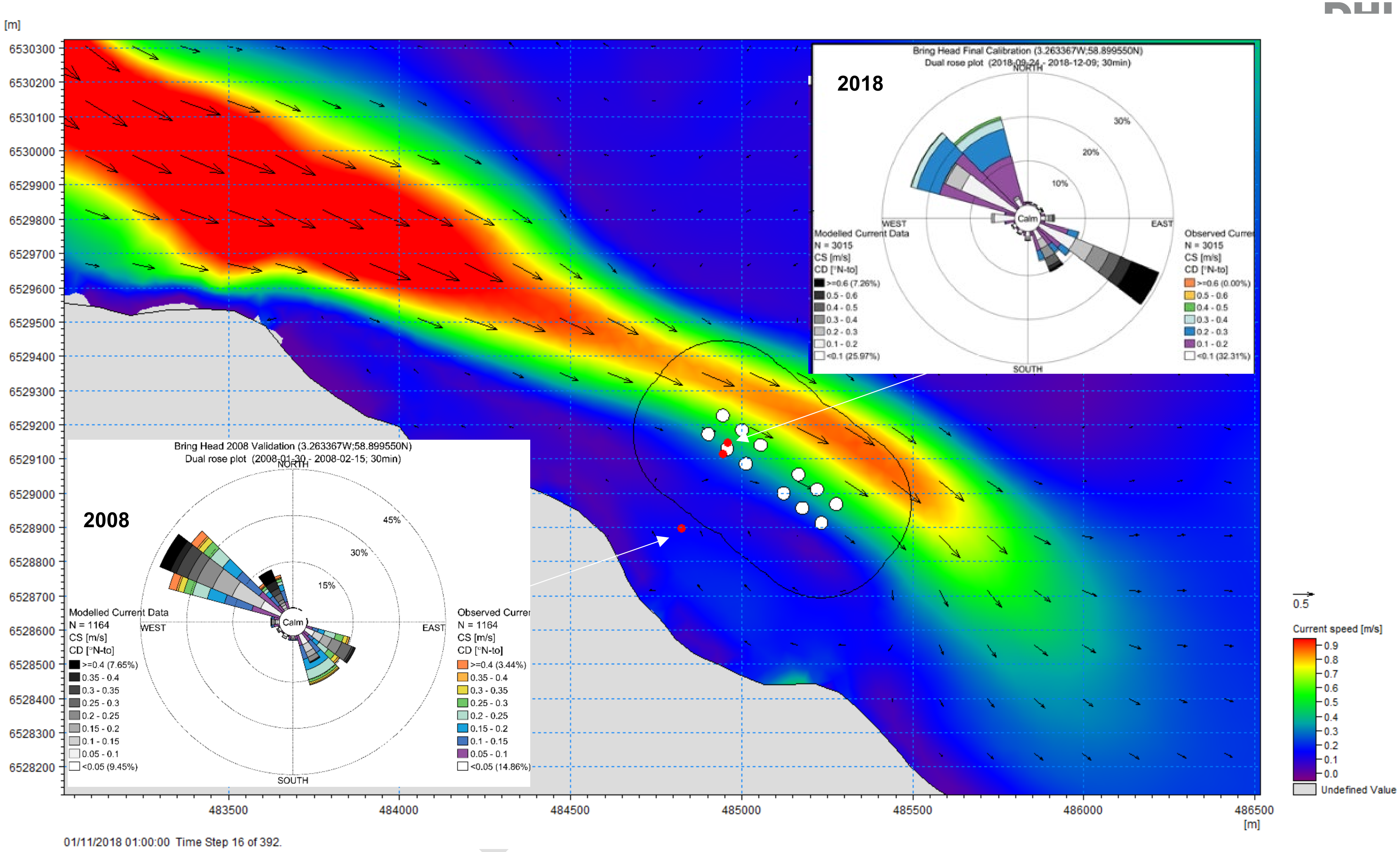


Figure 3.8 Current speed flow map for a flood tide snapshot and rose plots at Bring Head 2018 (top right) measurement site and at the 2008 nearshore site. Figure also shows position of proposed pens (white circles) and measurement locations (red dots).

3.5.3 Toyness

The full set of calibration plots for water level and current speed for Toyness are presented in Appendix A.1.2

As with Bring Head, the calibration of water levels shows good agreement (Figure A.8.7 and Figure A.8.8).

Figure 3.9 presents the rose plot comparison of current speeds at Toyness and shows a strong west southwest – east north east alignment, with currents running parallel to the coast and underlying bathymetry contours. There is a bias in the model towards currents flowing in the northeast direction. There is good agreement on current speed magnitudes between the observations and the model (Figure A.8.9 and Figure A.8.11).

In the model at Toyness the strong north easterly flow is an extension of flood current that propagates from Hoy Sound and around Houton Head, as illustrated in Figure 3.10.

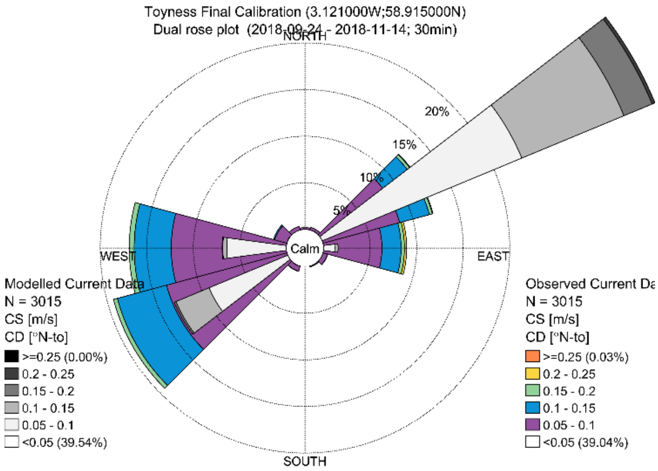


Figure 3.9 Rose plot of modelled and observed depth-average current speed at Toyness

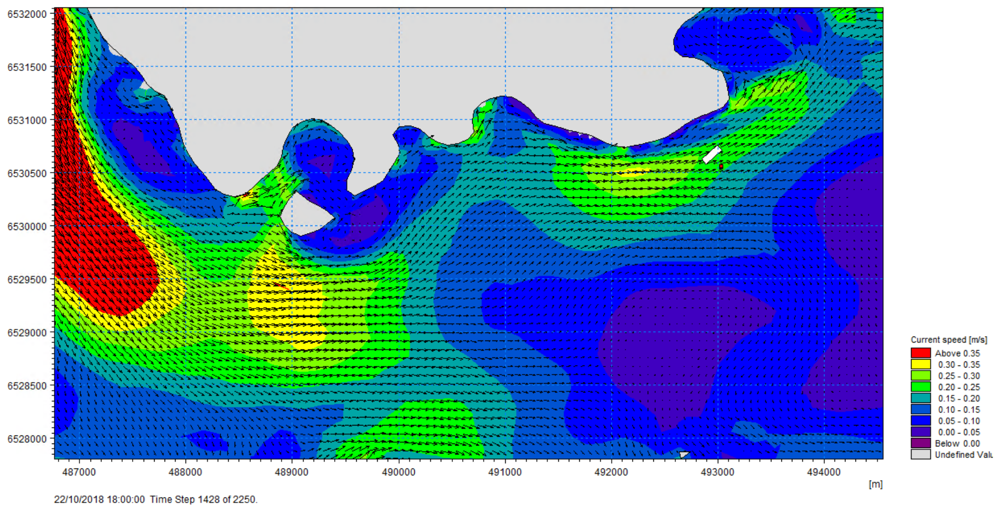


Figure 3.10 Illustration of current speed in Toyness region during a strong flood current

3.6 Validation

Validation of the Hydrodynamic model has involved running the model for additional periods that correspond to short measurement deployments 9~15 days) across Scapa Flow in 2005, 2008 and 2011 (see Section 2.3). It should be noted that with such short durations of measurement data it is difficult to draw any significant conclusions. They do, however, provide a useful opportunity to assess whether the model is capturing the general magnitude and direction of hydrodynamic circulation. A comprehensive selection of validation plots for all the locations are presented in Appendix A.2.

Figure 3.11 presents a summary of the results, showing the current speed scatter plots at each location. It can be clearly seen that the model accurately represents the sites on the eastern side of Scapa Flow, which are significantly less energetic than Bring Head and Toyness, with current speeds almost entirely less than 0.1m/s.

With regards to directionality, the model reflects the observations showing mainly bi-directional patterns with currents generally flowing parallel to the coast, as is expected with the general regime of Scapa Flow and the sites being so close to the coast.

The comparisons at Bring Head and Toyness show the same trends as discussed in Section 3.5.

It is noticeable from the directional roses in measurements and in the models, that the locations in the east of Scapa flow appear to be within a gyre that has previously been hypothesised to exist. If this is the case, it is likely that the eastern side of Scapa Flow is hydrodynamically distinct from the Western side, with a more dominant tidal regime in the latter and potentially more 3D effects dominating on the Eastern side.

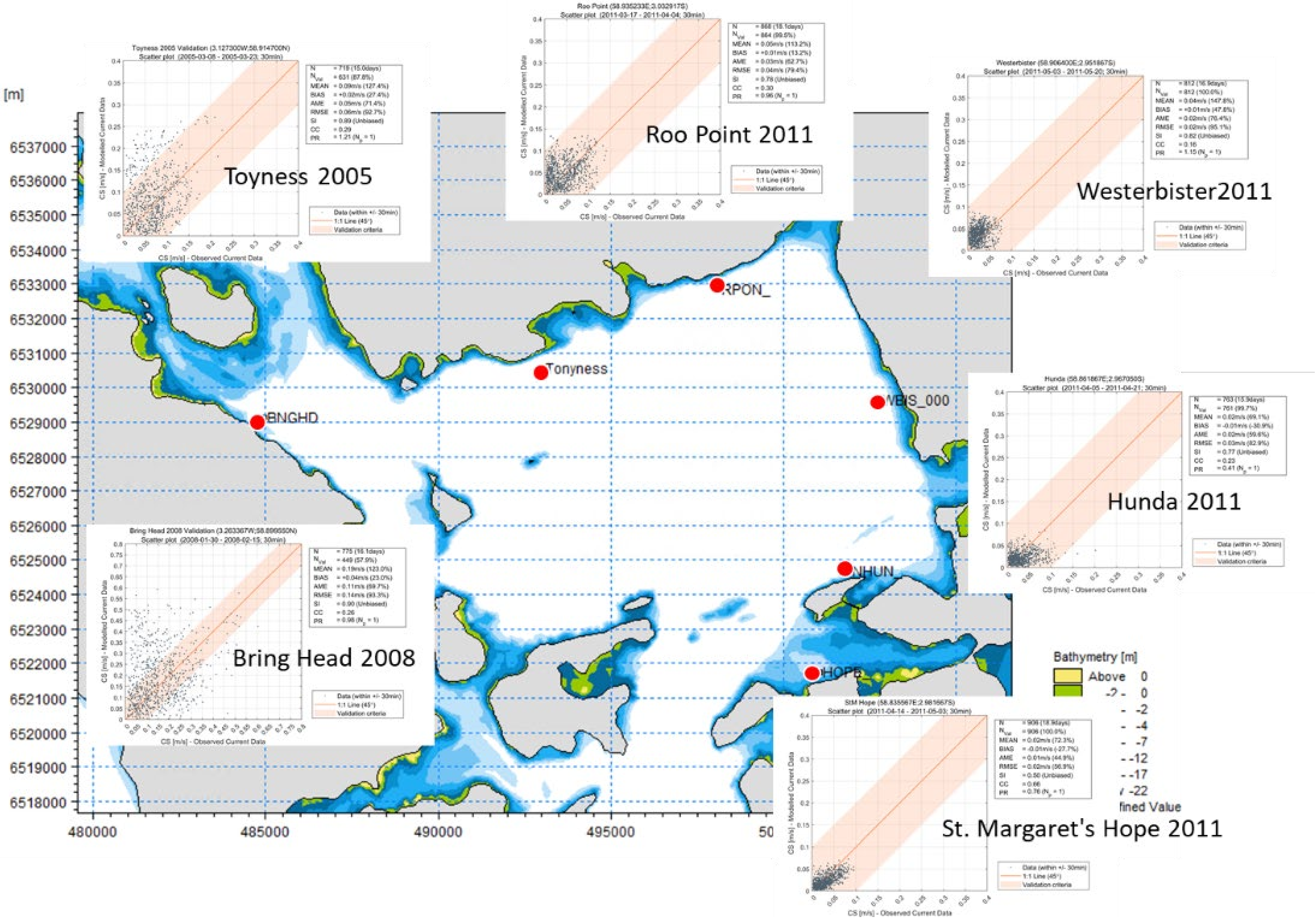


Figure 3.11 Summary map showing scatter plots of observed vs. modelled current speed at HD model validation sites (orange shading denotes SEPA's calibration standards – See appendix for detailed plots)

3.7 Discussion of calibration & validation

The following sections provides a discussion of features of interest identified during the calibration process of the hydrodynamic model.

3.7.1 Bring Head

The Bring Head site is located on a small shallow patch on the otherwise steeply shelving southern shore of Scapa Flow. Immediately to the North of the site are the Bring Deeps, which at in excess of 60m of water, are the deepest part of Scapa Flow.

Flow in this location is dominated by the two strong streams either side of the island of Graemsay during the flood tide, which are noticeable in satellite imagery (Figure 3.12).

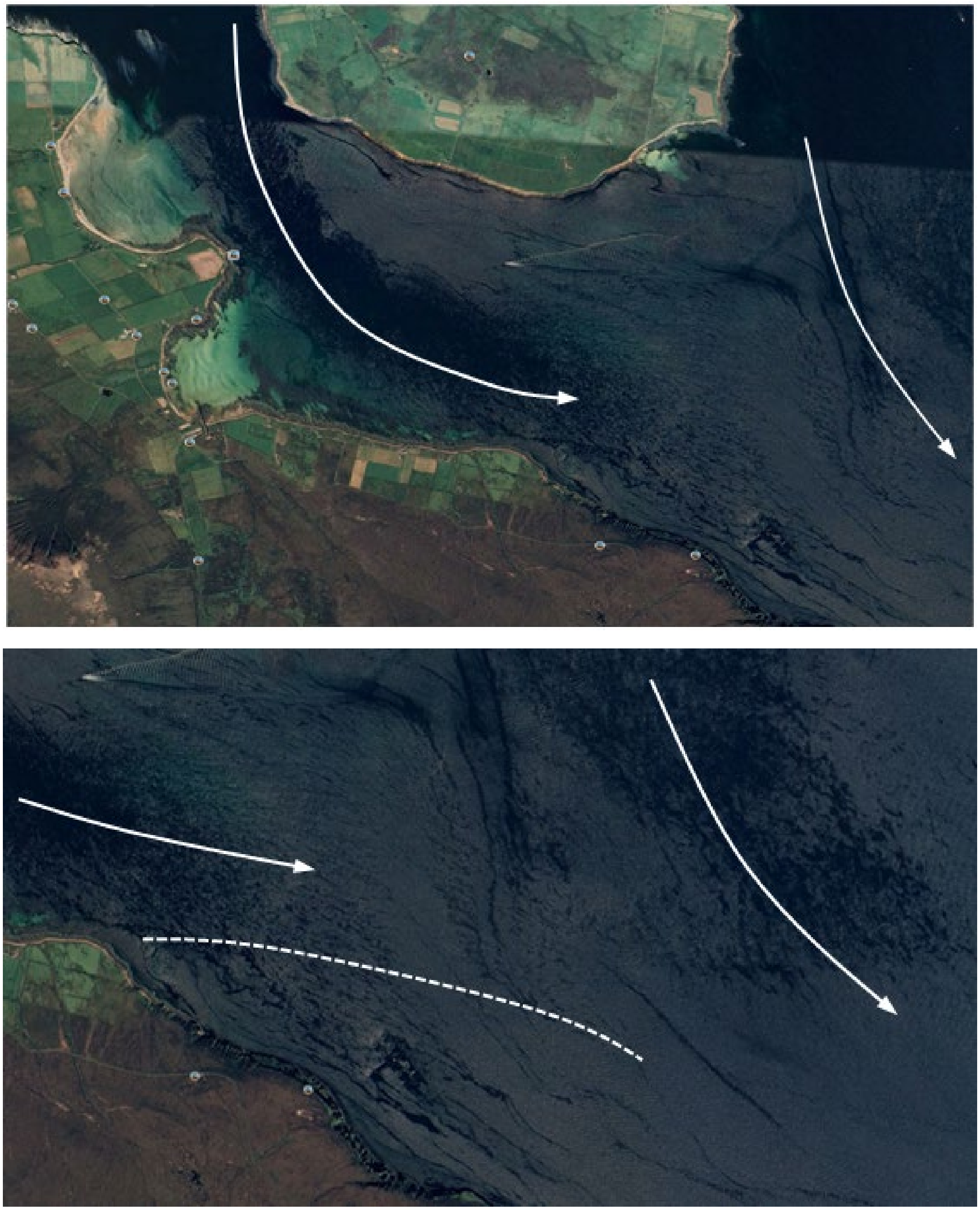


Figure 3.12 Satellite imagery showing the flood tide flows around Graemsay (top) and how they interact close to the Bring Head site (bottom)

The separation of the flood tide off the headland at Sea Geo is likely to control the flow within the site at Bring Head. As such, the flow varies rapidly in space.

The model outputs presented in Figure 3.7 show the development of a series of flood tide eddies that move eastwards, and this is likely to cause the directionally variable calibration seen in Section 3.4.

On the ebb tide, the current flows out to the northwest, again focused in the channels to the North and South of Graemsay, with the flow in the shallower sections being faster. Spatial variability of these zones of higher speed flow is rapid as the water depth deepens sharply.

What is apparent from this assessment of the tidal cycle is that as the tide floods through the shallow sill either side of Graemsay, the flow accelerates and then rapidly decelerates as it enters the Bring Deeps basin. This leads to the development of large scale eddies off the headlands, but also within the deep water zones (see Figure 3.8).

As the tide begins to ebb, these residual eddies then come back together into flows that are stronger where constrained by the land boundary (Figure 3.13). The timing and strengh of these flows is associated with the breakdown of the eddies.

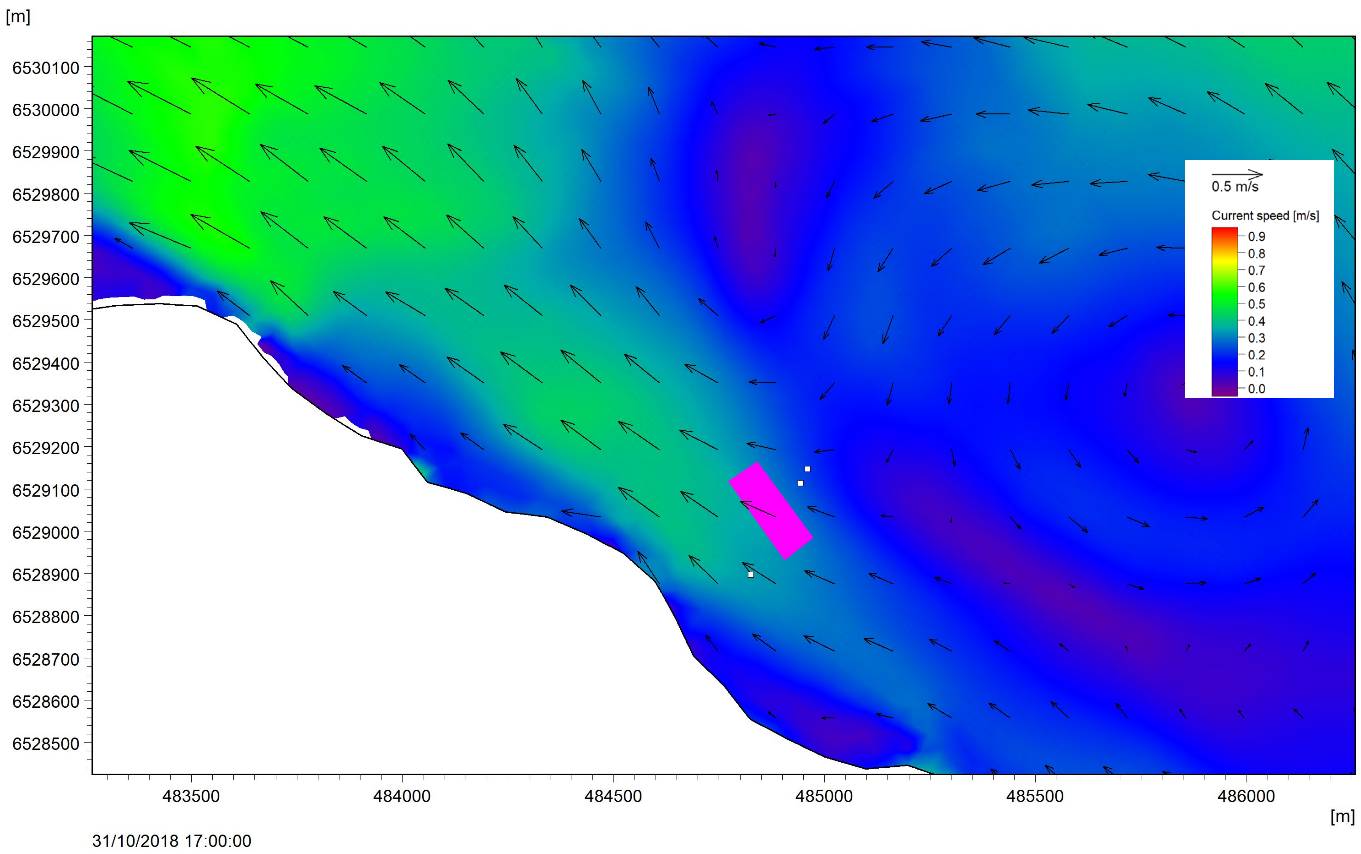


Figure 3.13 Model output showing the flow against the shore on the ebb tide

The calibration shows that generally the directions and magnitudes of the model are well matched to the measurements, given the rapid spatial variability of the site and the position of the measurement devices within a temporally varying eddy. It is noted that a deviation from the idealised 1:1 line is seen (see Figure A.8.3), with the model suggesting higher flow speeds than the measurements. These higher flow speeds are seen to be during the flood tide, as the flow accelerates.

Looking at the residual currents as calculated from the model (see Figure 3.14), the time varying ebb and flow leads to a residual eddy in the location of the Bring Head measurements. This correlates with the zones of higher flow seen in the aerial imagery and from the local knowledge of the area. The bathymetry data supports the general position of this residual eddy, as there is an area of shallows seen in the 2m multibeam, located just off the central axis of the eddy.

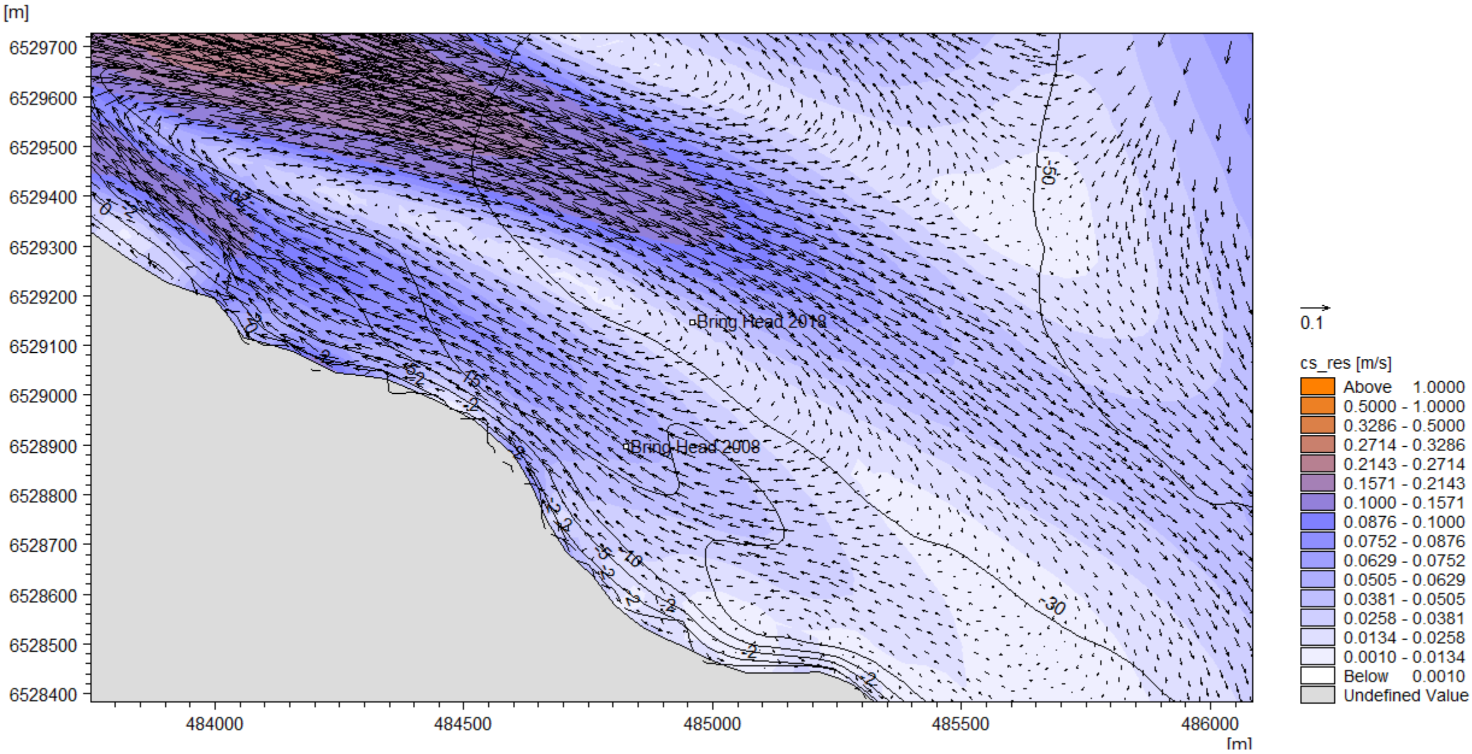


Figure 3.14 Residual currents showing the position of the residual eddy and the 2018 and 2008 measurement locations overlain on the bathymetry (black contour lines)

Importantly for the calibration process, the position of this residual eddy was seen to vary slightly between each of the model runs, suggesting sensitivity to model settings that control the exact position of the eddy.

This confirms that the model is generally a good fit. However it is important to note that it is likely that the model speeds are generally a little higher than in the measurements for short periods of time. For the purposes of the impact assessment modelling (see Sections 5 and 6), it is likely that these faster currents towards the North West will transport material from the Bring Head site into a location where they can then be transported South East on the stronger flood tides. As such, any minor differences between the measurement and the modelling for this location are unlikely to have a significant impact on the ultimate transport away from the site.

3.7.2 Toyness

Current speeds at Toyness are significantly lower than at Bring Head. The tidal dominance seen further west reduces, and non-tidal forces are likely of equivalent magnitudes to the tidal component of the flows.

Flow is broadly North North-east on the flood and South-Southwest on the ebb. It is seen that inshore of the Toyness farm site, current speeds are even lower.

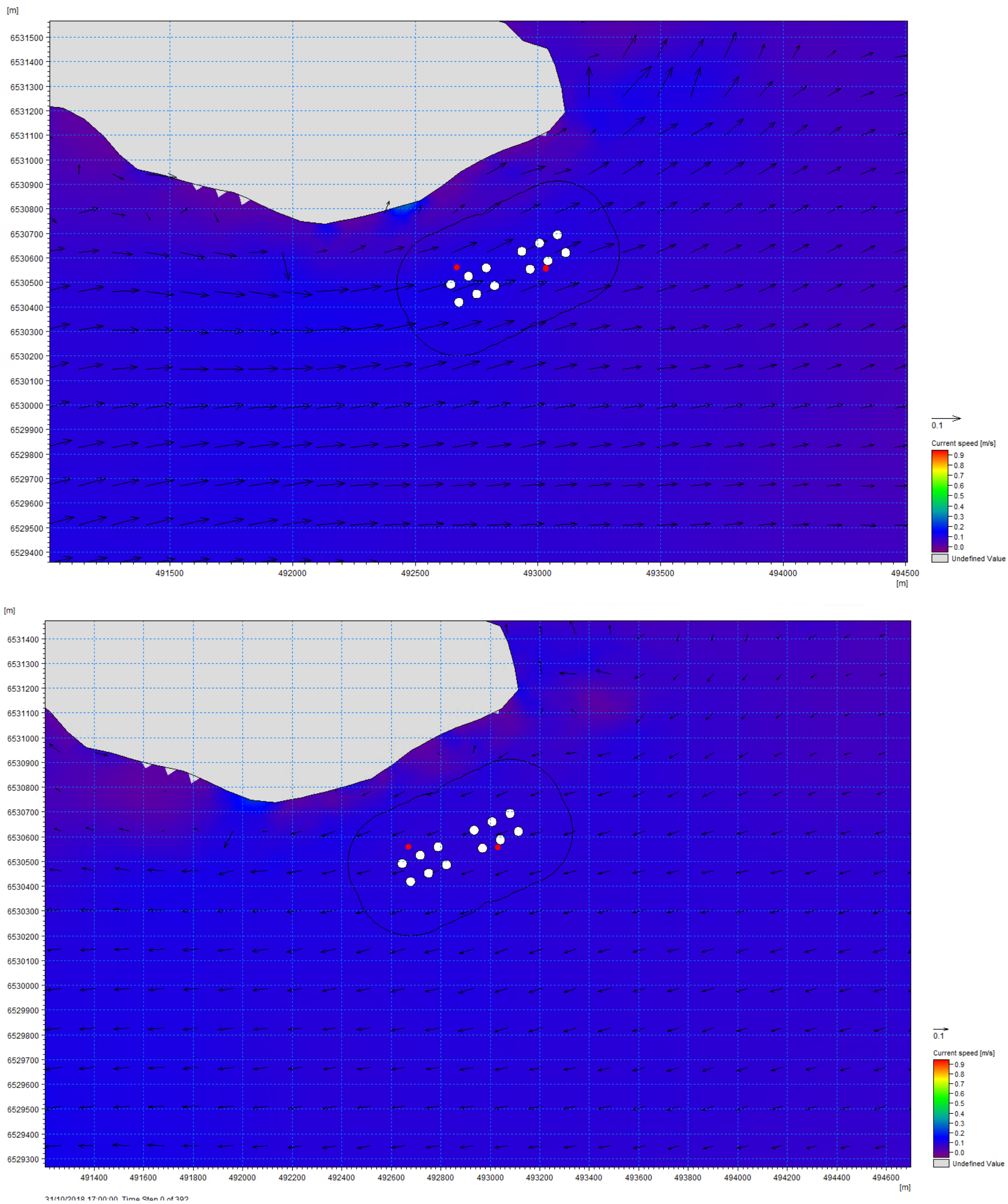


Figure 3.15 Peak Flood currents (top) and Peak Ebb currents (bottom).

The calibration generally fits well with the measurements, however, there is a noticeable dominance in the model of a north-northeast to easterly flow, with a concentration into the north-northeast sectors that is not seen in the measurements.

One aspect that is likely to be driving this residual flow is the wind forcing used in the model. The best available data source as described in Section 2.4.1 is a model database that takes no localised account of the height of the islands. With Hoy being a considerable height, this could lead to the model over-estimating the input of the wind. During calibration, with wind and without wind runs were tested and the with wind results provided a better overall match to the data.

As such, it is considered that the model is representative of the conditions experienced, though it is likely that consideration of the potential sensitivity of the flows in this area to the variability in flows due to sensitivity to non-tidal effects should be made during the impact assessment stages. A further, more detailed analysis of this is presented as a technical note in Appendix D.

3.7.3 Summary

Overall, the calibration shows the model performs well for the chosen parameters. Of importance to the impact assessment stages is the likely transport processes that could move feed, faeces, and medicines away from the MPFF sites. For this a summary map of the residual flow or net flow from the final calibration model has been provided to show the dominant circulation patterns within and around Scapa Flow (see Figure 3.16).

Previous studies [8] have discussed an anticlockwise circulation in Scapa Flow. This is seen in the main body of Scapa Flow within the developed model, however there are also additional boundary currents seen on the north shore that appear to be wind driven and significantly, the strong inflow of tide either side of Graemsay along with the water slope between the west coast of Orkney and the Pentland Firth, sets up a southerly flow along the western boundary of Scapa Flow.

Within this context, the Bring Head MPFF is in proximity to a zone of relatively high current with a persistent flood tide clockwise eddy just inside of the zone of peak tidal currents, with a strong north westerly flow on the ebb. This is likely to lead to transport initially north westwards at many stages of the tide, but a rapid entrainment into the south easterly flow which travels along the western shore of Scapa Flow.

For the Toyness MPFF, the relatively weak tidal currents are likely to lead to non-tidal circulation being the more dominant component, with flows to the north-east being typically driven by the dominant south-westerly winds. Due consideration of the relative sensitivity of the model results to these non-tidal effects needs to be taken in the ongoing model application.

Importantly for this type of assessment, an independent validation (see Section 3.6) to see how the model performs for other periods, provides an understanding of the model suitability under other climatic conditions. This supports the suggestion that the model is suitably representative of the condition experienced.

In the context of MPFF Impact Assessments, the spatial variability in flow and therefore the transport of materials away from a site is of importance. From Figure 3.16 the concept of a weaker eastern area dominated by the anticlockwise gyre and a western zone dominated by stronger tidal throughput is apparent.

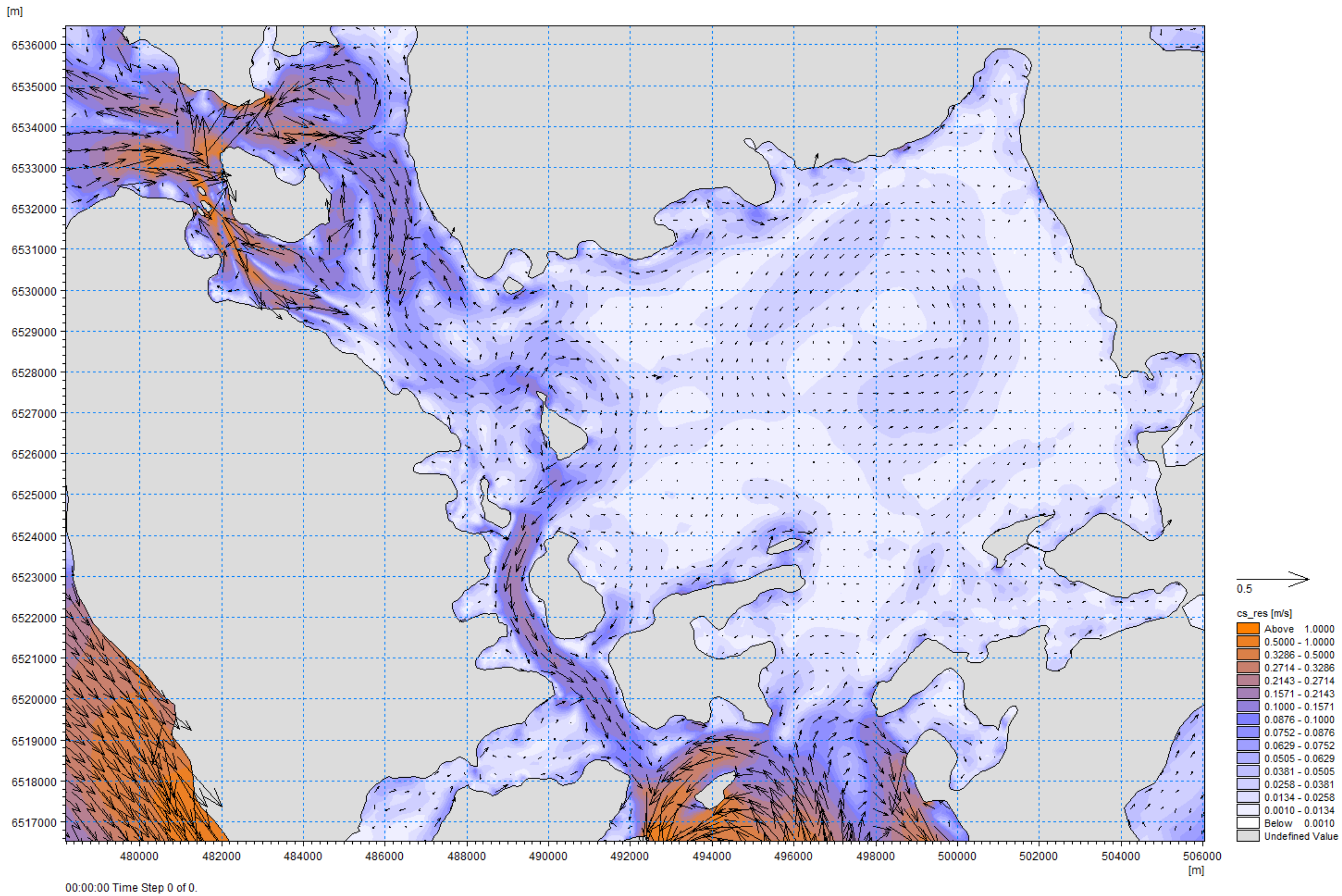


Figure 3.16 Residual flows from the ~ 45-day final calibration run in Scapa Flow with both magnitude and direction shown.

4 Production Run

The Orkney model climatology production run has been configured using the model set up as described in the Section 3 with the boundary conditions as described in Section 2.2.2 and Section 2.4.2. As this is based on the climatology, it is not possible to calibrate this model.

As a further validation, the results of the production run have been compared to data from the original Scottish Shelf Model (SSM) at four locations surrounding the Orkney archipelago, as shown in Figure 4.1. The results are provided in Appendix A.3.

