Fair Isle Harbour Improvement Works

A.13 Hydrodynamic Modelling

On behalf of **Shetland Isle Council (SIC)**

Shetland Islands Council

Project Ref: 11168 | Rev: Version 1.0 | Date: April 2023

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Fair Isle OBC Refinement

Hydrodynamic and Sediment Transport Modelling

March 2023

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March 2023

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Issue and Revision Record

Revision	Date	Originator	Checker	Approver	Description
01	2/5/2023	N del Estal SK, S Costa	JJW		Draft
02	25/05/2023	N del Estal SK, S Costa	JJW	JJW	Issued

Document reference: 100418429-001

Information class: Standard

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Executive summary

The Fair Isle Ferry Replacement Project (hereafter referred to as the Project) seeks to enhance the infrastructure to accommodate new vessels, improve access, and provide better protection against wave action. The project site is 24 miles off the southern tip of the Shetland Islands, Scotland, where the existing ferry terminal is nearing the end of its lifespan and no longer meets modern requirements. Mott MacDonald Ltd (MML) is working with Shetland Island Council (SIC) and ZetTrans to develop an Outline Business Case (OBC) for upgrade works to the Fair Isle Ferry Terminal. Dredging approximately 1,163 m^3 of sediment will be necessary for the improvement works.

As part of the works' OBC and environmental impact assessment (EIA), it has been necessary to analyse the present hydrodynamic and sediment transport conditions to establish the baseline for North Haven and identify any potential changes in the bay's processes after the scheme's implementation. Furthermore, understanding the potential consequences of spilt sediment during the dredging operation and changes to suspended sediment concentrations and deposition rates in the area is required.

MML has utilised a calibrated MIKE3 by DHI Flexible Mesh (FM) regional North Sea hydrodynamic (HD) model of the Scottish west coast (RNSM) to simulate tidal flows around Fair Isle. A more detailed local HD model was then set up using boundary conditions from the RNSM. Together with outputs from an existing MIKE21 spectral wave (SW) model, this detailed HD model drove sand transport (ST) and mud transport (MT) modules. The ST model simulated wave-current sand transport in North Haven under normal and extreme conditions. The MT module simulated the dispersion of cohesive sediments (silt and mud) disturbed during dredging. These modelling studies provide compelling evidence demonstrating that:

- Changes to the wave-current driven sand transport in North Haven attributable to the Project are small and will have a virtually undetectable impact on the present data processes or coastal morphology;
- An assumed 5% sediment loss during dredging would release around 147 m^3 of fine-grained sediments in short-lived plumes confined to a few hundred metres from dredging operations. Consequently, impacts will be small;
- The maximum suspended sediment concentration (SSC) reaches approximately 1.5 kg/m^3 (1050 mg/l) and is short-lived and confined to an area between the existing quay and the breakwater. Consequently, impacts will be small;
- Further from the dredging source, modelling shows that SSC values rapidly decrease as sediment quickly settles to the bed;
- The maximum accretion depth attributed to dredging is predicted to be only 0.04 m and is confined to an area defined approximately by the dredging footprint. Some of this deposited sediment will be removed during the dredging process; and
- Based on current observations, it is unlikely that there will be significant changes to the morphology or sediment characteristics of the beach. Any changes that do occur are likely to fall within the natural range of response associated with the spring-neap tidal cycle and storm events and may not be detectable;
- The increase in breakwater height and the reduction in porosity will reduce overtopping and wave transmission through the structure during extreme events and increase wave protection to the beach's eastern section used for recreational purposes; and
- Following SEPA guidance, climate change assessments included an allowance for a cumulative SLR for RCP8.5 for the 95th percentile of 0.52m and increases in offshore wave

height and wind speed of 10%. Differences between sediment transport with the proposed scheme in situ without and with climate change allowances are judged insignificant and probably undetectable from within the range of natural variability. The impact of the climate change conditions on the sediment patterns is therefore considered negligible.

1 Glossary

ADCP	Acoustic Doppler current profiler
AEP	Annual exceedance probability
BGS	British Geological Survey
BHD	Backhoe dredging
BODC	British Oceanographic Data Centre
C	Correlation coefficient
CD	Chart datum
Cefas	Centre for Environment, Fisheries and Aquaculture Science
Cg	Group deep water wave celerity
CIRIA	Construction Industry Research and Information Association
CS	Constant Smagorinsky formulation
CSD	Cutter suction dredging
DHI	Danish Hydraulic Institute
D50	Median grain diameter (mm)
ECMWF	European Centre for Medium-range weather forecasting
EIA	Environmental Impact Assessment
EMODnet	European Marine Observation and Data Network
ERA5	Fifth generation ECMWF reanalysis for the global climate
EVA	Extreme value analysis
FM	Flexible mesh
g	Acceleration due to gravity (9.81 m/s^2)
HAT	Highest Astronomical Tide
HD	Hydrodynamic
Hs	Significant wave height (m)
IHO	International Hydrographic Organisation
OBC	Outline business case
ODN	Ordnance datum Newlyn
LAT	Lowest Astronomical Tide
MAE	Mean Absolute Error
MHWN	Mean High Water Neaps
MHWS	Mean High Water Springs
MLWN	Mean Low Water Neaps
MLWS	Mean Low Water Springs
MML	Mott MacDonald Limited
MSL	Mean Sea Level
MWD	Mean wave direction (deg. N)
MT	Mud transport
PSA	Particle size analysis
RCP	Representative Concentration Pathway
RMSE	Root Mean Square Error
RNSM	Regional North Sea model
SEPA	Scottish Environment Protection Agency
SLR	Sea level rise
SIC	Shetland Island Council
SSC	Suspended sediment concentration
ST	Sand transport

SW	Spectral wave
Tp	Peak wave period (s)
TSHD	Trailing suction hopper dredging
Tz	Zero-crossing wave period
UKCP	UK Climate Projections
UKHO	UK Hydrographic Office
UTC	Coordinated Universal Time
WGS	World Geodetic System
Ws	Wind speed (m/s)
Wdir	Wind direction (deg. N)
ρ	Water density

The following conventions are adopted throughout (unless otherwise stated):

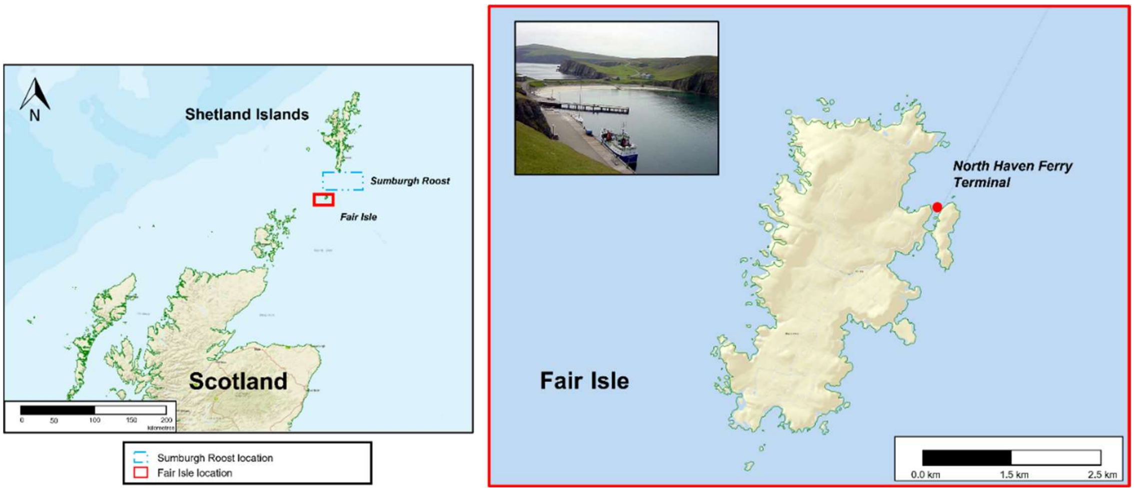
- Depths are provided relative to Ordnance Datum Newlyn (ODN);
- Current directions are quoted as directions to; and
- Wave and wind directions are quoted as directions from.

2 Introduction

2.1 Background

Mott MacDonald Ltd (MML) is working with Shetland Island Council (SIC) and ZetTrans to develop an Outline Business Case (OBC) for upgrade works to the Fair Isle Ferry Terminal. The project site is located 24 miles off the southern tip of the Shetland Islands, Scotland (Figure 1.1).

Figure 2.1: Location of the North Haven Ferry Terminal on Fair Isle.



Source: Mott MacDonald, 2023

As the existing terminal nears the end of its lifespan and no longer meets modern requirements, the Fair Isle Ferry Replacement Project (hereafter referred to as the Project) seeks to enhance the infrastructure to accommodate new vessels, improve access, and provide better protection against wave action. Dredging will be necessary as part of the improvement works, along with other activities.

It is necessary to analyse the present hydrodynamic and sediment transport conditions to establish the baseline for North Haven To support the OBC. This analysis will also identify the potential changes in the bay's processes after the scheme's implementation. Furthermore, understanding the potential consequences of spilt sediment during the dredging operation and changes to suspended sediment concentrations and deposition rates in the area. This analysis's outcome will help inform the Environmental Impact Assessment of the works.

MML has utilised a calibrated MIKE3 by DHI Flexible Mesh (FM) regional North Sea hydrodynamic (HD) model of the Scottish west coast (RNSM) to simulate tidal flows around Fair Isle. A more detailed local HD model was then set up using boundary conditions from the RNSM. Together with outputs from an existing MIKE21 spectral wave (SW) model, this detailed HD model drove sand transport (ST) and mud transport (MT) modules. The ST model simulated wave-current sand transport in North Haven under normal and extreme conditions. The MT module simulated the dispersion of cohesive sediments (silt and mud) disturbed during dredging.