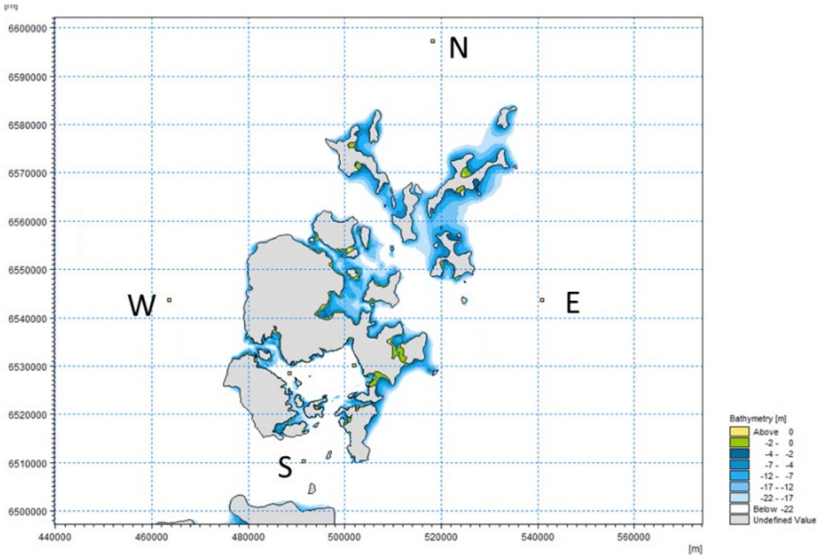


Figure 4.1 Map showing location of comparison sites between Orkney model production run and SSM model

The results suggest that the model is generally reproducing the SSM model in the areas around the Orkneys.

Within Scapa Flow, due to the difference in spatial resolution between models, point comparisons are unlikely to be a suitable validation comparison. Instead, the residual or net flow plot has been produced for the longer one-year period of the SSM model and the Production run. This can be compared to the shorter-term residual from the calibration period (Figure 3.16)

Key features that remain consistent between all three models are the anticlockwise circulation in the eastern part of Scapa Flow and the stronger tidally dominated flows along the western boundary (including at Bring Head) and through to the Pentland Firth in the South.

There is a divergence between the result of the models at Toyness, with the calibration model showing a stronger flow to the Northeast than the Production model and the measurements show dominant flow to the South West. The SSM model shows a residual flow divergence in the vicinity of Toyness with marginal flow to the Southwest.

This suggests that Toyness is on the border between the two hydrodynamic regimes of Scapa Flow, with the higher energy western side dominated by tidal processes and the lower energy eastern side being dominated by eddies. Due consideration of this sensitivity in the hydrodynamics should be made in the impact assessments in Sections 5 and 6.

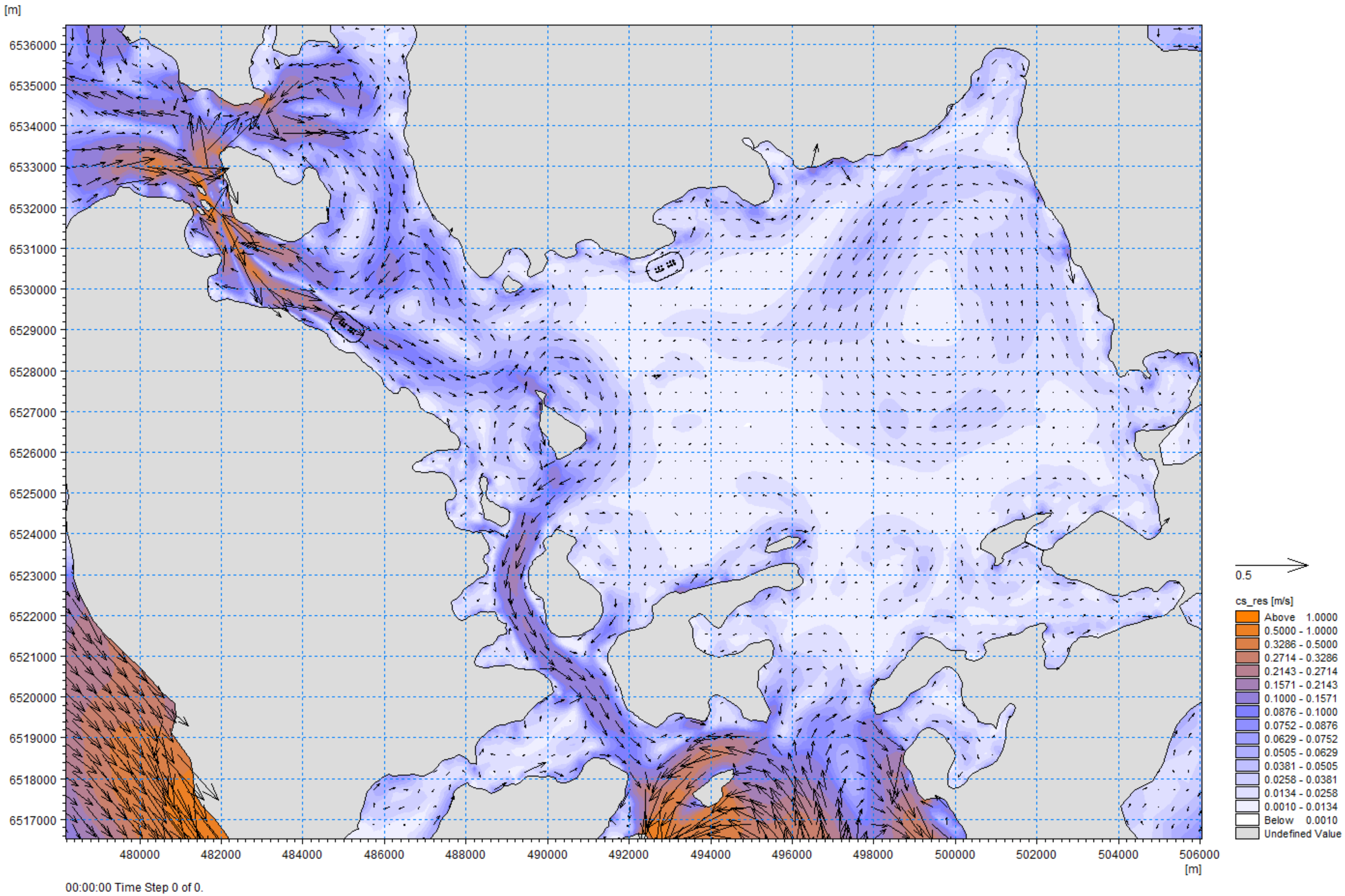


Figure 4.2 Residual plot from the one-year Production Run model

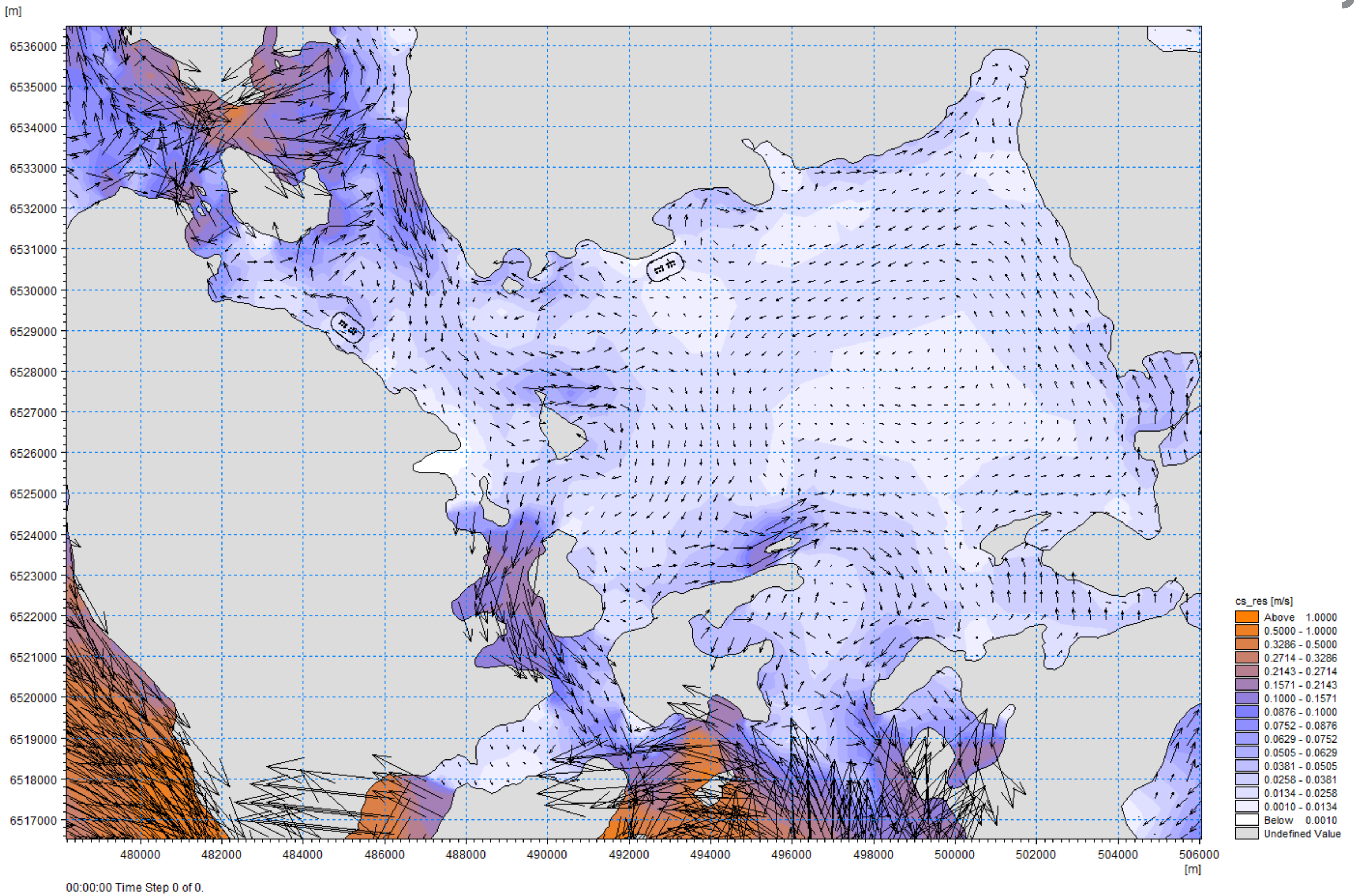


Figure 4.3 Residual plot from the one-year SSM model

5 Waste Solids

5.1 Model Configuration

This section describes the modelling methodology and results of the simulation of waste solids from the marine pen fish farm at Bring Head, Toyness, and neighbouring farms in Scapa Flow.

The waste solids modelling was performed using the Particle Tracking module within the MIKE21/3 Coupled Model FM [9], with hydrodynamic conditions provided by the 2-dimensional HD model described in Section 3.

The modelling methodologies for all impact assessments in this report were based on the application of the MIKE 21 Particle Tracking Module, which is briefly described below. More detail can be found in [10]. The individual setups for each impact assessment are contained in the relevant Sections with this section for Waste Solids and Section 6 for in-feed treatments.

The particle tracking (PT) module is a component of the MIKE 21/3 modelling system and has been used to model the transport and fate of suspended and sedimented substances discharged from fin fish aquaculture sites under the influence of the fluid transport and associated dispersion processes. The discharged substances are considered as particles being advected with the surrounding water body and dispersed because of random processes in two dimensions. The particles may settle with a constant settling velocity and settled particles may be resuspended if the bed shear stress exceeds a critical threshold. A corresponding mass is attached to each particle, which may be reduced during the simulation due to decay.

The following processes may be attached to individual particle classes:

- Settling
- Erosion/Resuspension
- Decay
- Dispersion

The model calculates the path of each particle and outputs the instantaneous concentrations of individual particle 'classes' based on the hydrodynamic model input. Particle tracking techniques can be an efficient way to study the fate of matter in the water environment. This technique uses a Lagrangian discretisation, splitting all mass in the system into several particles with specific coordinates and masses.

All of the impact assessment models in this study were performed using the PT module within the MIKE21/3 Coupled Model FM [9], with hydrodynamic conditions provided by the 2-dimensional HD model (see Section 3 and 4 for details). The position of particles during the model simulations were used to calculate the mass of the modelled substance in each model mesh element. This was based on a higher resolution flexible mesh covering the Orkney area model with a resolution of 1,250m^2 (which equates to approximate length scales on average of 28m , minimums of 11m and maximums of 48m), see Figure 5.1. This mesh was independent of the mesh used in the Hydrodynamic modelling setup (See Section 3.3) and was used for all depositional modelling.

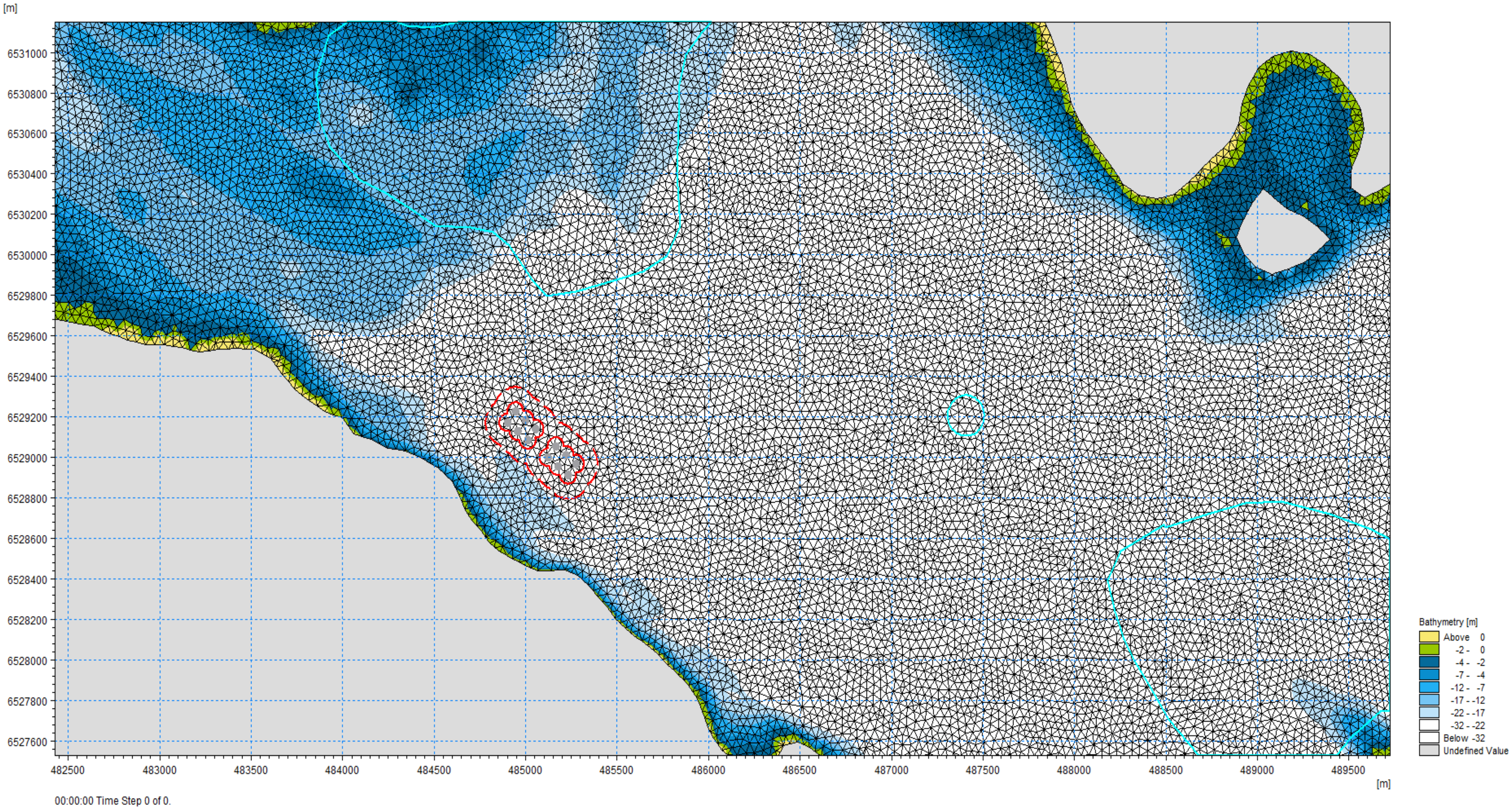


Figure 5.1 Example of the high-resolution numerical mesh used in the depositional modelling. The pens at Bring Head are designated within the 25m (red solid line) and 100m (red dashed line) buffers. The PMF's as light blue areas.

5.1.1 Particle Setup

A range of solid particles with varying properties are released from MPFF's. For practical reasons, it is not feasible to model such a large range of feed types all with different input rates, settling velocities, decay rates, and resuspension thresholds. Instead, we choose to model the behaviour of groups of particles. These groups (or particle "classes") share common characteristics which will behave in a broadly similar way.

There are two particle classes that represent waste solids in the waste solids modelling:

- Wasted (uneaten) feed
- Faeces

The properties of each of the particle classes are summarised in Table 5.1 and are based on the default particle parameters as specified in [11].

There are seven locations for the sources in the model setup representing the Bring Head and Toyness sites, plus all other fin fish aquaculture sites in the western part of Scapa Flow. The source locations are summarised in Table 5.2. The sources were specified at a depth of 5 m below the still water level, with release from the centre of each of the 12 proposed pens at Bring Head and Toyness respectively, and from the centre of the site for the other locations (single source outputs). For the existing situation Bring Head and Toyness were modelled as 10 pen layouts.

The mass associated with each particle class was specified as a constant flux released from the source location over the one-year model simulation. The input rates were proportional to the "on farm" biomass and were calculated following the method as outlined in Appendix B of [7] (also described in [11]).

The biomass for Bring Head and Toyness were both set as 2,500 tonnes (provided by SSF), and the biomass for all other source locations were adopted from the licensed levels. Table 5.2 summarises the input rate [kg/day] for each source location in the model setup.

In addition, the models were run with the existing licensed biomass values for the sources at Bring Head and Toyness to construct a comparative baseline

Table 5.1 General settings for solid waste model

Solid Waste Depositional Model Settings		
Model period	365 days (summer to summer)	
Hydrodynamic conditions	2-dimensional hydrodynamic model • Tidal conditions for one year period • Climatologically averaged wind forcing	
Model output time step [seconds]	900	
Sources	29 source locations representing MPFF sites for post scenario 25 source locations representing MPFF sites for pre scenario (Bring Head 10 pens, Toyness 10 pens) (see Table 5.2 for more details)	
Particle classes	Class 1: Waste feed	Class 2: Faeces
Number of particles per source and per time step	10	10
Total number of particles	8,059,200	8,059,200
Decay [/s]	0	0
Settling velocity [m/s]	0.095	0.035
Erosion threshold [Nm^{-2}]	0.02	0.02
Horizontal dispersion [m^2s^{-1}]	0.10	0.10
Vertical dispersion [m^2s^{-1}]	0.001	0.001

Table 5.2 Particle source locations and waste solid input rates as specified in the solid waste depositional model setup for the post modelling scenario

Group	Site Name	Site ID	Existing Biomass [tonnes]	Proposed Scenario Biomass [tonnes]	Location			Waste solids	
					Easting [m OSGB]	Northing [m OSGB]	Feed requirement, *F* [kg/day]	Waste Feed [kg/day]	Faeces [kg/day]
	Bring Head (12 pens)	BRHD	968 (10 pens)	2,500	327572	1002216	17,500	478	2,317
	Toyness (12 pens)	TOYN	1,343 (10 pens)	2,500	335385	1003586	17,500	478	2,317
Others (single source locations)	Chalmers Hope	CHAH	1,000*	1,000**	328614	1001123	7,000	191	927
	Fara West	FARW	800	800*	331963	995227	5,600	153	741
	Lyrawa Bay	LYRB	400	400*	330020	998900	2,800	76	371
	Pegal Bay	PEGB	400	400*	330400	997800	3,500	96	463
	South Cava	SHCA	2,500	2,500*	333300	998900	17,500	478	2,317

* from CAR License for site (Site Details (scotland.gov.uk))
** using existing values as Chalmers Hope is going through an updated licensing process at present.

Settling velocities

Settling characteristics of fish feed and faeces are likely to change depending on fish size, feed composition, and the physical properties of the seawater [12].

The mean value of the settling velocity recommended by SEPA in NewDEPOMOD was used for feed pellets (0.095 m/s) and salmon faeces (0.035 m/s) based on [11], respectively.

Dispersion

The horizontal and vertical dispersion coefficient are often used as a calibration parameter for the Particle Tracking model.

The dispersion coefficients from NewDEPOMOD were applied with horizontal dispersion of 0.1 m^2s^{-1} and vertical dispersion of 0.001 m^2s^{-1}.

Decay

The existing assessment methods (e.g., NewDEPOMOD) contain no allowances for decay of solids in the model. This is due to the benthic module being validated using total particulate material and associated benthic effects (i.e., solids not carbon), [13]. Consequently, no decay was specified for waste solids in the depositional model.

Resuspension/Erosion

As noted in Table 5.2 the SEPA interim guidance values [11] have been used as the basis for the Erosion Threshold.

It should be noted that no consideration of geotechnical stability of sedimented material (i.e., due to the variation in the seabed steepness) is included in the depositional model. For resuspension/erosion it is assumed that the seabed represents a level surface.

5.1.2 Model outputs

The output from the depositional model simulations included:

- Hourly values of the total, suspended, and sedimented solids for each particle class in every cell of the model domain

5.2 Environmental Quality Standards (EQS)

The current EQS standard applied by SEPA quantifies the impact of deposited solids on the environment with respect to the Infaunal Quality Index (IQI). The IQI is a multimetric index that expresses the ecological health of benthic macroinvertebrate (infauna) assemblages, reflecting how the structure and functioning of benthic macroinvertebrate assemblage changes over anthropogenic pressure gradients, for example from organic enrichment of sediments [14].. IQI is expected to decrease as organic enrichment increases as the proportion of species tolerant to organic enrichment increase, while evenness and species richness decreases.

An IQI score of 0.64 represents the ecological moderate/good status boundary for benthic macroinvertebrate (infauna) assemblages.

Table 5.3 Ecological status boundaries for IQI.

Status	IQI
High/Good	0.75
Good/Moderate	***0.64***
Moderate/Poor	0.44
Poor/Bad	0.24

The particle Tracking module within the MIKE21/3 Coupled Model FM does not explicitly model IQI conditions. Therefore, the following criteria should be used to identify a scenario which is likely to comply with local scale “mixing zone” standards.

Table 5.4 Criteria for compliance with local scale “mixing zone” standards (from [15]).

Standard	Type	Definition	Model requirement
Pen-edge	Intensity	>1 species of enrichment polychaete at densities >1000 m^{-2} at pen edge locations	Mean deposited mass within the 250 g m^{-2} impact area should not exceed 2000 g m^{-2} where wave exposure is less than 2.8, or 4000g m^{-2} where wave exposure is 2.8 or greater.
Mixing zone	Extent	Total area (m^2) impacted to worse that 0.64 IQI should not exceed the 100 m composite mixing zone area (m^2)	Total area (m^2) with a mean deposited mass in excess of 250 g m^2 should not exceed the 100 m mixing zone area (m^2) where wave exposure is less than 2.8, or 120% of the mixing zone area (m^2), where wave exposure is 2.8 or greater.

5.3 Waste Solids Results

A one-year model simulation (summer to summer) of the dispersion of solid waste was performed as described in Section 5.1. From the model results the total sedimented solids on the seabed (waste feed + faeces) were calculated for each model grid cell.

5.3.1 Toyness Waste Solids

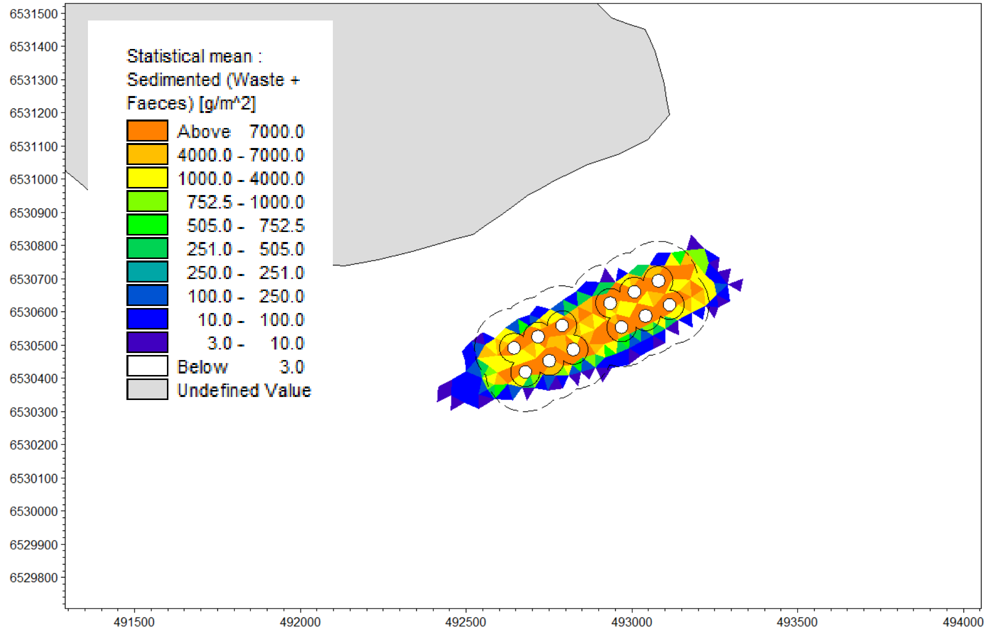
Figure 5.2 shows the extent and concentration of impact from Toyness as an average taken over the last 90 days of the model run. The right part Figure 5.2 shows the contour of the 250g/m^2 of deposited material.

The deposition of material is seen to be concentrated beneath the pens at Toyness, with the tidal currents being too low to lead to extensive transport or resuspension of waste solids. As such, Toyness appears to be independent from the other farms in the Western part of Scapa flow, and therefore is considered independently for the remainder of the waste solids assessment herein.

Table 5.5 Summary statistics of the depositional impact (waste and feed) at Toyness from proposed increased biomass

	Area (m^2) of the 250 g/m^2 contour (averaged over the last 90 days)	Mean concentration within the 250 g/m^2 contour (averaged over the last 90 days)
Toyness at existing Biomass Levels	124,522	3,719
Toyness at proposed Biomass Levels	134,199	6,412

Average over last 90 days – concentration plots



Average over last 90 days – exceedance plots

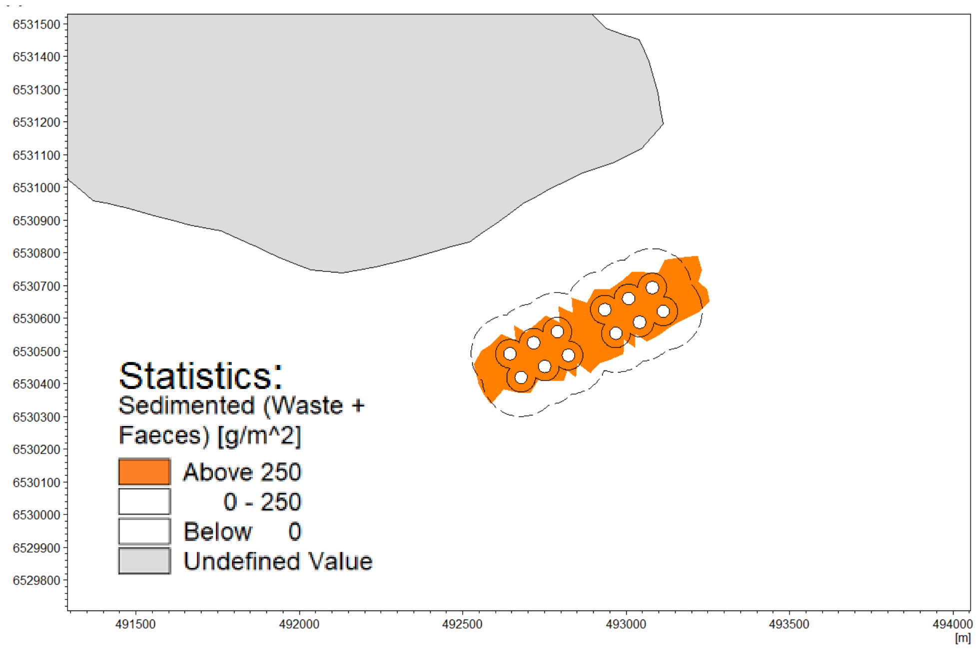


Figure 5.2 Map of the concentration of sedimented total waste solids (g/m^2) from Toyness. The concentration is the average value (left column) and exceedance (right column) of the last 90 days of the 1-year model simulation.

5.3.2 Bring Head Waste Solids

Figure 5.3 shows the extent and concentration of impact from Bring Head as an average taken over the last 90 days of the model run, with the right hand panel showing the contour of the 250g/m^2 of deposited material.

Whilst the spread of waste solids from the site is relatively extensive, the spatial extent exceeding the 250g/m^2 contour is limited to areas around the north end of Cava. Of note is the presence of a patch of deposition on the eastern edge of the area identified by SEPA that contains similar PMF records, hereafter known as PMF 2.

In addition to the conservative nature of the modelled assessment (the assumption of the constant 2,500 t biomass and associated waste loss in the entire model period), a fixed critical threshold was used for resuspension. It is noted that work within SEPA and the industry relating to the use of NewDepomod has found use of a simple criterion for resuspension in faster flow regimes can result in too much resuspension, potentially overestimating spreading.

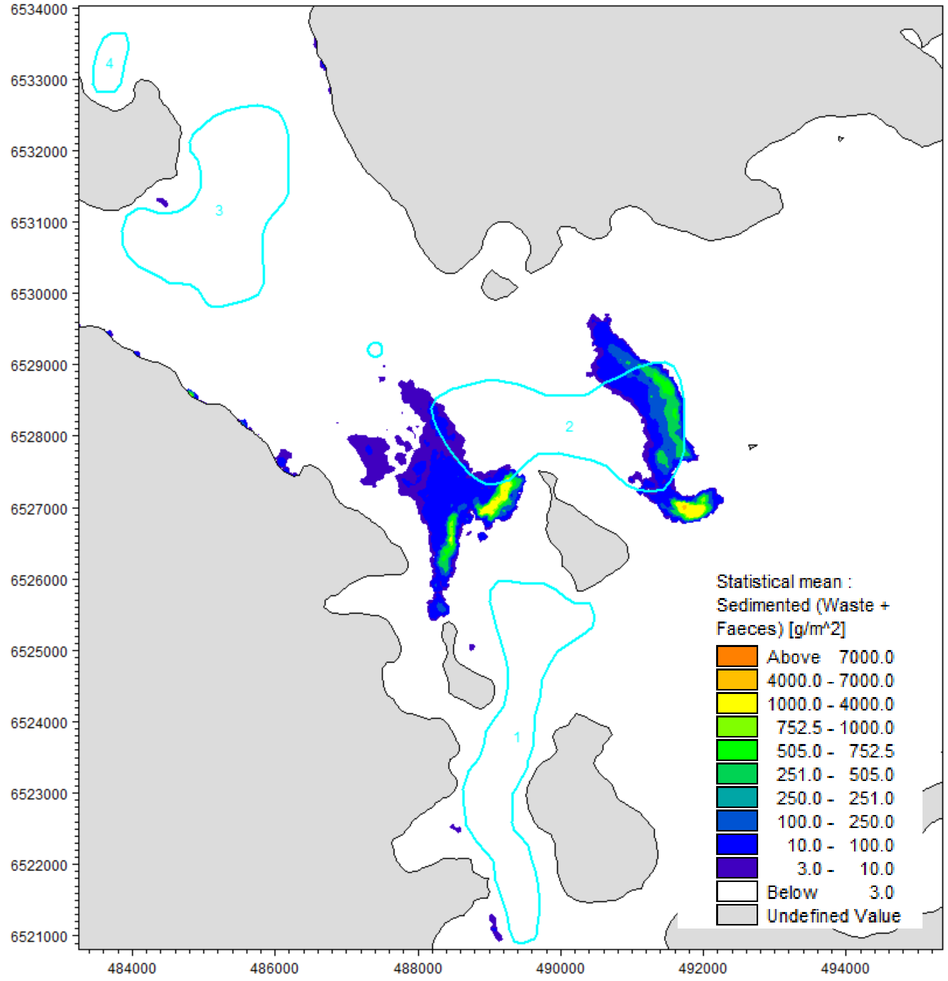
The deposition patterns shows that this area of Scapa Flow is already depositional, with build-up of material only and limited erosional power. As such it is likely to already be subject to deposition, with the benthic community being subject to sedimentation from a range of other sources.

Table 5.6 Summary statistics of the impact from Bring Head alone in the entire model domain from existing and proposed increased biomass

	Area of the 250 g/m^2 contour (averaged over the last 90 days)	Mean concentration within the 250 g/m^2 contour (averaged over the last 90 days)
Bring Head at existing biomass	234,863	549
Bring Head at proposed biomass	630,593	783

Average over last 90 days – concentration plots

Average over last 90 days – exceedance plots



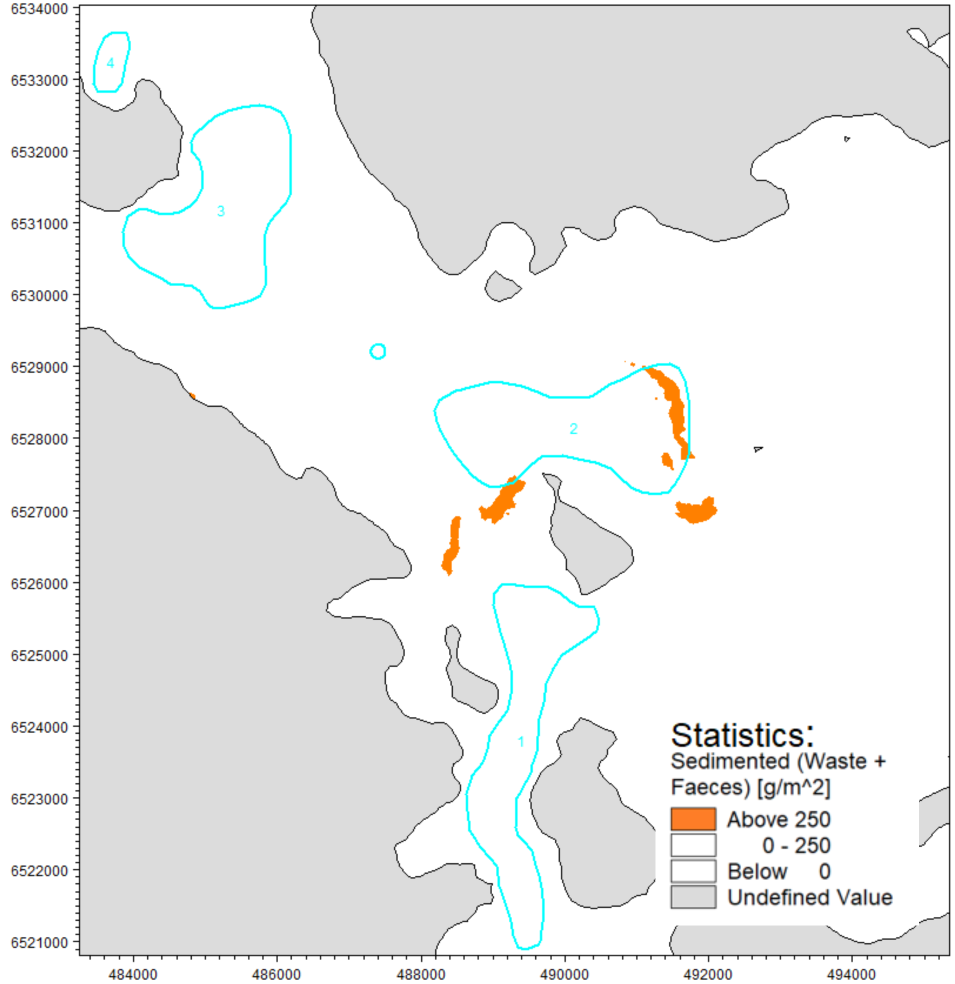


Figure 5.3 Map of the concentration of sedimented total waste solids (g/m²) from Bring Head in proposed Biomass configuration. The concentration is the average value (left column) and exceedance (right column) of the last 90 days of the 1-year model simulation. Blue lines show area identified by SEPA that contains similar PMF records.

.

Comparison of the average value of deposited waste solids over the last 90 days between the existing and proposed biomass at Bring Head allows us to understand the difference. All existing patches are shown to increase in extent, with the largest increase being within the eastern area of PMF 2. It is important to note that these depositional zones already exist in the pre situation.

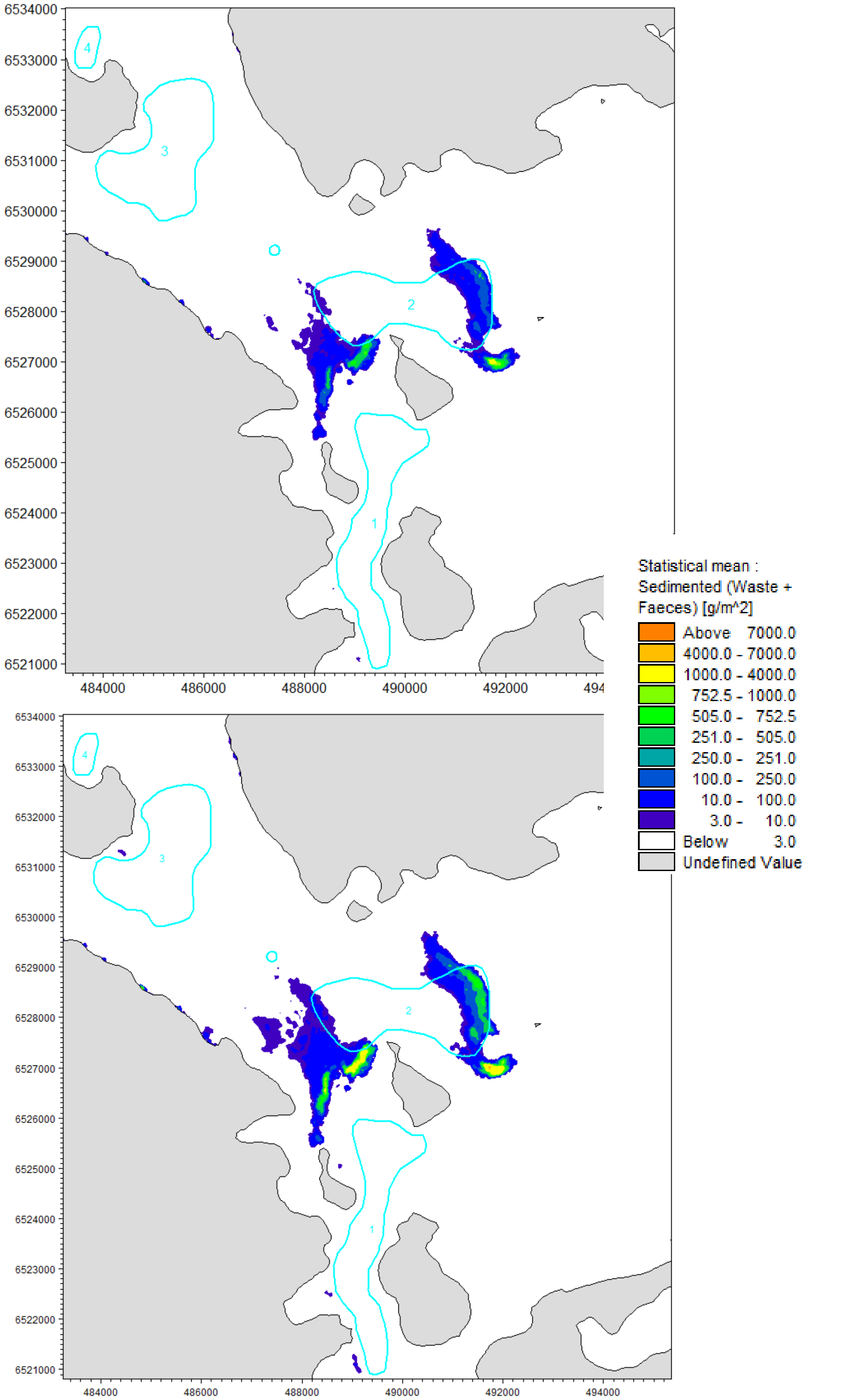


Figure 5.4 Map of the deposition for average concentration over the last 90 days of the 1-year simulation of sedimented waste solids (g/m^2) from Bring Head in pre (top) and post (bottom) biomass configurations. Blue lines show area identified by SEPA that contains similar PMF records.

5.3.3 Cumulative Waste Solids Results

The assessment of the cumulative impact for waste solids of all MPFF's in the western part of Scapa Flow has been assessed. This has been done by considering the impact of all additional sites within western Scapa Flow as "Others" as defined in Table 5.2

Toyness remains isolated with respect to waste solids, with the deposition taking place beneath the pens. Comparing the baseline situation of Bring Head at existing biomass and the Other operational farms, with the proposed situation of Bring Head at the new biomass and Others (Figure 5.5) , it is apparent that the areas of deposition are similar, with the same hot spots around the north end of Cava.

Of note is that several of the existing fish farms in the western part of Scapa flow have similar deposition patterns to Toyness, with much of their deposition directly below the pens. However, two other sites (Chalmers Hope and Fara West) appear to also contribute to deposition of waste material within the wider domain. In addition, the timeseries (Figure 5.6) highlights a series of individual events that lead to the larger depositions, associated with stronger tidal conditions.

With respect to the EQS of 250 g/m^2, which is typically applied with respect to impact from individual farms beneath pens, it is understood that the value is used to identify the potential risk of deposition in the far field.

It is noted that Bring Head has a particular impact to the northeast of Cava, which is directly related to the transport of material away from the site in the strong tidal currents and deposition within PMF 2. See Section 5.3.4 for further discussion of this.

Table 5.7 Summary statistics of the impact from Bring Head in relation to the other MPFF's for the entire model domain from existing and proposed increased biomass

	Area of the 250 g/m^2 contour (averaged over the last 90 days)	Mean concentration within the 250 g/m^2 contour (averaged over the last 90 days)
Bring Head at existing biomass and other MPFF's	591,931	2,558
Bring Head at proposed biomass and existing MPFF's	888,339	2,115

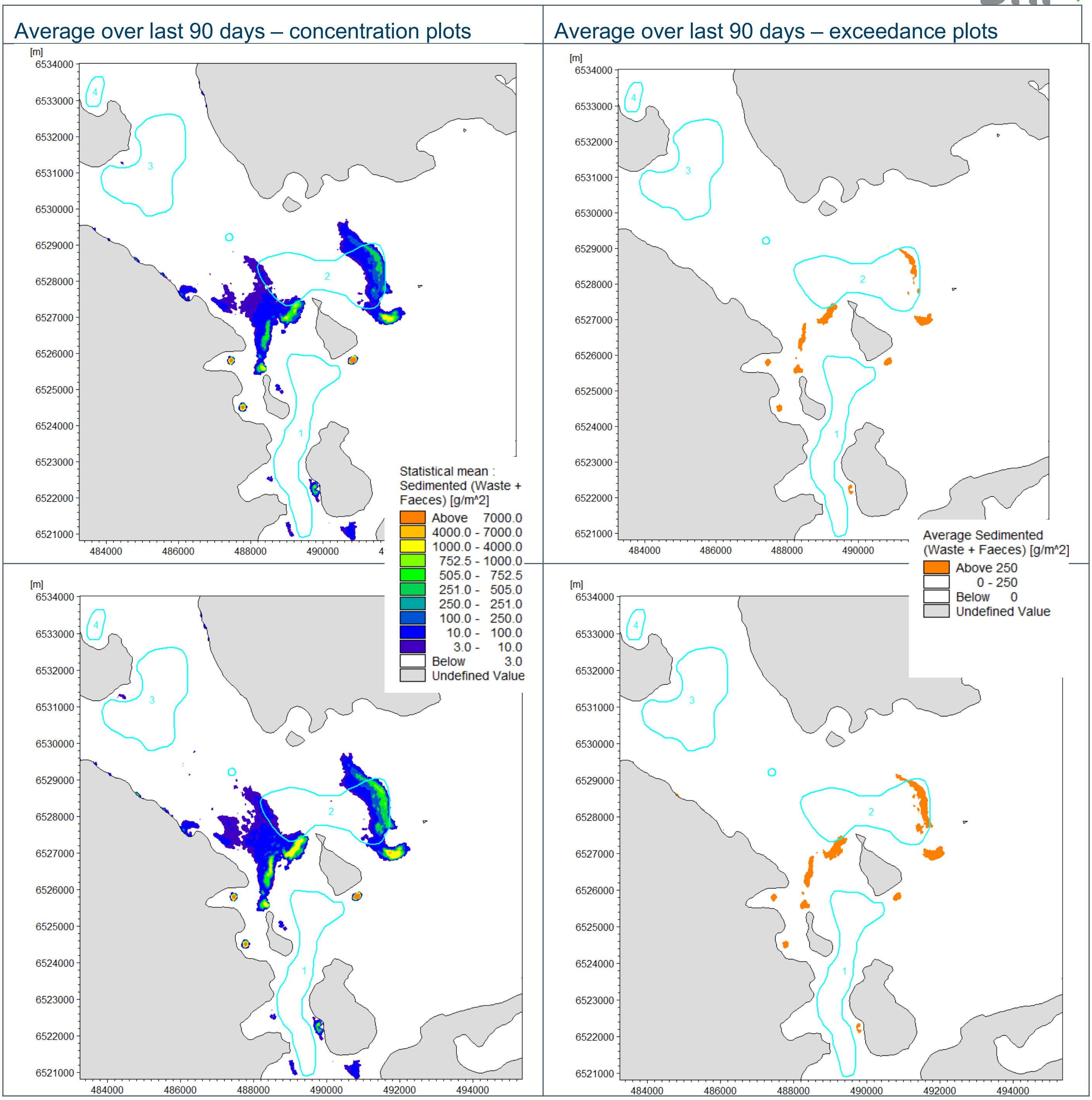


Figure 5.5 Map of the concentration of sedimented waste solids (g/m²) from combinations of sites. (top) existing Bring Head biomass and other sites, and (bottom) proposed Bring Head and other sites. The concentration is the average value of the last 90 days of the 1-year model simulation.

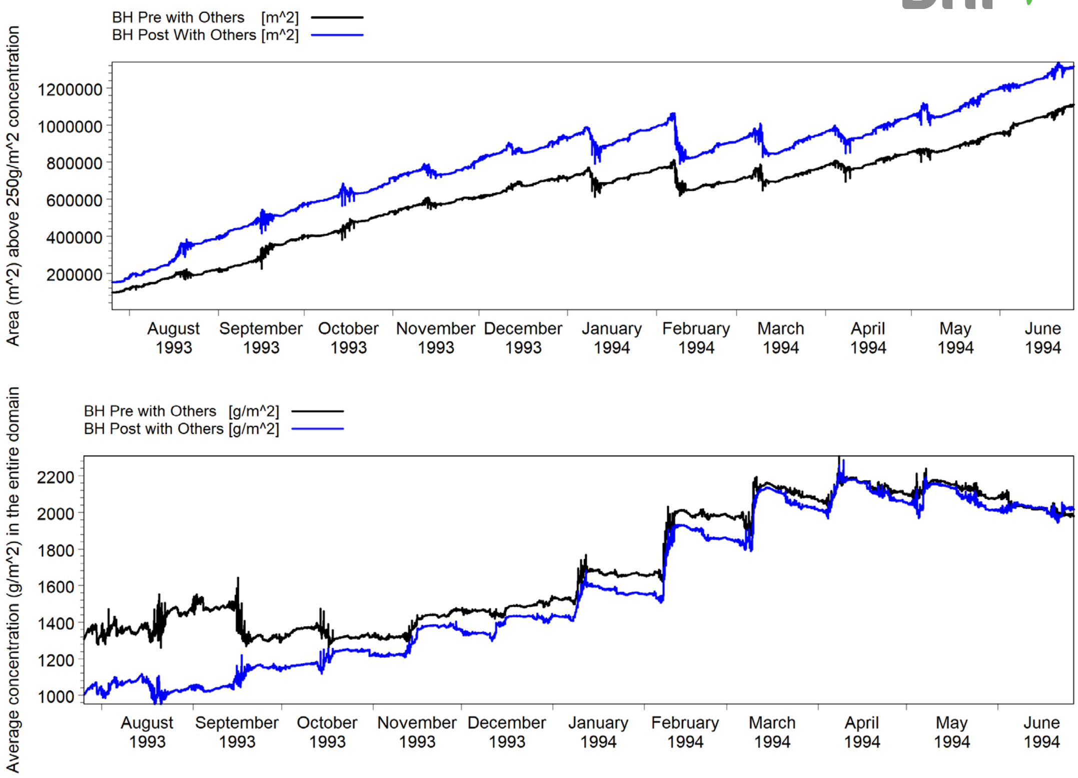


Figure 5.6 Time series of the area (in m^2) above 250 g/m^2 (top) and the average concentration (g/m^2) of deposition (bottom) within the entire model domain for the Baseline Scenario (existing Bring Head with other MPFF's) and the proposed Bring Head biomass with Other MPFF's for the whole year.

5.3.4 Impact at PMF's from Waste Solids

Waste solids from the model runs were extracted within the area of the PMF's to assess the potential impact of the proposed sites on these areas. As noted previously, the waste solids from Toyness do not leave the immediate environs of the site. Consequently, only Bring Head has the potential to impact PMF's remote from the site. Of the potentially impacted PMF's, only PMF 2 has areas where the 250 g/m^2 average value over the last 90 days is exceeded.

The following section provides additional information on the spread and concentration of waste solids within PMF2. Of note is that the area is already impacted by deposition from the existing discharges from Bring Head as well as the other MPFF's within Scapa Flow (see top section of Figure 5.8), however these are typically below the 250 g/m^2 value. Deposition is primarily faeces, as waste feed doesn't get deposited in the vicinity of PMF2. As seen in Figure 5.7, the build-up within PMF 2 with Bring Head in the post setup is generally higher by 15-20% on the area >250 g/m^2. Interestingly, the average concentration within the PMF is seen to vary, with the concentration generally being higher in the post situation, however, subject to the actual deposition pattern that occurs, there are periods were the average concentration in the post situation is lower than in the pre-situation, highlighting the variability that is likely to be seen in the results.

Spatially, the greatest deposition occurs on the eastern edge; however, there is a higher peak with smaller impacted area in the southwestern corner, which extends south outside of the PMF.

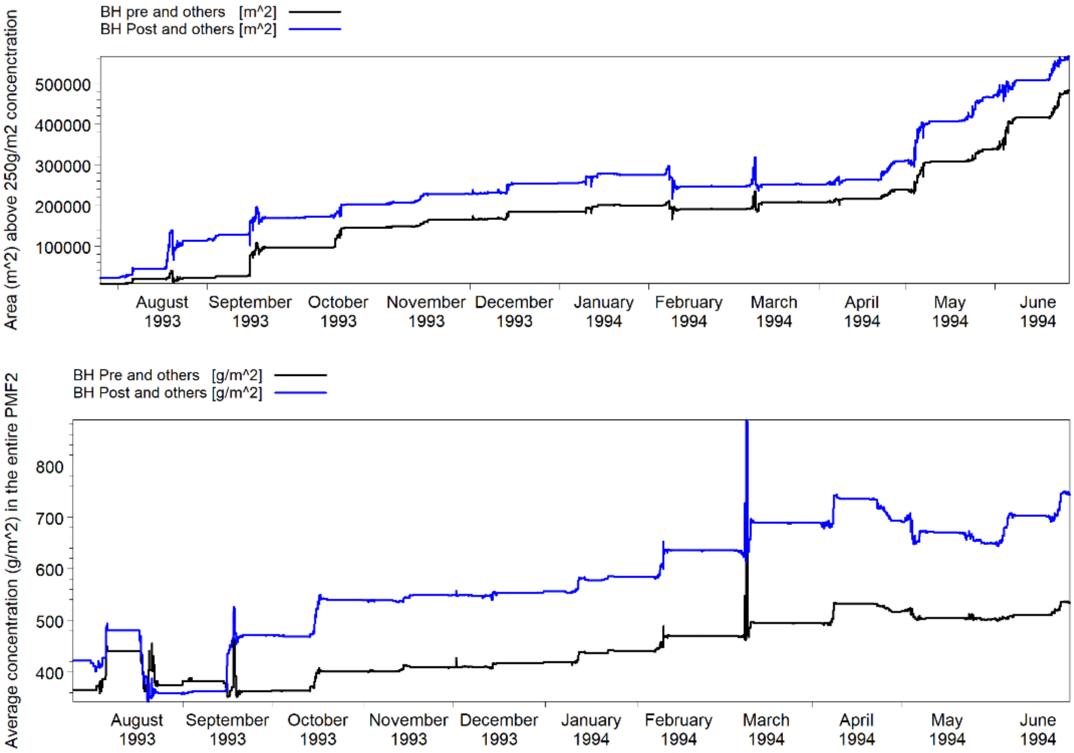


Figure 5.7 Time series of the area (in m^2) above 250 g/m^2 (top) and the average concentration (g/m^2) of deposition (bottom) within PMF2 for the Baseline Scenario (existing Bring Head with other MPFF's) and the proposed Bring Head biomass with Other MPFF's for the whole year.

Table 5.8 Summary statistics of the impact within PMF2 from MPFF's from the last 90 days of the model run

	Area (m^2) of the 250 g/m^2 contour within PMF2	% of the PMF 2 area (4,207,370 m^2)	Mean concentration (g/m^2) within the 250 g/m^2 contour
Bring Head at existing biomass and other MPFF's	159,222	3.8%	380
Bring Head at proposed biomass and existing MPFF's	315,566	7.5%	538
Bring Head at proposed biomass Only	249,621	5.9%	475

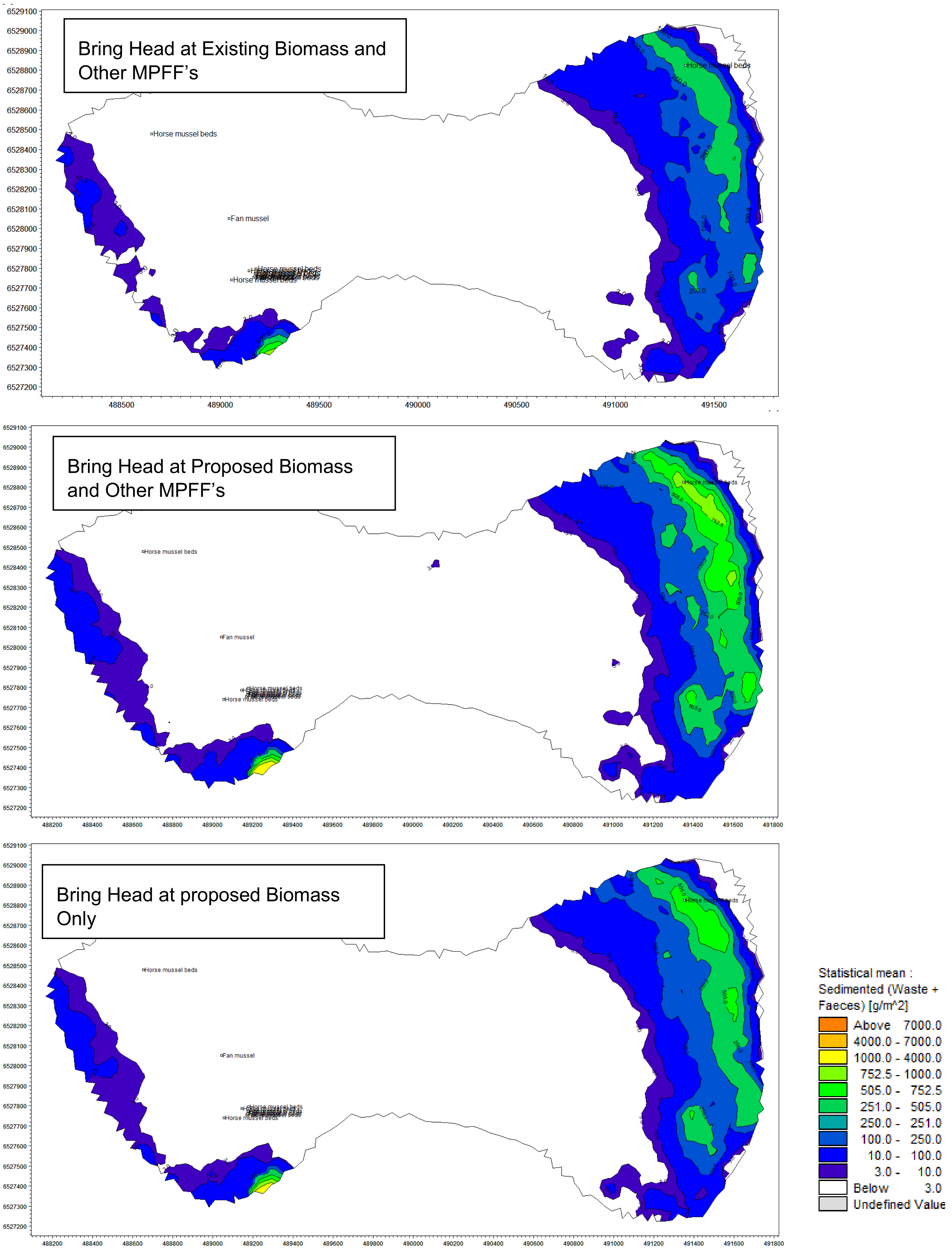


Figure 5.8 Waste Solid deposition at PMF 2. Average values for the last 90 days for Bring Head existing biomass with Others (top), Bring Head with proposed biomass (middle) and Bring Head Only (bottom).

6 In-feed treatment

6.1 Model configuration

This section describes the modelling methodology and results of the simulation of the fate of in-feed treatments at Bring Head, Toyness, and neighbouring farms in Scapa Flow. The in-feed treatment modelling was performed using the Particle Tracking module within the MIKE21/3 Coupled Model FM [9], with hydrodynamic conditions provided by a 2-dimensional HD model (as described in Section 5).

Emamectin Benzoate (EmBZ) is the active ingredient in the only in-feed sea lice treatment currently licensed by SEPA for use at MPFF's [7]. The medicine is wet or dry coated onto fish feed, thus the fate and behaviour of EmBZ in the marine environment is associated with the dispersion of waste feed and faecal matter (similar to waste solids described in Section 5). However, the predictive model for EmBZ is complicated due to the following factors:

- The input of EmBZ is limited to the treatment period of 7 days
- Fish excrete only a given proportion of the EmBZ load within the treatment period
- The EmBZ load in faeces decreases with time following the treatment period
- EmBZ breaks down in the marine environment into non-toxic sub-components

6.1.1 Particle Setup

There are three particle classes that represent EmBZ in the in-feed treatment model:

- Class 1: EmBZ load from wasted (uneaten) feed input during treatment period
- Class 2: EmBZ load that is excreted during the treatment period
- Class 3: EmBZ load that is excreted after the treatment period

As for the depositional model for waste solids, these particle classes represent groups of particles which share common characteristics, and which are considered to behave in a broadly similar way.

The properties of each of the three particle classes are summarised in Table 6.1, and are based on the default particle parameters as specified in [11].

Like the solid waste modelling, there are 29 point sources in the model setup representing the Bring Head and Toyness sites as individual pen releases, and all other fin fish aquaculture sites identified in the western part of Scapa Flow as a single source output. The source locations are summarised in Table 5.2, and were specified at a depth of 5m below the still water level.

The dosage of EmBZ input to the model simulation is linked to the biomass of each MPFF and was calculated according to Appendix B of [7]. This states that the recommended dose rate of 50 μg of EmBZ per kg of fish per day for seven consecutive days. The dosage was based on the peak farm biomass as specified in Table 5.2.

The discharge of EmBZ into the marine environment is complex, and variable over time, being dependent on the rate of excretion. In the model the EmBZ load consisted of:

- Wasted (uneaten) feed. It is assumed that 3% of the treated feed (therefore 3% of EmBZ load) is uneaten and passes through the fish pens and into the water column during the seven-day treatment period
- Of the remaining 97% that is ingested by fish, 10% of the EmBZ load is excreted during the 7-day treatment period.
- Over the subsequent 216 days, 99% of the remaining EmBZ load is excreted, by which time the excretion mass of EmBZ has decreased to 1.5% of its starting value.

The half-life of EmBZ once released into the water environment is around 250-days (see Section 1.2.2 of [7]). This is equivalent to a decay rate of 3.21×10^{-8} s^{-1}, and this value was specified for all particle classes in the in-feed treatment model setup (Table 6.1)

Table 6.1 General settings for in-feed treatment model

In-feed Treatment Model Settings			
Model period	229 days		
Hydrodynamic conditions	2-dimensional hydrodynamic model • Tidal conditions for one year period • Climatologically averaged wind forcing		
Model output time step [seconds]	900		
Sources	29 source locations representing MPFF sites for post scenario 25 source locations representing MPFF sites for pre scenario (Bring Head 10 pens, Toyness 10 pens)		
Particle classes	Class 1: Waste Feed	Class 2: Excreted during treatment	Class 3: Excreted after treatment
Number of particles per source and per time step	10	10	10
Total number of particles released from the pens.	154,560	154,560	4,791,360
Decay [/s]	3.21x10-8	3.21x10-8	3.21x10-8
Settling velocity [m/s]	0.095	0.035	0.035
Erosion threshold [Nm^{-2}]	0.02	0.02	0.02
Horizontal dispersion [m^2s^{-1}]	0.10	0.10	0.10
Vertical dispersion [m^2s^{-1}]	0.001	0.001	0.001

Settling Rates

As EmBZ is contained within feed or faeces, the settling rate for particles was consistent with that of uneaten feed and faeces used in the depositional modelling for total solids (see Section 5.1.1).

The mean value of the settling velocity recommended by SEPA in [11] was used for feed pellets (0.095 m/s) and salmon faeces (0.035 m/s), respectively.

Decay

The concentration of the particles released into the environment and deposited on the seabed may be subject to natural decay over time. The decay can be modelled individually for each particle class via an invariant or time-varying decay rate.

The decay rate is used to simulate the time evolution of the various particles in the environment.

In the model, the linear decay of a component is described by:

$$m = m_0 \cdot e^{-k \cdot t}$$

Where k is the decay constant, m is the mass of a particle, m0 is the initial mass of the particle, and t is the elapsed time.

Resuspension/Erosion

As EmBZ load is contained within feed or faeces, the resuspension threshold for particles shall be consistent with that of uneaten feed and faeces used in the depositional modelling for total solids (see Section 5.1.1).

The in-feed treatment model assumes a critical resuspension threshold velocity of 0.02 Nm^{-2} for all particle classes.

6.1.2 Model Outputs

The output from the depositional model simulations included:

- Hourly values of the total, suspended, and sedimented EmBZ for each particle class in every cell of the model domain

Note that the model provides mass of EmBZ per unit area, whereas deposition is typically assessed in terms of the mass of EmBZ per unit mass of bed sediment. A conversion relationship will therefore be applied to the model results following:

$$EQS = \frac{Mass\ of\ EmBZ}{Mass\ of\ wet\ sediment} = \frac{S_{EmBz}}{d \cdot \rho_s}$$

Where:

- S_{EmBZ} is the mass of sedimented EmBZ (kg/m^2)
- *d* is the depth of sediment
- ρ_S is the density of wet sediment

Following the approach described in Regulation and Monitoring of Marine Pen Fish Farming in Scotland, Annex H (2005) by SEPA [13], we assume that the deposited EmBZ is incorporated into the sediment to a depth of 5cm, and the wet sediment density is 1,400 kg/m^3.

To permit assessment of impact from deposition in Scapa Flow and at the identified PMF features, the area of deposition above 0.01175 µg/kg wet weight sediment is adopted (as per [15]). This is the interim EQS at the Mixing Zone edge that would be applied for the release of EmBZ at a new fish farm.

It should be noted that the quantities modelled herein were licenced before the adoption of this interim standard and that the quantities proposed for use at

Bring Head and Toyness are derived following current SEPA guidance for modifications to existing sites and the licenced quantities of EmBZ.

It has previously been determined by SEPA [7] that the maximum quantity of EmBZ in the environment occurs 118-days after the start of the treatment, and therefore the day that EQS levels are assessed in NewDEPOMOD. In this study, DHI evaluate the amount of EmBZ present at this point in the model as well as at 223 days after the start of treatment, when it is considered that nearly 99% of the body load of chemical has been excreted from the fish [13].

6.2 In-feed treatment results

The following sections show the results of the in-feed treatment modelling. From the model results the total sedimented EmBZ on the seabed (from waste feed and faeces) were calculated for each model grid cell.

Table 6.2 provides summary statistics before and after expansion at Bring Head and Toyness at 118 days from the start of the treatment. Further details on each impact are provided in the following sections.

Table 6.2 Area above 0.01175 µg/kg at 118 days from start of treatment for the following scenarios:

	Scenario	Area (km^2)
All sites	BH & TN existing	2.76
	BH & TN proposed	3.40
Toyness	Existing Biomass	0.19
	Proposed Biomass	0.21
Bring Head	Existing Biomass	1.76
	Proposed Biomass	2.56

6.2.1 Toyness In-Feed Treatment

Toyness shows a typical pattern of deposition of EmBZ beneath the pens and does not leave the vicinity of the site (see Figure 6.1). The extent of the deposition can be seen to be elongated along the long axis of the cage group.

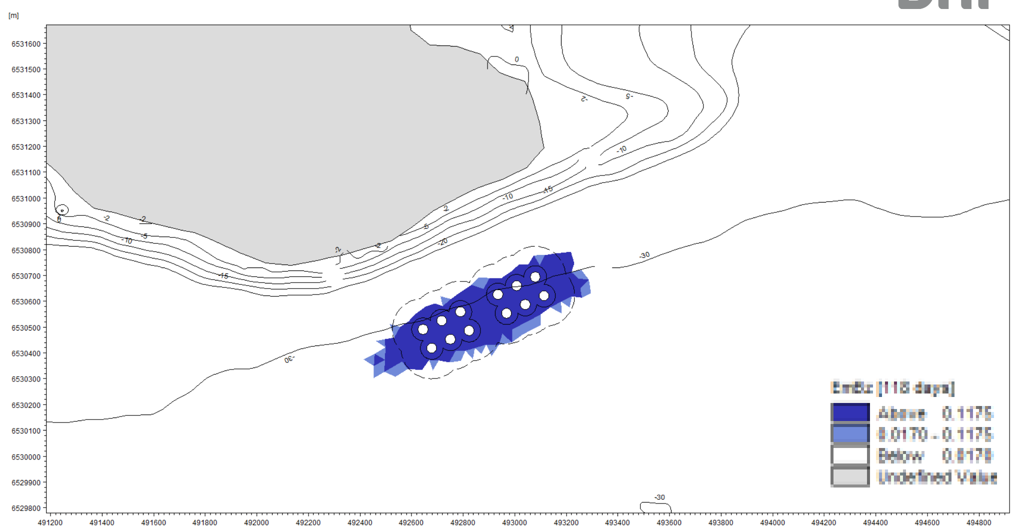


Figure 6.1 Deposition above 0.01175 µg EmBZ/kg sediment at 118 days after treatment at Toyness for the proposed scenario.

6.2.2 Bring Head In-feed Treatment

The results for EmBZ at Bring Head alone show that the dispersive nature of the site leads to most of the waste and the medicine being removed from the immediate area beneath the pens. As this in-feed treatment is sedimented and resuspended by the currents, it can be seen to move further afield than is typical for MPFF's.

Figure 6.2 below shows the resulting location of EmBZ after 118 days for the proposed scenario. Most deposition is between the island of Cava and the Barrel of Butter. An additional zone of deposition between Cava and Hoy is also noted. Further afield, it is noted that limited patches of EmBZ can be found in the Bay of Ireland, near Stromness, in the Bay of Quoys off Hoy and in Gutter Sound to the South. A similar pattern of dispersion is evident for the existing scenario (Figure 6.3).

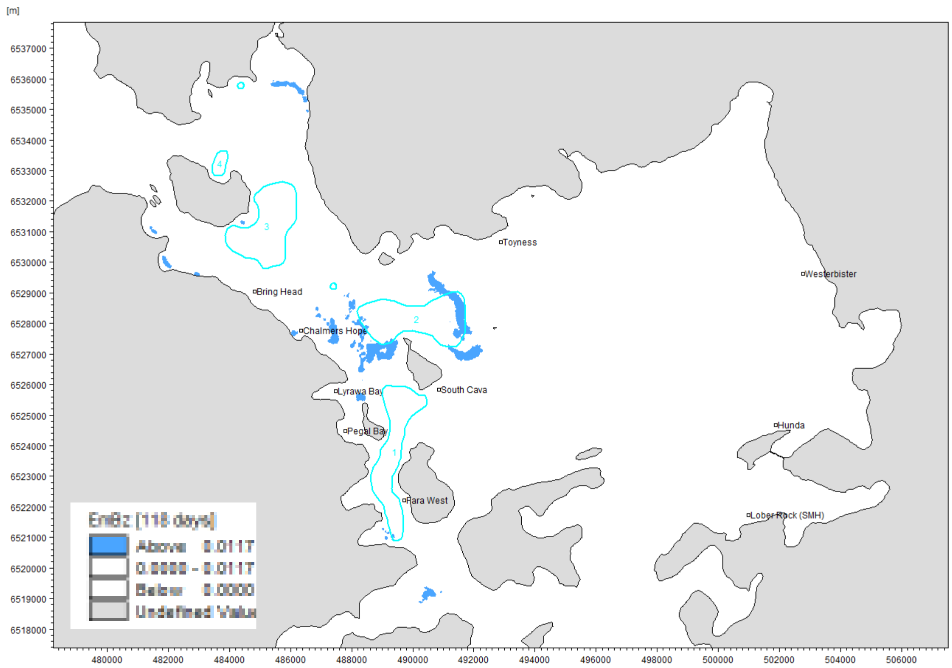


Figure 6.2 Deposition above 0.01175 µg EmBZ/kg sediment at 118 days after treatment at Bring Head for the proposed scenario. PMF areas shown in light blue

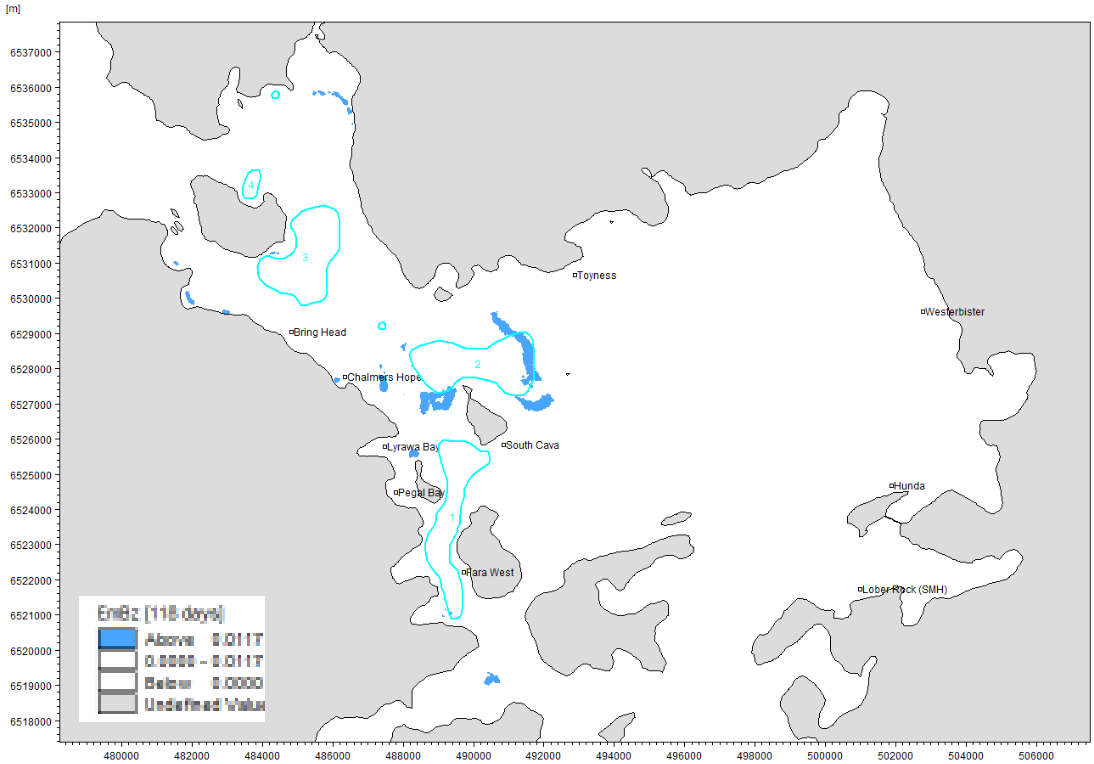


Figure 6.3 Deposition above 0.01175 µg EmBZ/kg sediment at 118 days after treatment at Bring Head for the existing scenario. PMF areas shown in light blue

6.2.3 Cumulative In-Feed Treatment Results

Deposition patterns of EmBZ across Scapa Flow were tested for a situation where all other fin fish farms were in operation with biomass as noted in Table 5.2, to assess the cumulative impact and to compare the impact of the proposed Bring Head and Toyness sites with the other farms in western Scapa Flow. As noted before, the impact of Toyness remains localised to immediate area of the site.

The following figures show the cumulative in-feed deposition at 0.01175 µg/kg at 118 days from start of treatment for the baseline situation, with Bring Head and Toyness at existing biomass, combined with the other western Scapa Flow sites (Figure 6.4). The proposed situation for Bring Head and Toyness is then also shown (Figure 6.5).

These both show very similar patterns of deposition, with the same areas being impacted in the proposed scenario as for the present. This is supported with reference to Table 6.2, where the areas are not seen to change significantly overall.

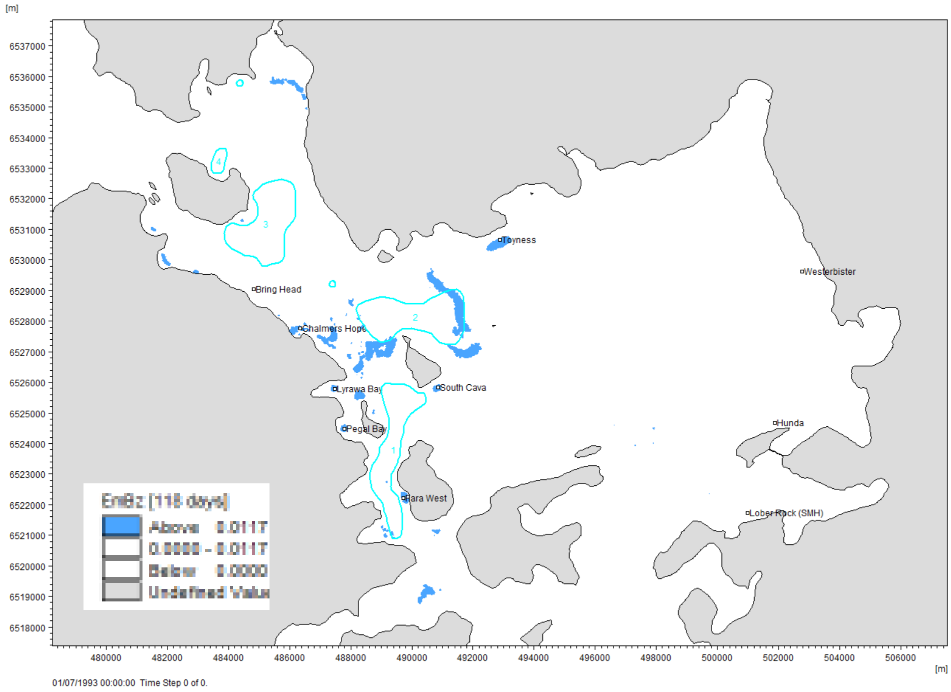


Figure 6.4 Baseline situation of Bring Head existing, Toyness existing & all other sites. Deposition above 0.01175 µg EmBZ/kg sediment at 118 days after start of the treatment prior to expansion at Bring Head and Toyness. PMF areas shown in light blue

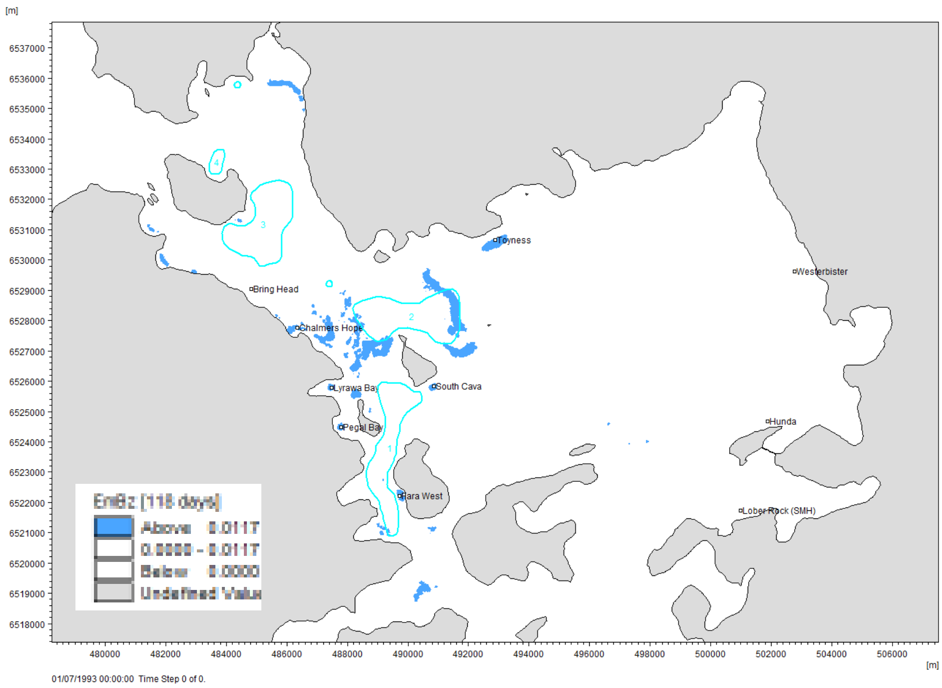


Figure 6.5 Proposed biomass with all other sites. Deposition above 0.01175 µg EmBZ/kg sediment at 118 days after start of the treatment prior to expansion at Bring Head and Toyness. PMF areas shown in light blue

6.2.4 Impact at PMF's from In-Feed Treatment

The impact of the in-feed treatment medicines at PMF's has been assessed by extracting results and assessing the source of the impact. As noted, in-feed treatment does not leave the Toyness site. Therefore, the results shown in Table 6.3 are with Bring Head pre and post expansion, in the all sites and with Bring Head alone.