2.2 Report Structure

The report presents the key modelling activities, data and results. It is structured as follows:

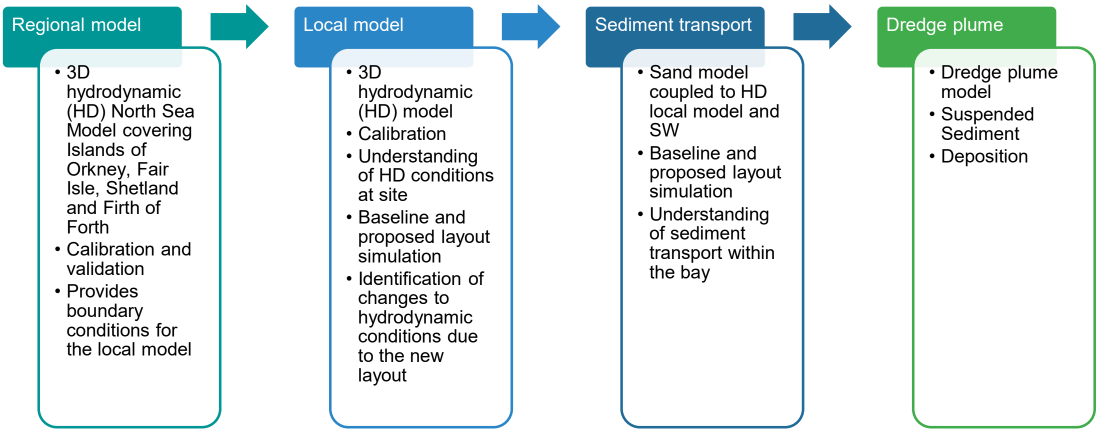
- Chapter 3: outlines the numerical modelling approach;

- Chapter 4: describes the bathymetric, water level, currents, wave and sediment data used to build the regional and local hydrodynamic models;
- Chapter 5: describes the regional hydrodynamic model built, calibration and validation;
- Chapter 6: describes the local hydrodynamic model built, calibration and validation;
- Chapter 7: presents the results of the local hydrodynamic model for the baseline and scheme;
- Chapter 8: describes the set up of coupled hydrodynamic, sand transport and spectral wave model used to describe the baseline sediments process at the site and to identify changes to it due to the new layout;
- Chapter 9: describes the set up of coupled hydrodynamic and mud transport model used to understand the impacts of the dredging operation; and
- Chapter 10: summarises and concludes the modelling work.

3 Modelling approach

To simulate the hydrodynamic and sediment transport regimes for both the baseline and proposed scheme layout, three-dimensional (3D) MIKE by DHI models were created for the North Haven and Fair Isle regions, regionally and locally. These models were validated and calibrated to ensure their accuracy. These models could predict changes to local bed levels and hydrodynamics resulting from the upgrade works to the existing ferry terminal at North Haven. The modelling approach is illustrated schematically in Figure 3.1.

Figure 3.1: Fair Isle modelling approach



Source: Mott MacDonald, 2023

4 Data

4.1 Introduction

The performance of a hydrodynamic model is closely related to: (a) the accuracy of the bathymetry/topography used to build the model; and (b) the boundary conditions used to drive the model. Care is needed to ensure that observed water levels and currents are represented as accurately as possible within the constraints imposed by the data available to the study.

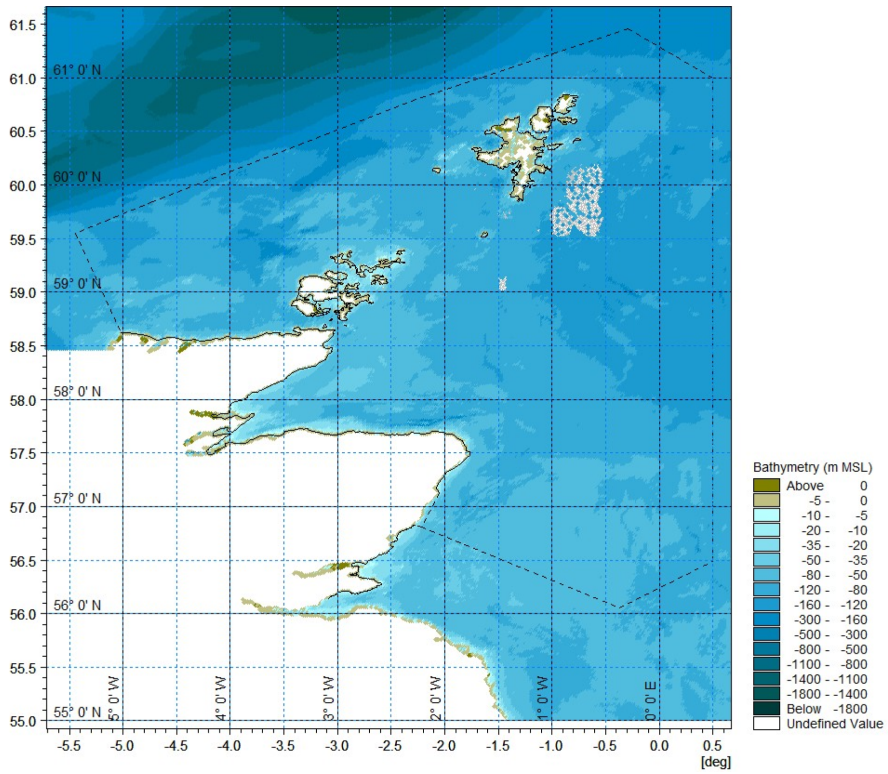
4.2 Systems and projections

Geographical data used in this study is referenced to a horizontal datum defined by geographical coordinates (longitude/latitude, WGS84). The vertical datum is referenced to mean sea level (MSL) for the regional model and Ordnance Datum Newlyn (mODN) for the local.

4.3 Bathymetry

The composite bathymetric data used to construct the regional and local models incorporated: (a) high-resolution local area survey bathymetry; (b) Admiralty bathymetry (2009 to 2021) from the UK Hydrographic Office (UKHO); and (c) EMODnet 2020 datasets. For the local model, high-resolution surveyed bathymetry collected by Aspect Ltd in June 2022 for the Fair Isle study area and data from the UKHO and EMODnet were used. All bathymetric data were referenced to Mean Sea Level (MSL).

Figure 4.1: Regional model domain and bathymetry



Source: Mott MacDonald, 2023. Contains EMODNET, UKHO and Survey bathymetric data

4.4 Water levels and current speeds

Table 4.1 shows the tide levels for Fair Isle based on Admiralty tide data. The tidal range is generally small, with spring and neap tides range of 1.6m and 0.7m, respectively.

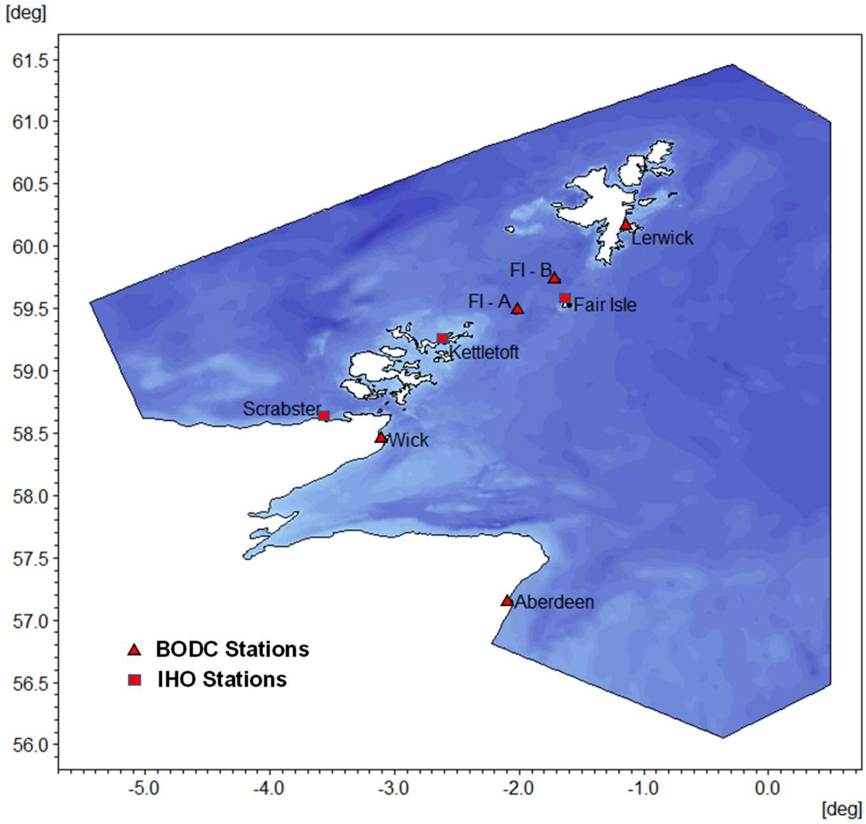
Table 4.1: Tide levels for Fair Isle.

Tidal level	Chart datum (mCD)	Ordnance datum Newlyn (mODN)
Highest Astronomical Tide (HAT)	2.70	1.78
Mean High Water Springs (MHWS)	2.20	1.28
Mean High Water Neaps (MHWN)	1.70	0.78
Mean Sea Level (MSL)	1.37	0.45
Mean Low Water Neaps (MLWN)	1.00	0.08
Mean Low Water Springs (MLWS)	0.60	-0.32
Lowest Astronomical Tide (LAT)	0.10	-0.82

Source: Admiralty Total Tide, 2023

Tidal data used to calibrate the regional Fair Isle model were obtained from British Oceanographic Data Centre (BODC) (Figure 4.2, Table 4.2). Additional predicted tide level data were derived at Kettleloft, Scrabster and Fair Isle from the Delft Dashboard IHO Tide database. Current speed data were also obtained from BODC at locations A and B (Figure 4.2, Table 4.2).

Figure 4.2: Location of water level and current speed calibration stations



Source: Mott MacDonald (2023), Contains data from BODC and IHO Stations

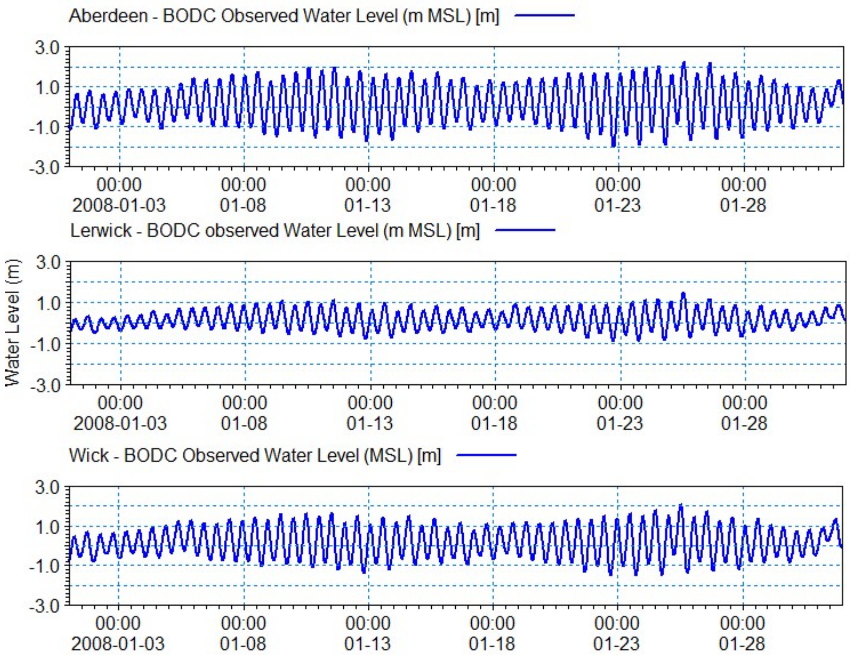
Table 4.2: Water level and current data source