Table 6.3 Area (km²) at 0.01175 µg/kg at 118 and 223 days from start of treatment at impacted PMF's

		Area of deposition at 0.01175 µg/kg (km²)			
PMF No.		All sites (Bring Head existing)	All sites (Bring Head proposed)	Bring Head alone existing	Bring Head alone proposed
PMF 1	118 days	0.011	0.010	0.004	0.006
	223 days	0.0005	0.0015	0.0000	0.0007
PMF 2	118 days	0.37	0.50	0.34	0.47
	223 days	0.58	0.54	0.51	0.52

It is noted that PMF2 is the area with the greatest impact from in-feed treatment. From the 118 day results, it is noted that the existing baseline situation has an impact on PMF2. With the additional biomass, the area affected can be seen to increase, though it is important to note that the increase between Bring Head on its own and all sites is a small increase in total area impacted, suggesting that this heavily depositional zone is already depositing at close to the maximum area possible. It is noted that the mean concentration of EmBZ, in the area is seen to be lower (see Table 6.4 in the Bring Head only runs, related to the lower Biomass, in addition the concentrations reduce over time following the end of the treatment and the decay of EmBZ. The spatial representation of these changes can be seen in Figure 6.6 to Figure 6.9.

Table 6.4 Mean concentration (µg/kg) in areas above 0.01175 µg/kg at 118 and 223 days from start of treatment at PMF 2

		Mean concentration of the areas above 0.01175 µg/kg (in µg/kg)			
PMF No.		All sites (Bring Head existing)	All sites (Bring Head proposed)	Bring Head alone existing	Bring Head alone proposed
PMF 2	118 days	0.91	1.51	0.58	1.20
	223 days	0.69	1.21	0.43	0.96

Table 6.3 also highlights that PMF 1 is only slightly impacted with the area of deposition above 0.01175 µg/kg being significantly lower than in PMF2. PMF's 3-6 show no impact from in-feed treatment medicines.

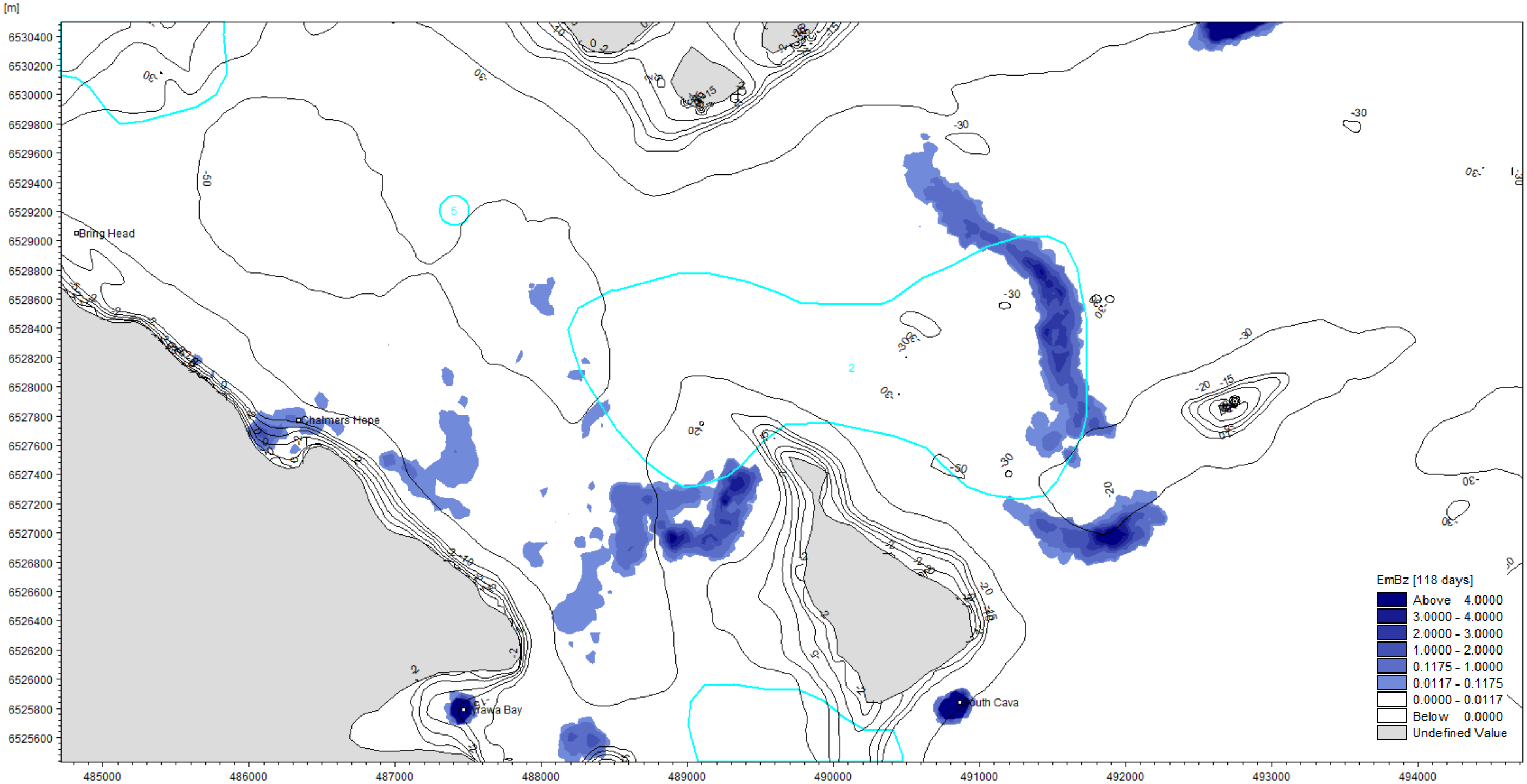


Figure 6.6 Areas of PMF2 that are in excess of 0.01175 ug/kg for all sites with Bring Head existing scenario at 118 days. PMF areas shown in light blue

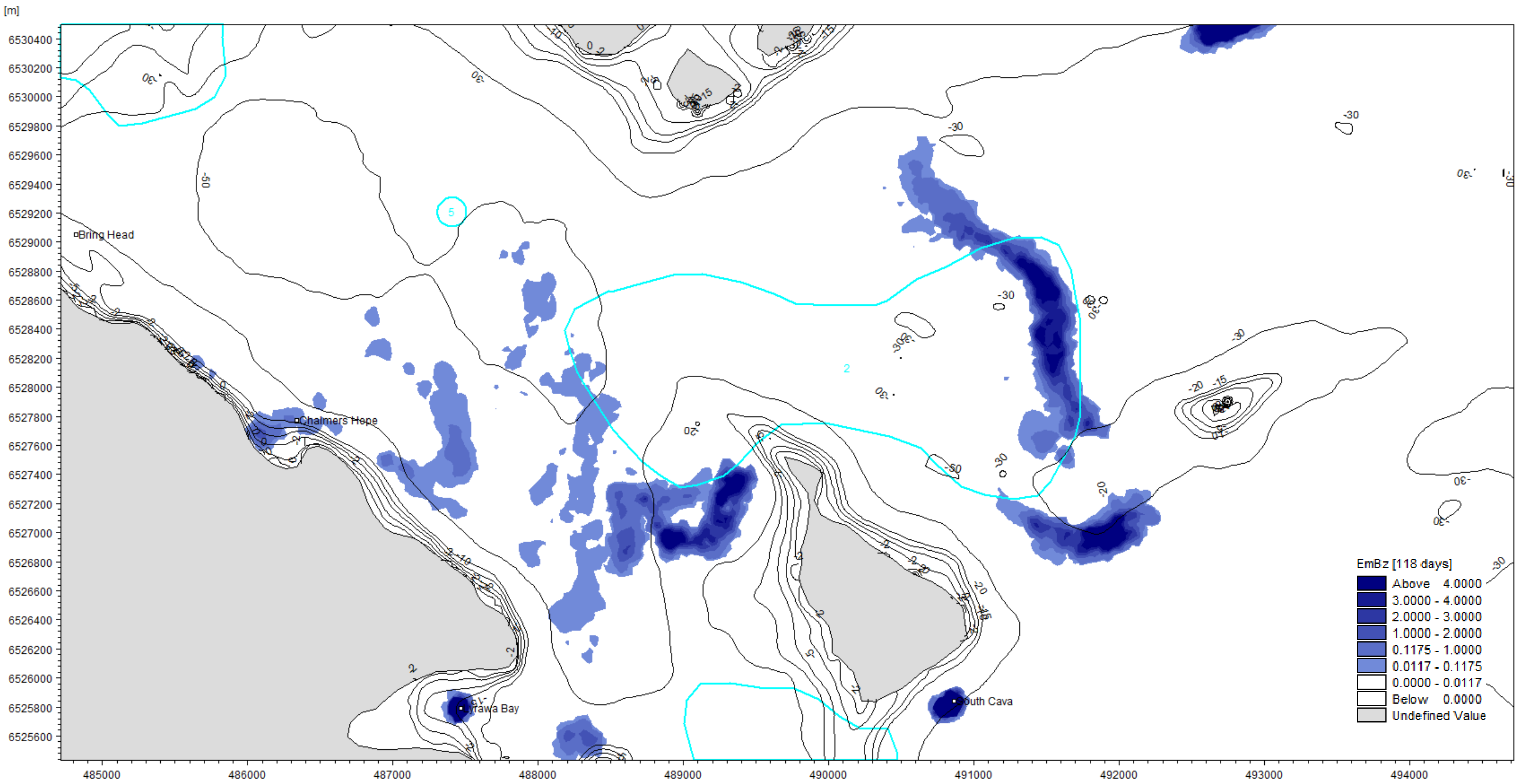


Figure 6.7 Areas of PMF2 that are in excess of 0.01175 ug/kg for the all sites with Bring Head proposed (bottom) scenarios at 118 days. PMF areas shown in light blue

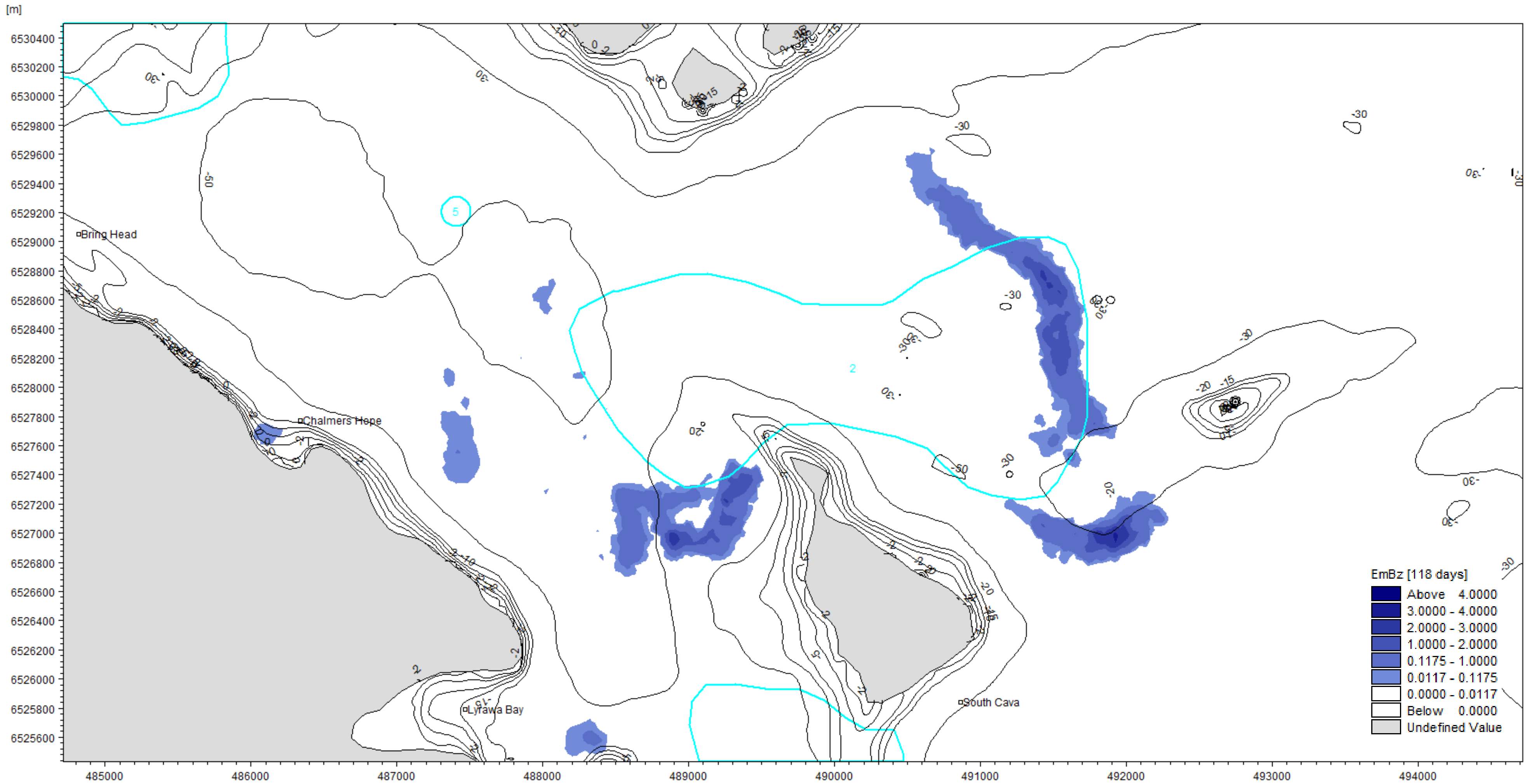


Figure 6.8 Areas of PMF2 that are in excess of 0.01175 ug/kg for Bring Head only with existing biomass scenario at 118 days. PMF areas shown in light blue

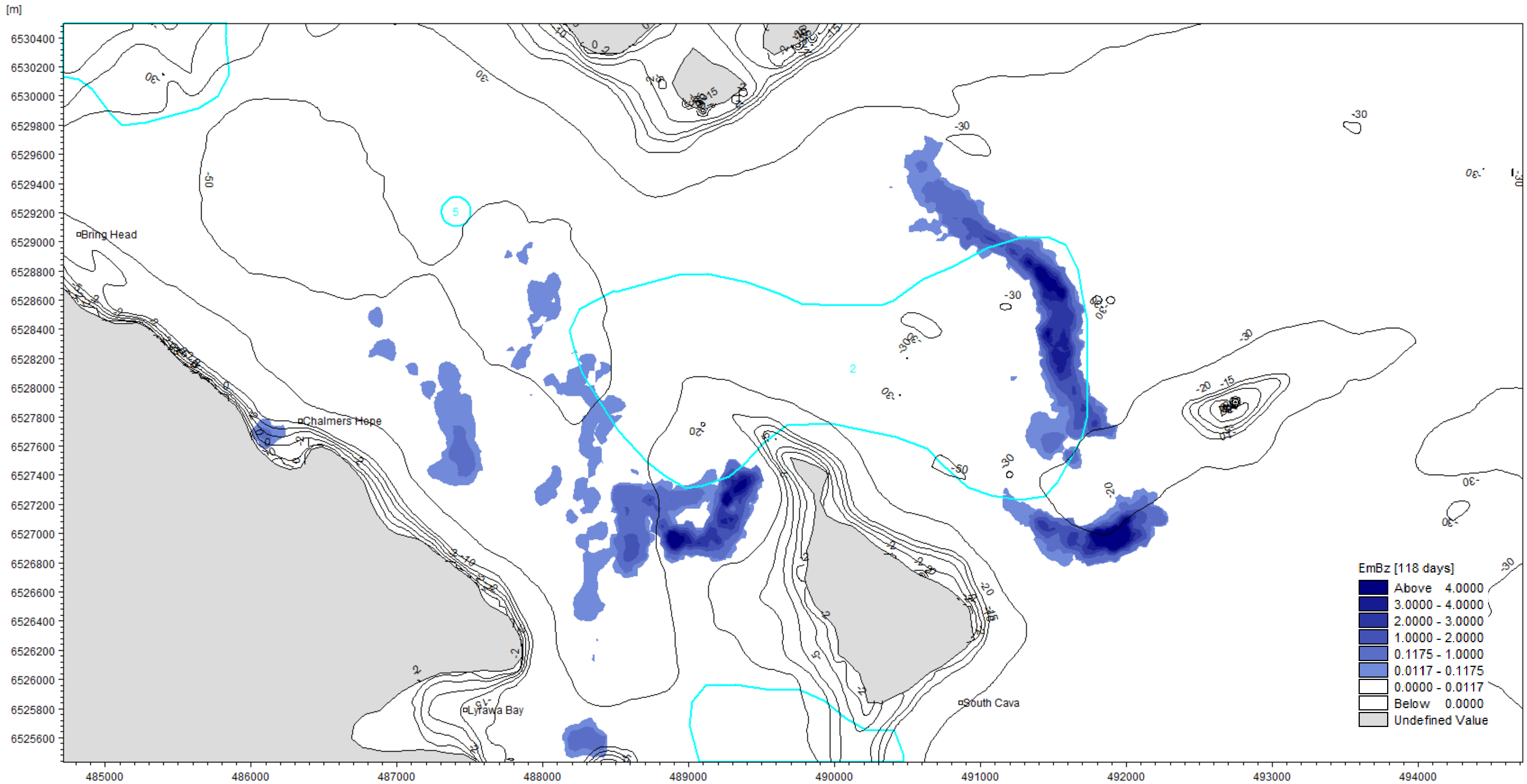


Figure 6.9 Areas of PMF2 that are in excess of 0.01175 ug/kg for Bring Head only with proposed biomass scenario at 118 days. PMF areas shown in light blue

7 Conclusions

7.1 Waste Solids

Assessment of the impact from the proposed MPFF's on the distribution of waste solids has been undertaken using the numerical models run for a one-year period. The assessment assumes that the sites run at peak biomass for the entire simulation, a conservative assumption in line with SEPA guidance, to assess the potential fate of waste solids from MPFF's. Of the two sites being assessed in this study, only Bring Head has the potential to impact PMF's remote from the producing site.

For Bring Head, the higher current speeds lead to a greater distribution of waste solids away from the site. Deposition can be seen to increase in areas to the north of the island of Cava. Of this, the zone in the east of PMF 2 shows the greatest increase in area, attributed to the increased biomass at Bring Head. It is important to note that this was already an area subject to deposition in the existing situation, with other farms such as Chalmers Hope having a potential cumulative impact.

As noted, the conservative nature of the modelled assessment (the assumption of the constant 2,500 t biomass and associated waste loss in the entire model period), as well as the use of a fixed critical threshold for resuspension is potentially likely to result in an overestimate of the spread of material. It is noted that the existing Bring Head site shows deposition remaining beneath the pens.

It is apparent from the results for Toyness that the deposited solids remain in the immediate vicinity of the site due to the current speeds being significantly lower in this area. Compared to the existing biomass, there is only a slight increase in the area in excess of 250g/m^2 towards the edge of the farm site, with an elongation along the central axis of the site.

When considered cumulatively with the results from the other Western Scapa sites, it is apparent that Bring Head contributes the waste solids into the same locations that are already depositional hotspots from other farm sites.

Consequently, there is likely to be a need to consider the potential impact of this increase in waste solids at the sensitive receptor areas identified within PMF2.

7.2 In-feed treatment

In feed treatments, in this assessment Emamectin Benzoate (EmBZ), have been assessed for the sites individually and cumulatively, as well as an assessment of the potential impact at PMF's. The results for EmBZ show a similar pattern to the waste solids results with respect to distribution.

Toyness shows a typical pattern of deposition of EmBZ beneath the pens and material does not leave the vicinity of the site. There is a marginal increase in the area of deposition reflecting the higher treatment quantity required for the increased biomass.

The results for EmBZ at Bring Head show that the dispersive nature of the site leads to most of the waste and the medicine being removed from the immediate area. As this in-feed treatment is sedimented and resuspended by the currents, it can be seen to move further afield than is typical for MPFF's.

Bring Head is seen to deposit EmBZ between the island of Cava and the Barrel of Butter. In addition, a zone to the west of Cava has been seen. Bring Head is likely to impact PMF2, similarly to the waste solids, but also is seen to have a potential impact on PMF1, though to a significantly lesser extent.

Again, there is likely to be a need to consider the potential impact of this increase in EmBZ use from a single treatment at the sensitive receptor areas identified within PMF's 1 and 2. However it is also noted that these hotspots are already zones of deposition from the existing farm sites and therefore the accumulations remain in the same areas.

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[14] G. R. Philips, A. Anwar, L. Brooks, L. J. Martina, A. C. Miles and A. Prior, “Infaunal quality index: Water Framework Directive classification scheme for marine benthic invertebrates. Environment Agency Report: SC080016,” Environment Agency, 2014.

[15] SEPA, “NewDepomod Draft Guidance 2021_06_25,” 2021.

[16] SEPA, “WAT-PS-17-03; INTERIM POSITION STATEMENT FOR PROTECTING THE WATER ENVIRONMENT UNTIL SUCH TIME AS A DIRECTION IS ISSUED ON AN EQS IN RELATION TO EMAMECTIN BENZOATE IN FINFISH FARM REGULATION,” SEPA, Jan 2021.

Appendix A.1 HD Model Calibration

Appendix A.1.1 Bring Head

The following pages provide the calibration plots comparing the observed and modelled total water level and current speed data at Bring Head.

- Figure A.8.1 Scatter plot of observed vs. modelled water level at Bring Head
- Figure A.8.2 Overlaid time series plot of observed and modelled water level at Bring Head
- Figure A.8.3 Scatter and rose plot of observed vs. model depth average total current speed at Bring Head
- Figure A.8.4 Overlaid frequency distributions of observed and modelled depth average total current direction (towards) at Bring Head
- Figure A.8.5 Overlaid frequency distributions of observed and modelled depth average total current speed at Bring Head
- Figure A.8.6 Overlaid time series plot of observed and modelled depth average total current speed at Bring Head

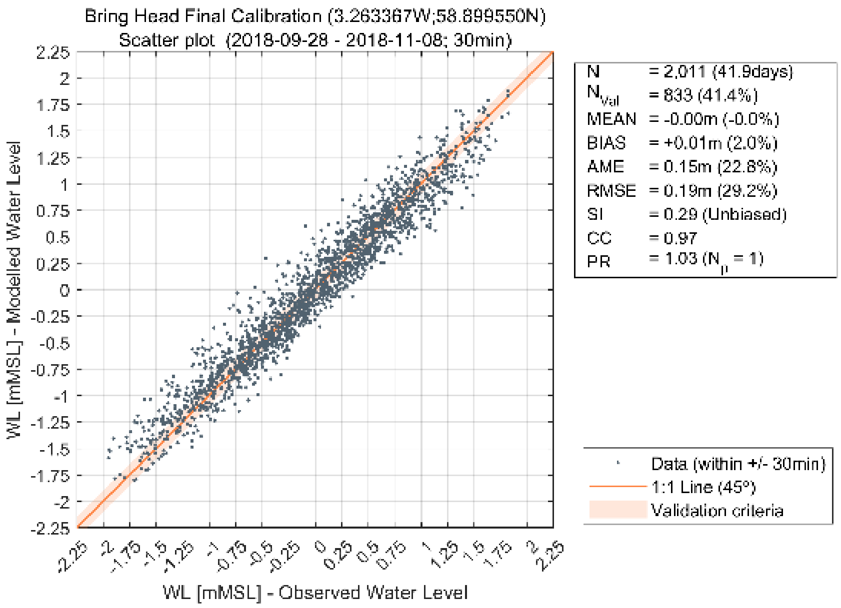


Figure A.8.1 Scatter plot of observed vs. modelled water level at Bring Head (orange shading denotes SEPA's calibration standards)

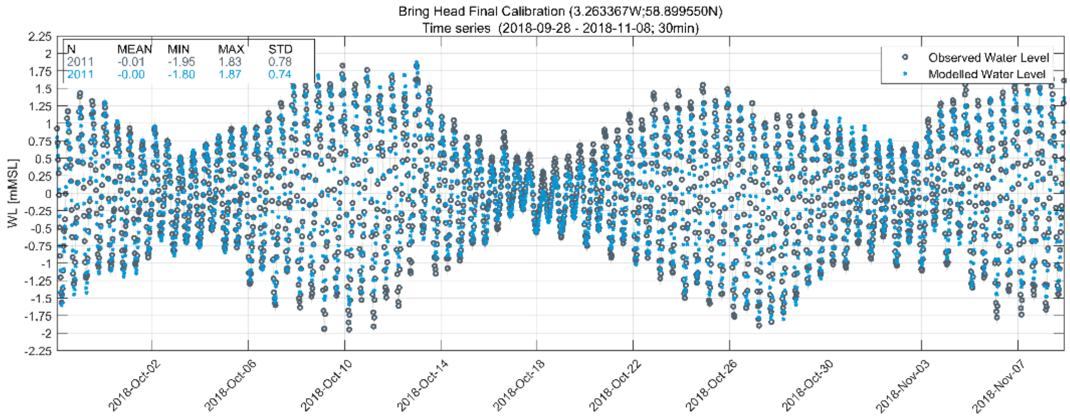


Figure A.8.2 Overlaid time series plot of observed and modelled water level at Bring Head

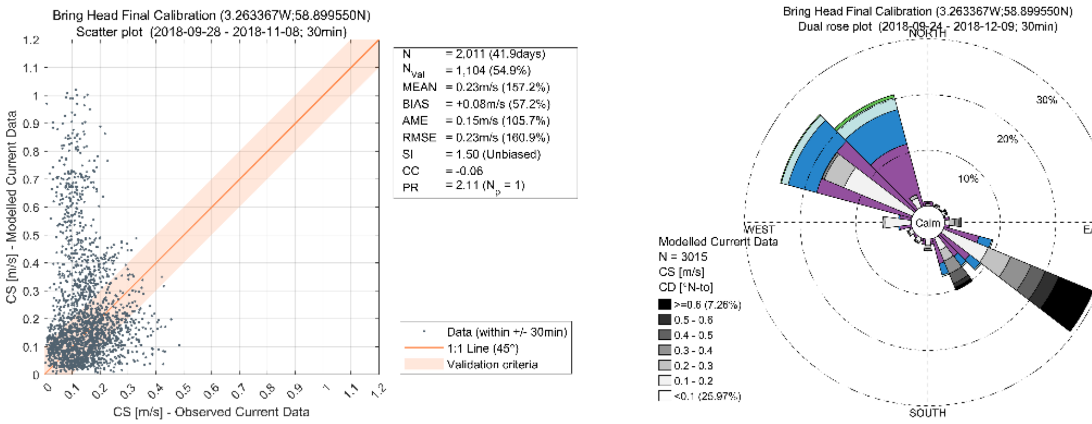


Figure A.8.3 Scatter and rose plot of observed vs. model depth average total current speed at Bring Head (orange shading denotes SEPA's calibration standards)

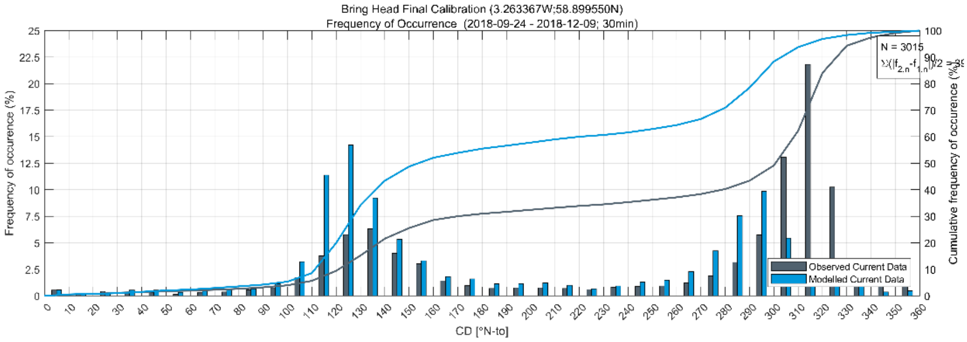


Figure A.8.4 Overlaid frequency distributions of observed and modelled depth average total current direction (towards) at Bring Head

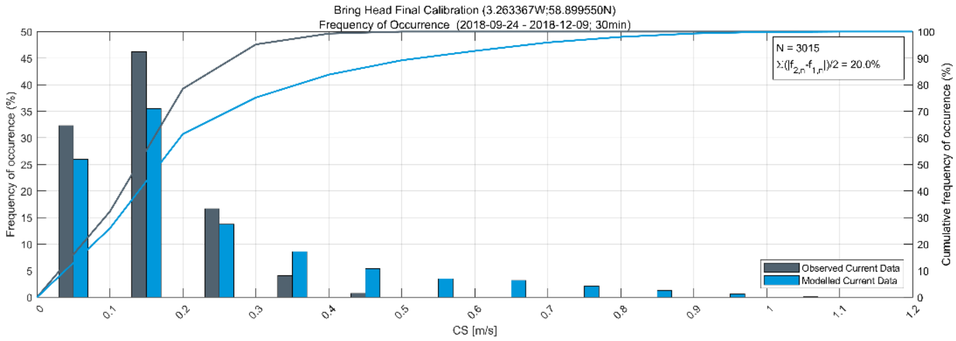


Figure A.8.5 Overlaid frequency distributions of observed and modelled depth average total current speed at Bring Head

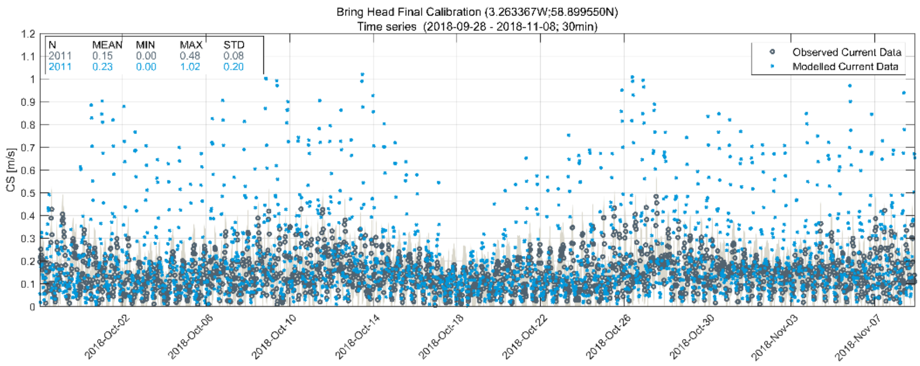


Figure A.8.6 Overlaid time series plot of observed and modelled depth average total current speed at Bring Head (grey shading denotes SEPA's calibration standards)

Appendix A.1.2 Toyness

The following pages provide the calibration plots comparing the observed and modelled total water level and current speed data at Toyness.

- Figure A.8.7 Scatter plot of observed vs. model water level at Toyness
- Figure A.8.8 Overlaid time series plot of observed and modelled water level at Toyness
- Figure A.8.9 Scatter and rose plot of observed vs model total current speed at Toyness
- Figure A.8.10 Overlaid frequency distributions of observed and modelled total current direction (towards) at Toyness
- Figure A.8.11 Overlaid frequency distributions of observed and modelled total current speed at Toyness
- Figure A.8.12 Overlaid time series plot of observed and modelled total current speed at Toyness

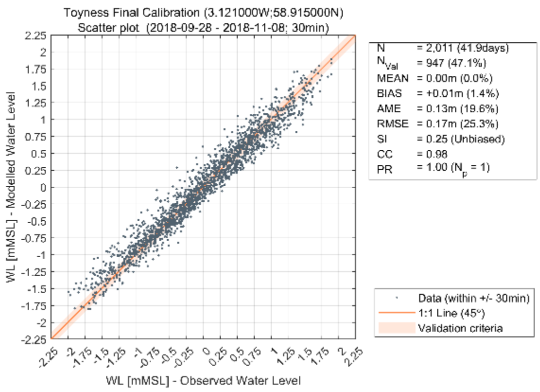


Figure A.8.7 Scatter plot of observed vs. model water level at Toyness (orange shading denotes SEPA's calibration standards)

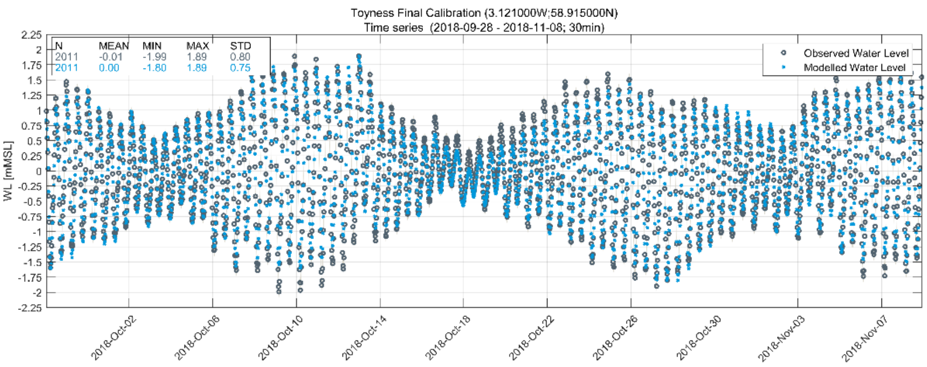


Figure A.8.8 Overlaid time series plot of observed and modelled water level at Toyness

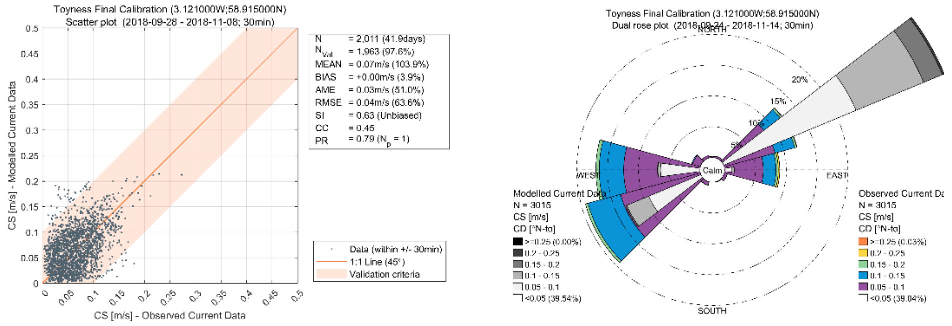


Figure A.8.9 Scatter and rose plot of observed vs model total current speed at Toyness (orange shading denotes SEPA's calibration standards)

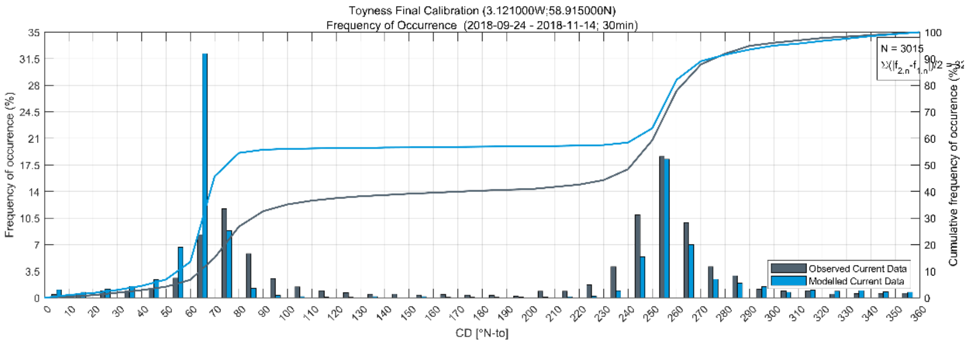


Figure A.8.10 Overlaid frequency distributions of observed and modelled total current direction (towards) at Toyness

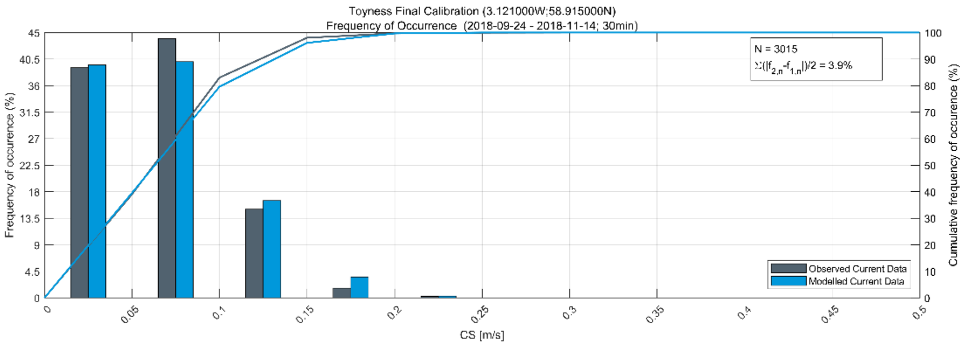


Figure A.8.11 Overlaid frequency distributions of observed and modelled total current speed at Toyness

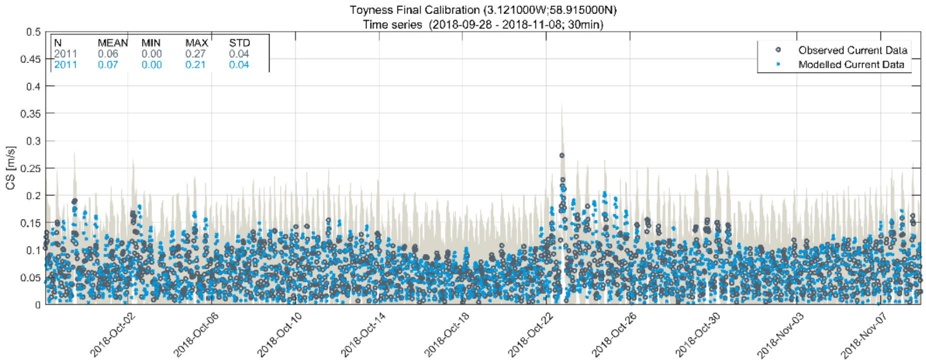


Figure A.8.12 Overlaid time series plot of observed and modelled total current speed at Toyness (grey shading denotes SEPA's calibration standards)

Appendix A.2 HD Model Validation

The following sections present the validation plots of water level and current speed of the model at other locations and periods within Scapa Flow (Figure 2.2), namely:

- Toyness: 8th March 2005 to 23rd March 2008
- Bring Head: 30th January 2008 to 15th February 2008
- Roo Point: 17-March-2011 to 4th April 2011
- Hunda: 5th April 2011 to 21st April 2011
- St. Margaret's Hope: 14th April 2011 to 3rd May 2011
- Westerbister: 3rd May 2011 to 20th May 2011

Appendix A.2.1 Toyness 2005

Figure A.8.13 to Figure A.8.16 present a range of comparison plots of observed versus modelled total water level and current speed at Toyness for the period 8th March 2005 to 23rd March 2008.

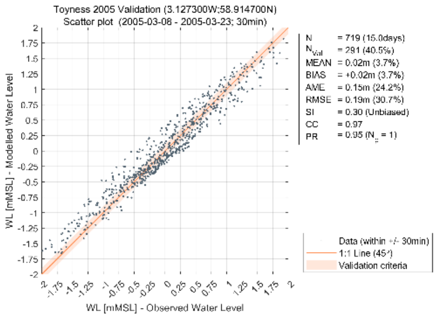


Figure A.8.13 Scatter plot of observed vs. model total water level at Toyness for 2005 validation period (orange shading denotes SEPA's calibration standards)

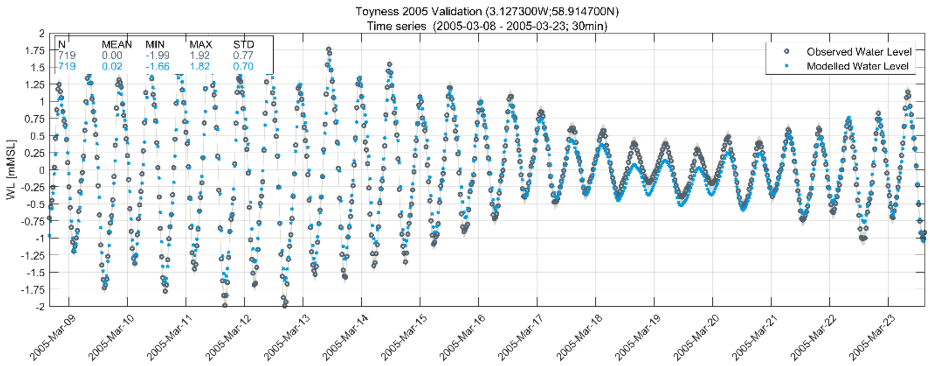


Figure A.8.14 Time series plot of observed vs. model total water level at Toyness for 2005 validation period

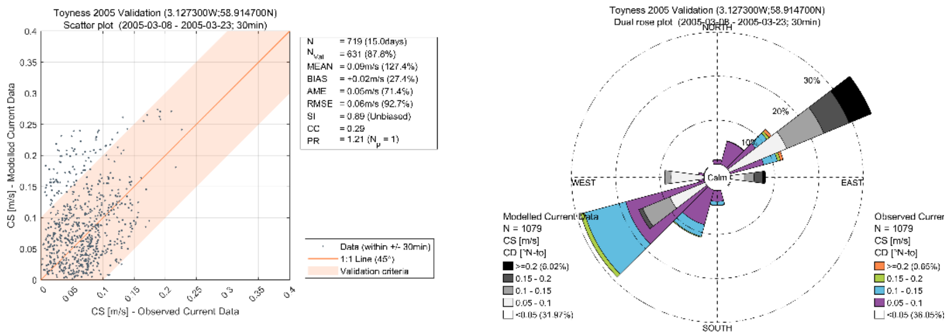


Figure A.8.15 Scatter plot and directional rose plot of observed vs. model total current speed at Toyness for 2005 validation period (orange shading denotes SEPA's calibration standards)

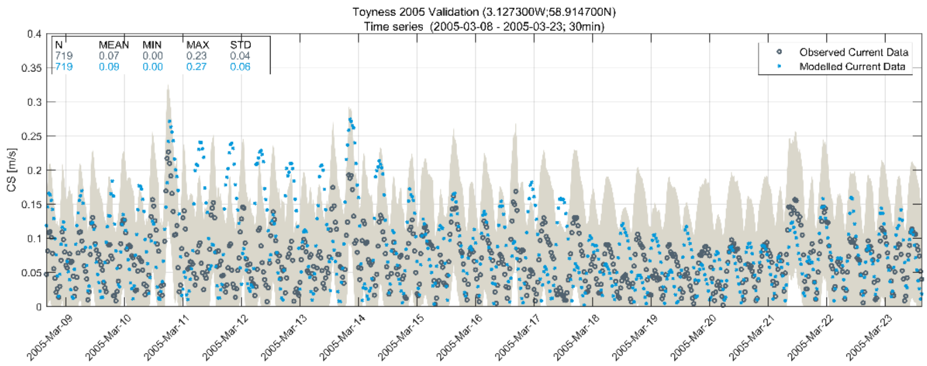


Figure A.8.16 Time series plot of observed vs. model total current speed at Toyness for 2005 validation period (grey shading denotes SEPA's calibration standards)

Appendix A.2.2 Bring Head 2008

Figure A.8.17 to Figure A.8.20 present a range of comparison plots of observed versus modelled total water level and current speed at Bring Head for the period 30th January 2008 to 15th February 2008.

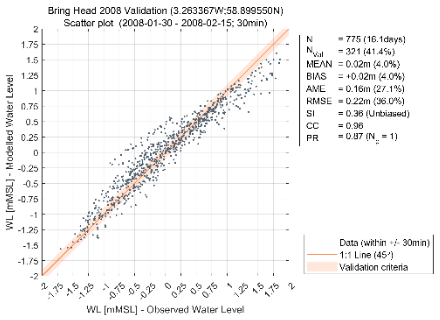


Figure A.8.17 Scatter plot of observed vs. model total water level at Bring Head for 2008 validation period (orange shading denotes SEPA's calibration standards)

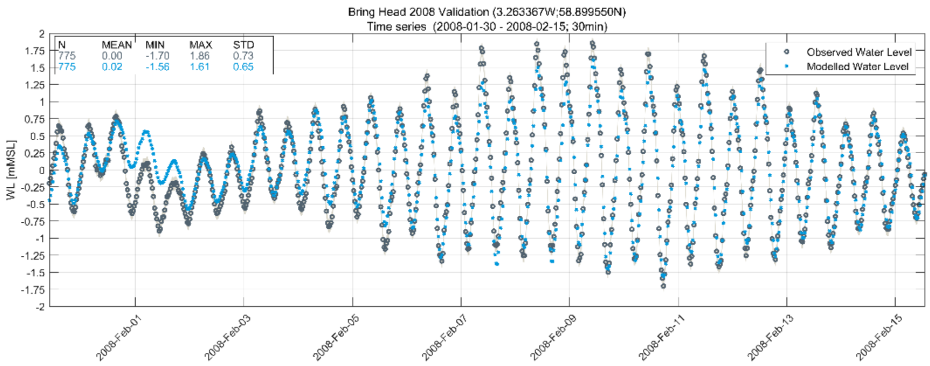


Figure A.8.18 Time series plot of observed vs. model total water level at Bring Head for 2008 validation period

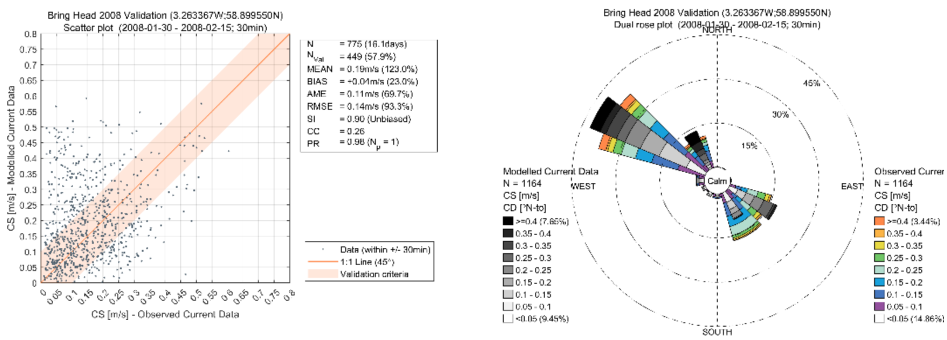


Figure A.8.19 Scatter plot and directional rose plot of observed vs. model total current speed at Bring Head for 2008 validation period (orange shading denotes SEPA's calibration standards)

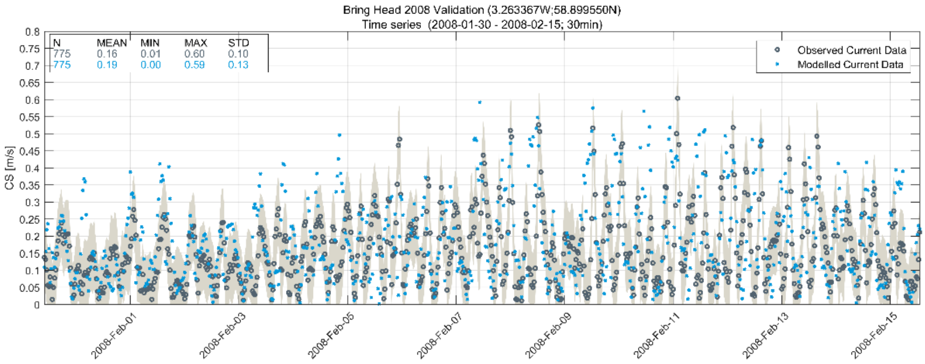


Figure A.8.20 Time series plot of observed vs. model total current speed at Bring Head for 2008 validation period (grey shading denotes SEPA's calibration standards)

Appendix A.2.3 Roo Point 2011

Figure A.8.21 to Figure A.8.24 present a range of comparison plots of observed versus modelled total water level and current speed at Roo Point for the period 17-March-2011 to 4th April 2011.

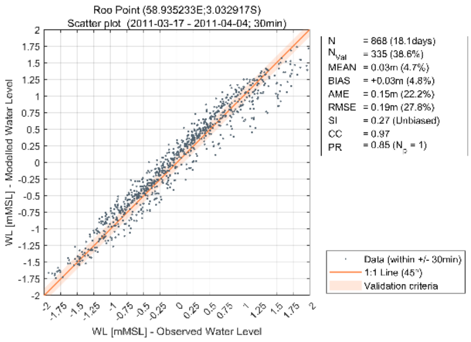


Figure A.8.21 Scatter plot of observed vs. model total water level at Roo Point for 2011 validation period (orange shading denotes SEPA's calibration standards)

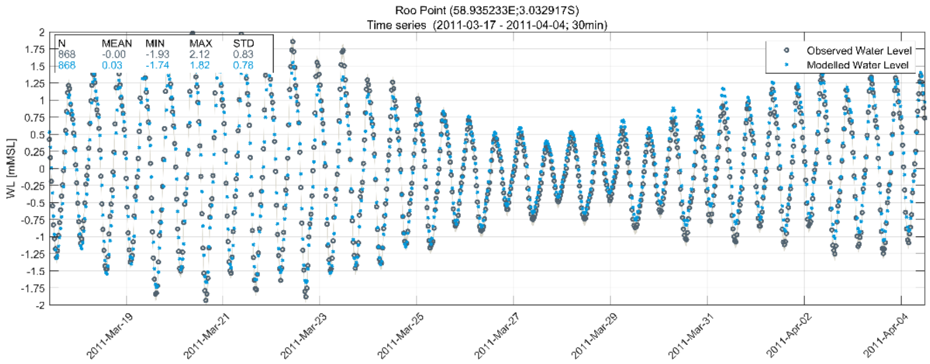


Figure A.8.22 Time series plot of observed vs. model total water level at Roo Point for 2011 validation period

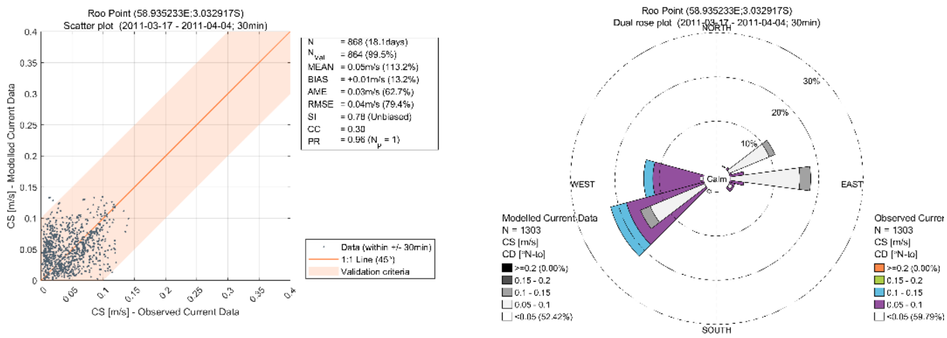


Figure A.8.23 Scatter plot and directional rose plot of observed vs. model total current speed at Roo Point for 2011 validation period (orange shading denotes SEPA's calibration standards)

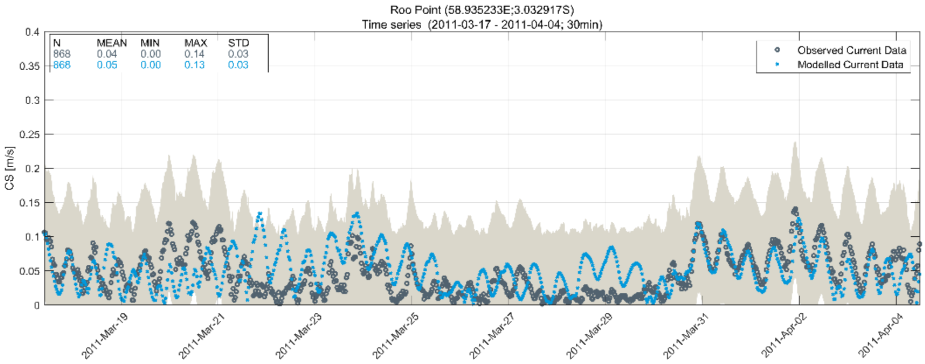


Figure A.8.24 Time series plot of observed vs. model total current speed at Roo Point for 2011 validation period (grey shading denotes SEPA's calibration standards)

Figure A.8.25 to Figure A.8.29 present a range of comparison plots of observed versus modelled total water level and current speed at Hunda for the period 5th April 2011 to 21st April 2011.

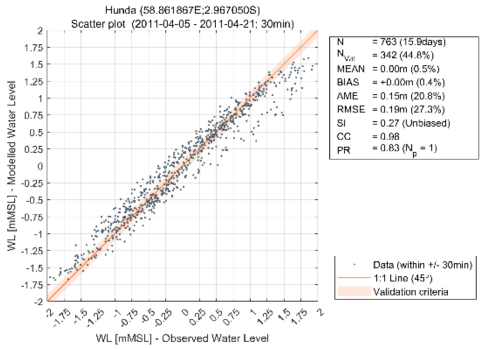


Figure A.8.25 Scatter plot of observed vs. model total water level at Hunda for 2011 validation period (orange shading denotes SEPA's calibration standards)

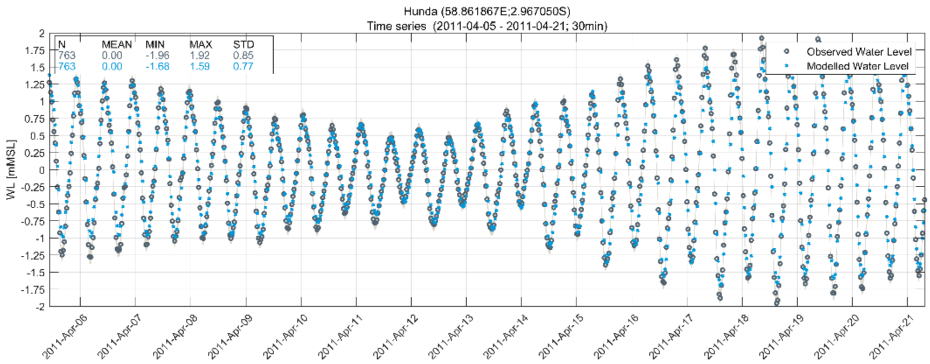


Figure A.8.26 Time series plot of observed vs. model total water level at Hunda for 2011 validation period

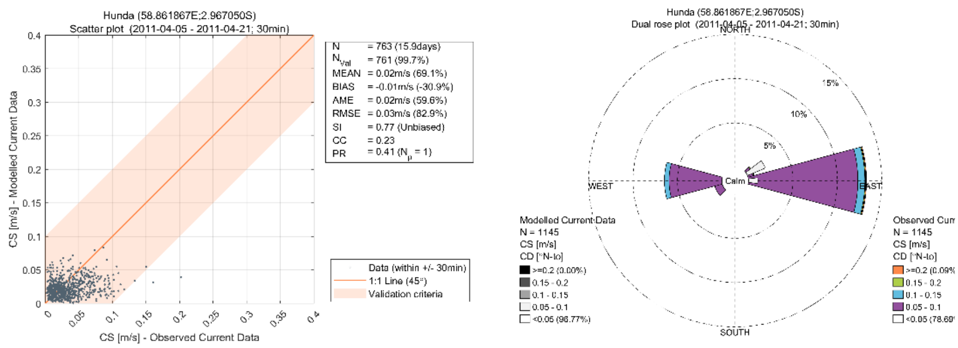


Figure A.8.27 Scatter plot and directional rose plot of observed vs. model total current speed at Hunda for 2011 validation period (orange shading denotes SEPA's calibration standards)

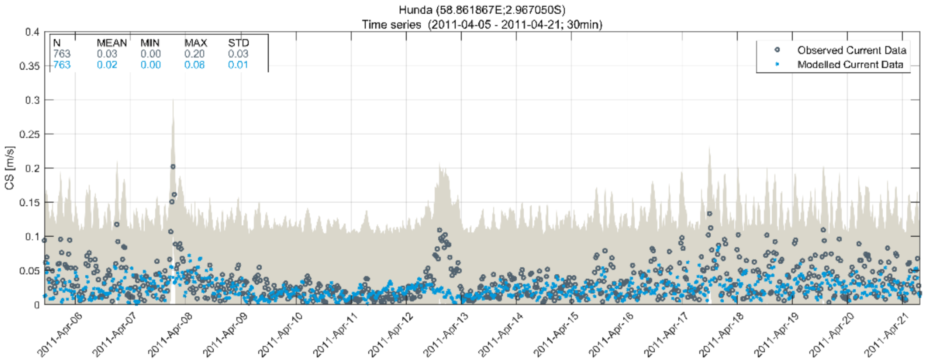


Figure A.8.28 Time series plot of observed vs. model total current speed at Hunda for 2011 validation period (grey shading denotes SEPA's calibration standards)

Appendix A.2.5 St. Margaret's Hope 2011

Figure A.8.29 to Figure A.8.32 present a range of comparison plots of observed versus modelled total water level and current speed at St. Margaret's Hope for the period 14th April 2011 to 3rd May 2011.

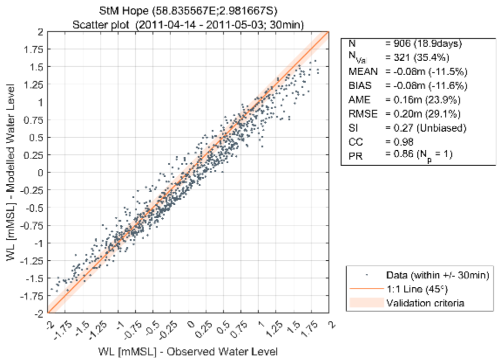


Figure A.8.29 Scatter plot of observed vs. model total water level at St. Margaret's Hope for 2011 validation period (orange shading denotes SEPA's calibration standards)

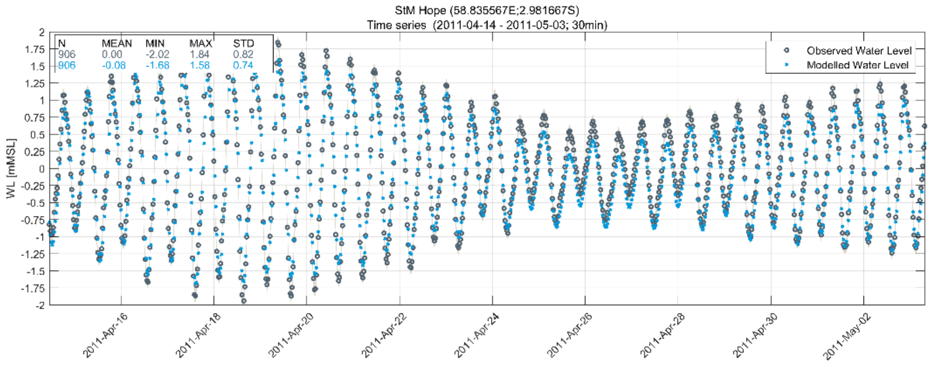


Figure A.8.30 Time series plot of observed vs. model total water level at St. Margaret's Hope for 2011 validation period

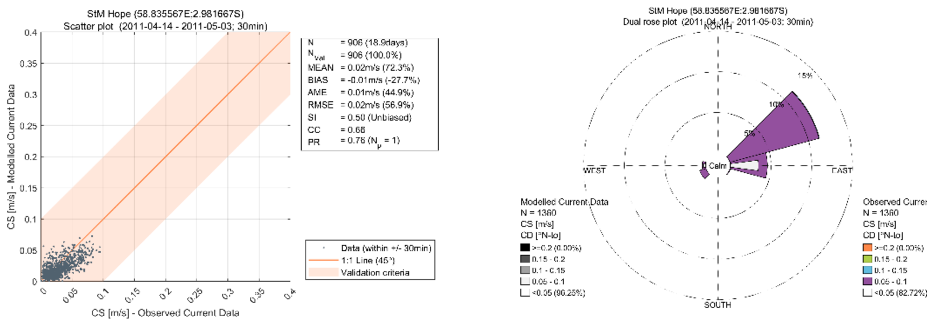


Figure A.8.31 Scatter plot and directional rose plot of observed vs. model total current speed at St. Margaret's Hope for 2011 validation period (orange shading denotes SEPA's calibration standards)

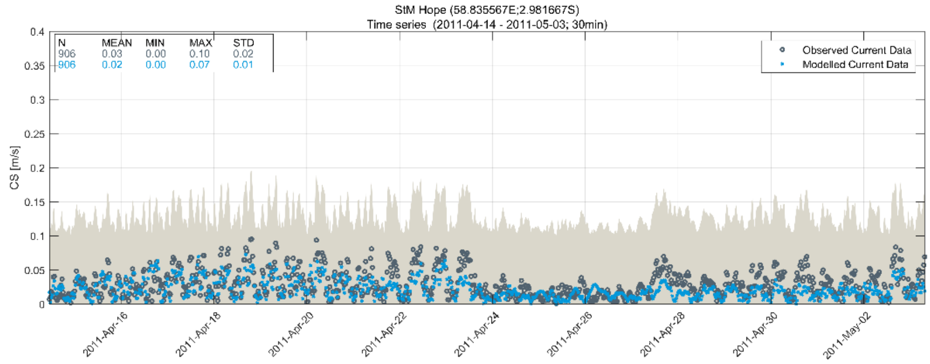


Figure A.8.32 Time series plot of observed vs. model total current speed at St. Margaret's Hope for 2011 validation period (grey shading denotes SEPA's calibration standards)

Figure A.8.33 to Figure A.8.36 present a range of comparison plots of observed versus modelled total water level and current speed at Westerbister for the period 3rd May 2011 to 20th May 2011.

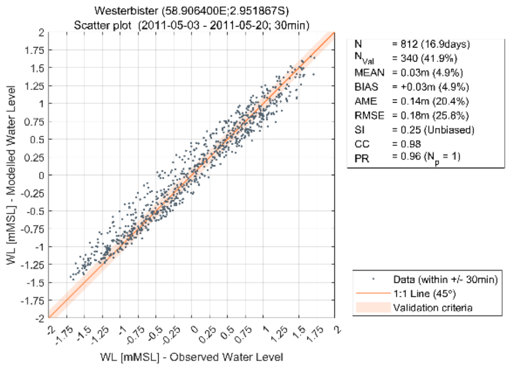


Figure A.8.33 Scatter plot of observed vs. model total water level at Westerbister for 2011 validation period (orange shading denotes SEPA's calibration standards)

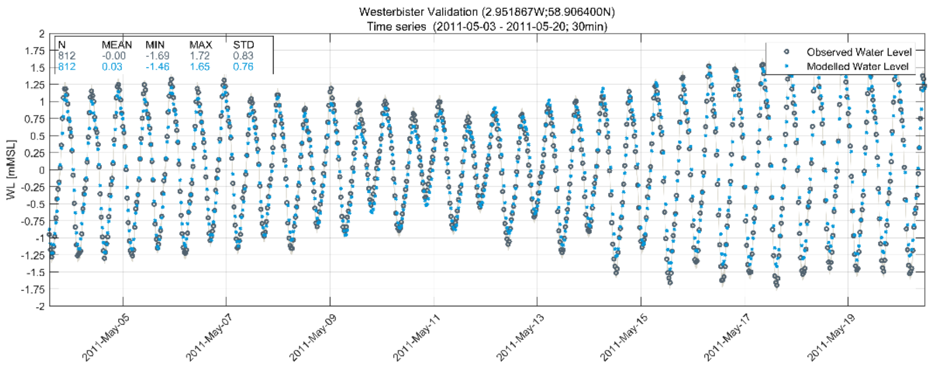


Figure A.8.34 Time series plot of observed vs. model total water level at Westerbister for 2011 validation period

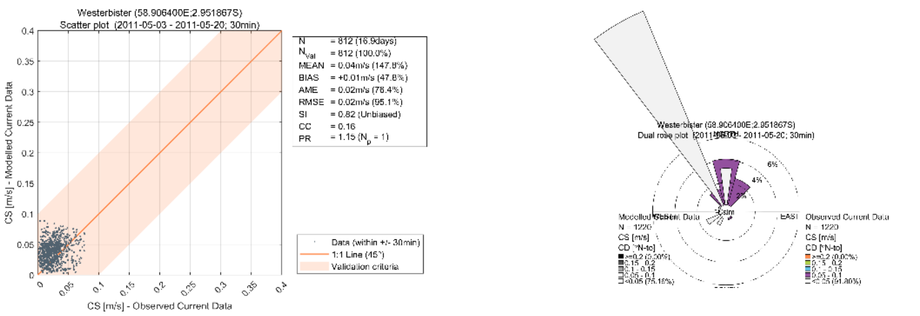


Figure A.8.35 Scatter plot and directional rose plot of observed vs. model total current speed Westerbister for 2011 validation period (orange shading denotes SEPA's calibration standards)

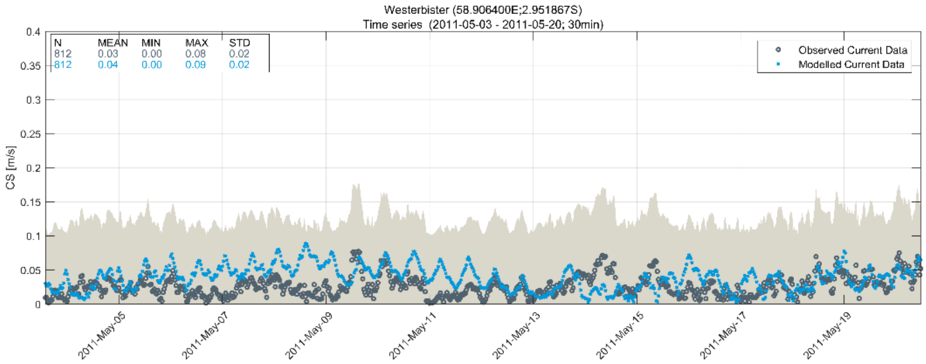
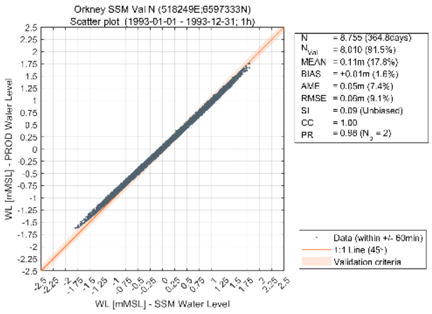


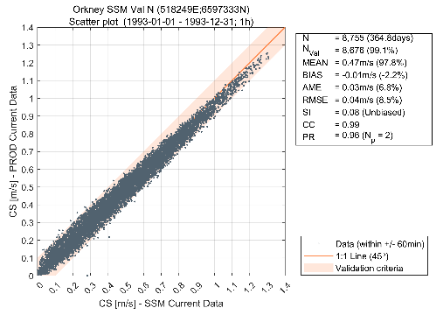
Figure A.8.36 Time series plot of observed vs. model total current speed at Westerbister for 2011 validation period (grey shading denotes SEPA's calibration standards)

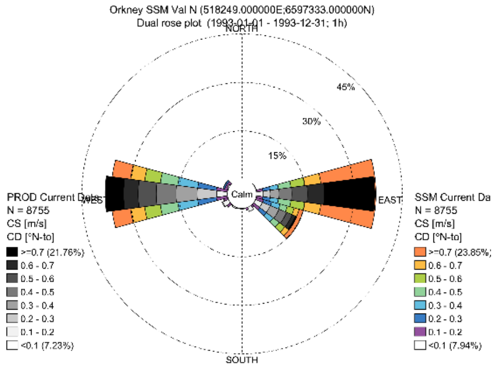
Appendix A.3 HD Model Production Run Validation

the following sections present the results of the production run compared to data from the original Scottish Shelf Model (SSM) at four locations surrounding the Orkney archipelago (see Section 4).

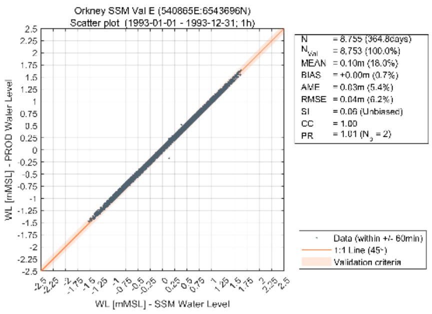
Appendix A.3.1 Production Run site N

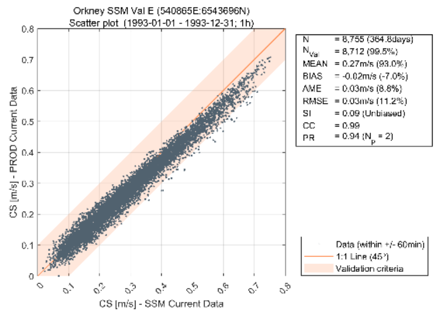


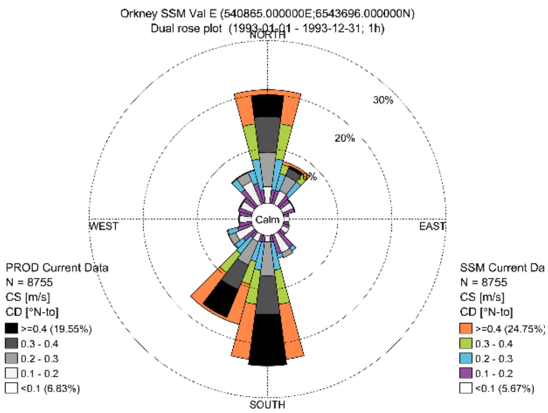




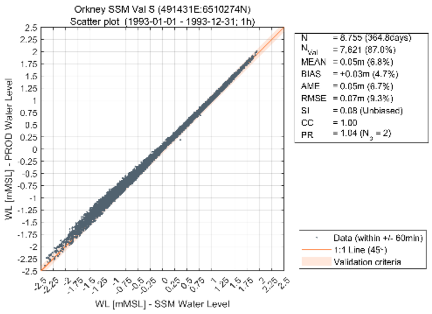
Appendix A.3.2 Production Run site E

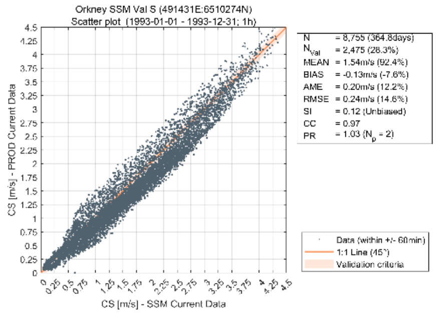


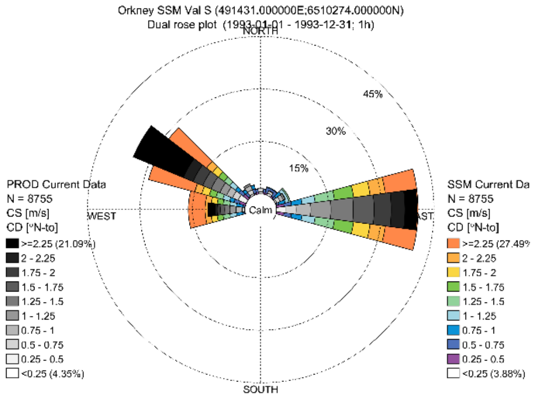




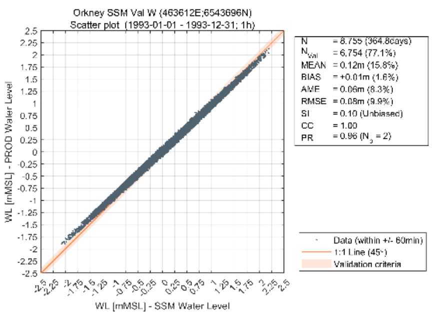
Appendix A.3.3 Production Run site S

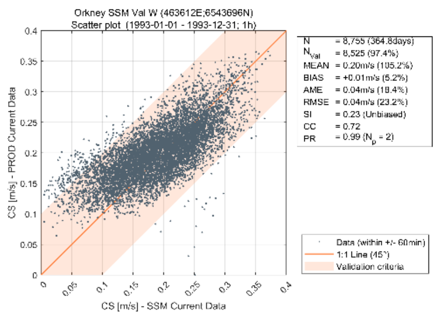


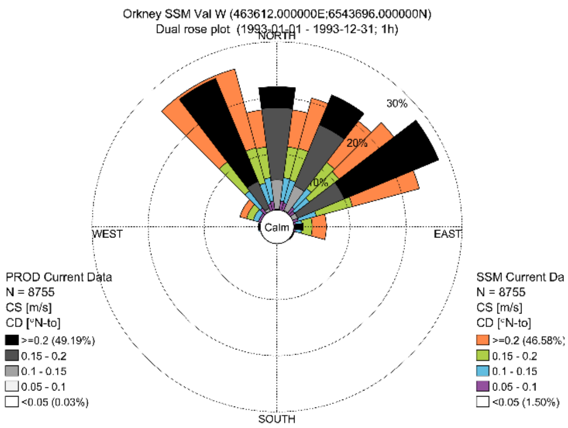




Appendix A.3.4 Production Run site W







Appendix B Model Quality Indices and Calibration Limits

Appendix B.1 Quality Indices

To obtain an objective and quantitative measure of how well the model data compared to the observed data, several statistical parameters so-called quality indices (QI's) are calculated.

Prior to the comparisons, the model data are synchronised to the time stamps of the observations so that both time series had equal length and overlapping time stamps. For each valid observation, measured at time t, the corresponding model value is found using linear interpolation between the model time steps before and after t. Only observed values that had model values within ± the representative sampling or averaging period of the observations are included (e.g. for 10-min observed wind speeds measured every 10 min compared to modelled values every hour, only the observed value every hour is included in the comparison).

The comparisons of the synchronised observed and modelled data are illustrated in (some of) the following figures:

- Time series plot including general statistics
- Scatter plot including quantiles, QQ-fit and QI's (dots coloured according to the density)
- Histogram of occurrence vs. magnitude or direction
- Histogram of bias vs. magnitude
- Histogram of bias vs. direction
- Dual rose plot (overlapping roses)
- Peak event plot including joint (coinciding) individual peaks

The quality indices are described below, and their definitions are listed in Table B.1. Most of the quality indices are based on the entire data set, and hence the quality indices should be considered averaged measures and may not be representative of the accuracy during rare conditions.

The MEAN represents the mean of modelled data, while the BIAS is the mean difference between the modelled and observed data. AME is the mean of the absolute difference, and RMSE is the root mean square of the difference. The MEAN, BIAS, AME and RMSE are given as absolute values and relative to the average of the observed data in percent in the scatter plot.