Sl.no	Station	Parameter	Data Type	Source	Period
1	Aberdeen	Water Level	Measured	BODC	Jan 2008 to Dec 2009
2	Wick	Water Level	Measured	BODC	Jan 2008 to Dec 2009
3	Lerwick	Water Level	Measured	BODC	Jan 2008 to Dec 2009
4	Kettleloft	Water Level	Predicted	IHO	Jan 2008 to Dec 2009
5	Scrabster	Water Level	Predicted	IHO	Jan 2008 to Dec 2009
6	Fair Isle	Water Level	Predicted	IHO	Jan 2008 to Dec 2009
7	Fair Isle A	Current	Measured	BODC	Oct 2008 to Feb 2009
8	Fair Isle B	Current	Measured	BODC	Oct 2008 to May 2009

Source: Mott MacDonald (2023), Contains data from BODC and IHO

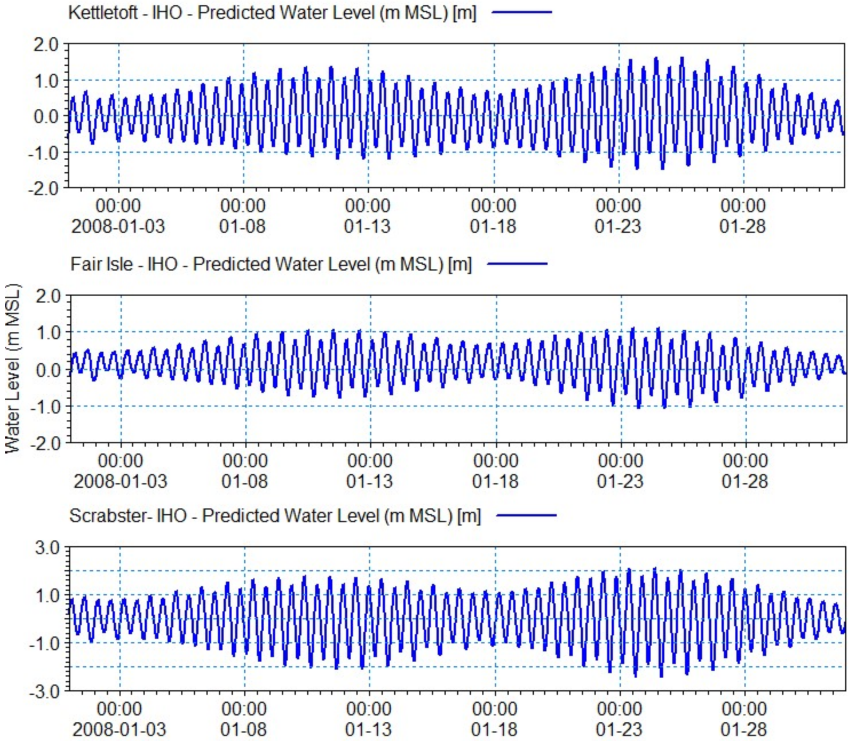
Figure 4.3 shows examples of measured water level data from BODC from October 2008 to May 2009 at Aberdeen, Lerwick and Wick. Figure 4.4 shows the predicted water level data at Kettletoft, Scrabster and Fair Isle from Delft Dashboard IHO tidal constituents from October 2008 to May 2009. Tide data show dominantly semi-diurnal characteristics.

Figure 4.3: Observed water level at the BODC tide gauge stations



Source: Mott MacDonald, 2023, contains data from BODC

Figure 4.4: Predicted water level at the IHO tide gauge stations

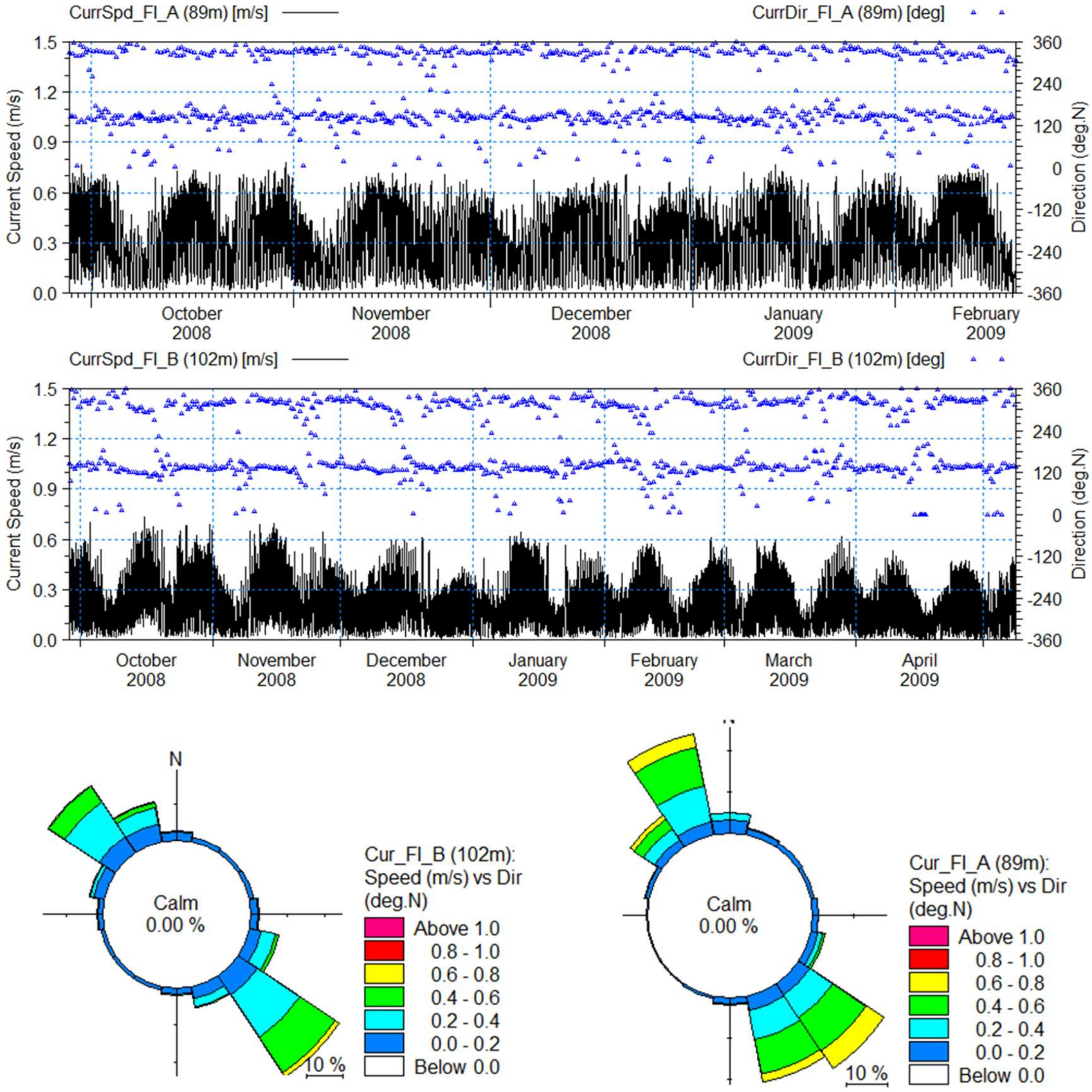


Source: Mott MacDonald, 2023, contains data from IHO

BODC current measurements were obtained at Fair Isle stations A and B, deployed in water depths 89m and 102m, respectively (Figure 4.2). The measurement span 27 September 2008 to 19 February 2009 and 28 September 2008 to 8 May 2009, respectively.

Figure 4.5 shows the observed current speed and direction locations A and B. Spring tidal current speeds reach around 0.8m/s. The dominant direction of the approximately rectilinear tidal flow at A and B is from northwest to southeast (Figure 3.5).

Figure 4.5: Current measurement deployment at Fair Isle A and B



Source: Mott MacDonald (2023), Contains data from BODC

4.5 Waves

4.5.1 Wave parameters definition

Wave parameters used in this report are defined as:

- **Significant wave height:** The significant wave height, Hs (m), is the mean of the highest third of the waves in a time series representing a particular sea state. Hs corresponds well with the average height of the highest waves in a wave group;
- **Peak wave period**: The peak wave period, Tp (s), defined by spectral analysis, corresponds to the wave period with the highest energy; and
- **Mean wave direction:** The mean wave direction, MWD (expressed as degrees from north), is the mean of all the individual wave directions in a time series representing a particular sea state.

4.5.2 Wave data

Modelled wave data quantifying Hs, Tp and MWD included:

- Hourly model hindcast wave data from 1979 to 2020 (42 years) from The European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 dataset with a 0.5-degree spatial resolution. This dataset was extracted at the grid location shown in Figure 4.6; and
- Historical measured wave data at Lerwick (Figure 4.6), quantifying Hs and zero-crossing wave period (Tz), were obtained from Cefas database[1]. MWD data were not available.

Figure 4.6: ERA-5 extraction location (blue dashed rectangle) and Lerwick buoy (red dot). Fair Isle is highlighted in the red square.

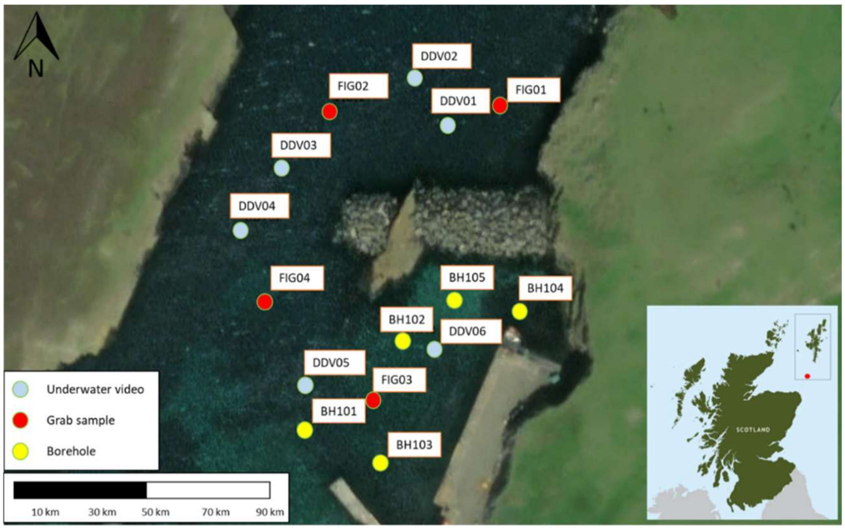
Source: Mott MacDonald, 2023

4.6 Sediment data

Although borehole sediment cores were collected during a geotechnical investigation at North Haven (Figure 4.7), laboratory analysis of the boreholes has not been undertaken when preparing this report. As part of a benthic ecological survey, ABPmer obtained sediment grab samples and underwater video in February 2023 (ABPmer, 2023). Data from the particle size analysis of these samples (see example in Figure 4.8) have been used to define the characteristics of the surficial sediment in the proposed dredging area. The grab samples show the bed sediment comprised of particle sizes spanning medium sand to clay. The median grain size value (D50) of 0.24 mm indicates that sand dominates the area.

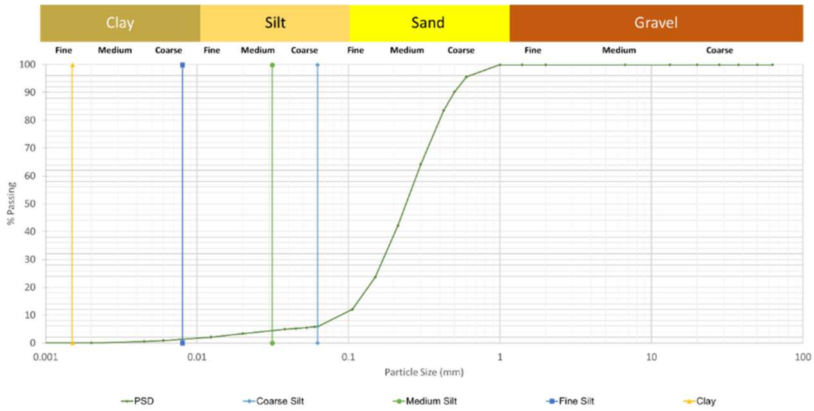
[1] http://wavenet.cefas.co.uk/Map?ZoomTo=0.4755%2C53.0582

Figure 4.7: Location of boreholes and grab samples.



Source: Mott MacDonald, 2023

Figure 4.8: PSD plot of sediment samples from North Haven



Source: Mott MacDonald, 2023. Contains ABPmer, 2023 data.

5 Regional hydrodynamic Model

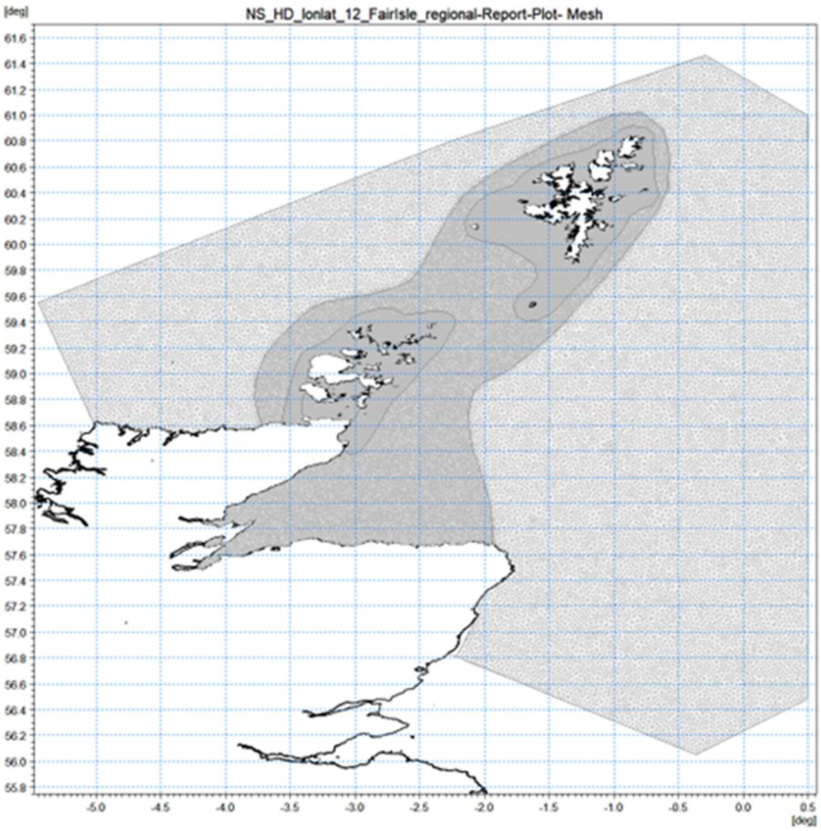
5.1 Introduction

A regional MIKE3 Flexible Mesh (FM) Hydrodynamic (HD) North Sea model (RNSM) was developed to generate the boundary conditions for the local Fair Isle MIKE3 FMHD model. The RNSM extends from 5.5°W to 0.5°E and 56.0° N to 61.5°N (Figure 5.1). It covers the Islands of Orkney, Fair Isle, the North Isles of Shetland and the Firth of Forth. The model uses an unstructured flexible mesh with a coarse resolution in deep water with relatively high resolution in the network of channels and straits. Predicted tidal elevations from the MIKE21 global tide model (0.125-degree grid resolution) were applied along the open boundaries to force the RNSM.

5.2 Model mesh and bathymetry

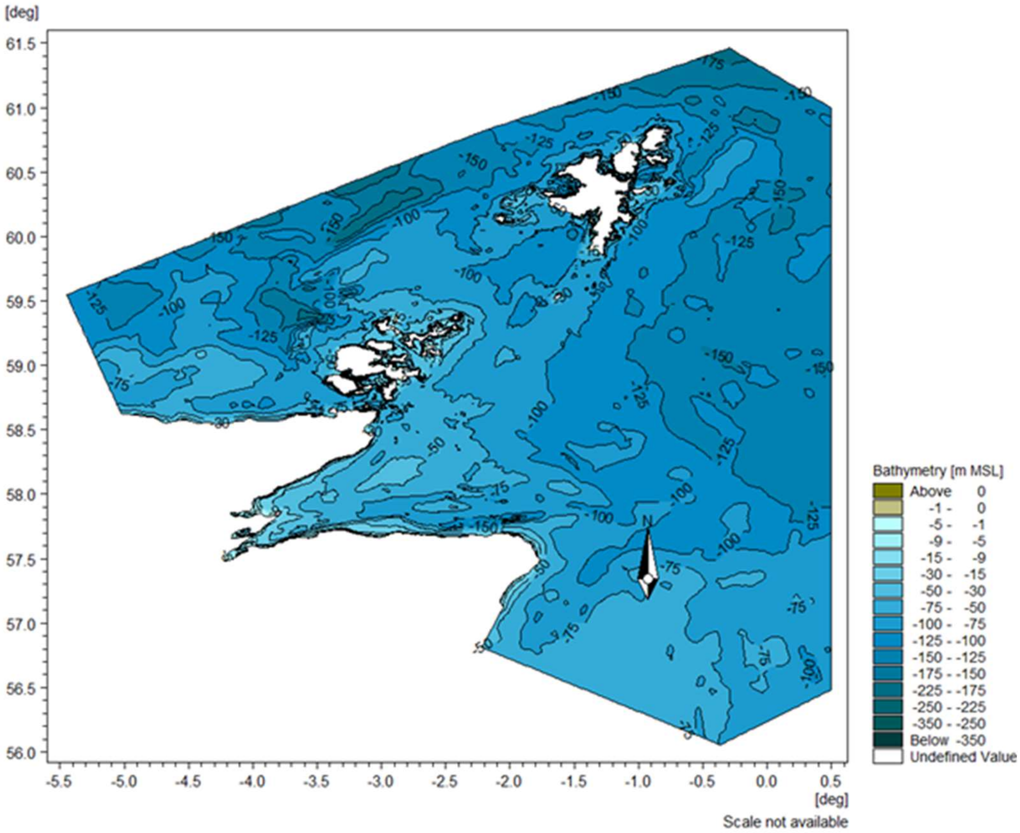
Bathymetric data sources used to build the RNSM included UKHO Admiralty, EMODnet and high-resolution survey data from the study area. Figure 5.1 and Figure 5.2 show the RNSM mesh and interpolated bathymetry, respectively. The model mesh resolution varies from over 3000m offshore to less than 250m in the nearshore region. The RNSM was built to simulate the general flow characteristics under tides, currents and winds. It was set up with a vertical mesh based on sigma coordinates with six layers with equal thickness. The vertical layer structure of the water column can adequately resolve the tidal circulation associated with variable bathymetry.

Figure 5.1: Variable resolution flexible mesh (FM) for Regional North Sea model (RNSM)



Source: Mott MacDonald, 2023

Figure 5.2: Bathymetry of the Regional North Sea Model (RNSM)

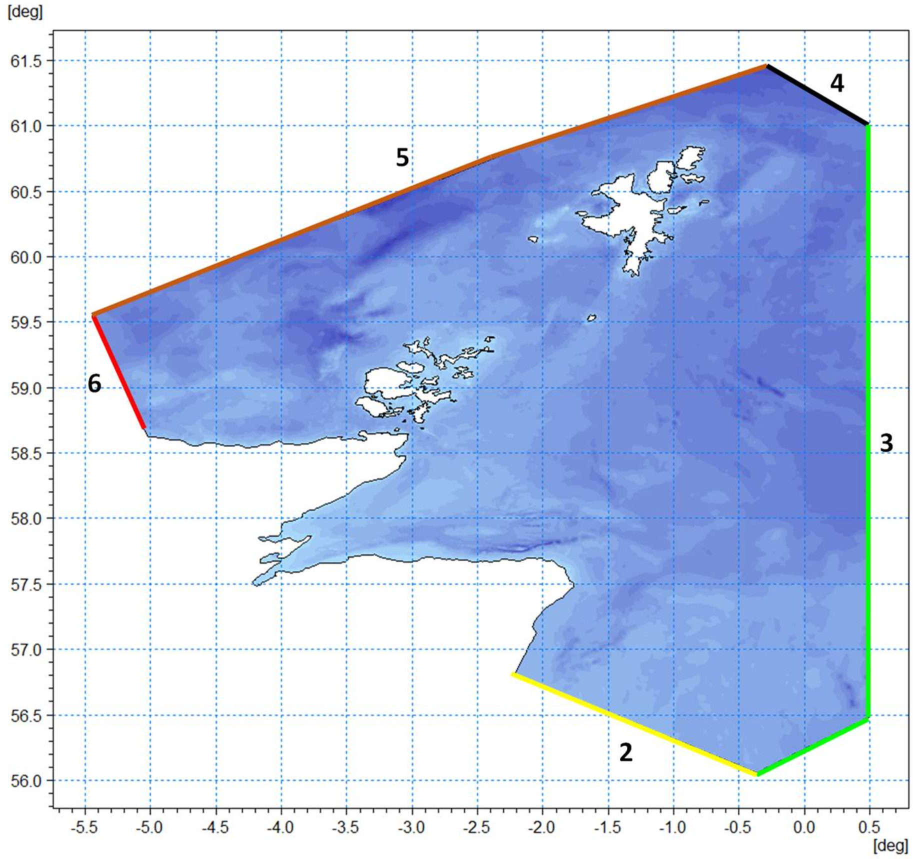


Source: Mott MacDonald, 2023

5.3 Boundary conditions

The MIKE global tide model of 0.125 x 0.125-degree grid resolution provided predictions of water level referenced to mean sea level using the ten major tidal constituents, including semi-diurnal M2, S2, K2, N2, the diurnal S1, K1, O1, P1 Q1 and the shallow water constituent M4. Model boundaries are defined by five unique boundary codes (Figure 5.3). The selected boundaries for the RNSM model are located far enough away from the study area to resolve the regional flow condition adequately.