The scatter index (SI) is a non-dimensional measure of the difference calculated as the unbiased root-mean-square difference relative to the mean absolute value of the observations. In open water, an SI below 0.2 is usually considered a small difference (excellent agreement) for significant wave heights. In confined areas or during calm conditions, where mean significant wave heights are generally lower, a slightly higher SI may be acceptable (the definition of SI implies that it is negatively biased (lower) for time series with high mean values compared to time series with lower mean values (and same scatter/spreading), although it is normalised).

EV is the explained variation and measures the proportion [0 - 1] to which the model accounts for the variation (dispersion) of the observations.

The correlation coefficient (CC) is a non-dimensional measure reflecting the degree to which the variation of the first variable is reflected linearly in the variation of the second variable. A value close to 0 indicates very limited or no (linear) correlation between the two data sets, while a value close to 1 indicates a very high or perfect correlation. Typically, a CC above 0.9 is considered a high correlation (good agreement) for wave heights. It is noted that CC is 1 (or -1) for any two fully linearly correlated variables, even if they are not 1:1. However, the slope and intercept of the linear relation may be different from 1 and 0, respectively, despite CC of 1 (or -1).

The Q-Q line slope and intercept are found from a linear fit to the data quantiles in a least-square sense. The lower and uppermost quantiles are not included on the fit. A regression line slope different from 1 may indicate a trend in the difference.

The peak ratio (PR) is the average of the Npeak highest model values divided by the average of the Npeak highest observations. The peaks are found individually for each data set through the Peak-Over-Threshold (POT) method applying an average annual number of exceedance of 4 and an inter-event time of 36 hours. A general underestimation of the modelled peak events results in PR below 1, while an overestimation results in a PR above 1.

An example of a peak plot is shown in Figure B.1. ‘X’ represents the observed peaks (x-axis), while ‘Y’ represents the modelled peaks (y-axis), based on the POT methodology, both represented by circles (‘o’) in the plot. The joint (coinciding) peaks, defined as any X and Y peaks within ±36 hours of each other (i.e. less than or equal to the number of individual peaks), are represented by crosses (‘x’). Hence, the joint peaks (‘x’) overlap with the individual peaks (‘o’) only if they occur at the same time exactly. Otherwise, the joint peaks (‘x’) represent an additional point in the plot, which may be associated with the observed and modelled individual peaks (‘o’) by searching in the respective X and Y-axis directions, see example with red lines in Figure B.1. It is seen that the ‘X’ peaks are often underneath the 1:1 line, while the ‘Y’ peaks are often above the 1:1 line.

![DHI logo]

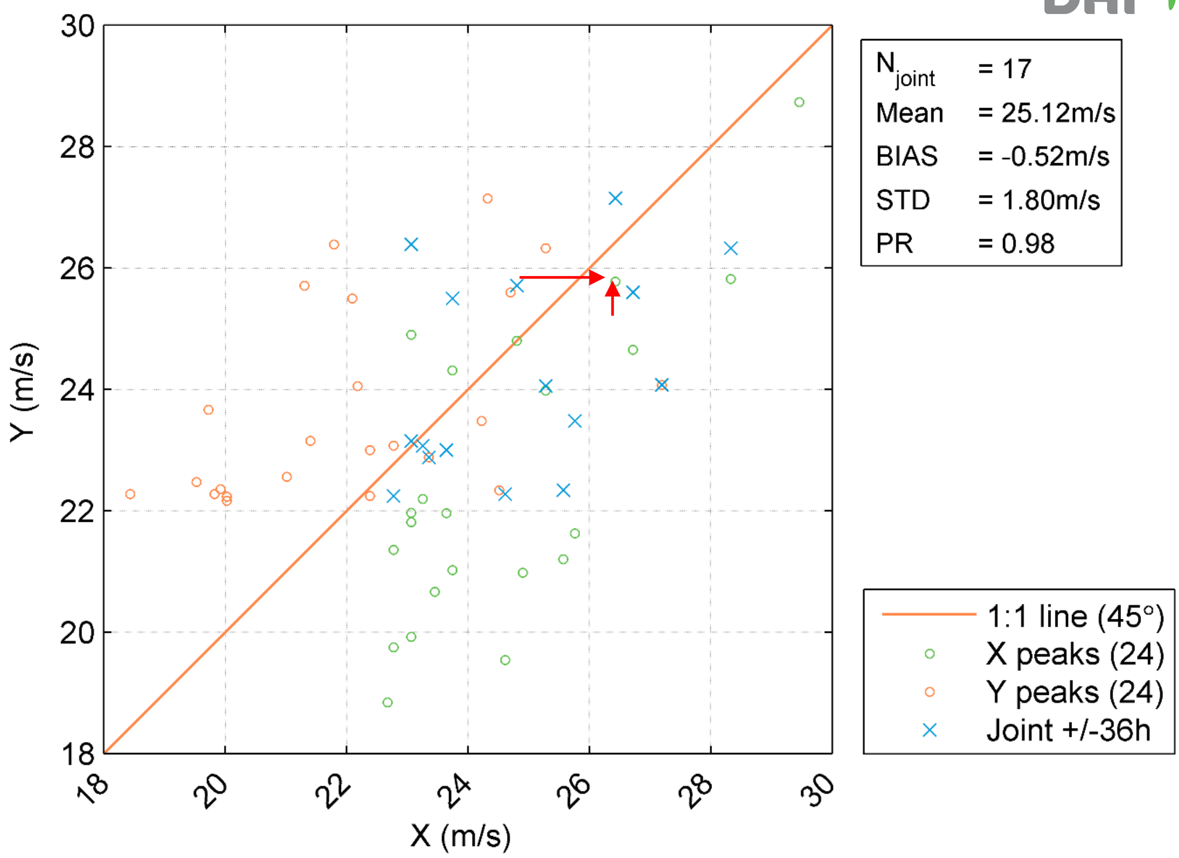


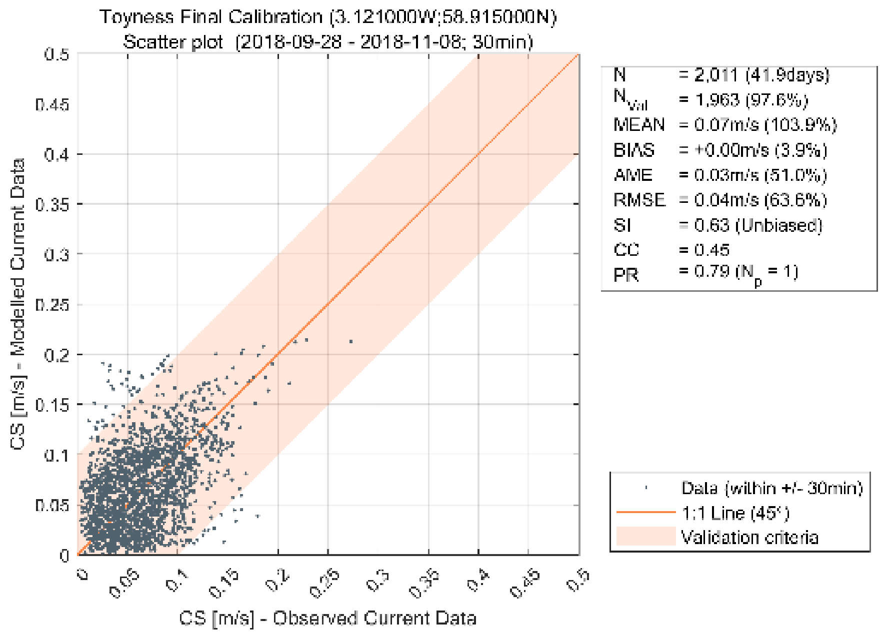
Figure B.1 Example of peak event plot (wind speed).

Appendix B.2 SEPA Modelling Guidance

The SEPA modelling Guidance [7] provides the following criteria for key hydrodynamic conditions within the model calibration process.

Parameter	Standard	
Hydrodynamics	*Absolute*	*Percentage*
Water level	+/- 0.1 m	+/- 10% Spring range
		+/- 15% Neap range
Flow speed	+/- 0.1 m/s	+/- 10-20%
Flow direction	+/- 30 degrees	
Timing of high water / phase	+/- 15 mins	

Figure B.2 SEPA model parameters and standards.



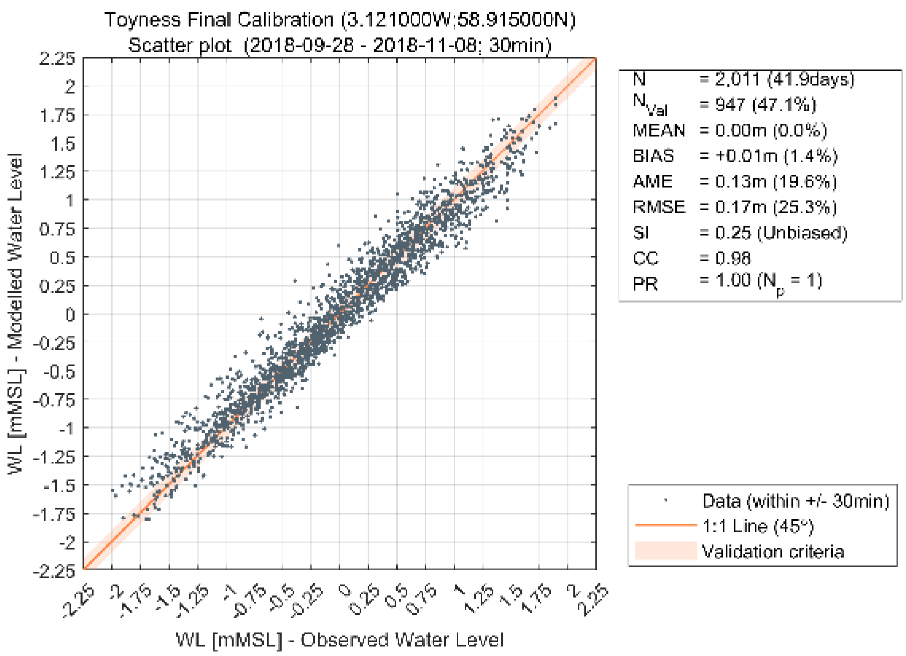


Figure B.3 Example of how the SEPA model standards appear in the DHI calibration plots (orange hashed area).

Appendix C Technical Note

Response to SEPA statement on Calibration

Orkney Hydrodynamic Modelling – Response to SEPA statement on Calibration

Technical Note

Document Information

Project No.	26801744
Project Title	Orkney Hydrodynamic Modelling
Project Manager	[redacted]
Subject	Response to SEPA statement on Calibration

Rev	Rev Date	Description of Change/ Reason for Issue	Prepared by	Checked by	Approved by
03	Nov 5, 2021	Update with final client comments	[redacted]	[redacted]	[redacted]
02	Oct 21, 2021	Update with client comments	[redacted]	[redacted]	[redacted]
01	Oct 01, 2021	For Client Review	[redacted]	[redacted]	[redacted]

[redacted]

1 Introduction

1.1 General

This document has been prepared following submission of a hydrodynamic modelling method statement to SEPA and the response from SEPA on those documents.

DHI has developed a Hydrodynamic model for use within the ongoing assessment as part of a CAR license application. SEPA's response was that they did not find the hydrodynamic model calibration acceptable and proposed several alterations that might help improve the calibration, which is required before the model could be used to support permit/license applications.

The purpose of this technical note is to provide supporting information on the reasons that the model deviates from the measurements in this location.

It is specifically noted that SEPA's justification for refusal is that they "*have evidence that it is possible to achieve a good calibration in the vicinity of the proposed sites*"

SEPA propose 2 remedies to the situation, all of which had been previously tested but not specifically reported in the supplied method statement. These are:

1. Increased mesh refinement, particularly focused on the North and South Channels to the West of Bring Head along with re-interpolating the bathymetry onto the mesh

2. Checking the boundary forcing for issues

1.2 Technical Note layout

The remaining sections of this report are organised as follows.

- Section 1 (this section): outlines the background to the study and the scope of work;
- Section 2: The additional supporting information at the two sites
- Section 3: A summary of the justifications

2 Additional supporting information

2.1 Boundary conditions tested

DHI utilised the following boundary conditions as part of the development of the HD model for Scapa Flow.

- DTU10 – water level only
- DTU10 water levels with Hycom UV (Flather Boundary)
- Boundaries from DHI's previous Orkney Model of the area (different locations)

By testing several versions of the boundary and also changing the position of the boundary conditions, it was possible to assess the effect of the boundary on the flows within Scapa.

Moving to a Flather boundary and incorporating the UV from the HYCOM regional model led to more stable conditions at the boundary with limited change to the wider model due to the distance of the boundaries from the area of interest. The figure below shows a check of the modelled current speeds against predicted tidal currents (from Admiralty tidal diamonds) at four points around the Orkney Islands. This plot shows that the propagation of the boundary conditions within the model towards the islands is being handled correctly, suggesting the boundaries are not a significant issue in deeper waters.

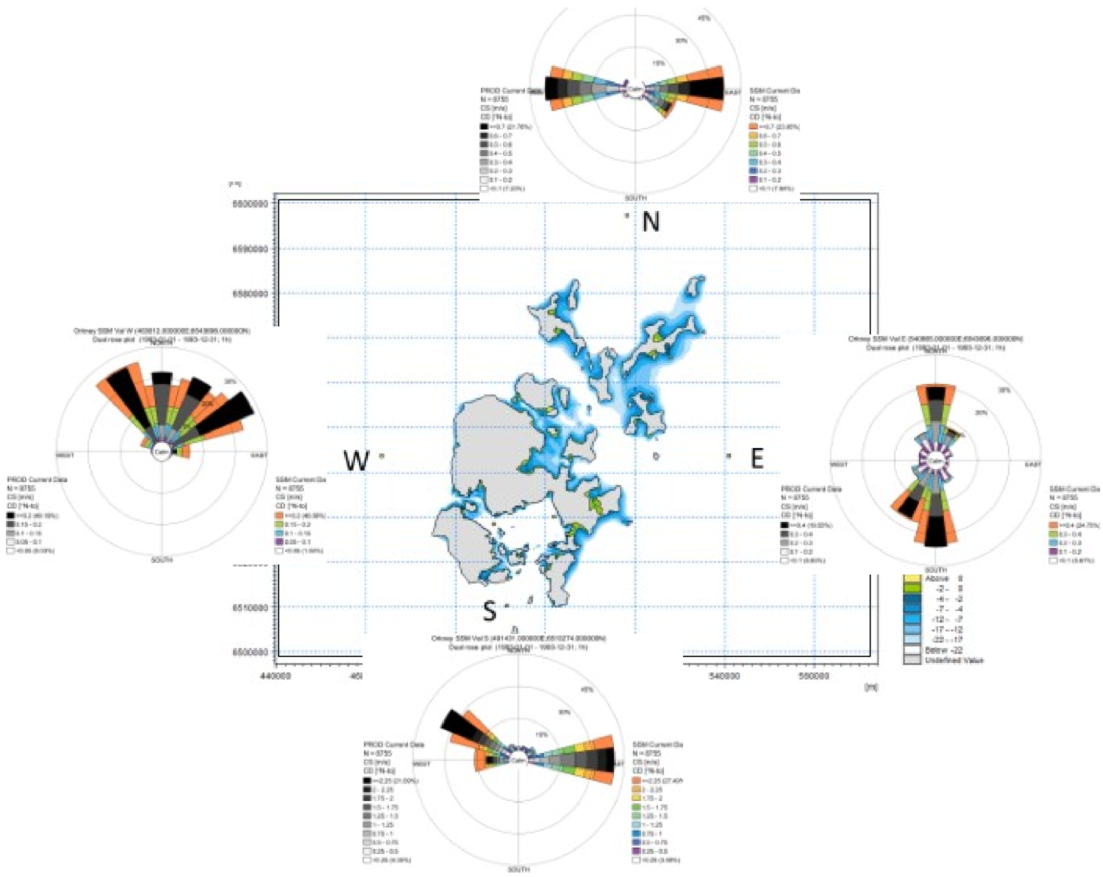


Figure 2.1 Comparison of predicted and modelled tidal currents around the Orkneys to confirm the validity of the boundaries applied (HYCOM and DTU 10)

The model results using DHI's previous model of the Orkneys as local boundaries just outside of Scapa Flow also showed limited changes to the resultant flows within Scapa.

All models showed an eddy in the residual flows around Bring Head. Also the models with wind on showed a weak residual counter clockwise eddy in the middle of the Eastern part of Scapa Flow. What was apparent is that the Eastern parts of Scapa have a weak tidal flow, though still with a tidal signal.

2.2 Model resolutions tested

Early on in the calibration process, DHI identified the channel to the South of Graemsay and the Bay of Quoys as important areas to resolve in the model. In particular the constraint of flow through the skerries between Graemsay and Hoy was important to resolve the region of strong flow that is apparent in proximity to Bring Head. Limited bathymetric data was available in this area and in particular the beaches of the Bay of Quoys. Bathymetric charted information was added to the available multibeam datasets in the wider area.

Testing of the model also highlighted the need to resolve the skerries more suitably, something which all the other regional models in the area neglect. In this model it required the inclusion of the skerries as "land" rather than allowing the sparse bathymetry data to be interpolated, which led to the area being deeper. The result was the below mesh which had length scales of 25-30m in the channel south of Graemsay and 120-140m in the channel to the North.

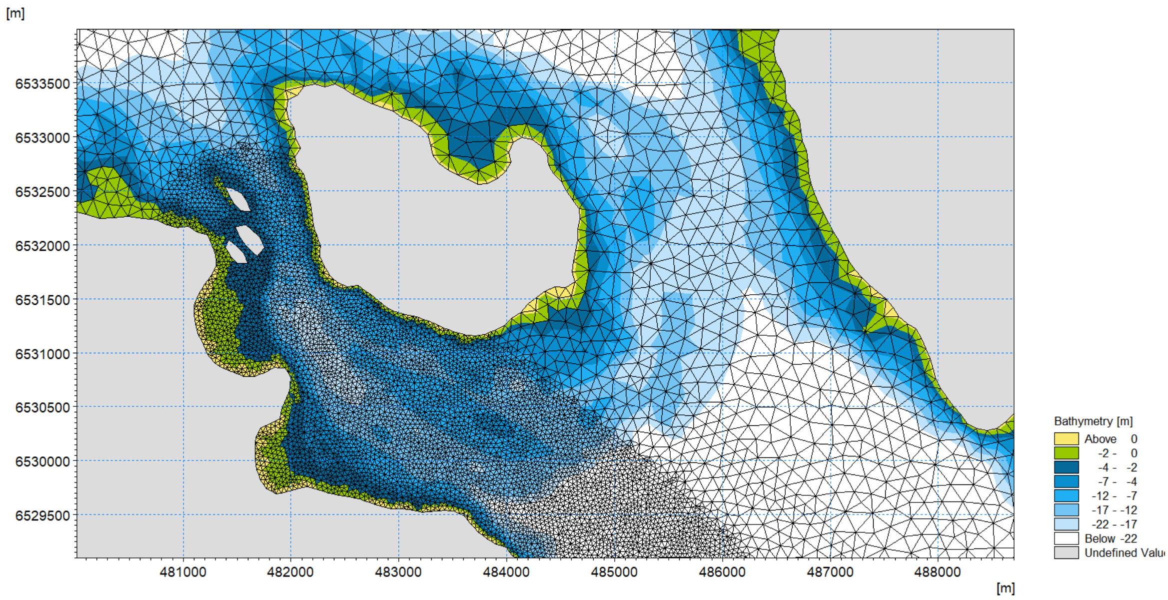


Figure 2.2 Model resolution in the final production model

Additional models also tested the use of a higher resolution through the North Channel and around the farm site (see mesh below) with no change to the resultant model calibration.

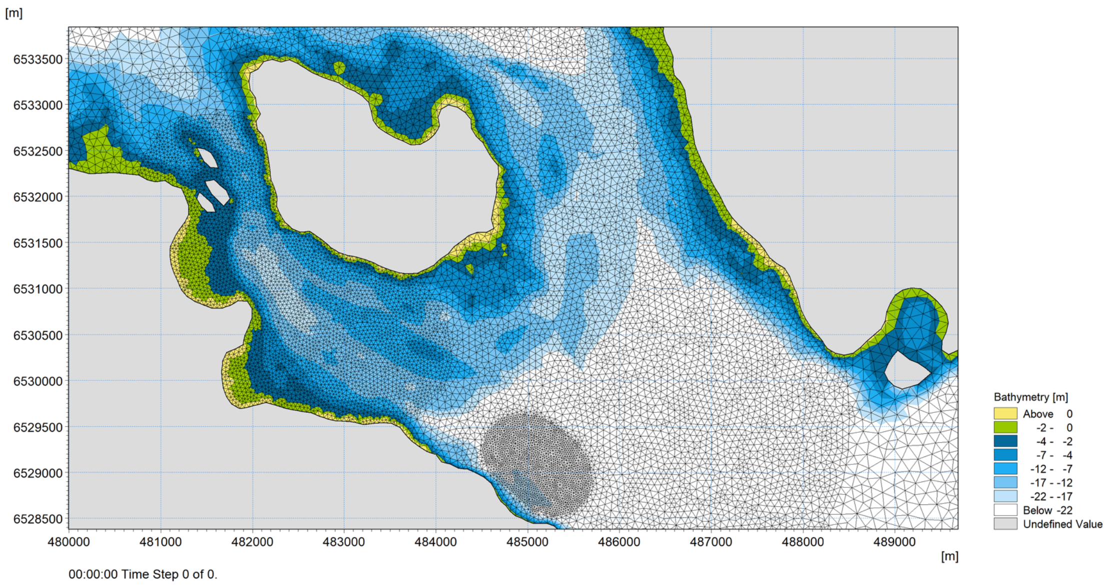


Figure 2.3 Tested high resolution model domain through the entire Graemsay channel area

2.3 Bring Head

DHI's understanding of the validation requirements for hydrodynamic models for use in aquaculture assessment is that the criteria for acceptance are based on a series of thresholds.

DHI provided a summary for Bring Head for the final selected calibration plot. This showed a divergence between the model and the measurements, particularly with respect to higher speeds within the model. It is noted that much of the model data resides within the validation limits, with the exception of the higher speed bursts. With respect to direction, it was also noted that the model showed more flow towards the south east than the measurements.

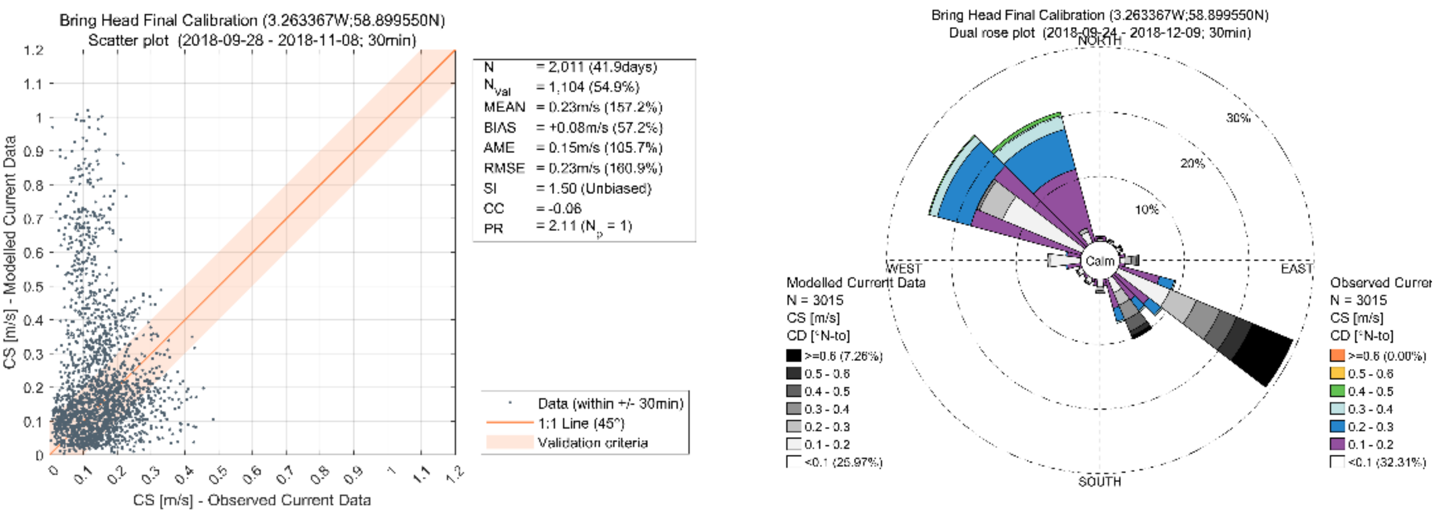


Figure 2.4 Bring Head final calibration plots for 2018 period

Much time was spent in seeking a resolution to the problem of this discrepancy in flow for the point, including the testing of bathymetry and boundary conditions as well as mesh resolution. Following extensive investigation of the situation from sources including aerial photography and local observation it was identified that the area of strong flow from the channel to the South of Graemsay extended some way eastwards towards the Bring Head site.

From examination of the model residual or mean flow for the period, a persistent eddy was noted (see image below). This eddy was seen through the tidal cycle to rapidly form and then disperse as the tide flooded. This correlated with the zones of higher flow seen in the aerial imagery and from the local knowledge of the area.

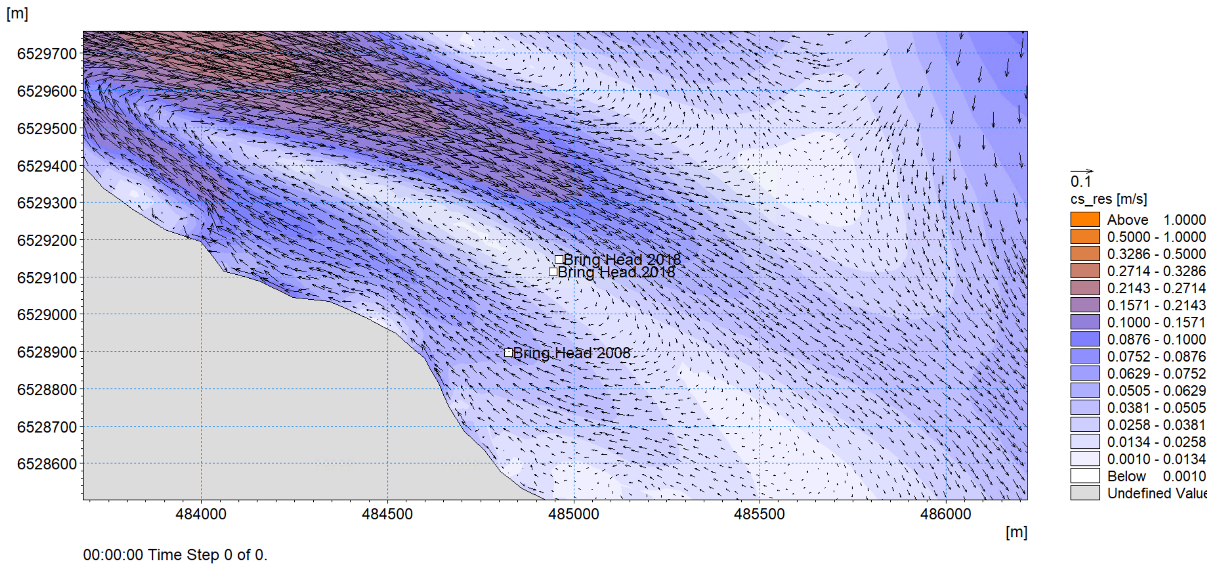


Figure 2.5 Residual eddy position in the finally selected model presented in the reporting to date

The bathymetry data supports the general position of this residual eddy, as there is an apparent area of shallows seen in the 2m multibeam of the area, located between the 2008 deployment and the 2018 deployments and following the central axis of the eddy.

The 2008 measurement data, from a point closer inshore, shows the inshore north-westward movement of water and in this area the model shows a good comparison with the measurements when compared against the rose plot. For the 2018 data, it is suggested that the position of the eddy means that the comparison points from the real world measurements may not be precisely located with respect to the model eddy structure.

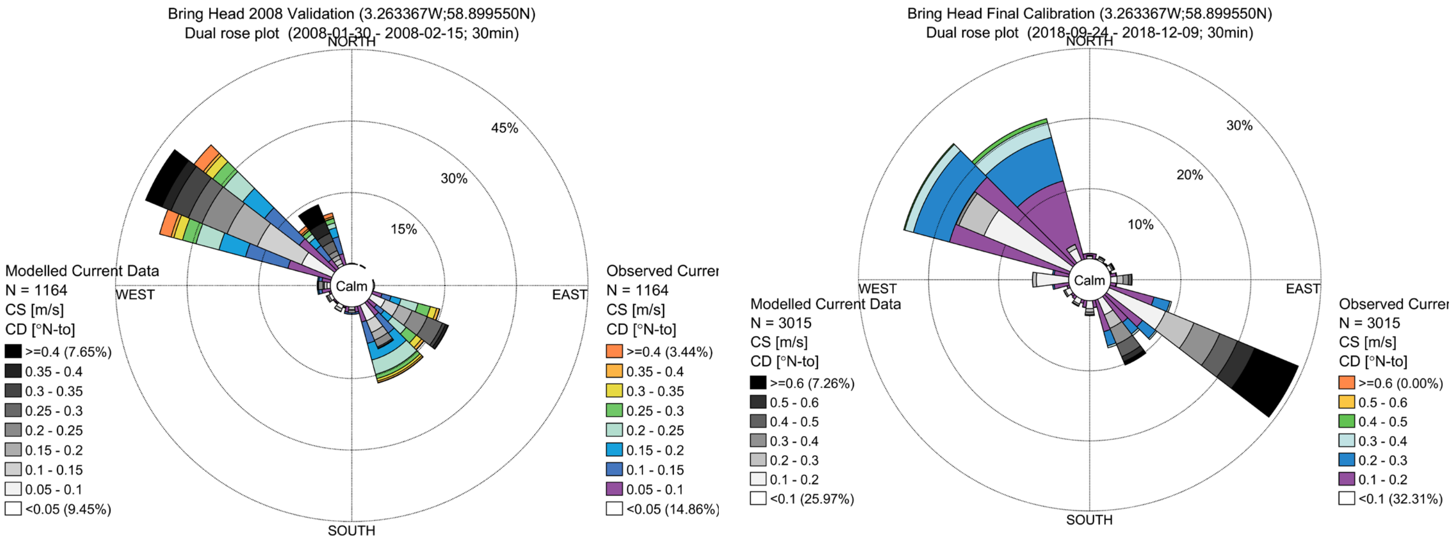


Figure 2.6 Rose plot comparing the inshore (2008) position with the offshore (2018) position

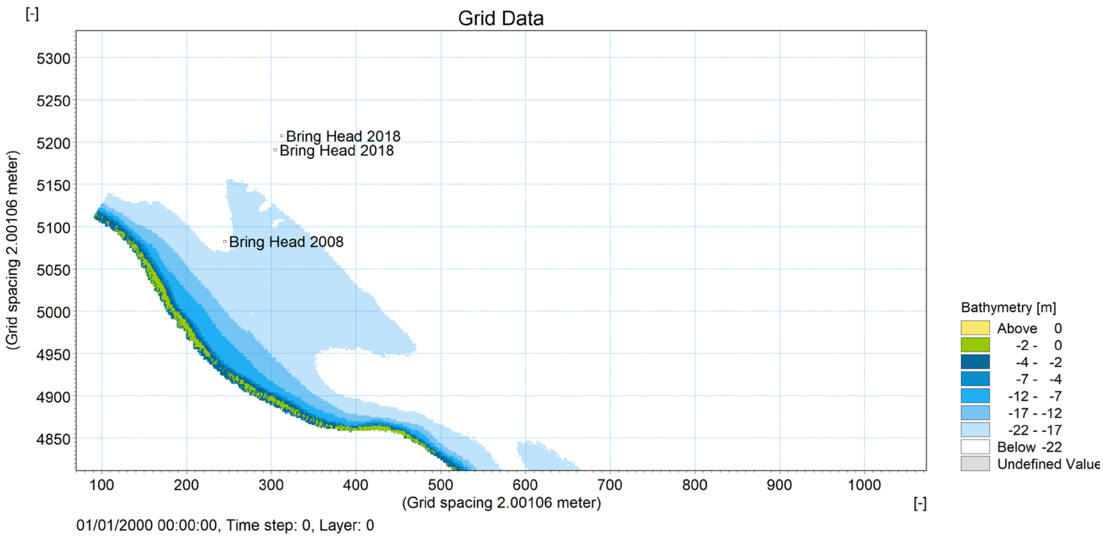


Figure 2.7 Raw bathymetry data in the region of Bring Head, highlighting the apparent zone of sediment deposition associated with the residual eddy.

Importantly for the calibration process, the position of this residual eddy was seen to vary slightly between each of the model runs, suggesting sensitivity to model settings that control the exact position of the eddy. The following series of plots provides the residual flow outputs from a range of the developed models from the calibration process. These include tests of the boundaries, the mesh resolution and the results of the tide only run.

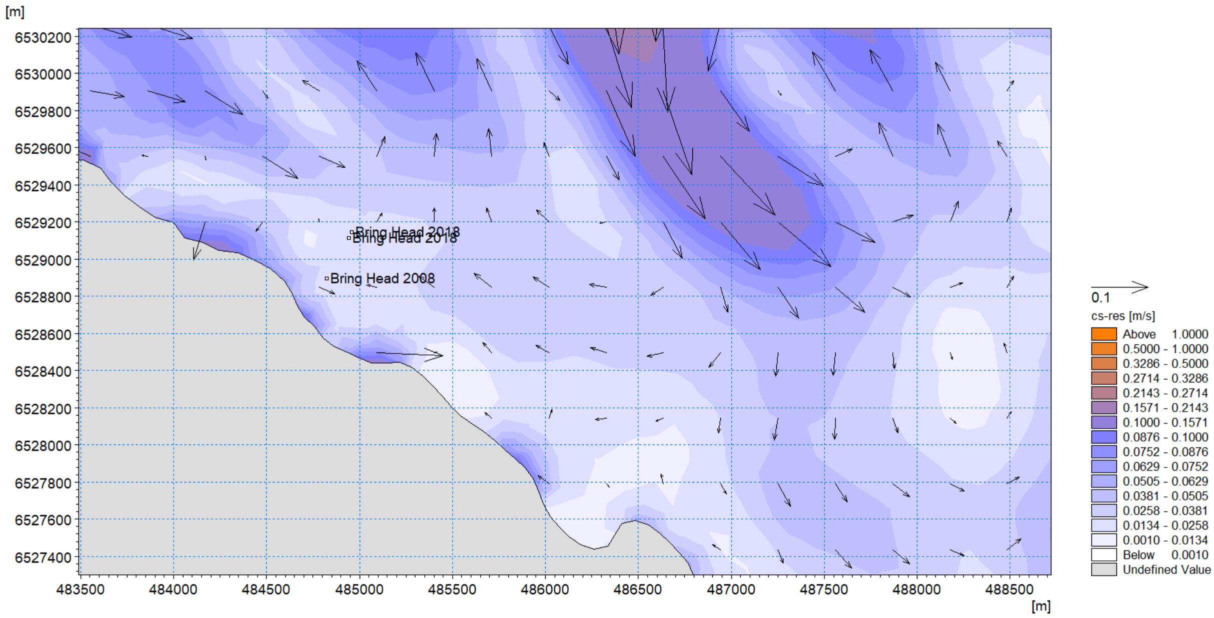


Figure 2.8 Test A – Boundary using DHI's previous model (initial coarse domain – limited resolution in Greamsay Channel).

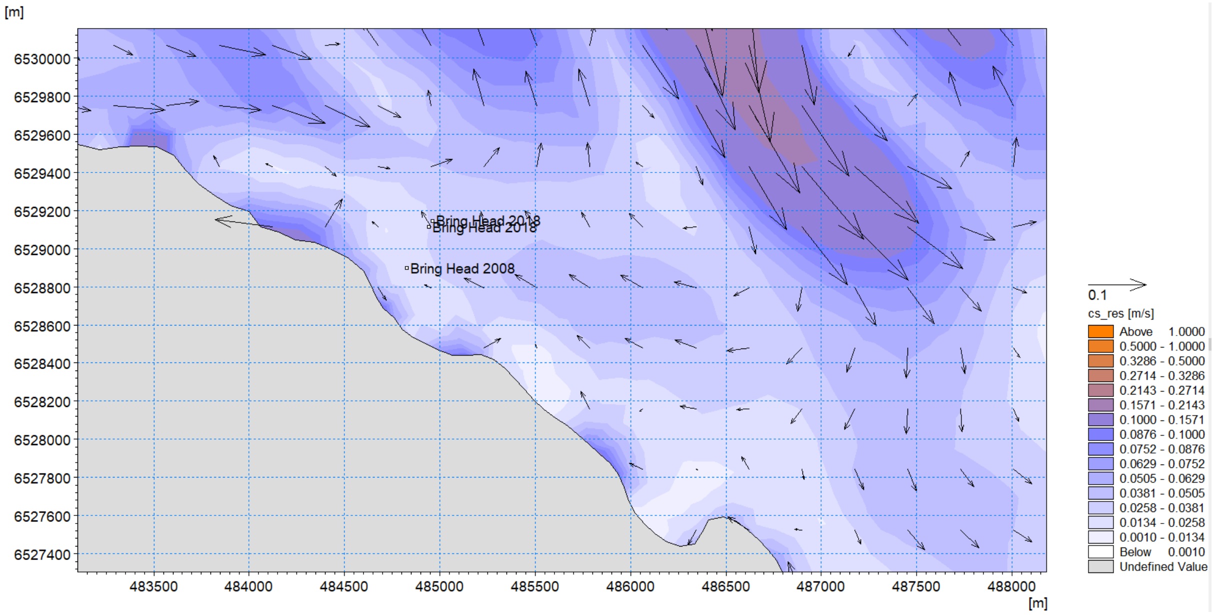


Figure 2.9 Test B – Boundary using SSM model (initial coarse domain same as Test A – limited resolution in Greamsay Channel).