Figure 5.3: RNSM boundary code definition



Source: Mott MacDonald, 2023

5.4 Guidelines for model performance

Guidelines to establish calibration standards for a minimum level of performance for coastal and estuarine hydrodynamic and sediment models are summarised in Table 5.1(Williams & Esteves, 2017). The guidelines are based on practical experience gained in projects and account for the frequent limitations imposed on model calibration processes and the accuracy and temporal and spatial resolutions of calibration data. Model conformity with these guidelines would not be expected at all locations in the model domain, and data availability may mean these criteria need to be relaxed.

The following model performance statistics have been used:

- Root Mean Square Error (RMSE) - measures the residuals between the model prediction and measured observation. A smaller value indicates a better agreement;
- Bias –expresses the difference between an estimator's expectations and the actual value of the parameter and can be defined as being equal to the mean error statistics in the data;
- Mean Absolute Error (MAE) – Measures the difference between two continuous variables. A smaller value indicates a better agreement; and
- Correlation (R) – Measures the agreement between measured and model prediction. A value of 1 is a perfect linear relationship.

Table 5.1: Example statistics to demonstrate the level of agreement between observed/simulated data and model prediction. O_i and S_i are the observed and simulated

values of a given parameter at time t_i, respectively, and N_i is the total number of data points

Quality Index	Statistical Parameter	Definition
Accuracy	Root Mean Square Error	$RMSE = \sqrt{\frac{1}{N_i}\sum_{i=1}^{N_i}(S_i - O_i)^2}$
Bias	Average Bias	$Bias = \frac{1}{N_i}\sum_{i=1}^{N_i}(S_i - O_i)$
Mean Error	Mean Absolute Error	$MAE = \frac{1}{N_i}\sum_{i=1}^{N_i}(S_i - O_i)$
Correlation	Pearson product-moment coefficient $\overline{O}_i = \frac{1}{N_i}\sum_{i=1}^{N_i} O_i$ and $\overline{S}_i = \frac{1}{N_i}\sum_{i=1}^{N_i} S_i$	$R = \frac{\sum_{i=1}^{N_i}(S_i - \overline{S}_i)(O_i - \overline{O}_i)}{\sqrt{\sum_{i=1}^{N_i}(S_i - \overline{S}_i)^2}\sqrt{\sum_{i=1}^{N_i}(O_i - \overline{O}_i)^2}}$

Source: Williams & Esteves, 2017

Considering model accuracy, the difference between the measured and modelled water level data should not generally exceed 10% of the measured level on the coast and up to 15 to 25% within an estuary. However, this will be highly variable depending on the parameter being considered and the accuracy of the calibration data used in the model. The accuracy of the modelled data can also be quantified using RMSE statistics (Table 5.2). The RMSE value is often expressed as a percentage, where lower values indicate less residual variance and, thus, better model performance. The bias expresses the difference between an estimator's expectation and the actual value of the estimated parameter. It can be defined as equal to the mean error in the data. Systematic bias reflects external influences that may affect the accuracy of statistical measurements.

The agreement or otherwise between measured/observed data and model prediction time series is frequently quantified using the Pearson product-moment correlation coefficient, R (Table 5.2). It is essential to test the statistical significance of the correlation coefficient.

Table 5.2: Statistical guidelines to establish calibration standards for a minimum level of performance for coastal and estuarine hydrodynamic and sediment models.

Predictions	RMSE	Bias	R
Water level (coast)	± 10% of the measured level.	< 0.10	> 0.95
Water level (estuary)	± 10% (mouth); ± 25% (head) of the measured level.	< 0.20	> 0.95
Water level phase (coast)	± 15% of the measured phase.	< 0.20	> 0.90
Water level phase (estuary)	± 15% (mouth); ± 25% (head) of the measured phase.	< 0.25	> 0.90
Average current speed	± 10% to 20% of the measured speed.	< 0.10	> 0.95
Peak current speed	Within <0.05m/s (very good), <0.1m/s (good); <0.2m/s (moderate) & < 0.3m/s (poor) of the measured peak speed.	< 0.15	> 0.90
Current direction (coastal)	± 10° of the measured direction.	< 0.25	> 0.90

Predictions	RMSE	Bias	R
Current direction (estuary)	± 15° of the measured direction.	< 0.30	> 0.90
Bed shear stress	± 10% N/m2 of the measured mean stress.	< 0.10	> 0.95

Source: Williams & Esteves, 2017

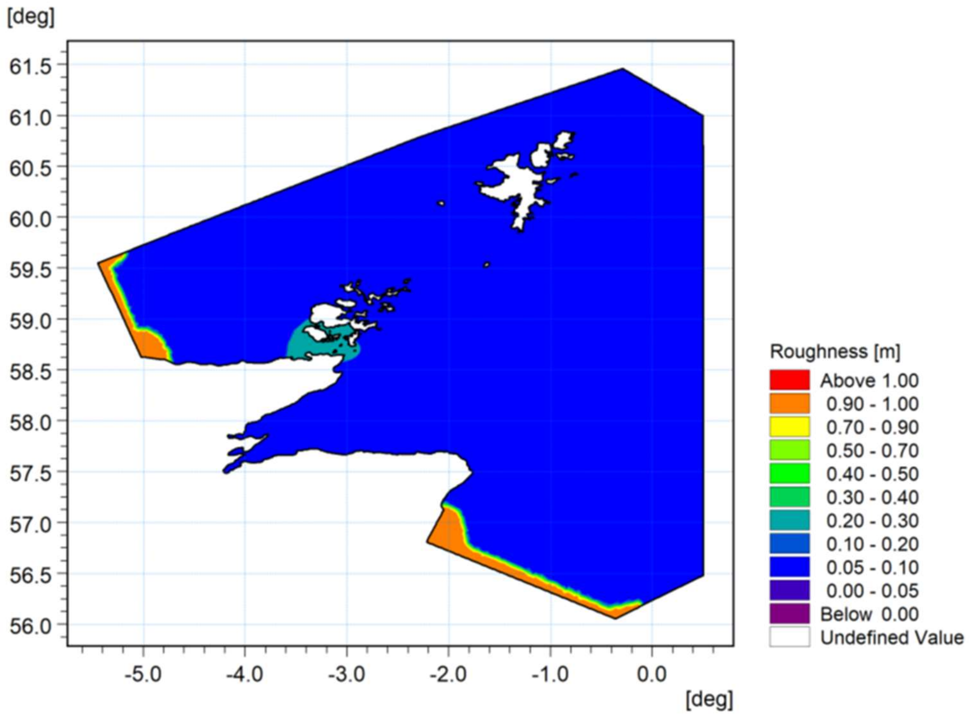
In addition to a visual intercomparison between model predictions and measured data, the statistical guidelines demonstrate the level of agreement between observed data and model predictions at a chosen location in the model domain.

5.5 RNSM calibration

5.5.1 Bed roughness

RNSM model calibration was undertaken from 3 to 19 February 2009 using water levels and current speeds data described in section 4.4. Values for bed friction were defined in the RNSM by the roughness length, which was varied iteratively to achieve the best agreement between measured and predicted water levels across the whole model domain. The calibration process included sensitivity simulations varying the roughness between 0.05 to 0.1m (within the recommended range). The calibrated RNSM adopted a uniform roughness of 0.1m throughout the model domain (Figure 5.4). However, a high roughness value of 1m was used along some of the boundaries (Figure 5.4) to eliminate numerical instabilities.

Figure 5.4: RNSM bed roughness map

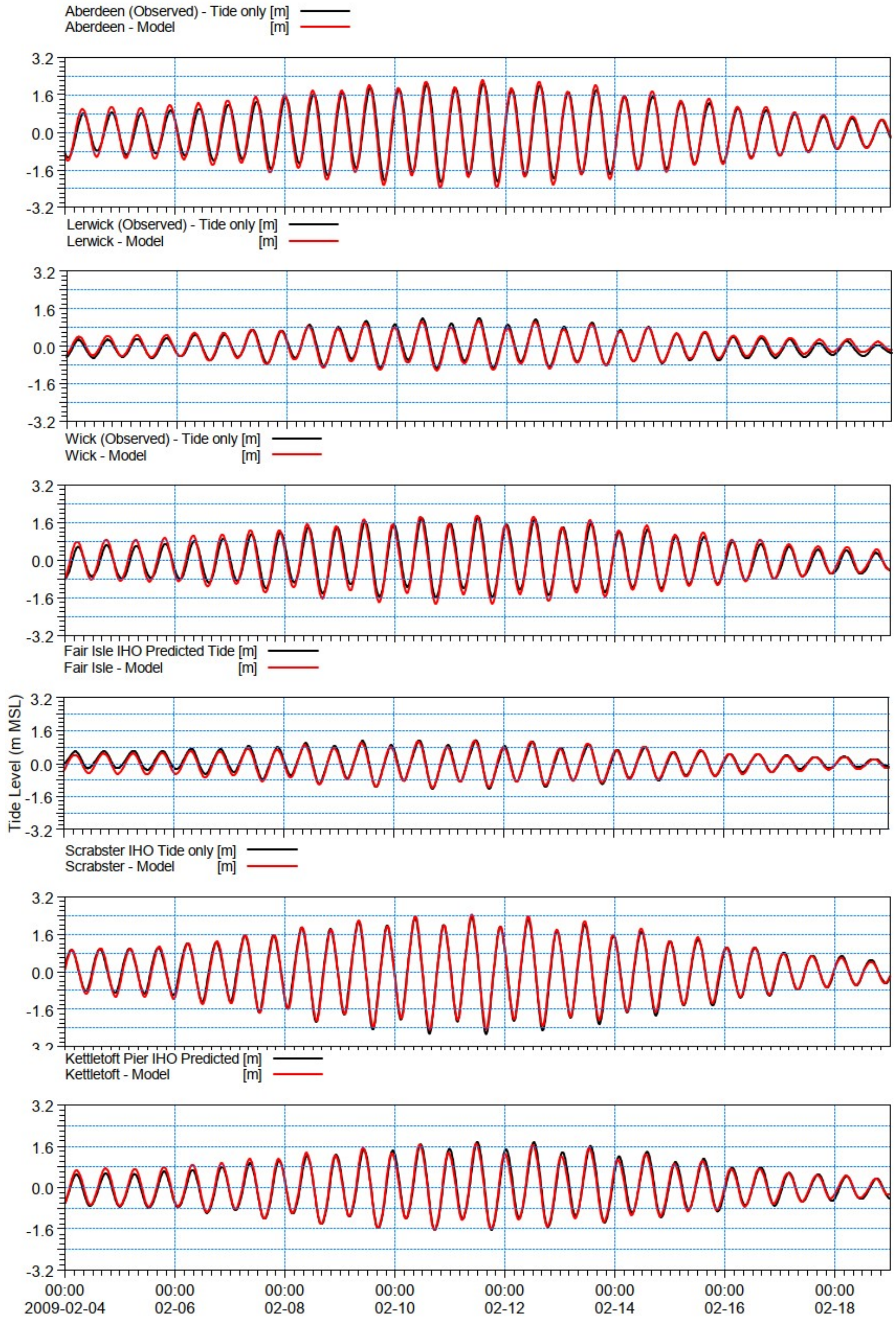


Source: Mott MacDonald, 2023

5.5.2 Water level

Measured water levels at Aberdeen, Lerwick and Wick and data from IOH stations at Fair Isle, Scrabster and Kettletoft are compared with the modelled water levels in Figure 5.5. The comparisons between the modelled and predicted water levels show a good visual agreement during the calibrated period.