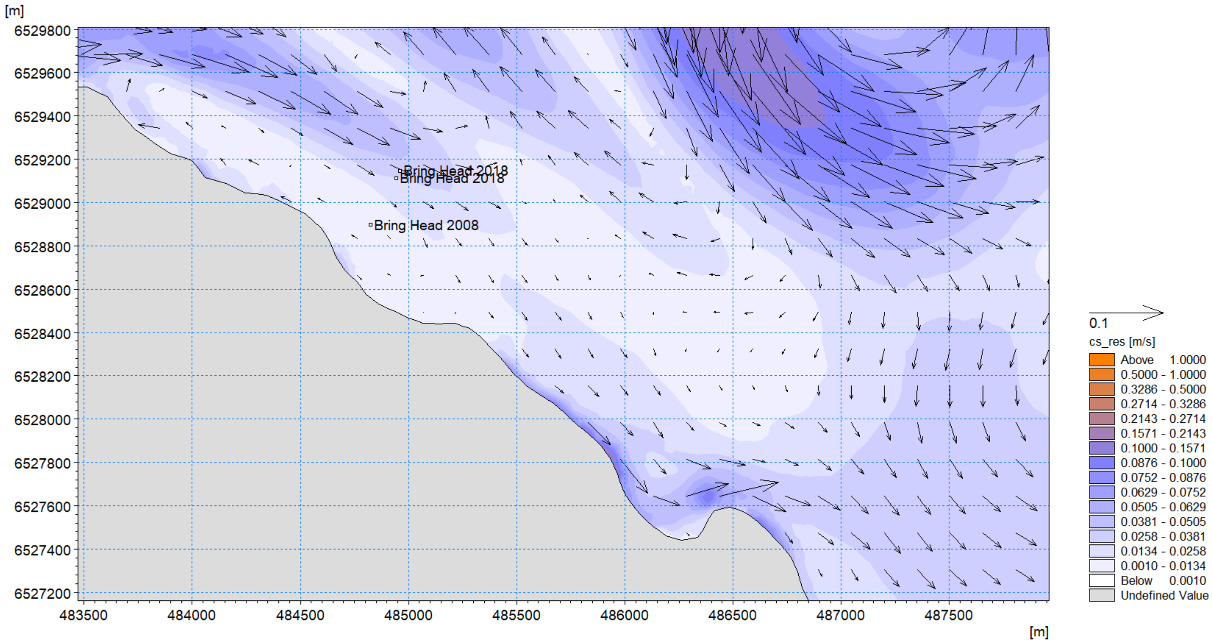


Figure 2.10 Test C – Same boundaries as Test A with higher resolution mesh.

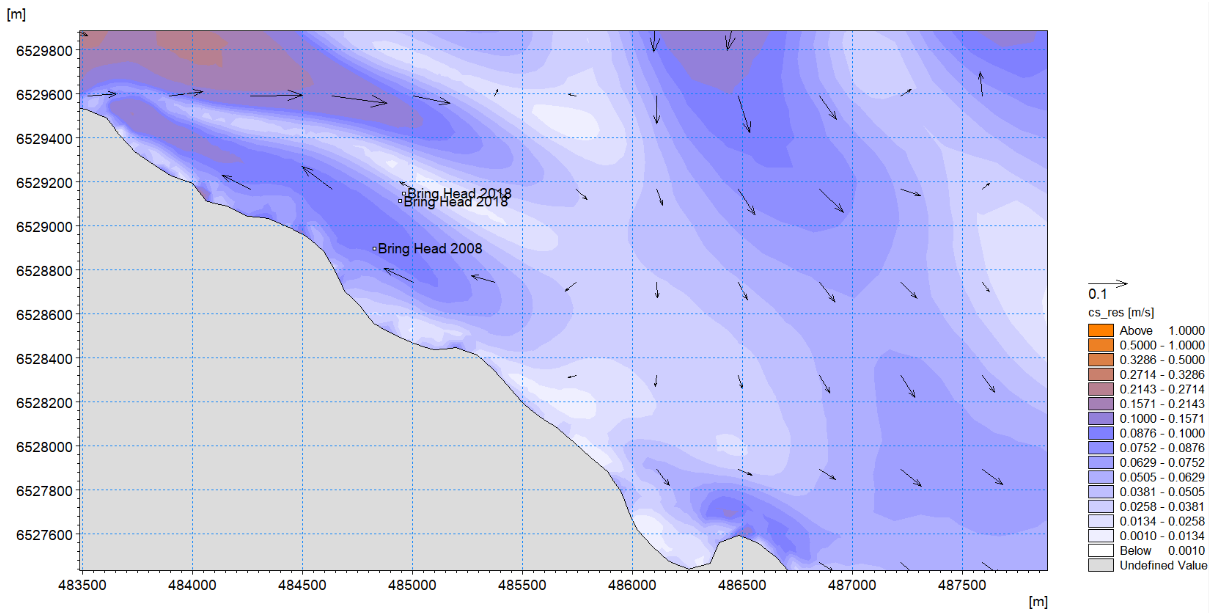


Figure 2.11 Test D - Early calibration run with HYCOM/DTU boundaries and poor resolution of Graemsay channel

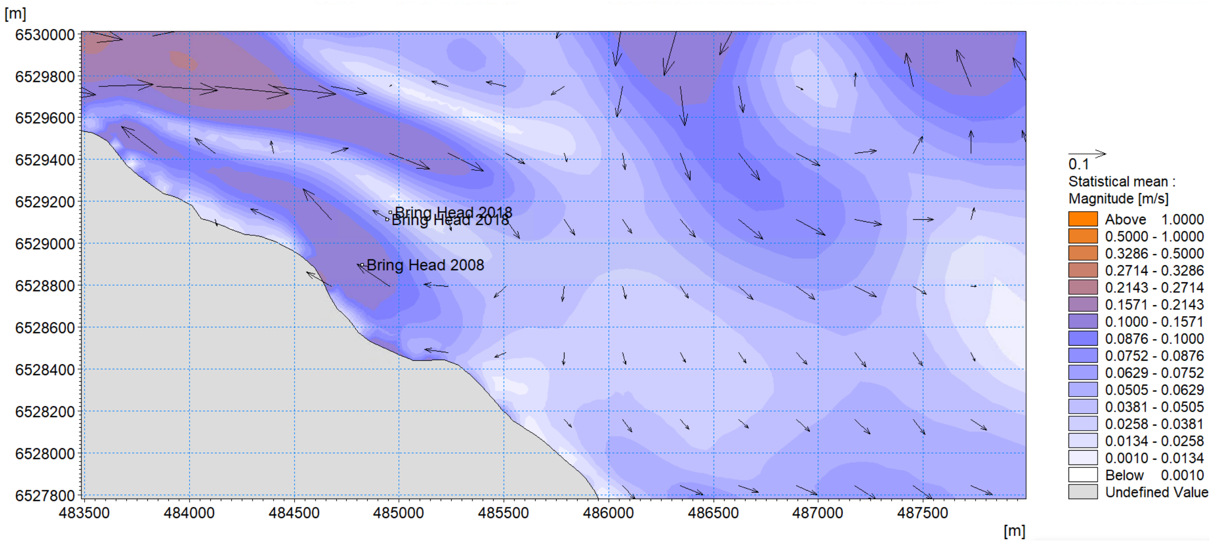


Figure 2.12 Test E - Refinement of mesh through Graemsay south channel

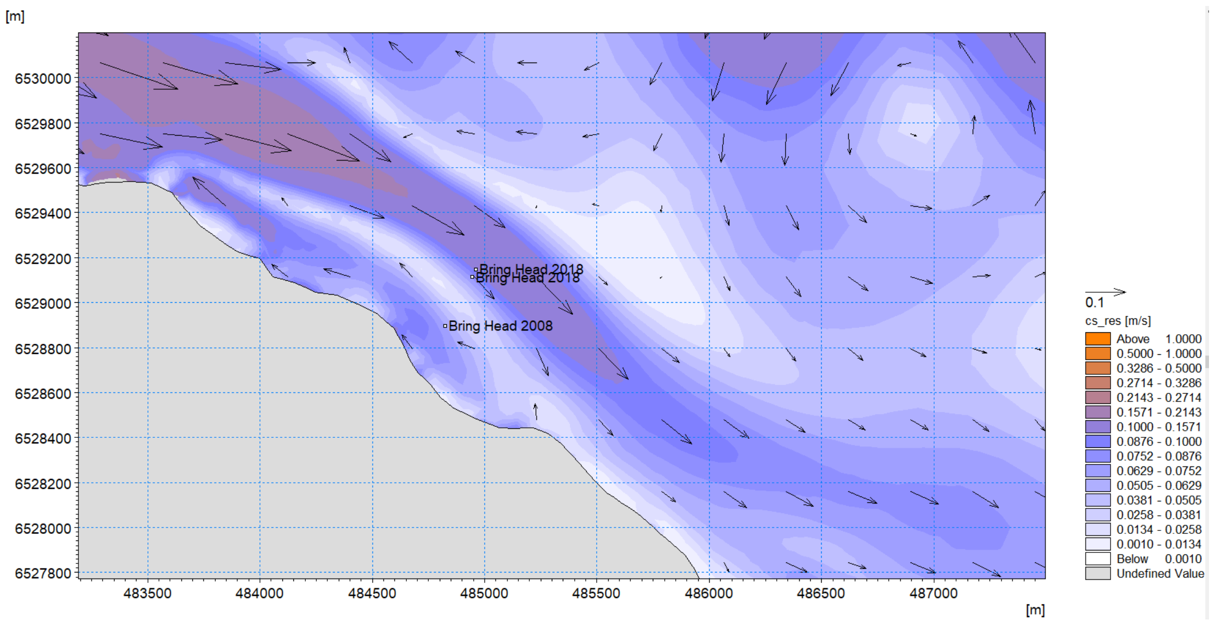


Figure 2.13 Test F - Selected calibration run with tide only

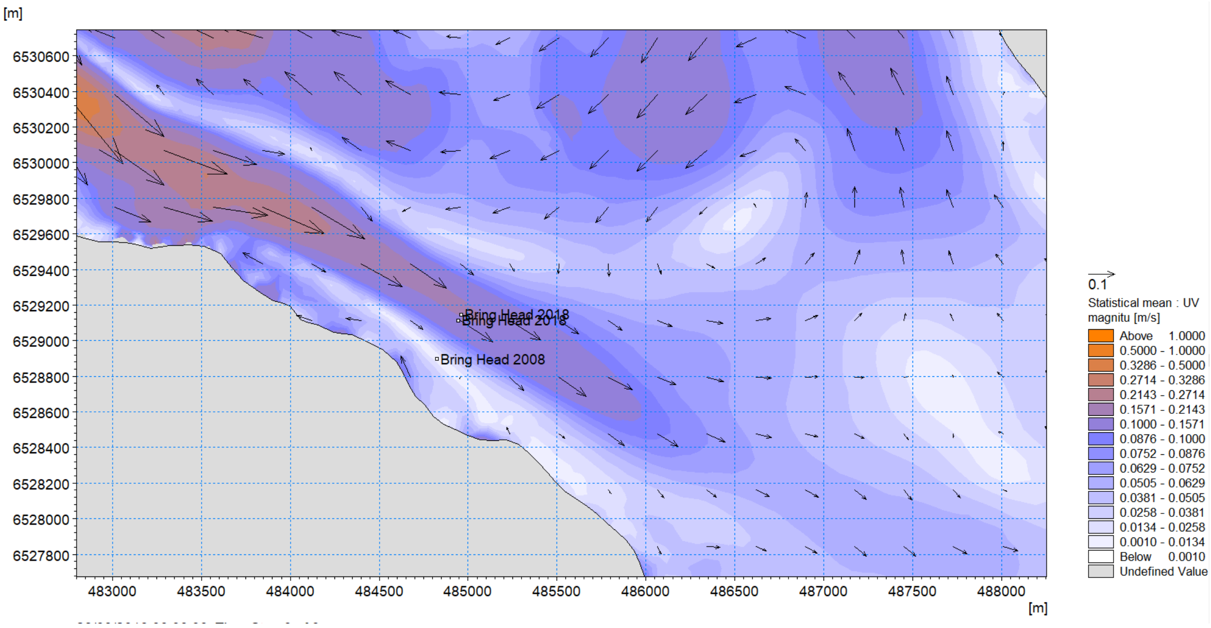


Figure 2.14 Test G - Selected calibration run – with higher mesh resolution (See Figure 2.3)

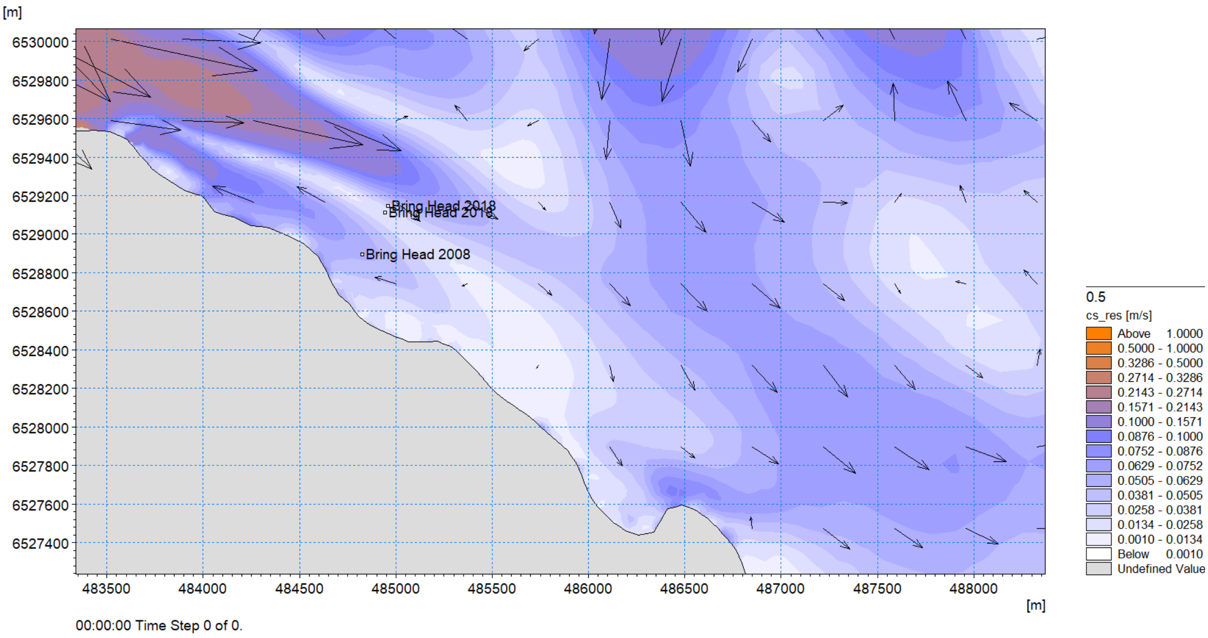


Figure 2.15 Finally selected calibration run

What is apparent from all of these runs is the persistent appearance of the residual eddy in the vicinity of Bring Head. However what is also noticeable is that the exact position of the upper part of the eddy and the lower part of the eddy moves, with the central lower residual current zone also shifting.

As such, this would lead to the model to show results for the faster flowing jet further offshore. It was considered through the calibration process that the position of the farm further offshore than previously would mean that more of the farm was exposed to these higher currents, therefore it was prudent to utilise these results, even though the spot measurement of currents suggested different behaviour.

It was also proposed that for the fate of bath treatment chemicals, the position of the eddy was likely to lead to transport ultimately to the south east, any flows to the northwest would be entrained back into the faster offshore flows where the eddy met the headland.

Consequently, a reasoning was put forward in the study explaining this.

2.4 Toyness

At Toyness, the current speeds are significantly lower than at Bring Head. Prior to selecting the model to be run there was a concern that the weak current speeds could be controlled by more non-tidal conditions. With these lower current speeds, it was considered unlikely that there would be a significant impact with respect to deposition in areas away from the seabed beneath the cages and that any variability would likely be focused on bath treatment chemicals remaining in suspension. Importantly, the validation plots for the model runs are within the acceptable limits for velocity, however the residual flow in the model is in a north-eastward direction, whilst the measurements show a south-westward residual.

The calibration process sought to achieve the same outcomes for Toyness and included a range of tests including the boundaries. However, understanding the controlling processes for flow in the eastern part of Scapa flow was of more relevance for this stage, as the presence of an anticlockwise circulation pattern has been previously proposed as being the dominant control on the circulation.

The tide only run for the 2D model didn't show this expected circulation as shown in the residual plot below. Incorporating wind then started to produce circulation patterns that were considered more along the lines of what was anticipated within the system, with an anticlockwise gyre being present in the main body of Scapa Flow, however there remained a persistent boundary current along the coast inshore of Toyness. Additional effort was made on further resolution within the bathymetry of this steep coastline to ensure that the effect of this was suitably captured (see Figure 2.16).

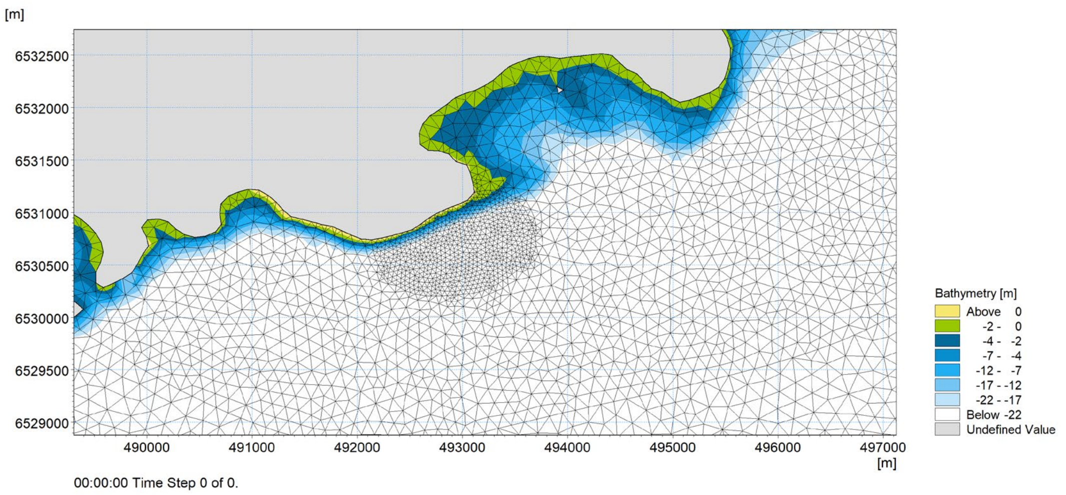


Figure 2.16 Mesh resolution and bathymetry around the bays either side of Toyness

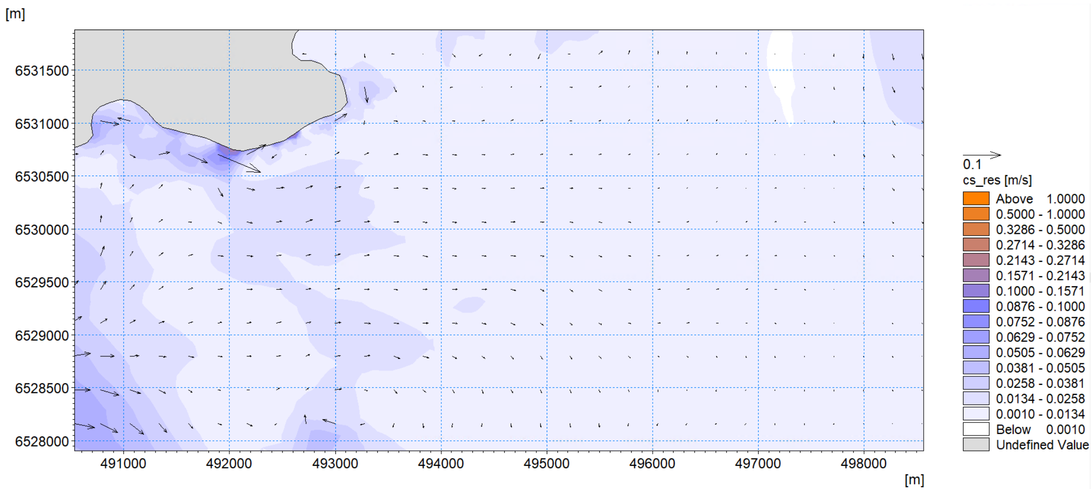


Figure 2.17 Tide only model run at Toyness

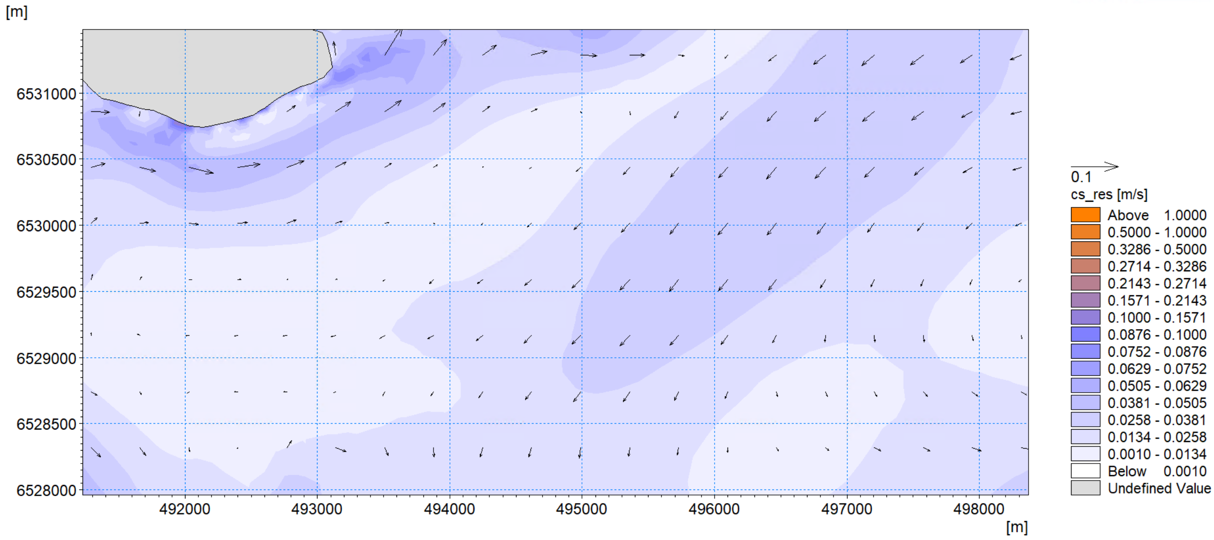


Figure 2.18 Tide and wind model run at Toyness

Following submission of the hydrodynamic report, additional tests were made on a short 3D model to assess the potential effect of the entire water column being resolved. The outcome was similar to the 2D model, however the position of the zone of flow towards the shore was significantly further inshore and with a weaker residual.

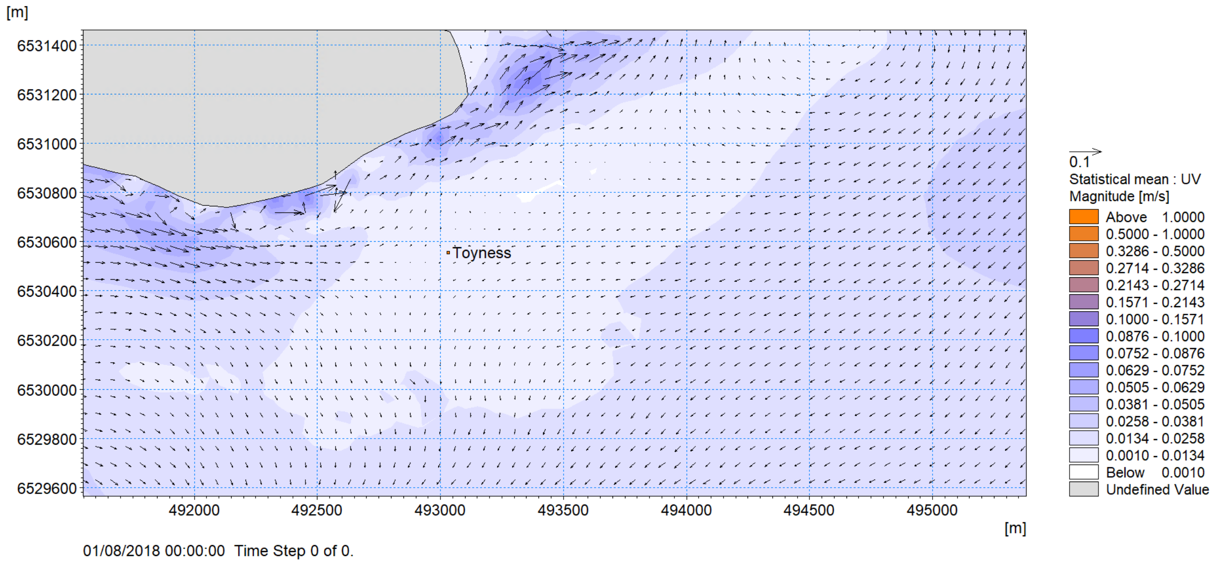


Figure 2.19 3D model output in the vicinity of Toyness

Rose plots of the measurements (for the two deployment periods), the 2D model and the 3D (depth averaged) output are provided in the following section. Of note is that there is some significant difference between the two periods of measurement, with one showing a more dominant flow to the southwest and the other a much more even spread of conditions.

Whilst the 3D model shows a residual that is more to the south-west, overall it is a poorer match to observations than the 2D model, which has some peaks of flow to the north-east. As such it is assessed that the 2D model is a closer overall match, even with the discrepancy towards the north-east.

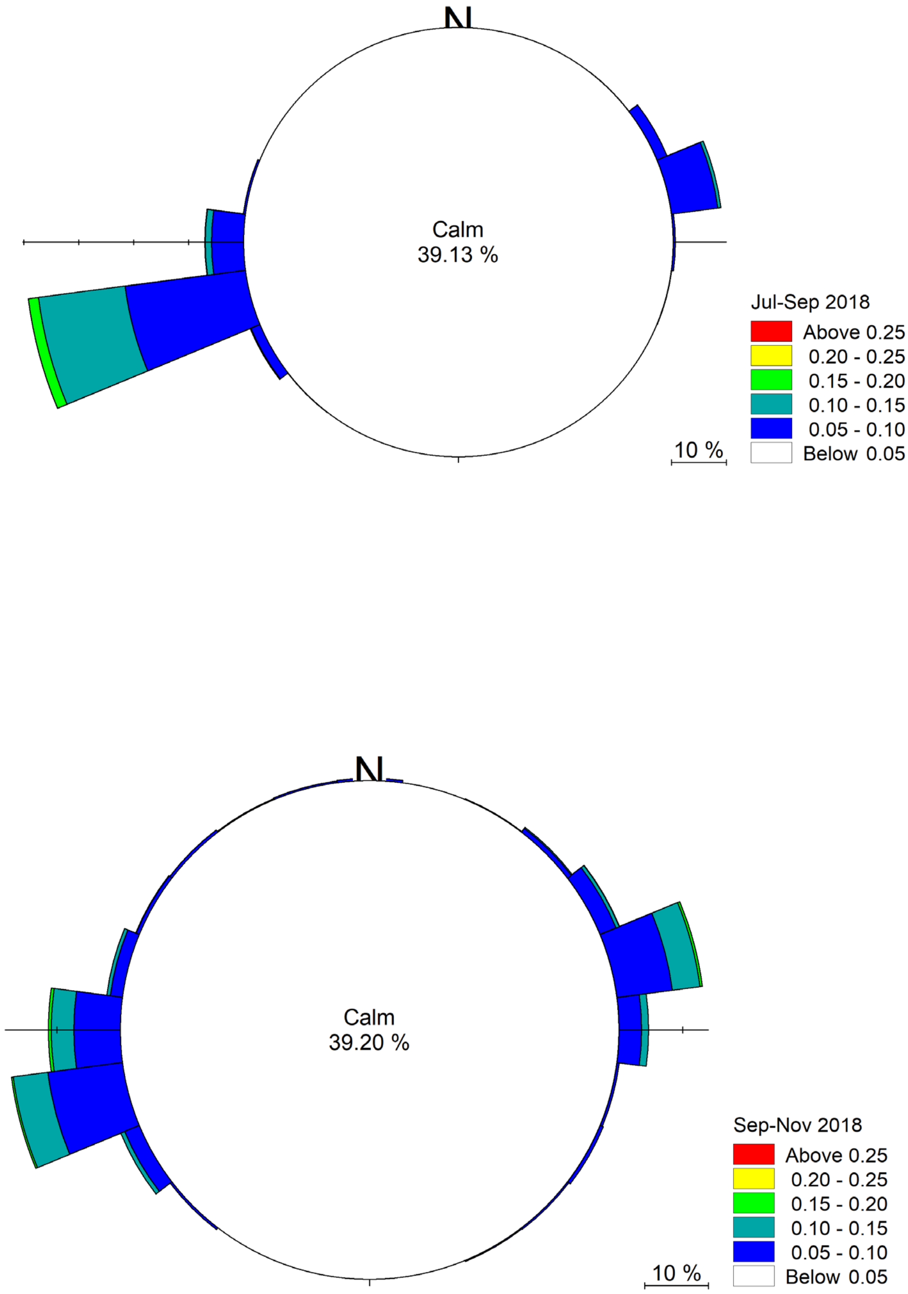


Figure 2.20 Measured current speeds for the two deployment periods at Toyness in 2018 (Jul-Sep top and Sep-Nov bottom)

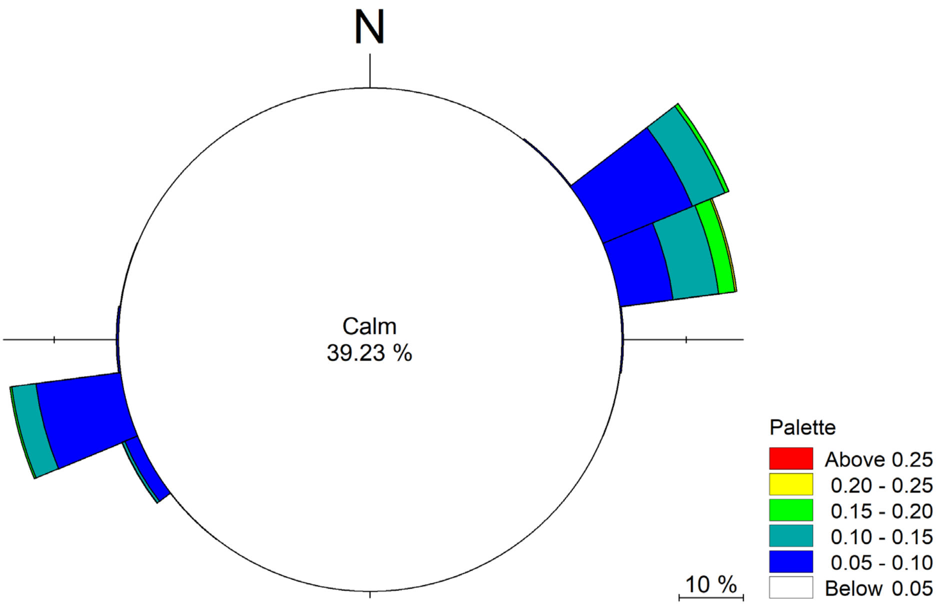
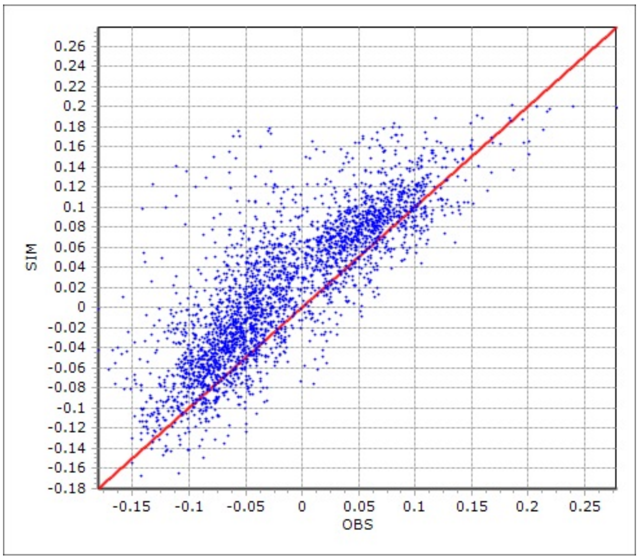


Figure 2.21 Rose plot of 2D modelled results at Toyness



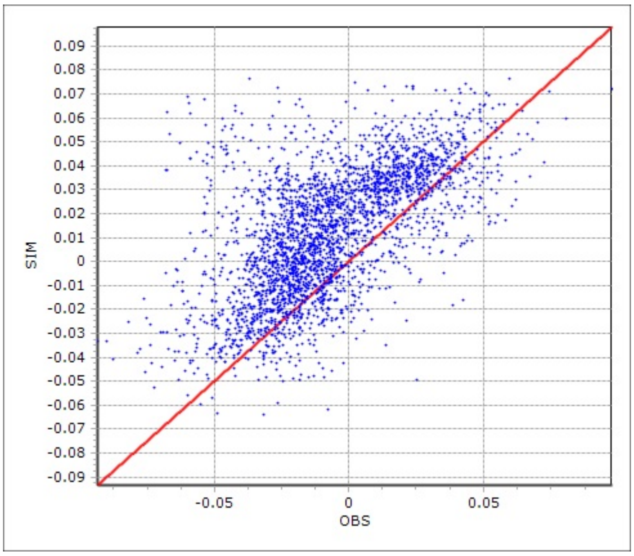


Figure 2.22 Scatter plot comparison of 2D model simulations results and observations at Toyness for u velocity (m/s left) and v velocity (m/s right) for the period 28th Sept -8th November 2018

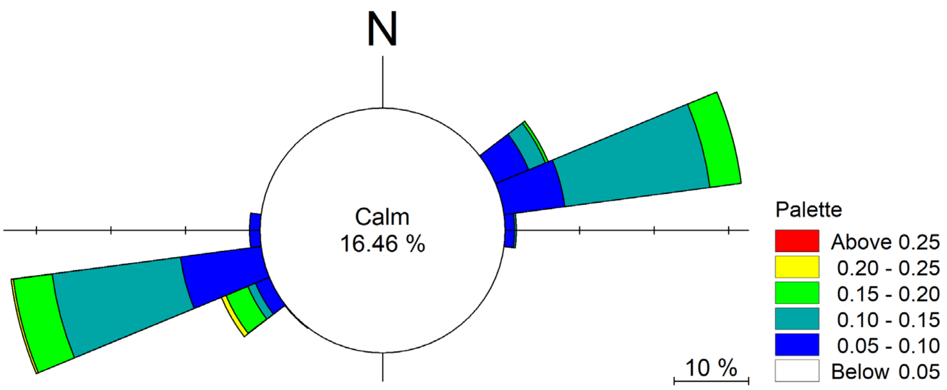


Figure 2.23 Rose plot of 3D modelled results at Toyness

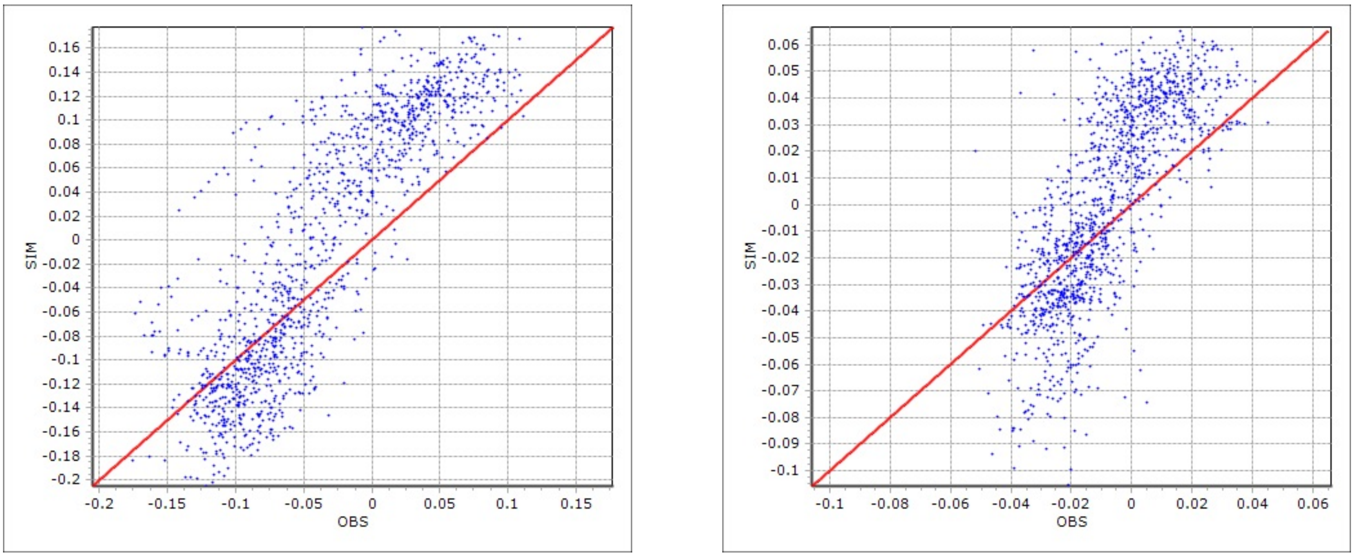


Figure 2.24 Scatter plot comparison of 3D model simulations results and observations at Toyness for u velocity (m/s left) and v velocity (m/s right) for the period 28th Sept -8th November 2018

3 Summary of justifications and way forward

3.1 Summary

Some discrepancies between the model and the measurements were noted and have been explained in both the model setup report and in this additional technical note. They are:

- Bring Head deviations between the model and the measurements can be explained by the position of the residual eddy. Due to the eddy the model suggests more flow towards the southeast whilst the inner part of the eddy supports the flow to the northwest. The position and temporal variability of the eddy in the real world is likely to vary, with length scales at or larger than the farm itself, leaving some of the pens in different flow regimes.
- Toyness deviations between the model and the measurements are considered likely to be due to the model ability to represent the wider eastern Scapa Flow circulation pattern, which appears in part to be controlled by the wind. The wind forcing in the model is likely to be much smoother temporally and also coarser in spatial resolution than in reality and this may lead to the differences in the residual directions. Sensitivity of this low flowing area could be high.

It is considered that the previously undertaken calibration process, which includes both of the recommended alterations to the model proposed by SEPA in their review (and summarised in Section 1.1 of this report), has resulted in the present model which is considered to be representative of the entirety of Scapa Flow.

Of particular note is the statement of “it is possible to achieve a good calibration in the vicinity of the proposed sites” whilst this is a useful gauge for understanding other sites, it is DHI’s experience that often local anomalies, such as the eddy seen at Bring Head can render measurement data overly biased. As such, calibration exercises need to have due consideration of the explainable reasons for differences.

With this in mind, the wider applicability of the model throughout Scapa Flow was also presented in the HD modelling report with the validation plots and is reiterated here for reference (Figure 3.1), suggesting the model does achieve the SEPA standards in most locations around Scapa Flow.

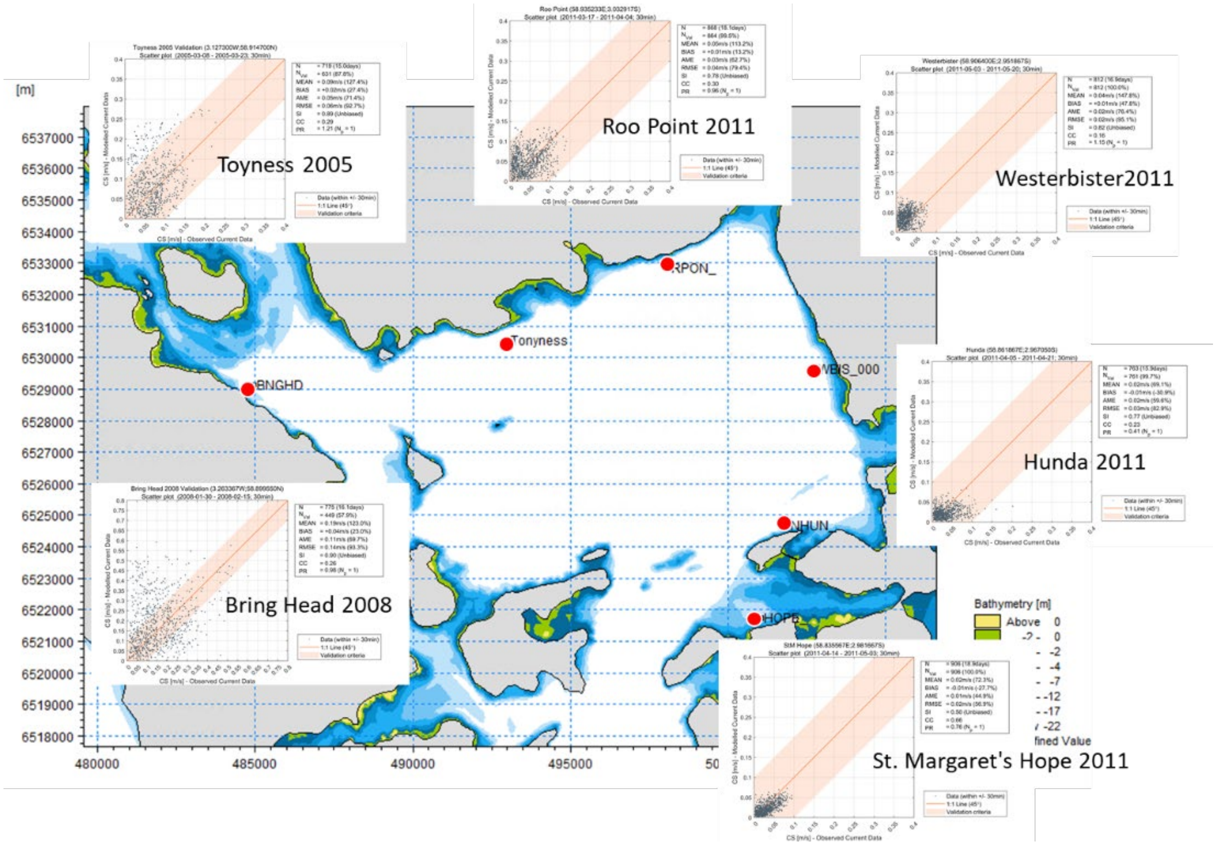


Figure 3.1 Summary map showing scatter plots of observed vs. modelled current speed at HD model validation sites (orange shading denotes SEPA's calibration standards

Whilst not performing perfectly compared to the measurements at Bring Head and Toyness, the explanation provided suggests that acceptance of the deviation is made and there is a need to undertake additional sensitivity testing for the resultant depositional modelling by changing the location of the Bring Head site to a position inshore of the proposed location to place it in the inner northwestward part of the eddy. With this sensitivity test, it will be possible to provide additional envelopes of impact from the farm based on the uncertainties that remain from the hydrodynamic stages of the modelling

Appendix D Waste Solids – Chalmers Hope Cumulative Impacts

Appendix D Waste Solids – Chalmers Hope Cumulative Impacts

Appendix D.1 Introduction to updated Waste Solids assessment

Following SEPA review of the modelling report for the proposed Bring Head and Toyness sites, a request to include the proposed increase in biomass at the Cooke Aquaculture site at Chalmers Hope was made, in order to adequately address risks of cumulative solids impacts in the surrounding area (SEPA Marine Modelling Response Form dated 2022/06/02). This document summarises the outcomes of this work.

The biomass for Bring Head and Toyness remained as previously set as 2,500 tonnes (provided by SSF), and the biomass for all other source locations were adopted from the licensed levels or from the proposed levels in the case of Chalmers Hope (2,500 tonnes). Table D.1 summarises the input rate [kg/day] for each source location in the model setup for the proposed biomass levels.

In addition, the models were run with the existing licensed biomass values for the sources at Bring Head and Toyness to construct a comparative baseline. The sources for the Bring Head and Toyness sites were as per the proposed pen layouts, whilst Chalmers Hope and all other sites were a single source release due to uncertainty on the potential layout.

Table D.1 Particle source locations and waste solid input rates as specified in the solid waste depositional model setup for the post modelling scenario – with Chalmers Hope

Site Name	Site ID	Existing Biomass [tonnes]	Proposed Scenario Biomass [tonnes]	Location		Proposed Waste solids values		
				Easting [m OSGB]	Northing [m OSGB]	Feed requirement, *F* [kg/day]	Waste Feed [kg/day]	Faeces [kg/day]
Bring Head (12 pens)	BRHD	968 (10 pens)	2,500	327572	1002216	17,500	478	2,317
Toyness (12 pens)	TOYN	1,343 (10 pens)	2,500	335385	1003586	17,500	478	2,317
Chalmers Hope	CHAH	1,000*	2,500**	328614	1001123	17,500	478	2,317
Fara West	FARW	800	800*	331963	995227	5,600	153	741
Lyrawa Bay	LYRB	400	400*	330020	998900	2,800	76	371
Pegal Bay	PEGB	400	400*	330400	997800	3,500	96	463
South Cava	SHCA	2,500	2,500*	333300	998900	17,500	478	2,317

* from CAR License for site (Site Details (scotland.gov.uk))
** using proposed values at Chalmers Hope.

Appendix D.2 Waste Solids Results

As per the main study, a one-year model simulation (summer to summer) of the dispersion of solid waste was performed. From the model results the total sedimented solids on the seabed (waste feed + faeces) were calculated for each model grid cell. For this assessment, the cumulative results for the combination of farm sites was of interest.

As such the three scenarios tested were:

1. Toyness Proposed Biomass, Chalmers Hope Proposed and Bring Head at existing biomass and other MPFF's at existing
2. Bring Head Proposed Biomass, Chalmers Hope Proposed and Toyness at existing biomass and other MPFF's at existing
3. Chalmers Hope Proposed Biomass, Bring Head Proposed Biomass and Toyness at Proposed biomass and other MPFF's at existing

Appendix D.2.1 Cumulative Waste Solids Results

The updated assessment herein shows that overall, the impact of including the Chalmers Hope site at the proposed biomass is to increase the area over the 250 g/m^2 value. Figure D.1 shows the results from Scenarios 1 and 2 comparing the relative impact of Bring Head and Toyness in pre-development layout combined with Chalmers Hope.

Figure D.2 shows the results of all 3 sites at the proposed 2,500 tonne biomass. Again, of note is that the impact of Toyness is constrained to immediately below the site, and therefore the size of the footprint doesn't increase significantly in Scenario 3, however there is an increase in the mean concentration.

Table D.2 Summary statistics of the cumulative impact from Bring Head, Toyness and Chalmers Hope in relation to the other MPFF's for the entire model domain from existing and proposed increased biomass

	Area of the 250 g/m^2 contour (averaged over the last 90 days)	Mean concentration within the 250 g/m^2 contour (averaged over the last 90 days)
Toyness **Proposed** Biomass Chalmers Hope **Proposed** Bring Head at **existing** biomass and other MPFF's at existing	972,794	2,761
Bring Head **Proposed** Biomass Chalmers Hope **Proposed** Toyness at **existing** biomass and other MPFF's at existing	1,184,942	2,249
Chalmers Hope **Proposed** Biomass Bring Head **Proposed** Biomass Toyness at **Proposed** biomass and other MPFF's at existing	1,194,799	2,565

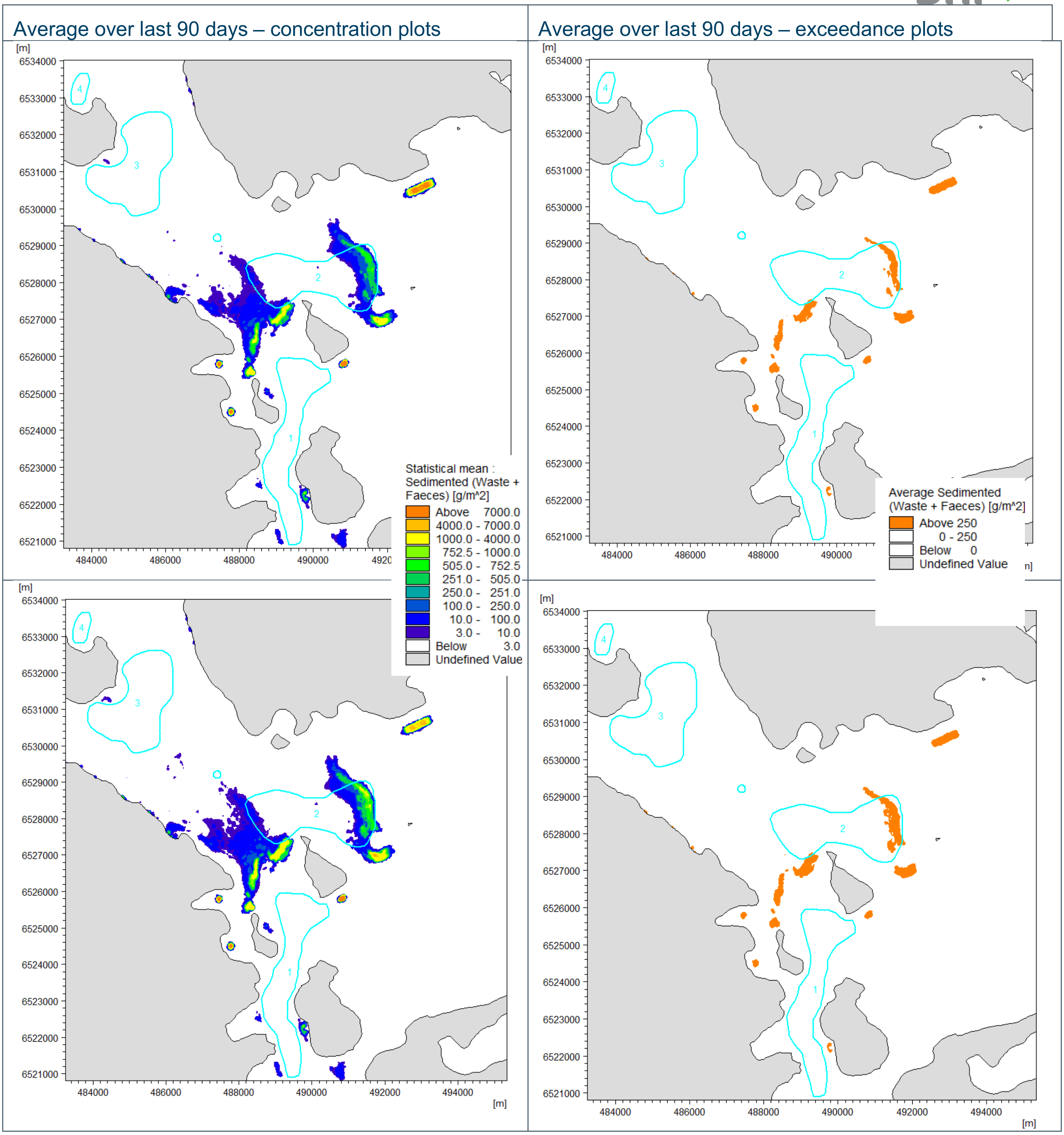
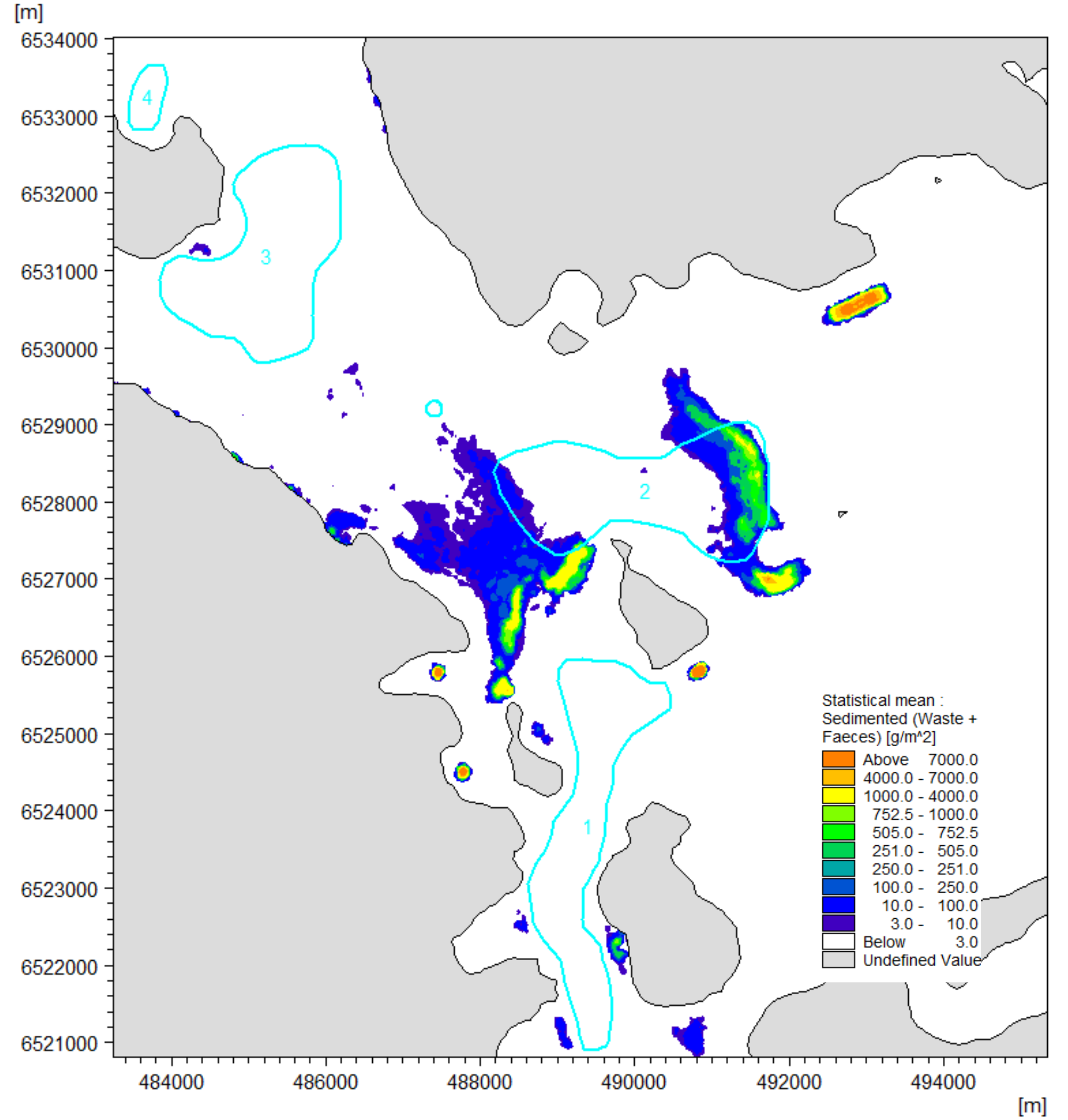


Figure D.1 Map of the concentration of sedimented waste solids (g/m^2) from combinations of sites. Proposed biomass at Toyness and Chalmers Hope and existing Bring Head biomass and other sites (top) and Proposed biomass at Bring Head and Chalmers Hope and existing Toyness biomass and other sites (bottom). The concentration is the average value of the last 90 days of the 1-year model simulation.

Average over last 90 days – concentration plots

Average over last 90 days – exceedance plots



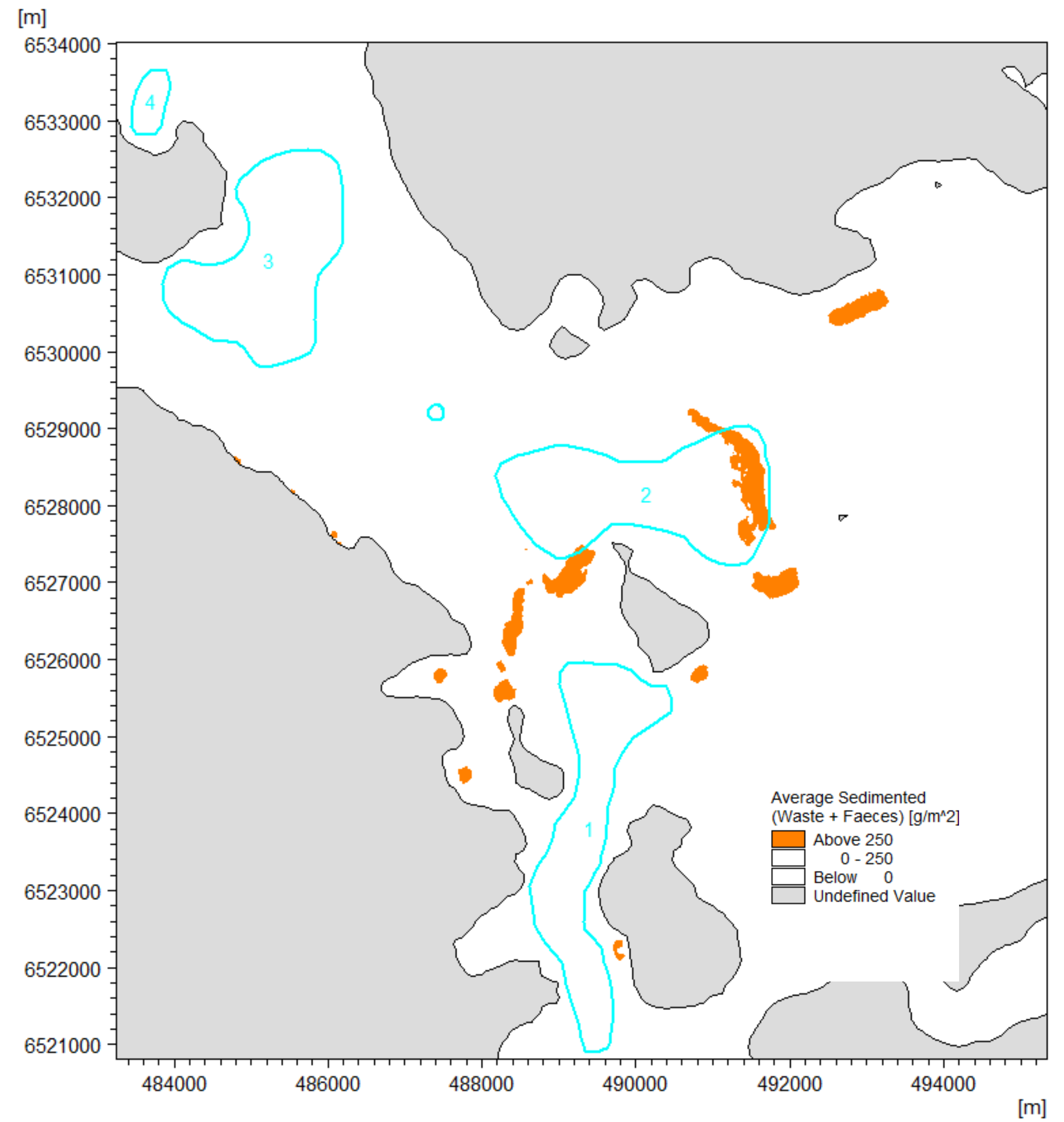
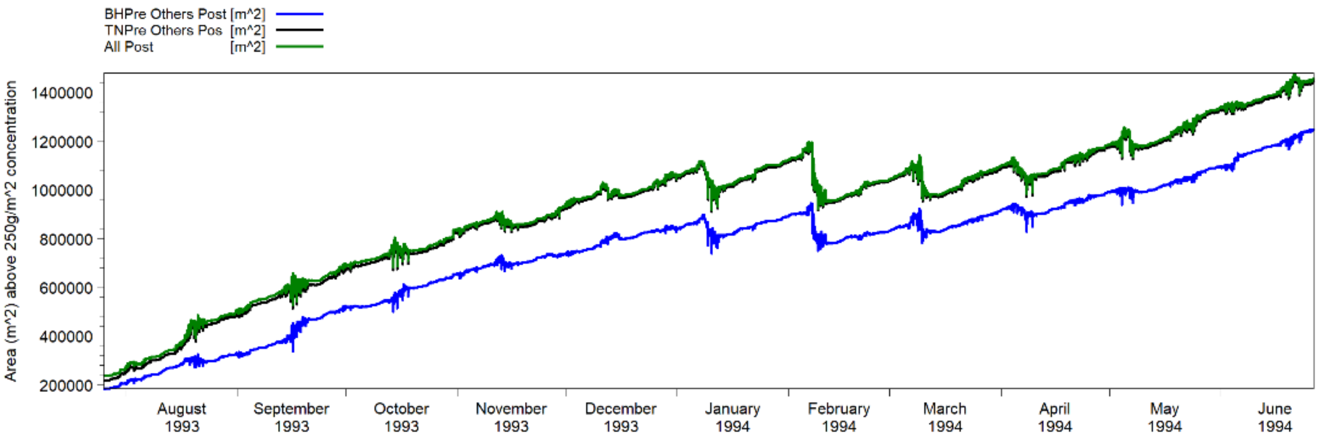


Figure D.2Map of the concentration of sedimented waste solids (g/m^2) from combinations of site. Proposed biomass at Chalmers Hope, Bring Head and Toyness, with other sites at existing. The concentration is the average value of the last 90 days of the 1-year model simulation.



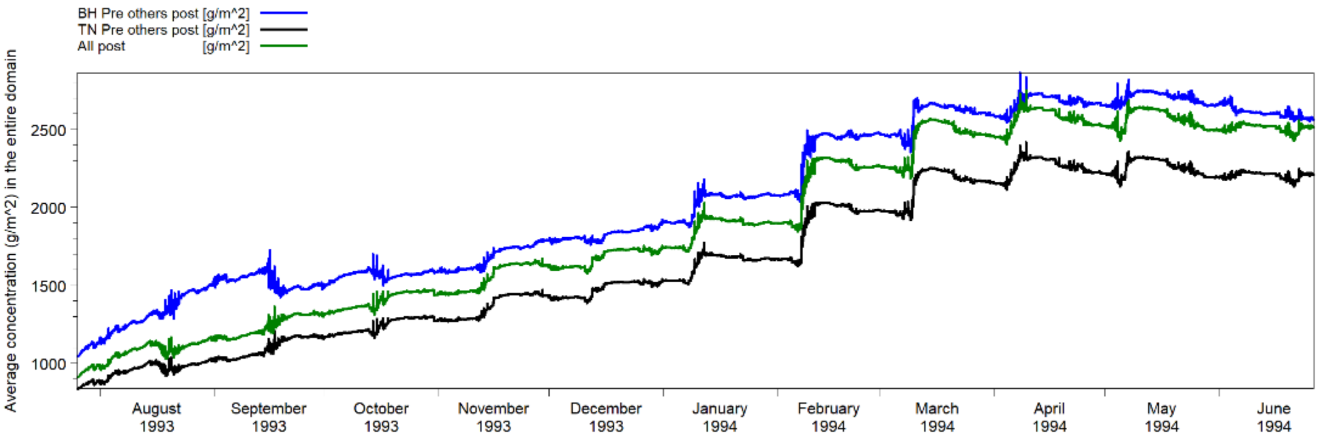


Figure D.3 Time series of the area (in m^2) above 250 g/m^2 (top) and the average concentration (g/m^2) of deposition (bottom) within the entire model domain for the three scenarios

Appendix D.2.2 Impact at PMF's from Waste Solids

Waste solids from the model runs for the cumulative assessment were extracted within the area of the PMF's to assess the potential impact of the proposed sites on these areas. As noted previously, the waste solids from Toyness do not leave the immediate environs of the site.

Consequently, only Bring Head and Chalmers Hope have the potential to impact PMF's remote from the site. Of the potentially impacted PMF's, only PMF 2 has areas where the 250 g/m^2 average value over the last 90 days is exceeded consistently. PMFs 1, 3 and 5 all show minor impact which is assumed related to the introduction of the Chalmers Hope site, as previously these PMFs were not directly impacted. As such Figure D.4, shows the area and the average concentration of these intermittent patches of deposition within the PMFs. Of note however is that the mechanism of deposition also leads to erosion, such that there is no significant accumulation in the final 90 days.

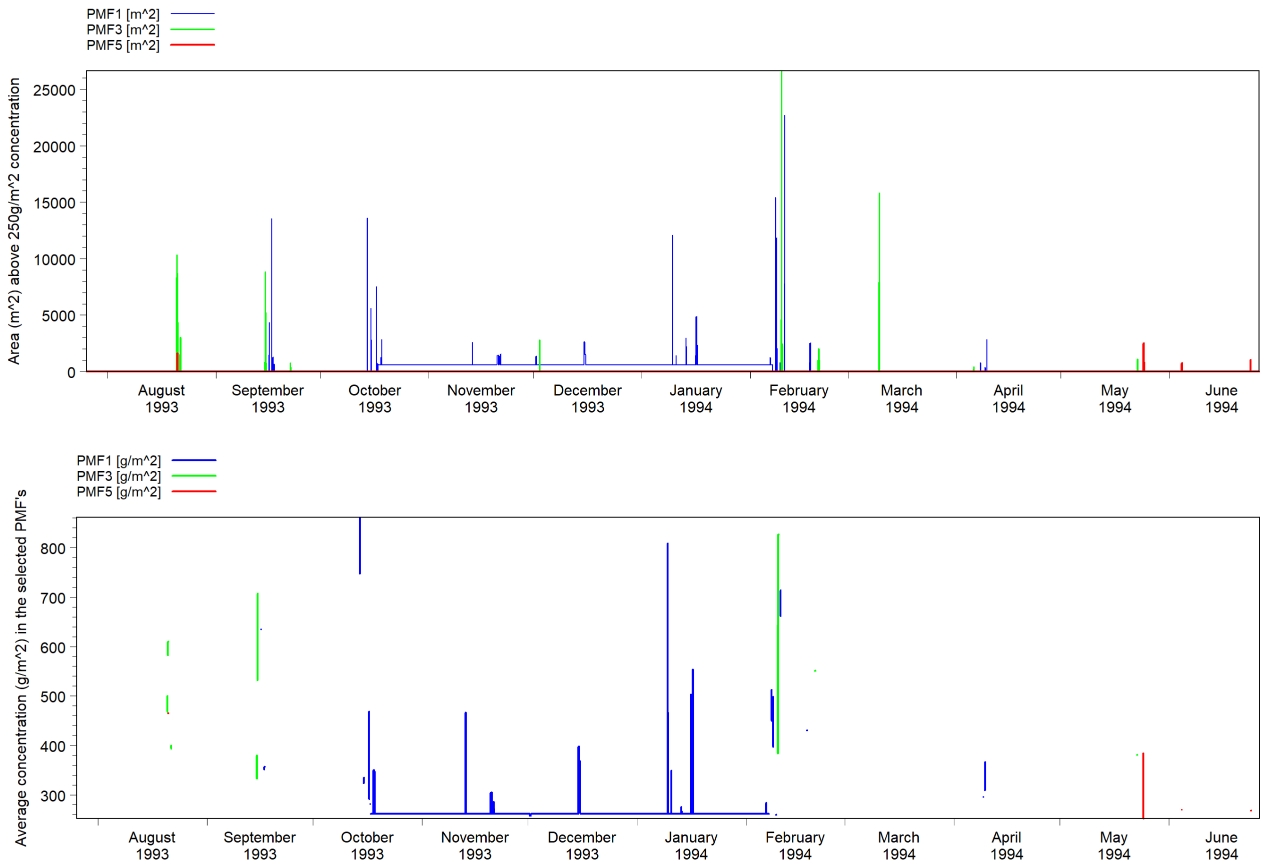
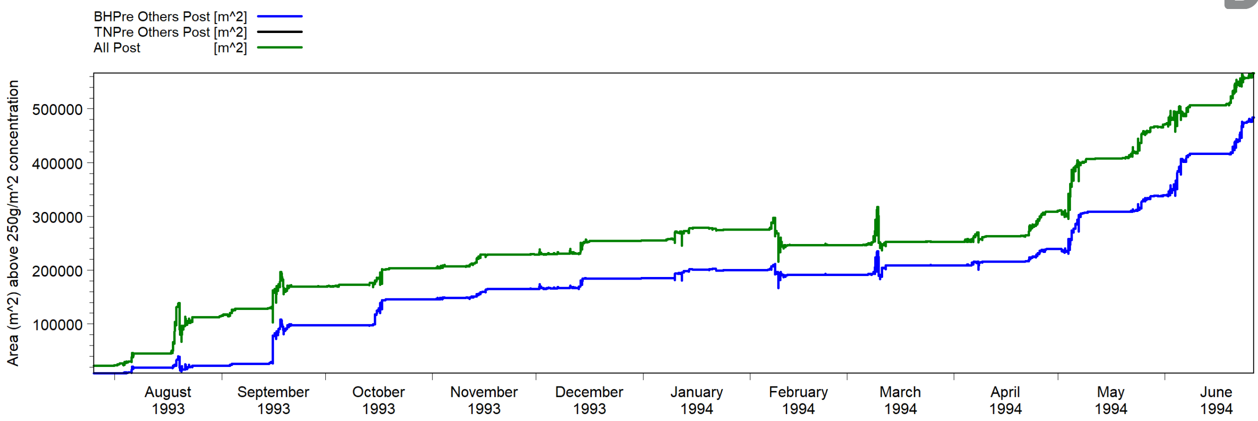


Figure D.4Time series of the area (in m^2) above 250 g/m^2 (top) and the average concentration (g/m^2) of deposition (bottom) within PMFs 1, 3 and 5 for the All Post scenario.

The following section provides additional information on the spread and concentration of waste solids within PMF2.

Spatially, the greatest deposition occurs on the eastern edge (see Figure D.6); however, there is a higher peak with a smaller impacted area in the southwestern corner, which also extends south outside of the PMF.

The summary statistics in Table D.3 show that there is no impact of increasing biomass at Toyness on PMF2, and if Chalmers Hope is at 2,500 tonnes already then Bring Head only increases the % area over 250 g/m^2 by 2% with an associated mean concentration change from 512 to 619 g/m^2



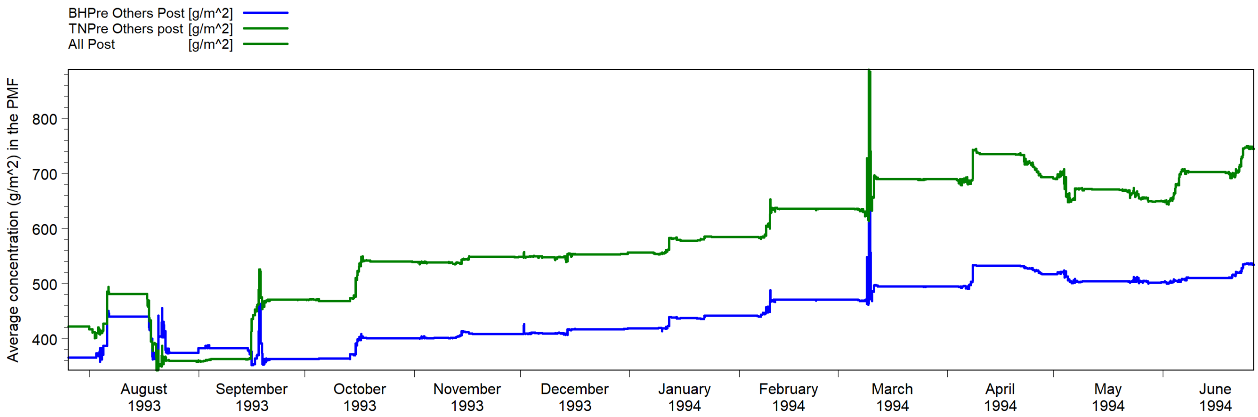


Figure D.5Time series of the area (in m^2) above 250 g/m^2 (top) and the average concentration (g/m^2) of deposition (bottom) within PMF2 for the three scenarios. NB the black line of Toyness Pre is directly beneath the All Post, due to the constrained nature of deposition below Toyness.

Table D.3 Summary statistics of the impact within PMF2 from MPFF's from the last 90 days of the model run

	Area (m^2) of the 250 g/m^2 contour within PMF2	% of the PMF 2 area (4,207,370 m^2)	Mean concentration (g/m^2) within the 250 g/m^2 contour
Toyness **Proposed** Biomass Chalmers Hope **Proposed** Bring Head at **existing** biomass and other MPFF's at existing	304,142	7.2%	512
Bring Head **Proposed** Biomass Chalmers Hope **Proposed** Toyness at **existing** biomass and other MPFF's at existing	386,779	9.2%	693
Chalmers Hope **Proposed** Biomass Bring Head **Proposed** Biomass Toyness at **Proposed** biomass and other MPFF's at existing	386,779	9.2%	693

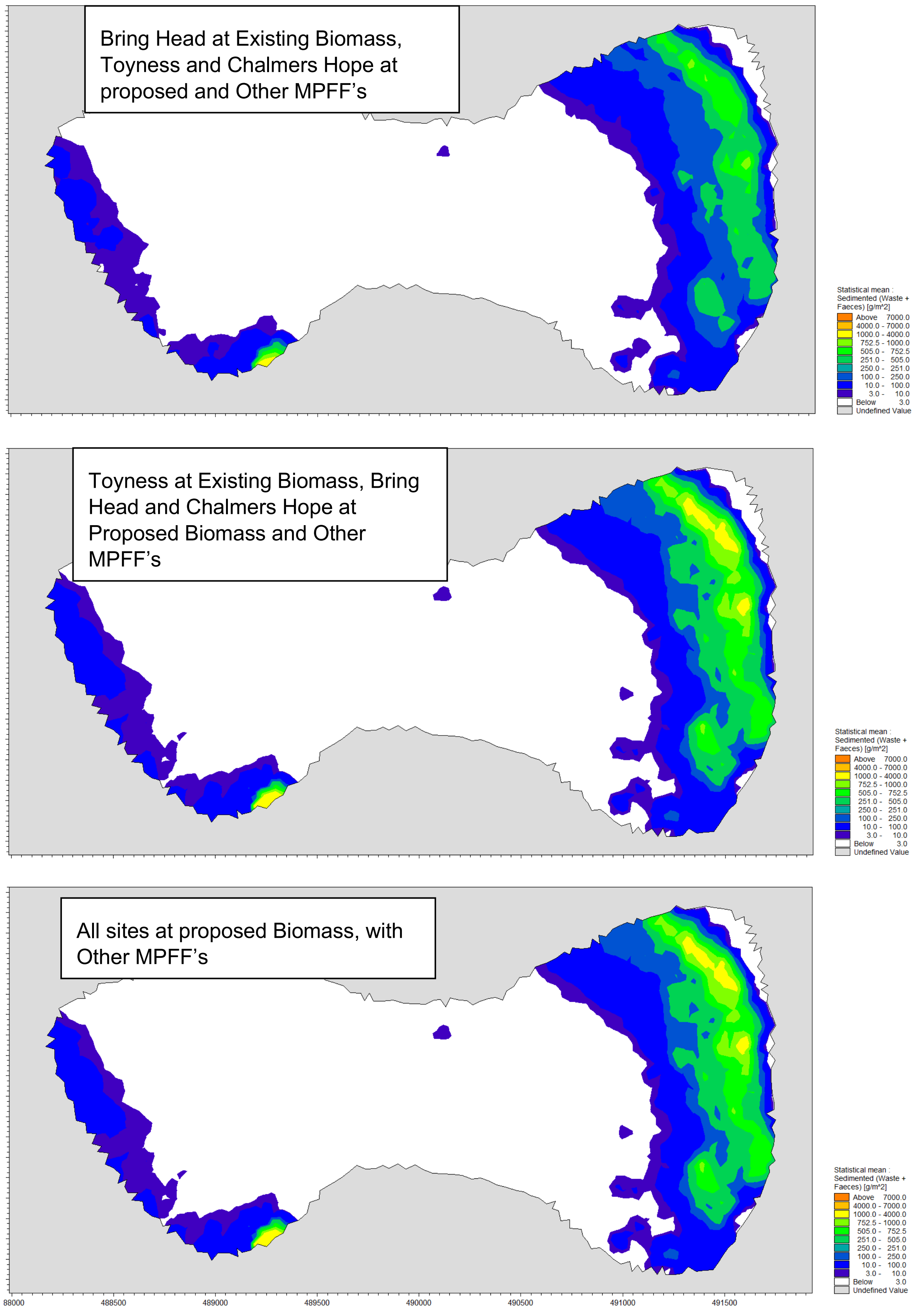


Figure D.6Waste Solid deposition at PMF 2. Average values for the last 90 days for Bring Head existing biomass with Toyness and Chalmers Hope at proposed with Other MPFF’s (top), Toyness existing biomass with Bring Head and Chalmers Hope at proposed with Other MPFF’s (middle) and All sites at proposed Biomass (bottom).