Figure 5.5: Comparison between predicted and measured water level at Aberdeen, Lerwick and Wick and IOH stations.

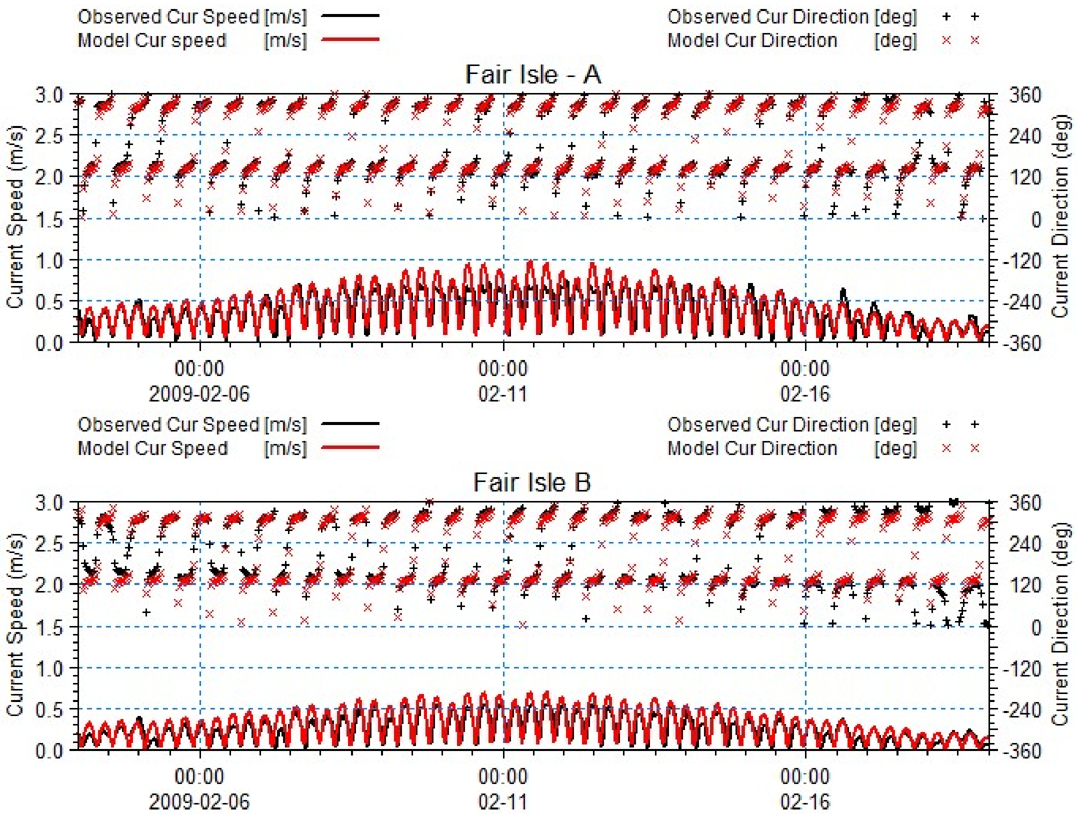


Source: Mott MacDonald, 2023. Contains BODC and IOH data.

5.5.3 Current speed and direction

The model was calibrated against measured tidal current speed and directions data at Fair Isle locations A and B (Figure 4.2, Table 4.2). The time series comparison of the measured current speed and direction against modelled (Figure 5.6) shows a reasonable fit. The current speed is overestimated by around 0.12 m/s at Fair Isle A and by 0.09m/s at Fair Isle B. Overall, it is considered that the currents speeds predicted by the model: (a) compare well against measured data; (b) meet expected model performance criteria (Table 5.2); and (c) demonstrate that model is well-calibrated.

Figure 5.6: Comparison between measured (black) and simulated (red) current speed and direction from the calibrated model at Fair Isle locations A and B from 4 to 19 February 2009.



Source: Mott MacDonald, 2023. Contains BODC data.

5.6 RNSM calibration error statistics

The error statistics for the water level data from the RNSM are shown in Table 5.3**Error! Reference source not found.**. The RMSE statistic shows good agreement with the observed data with RMS errors of less than 0.21m (i.e. a general difference of less than 6% of the observed spring tidal range). Overall model calibration is within the guideline RMS difference percentage of 10% for a coastal area. The overall correlation R between the predicted and the simulated value is 0.99 indicating a statistically significant fit and, therefore a good calibration.

Table 5.3: Water level error statistics for calibration of RNSM model (RMSE (%): +/- 10% of (coast) and +/- 25% of (estuary head); bias (m): < 0.10m (coast) and 0.20m; and R > 0.95m)

Tide Station	Bias (m)	MAE (m)	RMSE (m)	RMSE (%)	R
Aberdeen	-0.10	0.15	0.19	4.2	0.99
Lerwick	0.09	0.09	0.11	5.1	0.99
Wick	-0.01	0.19	0.21	6.0	0.98
Fair Isle	**0.06**	**0.09**	**0.11**	**5.0**	**0.99**
Kettletoft	0.00	0.08	0.10	2.0	1.00
Scravster	-0.03	0.11	0.13	3.9	0.99

Source: Mott MacDonald, 2023

Error statistics for the simulated current speeds (Table 4.4**)** show model correlation R values meeting expected performance. The difference in the RMS error percentage is less than 15% and is therefore acceptable when the input measured data's limitations are considered. The model performs well at all locations, with an RMS error of 0.15m/s and a correlation of 0.90 - 0.93.

Table 5.4: Current Speed error statistics for calibration of RNSM model (RMSE (%): +/- 10 to 20 % of current speed; Bias (m): <0.10m/s and <0.15m/s; and R > 0.95 and > 0.90)

Tide Station	Bias (m/s)	MAE (m/s)	RMSE (m/s)	RMSE (%)	R	Model performance metrics
Fair Isle A	-0.03	0.10	0.12	12.3	0.92	RMSE (%) : +/- 10 to 20 % of cur speed; Bias (m): <0.10m/s and <0.15m/s; and R > 0.95 and > 0.90
Fair Isle B	-0.05	0.08	0.09	13.4	0.92	

Source: Mott MacDonald, 2023

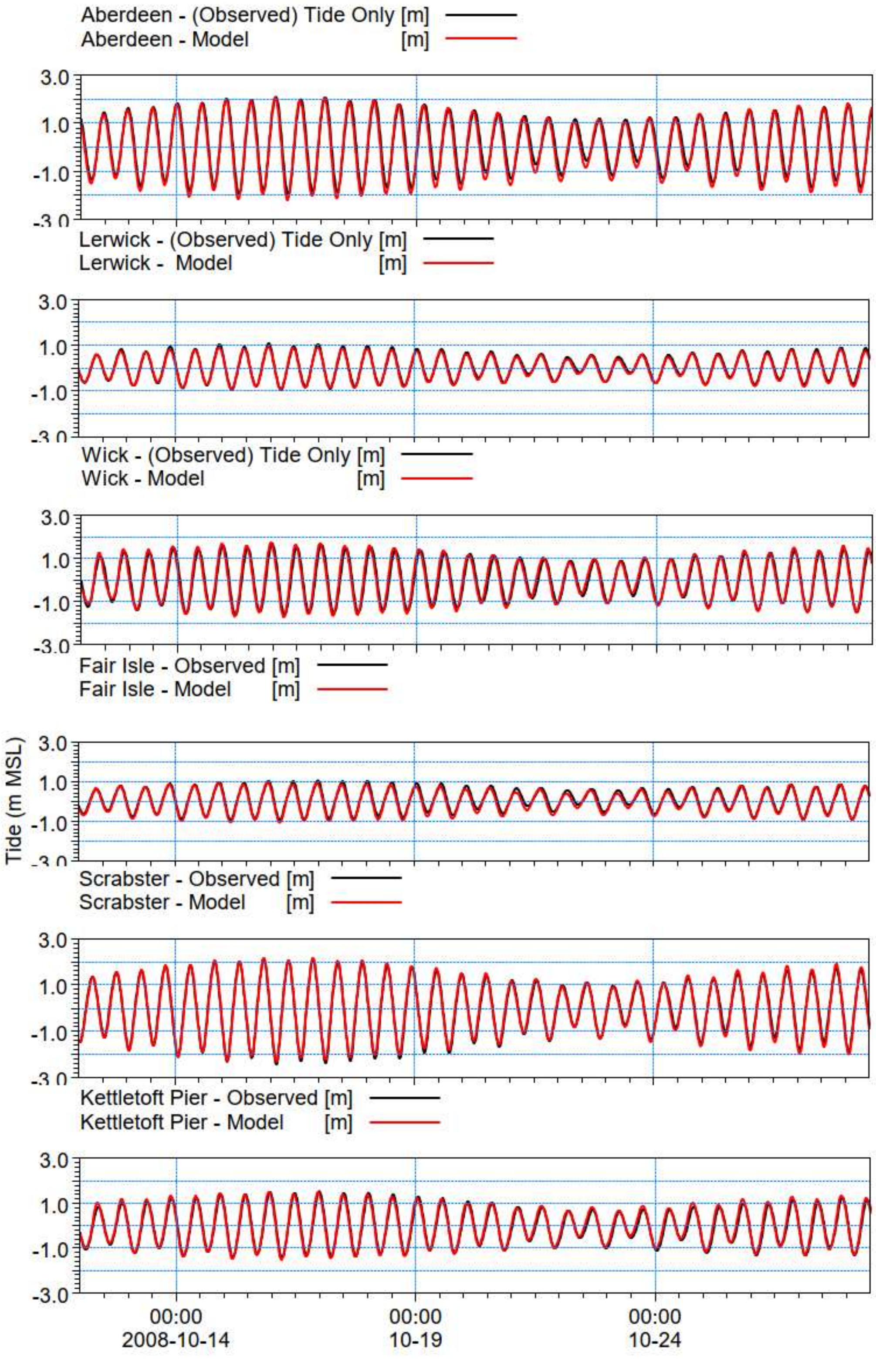
5.7 RNSM validation

Model validation with the observed data from a different period provides confidence in the model build and calibration accuracy. Irrespective of period and location, the model should replicate the tidal and current speed characteristics compared with the measured data.

5.7.1 Water level

Time series of simulated and observed water levels at tide stations from 12 October to 28 October 2008 show good visual agreement (Figure 5.7). The difference in the simulated water levels ranged between 2.5 to 6.5% at the validation stations. The overall correlation R between the predicted and the simulated value is 0.99 indicating a statistically significant fit. Error statistics and visual comparison of model results during the validation period show good calibration when simulated for different periods. The statistical bias between the simulated and astronomical stations is less than 0.12m at all tide stations. The model shows a good correlation between the predicted and the simulated tide, which is around 0.99.

Figure 5.7: Comparison between measured (black) and predicted (red) water levels at Aberdeen, Lerwick and Wick and IOH stations for validation period 12 to 28 October 2008.



Source: Mott MacDonald, 2023. Contains BODC and IOH data.

Table 5.5: Water level error statistics for calibration of RNSM model (RMSE (%): +/- 10% of (coast) and +/- 25% of (estuary head); Bias (m): < 0.10m (coast) and 0.20m; and R > 0.95m).

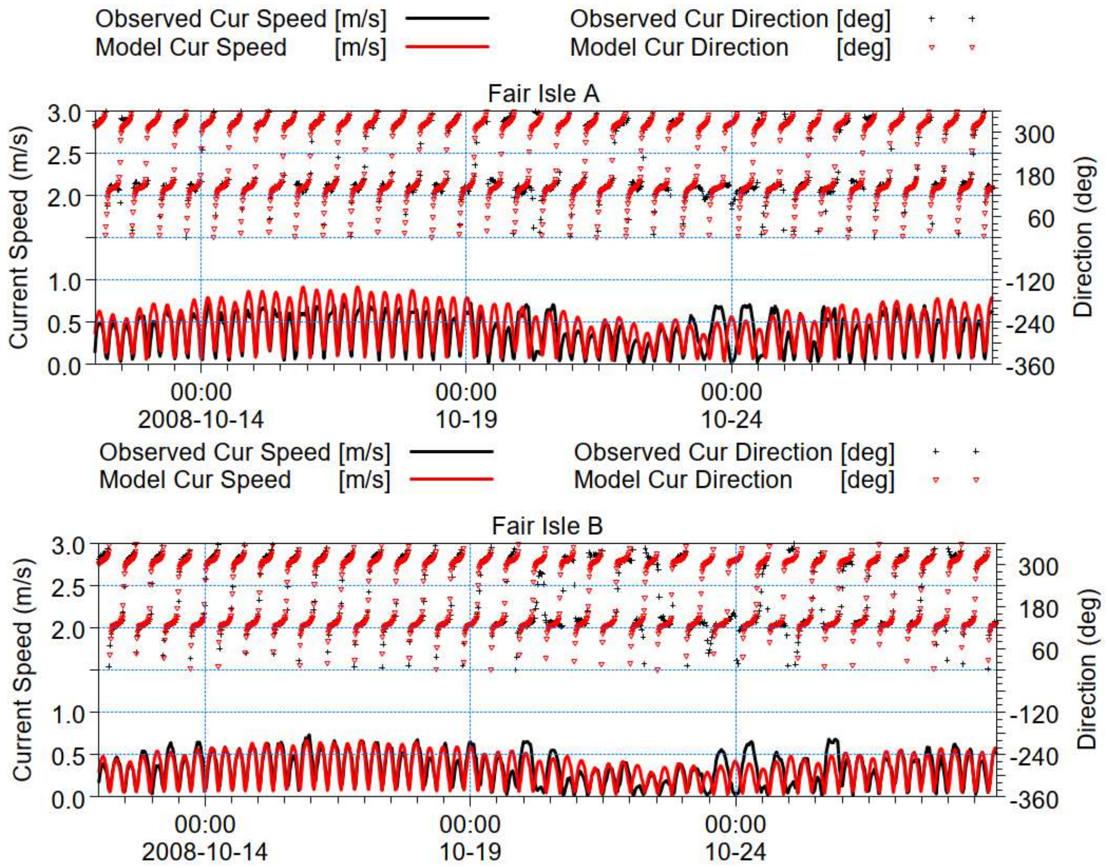
Tide Station	Bias (m)	MAE (m)	RMSE (m)	RMSE (%)	R
Aberdeen	0.12	0.20	0.24	5.6	0.99
Lerwick	0.05	0.06	0.07	4.0	0.99
Wick	-0.01	0.19	0.22	6.4	0.99
Fair Isle	0.08	0.10	0.12	6.1	0.99
Kettletoft	-0.01	0.09	0.11	2.5	1.00
Scravster	-0.03	0.12	0.14	4.8	0.99

Source: Mott MacDonald, 2023

5.7.2 Current speed and direction

The time-series plot in Figure 5.8 compares measured and predicted current speed and direction at the Fair Isle station A and B locations (Figure 4.2, Table 4.2). These plots demonstrate visually good agreement between measured and modelled current speed and direction. The model performs well in reproducing the current speed at both stations. The current speeds at Fair Isle station A are observed to have marginally higher current speeds, but in general, the model comparison is good. Small deviations from the observed speeds are attributable to other non-astronomical factors, such as wind and instrumental limitations. While the peak current speeds are marginally under-predicted at times, this would tend to reduce the transport and dispersion in the model and thus is conservative.

Figure 5.8: Comparison between measured (black) and predicted (red) current speed direction at Fair Isle locations A and B for the validation period 12 to 28 October 2008.



Source: Mott MacDonald, 2023. Contains BODC data

5.8 RNSM validation error statistics

Table 5.6 shows the error statistics for the validation period. The model performance is satisfactory at both stations, having an RMS error of 0.16m/s and 0.11 m/s and a corresponding correlation of 0.85 and 0.89. Overall the data in Table 5.6 confirm the model calibration is good for spring and neap tides.

Table 5.6: Current speed error statistics for calibration of RNSM model (RMSE (%): +/- 10 to 20 % of current speed; Bias (m): <0.10m/s and <0.15m/s; and R > 0.95 and > 0.90).

Tide Station	Bias (m/s)	MAE (m/s)	RMSE (m/s)	RMSE (%)	R
Fair Isle A	-0.09	0.13	0.16	17.50	0.85
Fair Isle B	0.00	0.09	0.11	17.00	0.89

Source: Mott MacDonald, 2023

6 Local hydrodynamic Model

6.1 Introduction

A detailed local MIKE3 FMHD model of North Haven was set up to resolve the site's features. Using a flexible mesh (FM) in the MIKE3 HD (hydrodynamic) model for North Haven allows the resolution to be varied across the model domain. This approach allows higher resolution in the areas of interest and reduces resolution further away or in areas with less variability in the bathymetry. This approach makes the model computationally more efficient than having a fixed resolution everywhere. The HD model is later coupled with the MIKE21 FMSW wave model and Sand Transport and Mud Transport modules described in Chapters 8 and 9, respectively.

6.2 Model set up

Although the local MIKE3 FMHD model set up follows almost the same process as the one described in Chapter 5 for the regional model, several changes were necessary, as described below.

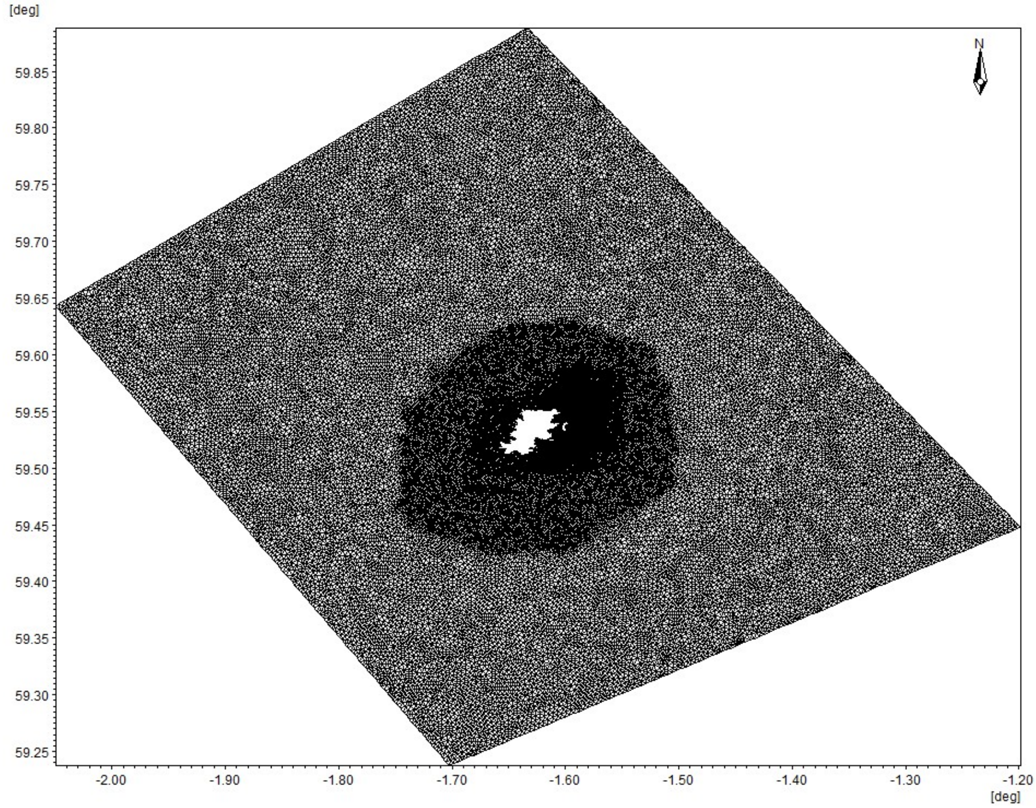
6.2.1 Horizontal and vertical references

In common with the regional model, the local model was set up using a Geographic coordinate system based on the WGS84 horizontal datum. The vertical reference datum used was Ordnance Datum Newlyn, which is 0.92m above Chart Datum at North Haven, Fair Isle.

6.2.2 Local model mesh and extent

The local MIKE3 FMHD model mesh extends 20 km around Fair Isle. Figure 6.1 and Figure 6.2 show the overall model mesh and details of the high resolution around the project site, respectively. The local model mesh is generally fine, with a resolution of approximately 200m at the boundary to 2m at North Haven. This mesh can resolve the existing structures and features at the site adequately. The local model was set up with a vertical mesh based on sigma coordinates with two layers with equal thickness. The vertical layer structure of the water column can adequately resolve the tidal circulation associated with variable bathymetry.

Figure 6.1: Local MIKE3 FMHD model domain and mesh



Source: Mott MacDonald, 2023

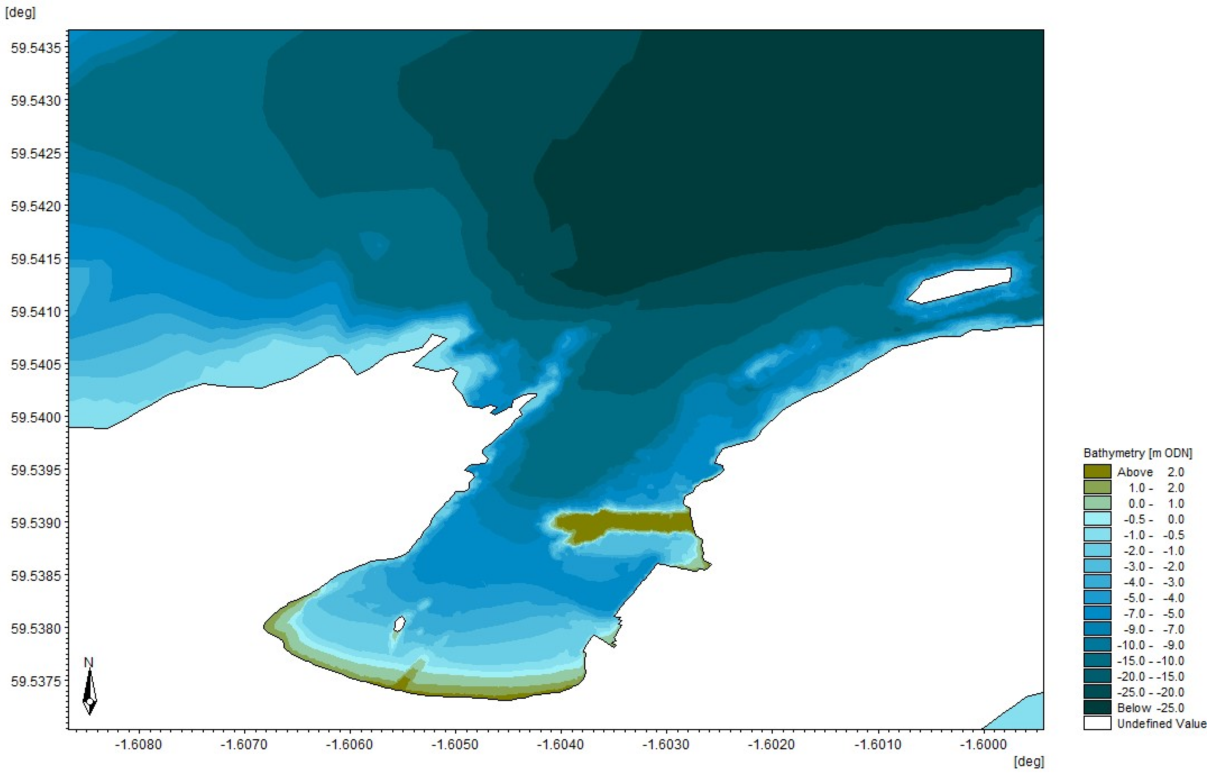
Figure 6.2: Refined local MIKE3 FMHD model mesh at North Haven

Source: Mott MacDonald, 2023

6.2.3 Local model bathymetry

The local model bathymetry used the same dataset described in Section 4.3. The data were interpolated onto the local model mesh to define the bathymetry across the local model domain. Figure 6.3 shows the detailed bathymetry around the study area at North Haven.

Figure 6.3: Detailed model bathymetry in the study area.



Source: Mott MacDonald, 2023. Contains data from the Aspect Ltd survey in June 2022.

6.2.4 Model boundary conditions

Model boundary conditions defining water levels and current speeds were obtained from the calibrated RNSM model and applied to the local model boundaries.

6.2.5 Bed roughness

As per the RNSM model, a uniform roughness of 0.1m was applied across the local model domain

6.2.6 Eddy viscosity

Eddy viscosity expresses the distribution of shear stress in a fluid and is related to the amount of flow turbulence. The local MIKE3 FMHD model used a horizontal eddy viscosity with a constant Smagorinsky (CS) formulation with the recommended CS value of 0.28.

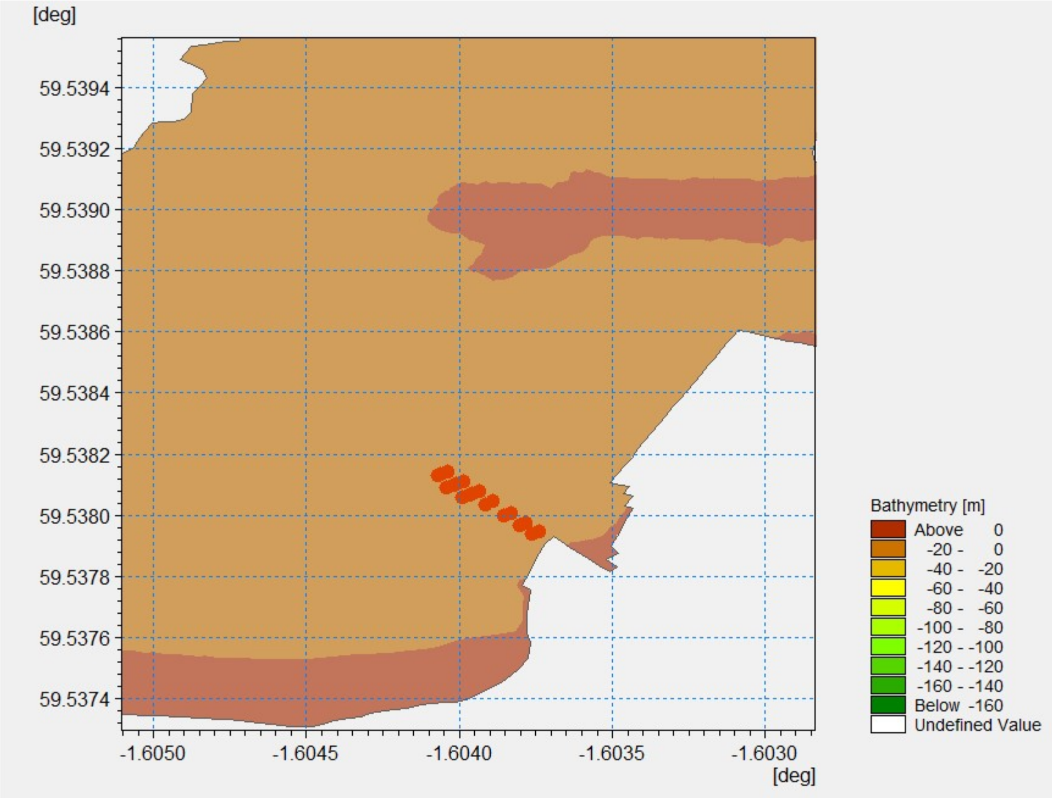
6.2.7 Structures

The existing structures at North Haven include:

- Breakwater – this rocky structure is included in the model bathymetry and interacts directly with the modelled water levels and currents;

- Pier – the individual piles of the pier are included in the model as subgrid structures (Figure 6.4). A simple drag law in the model captures the increasing resistance imposed by the piers as the flow speed increases; and
- Slipway – The slope of the slipway is also included in the model bathymetry.

Figure 6.4: Individual piles included in the local model as subgrid structures representing the existing pier.

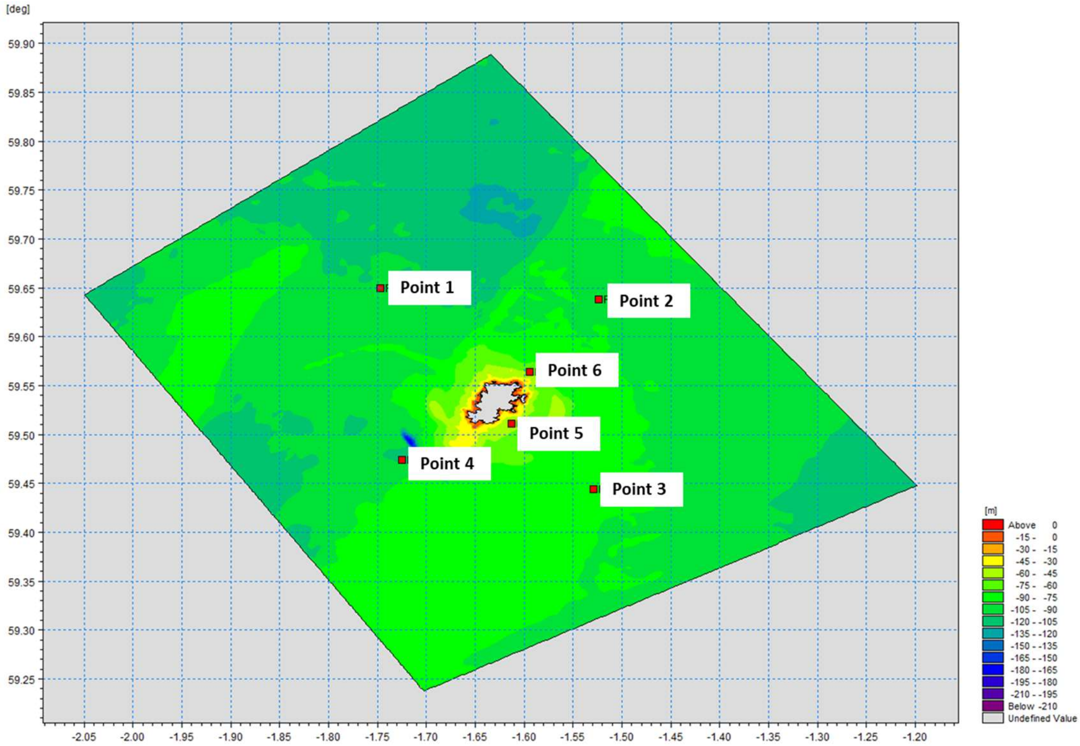


Source: Mott MacDonald, 2023

6.3 Hydrodynamic model validation

No measured water level or current speed/direction data was used to calibrate the local MIKE3 FMHD model. Instead, the local model results were validated at six locations (Figure 6.5) using the results from the RNSM. This work demonstrated that the local model correctly simulated water levels and current speeds.

Figure 6.5: Extraction points for validation of the local MIKE3 FMHD model



Source: Mott MacDonald, 2023

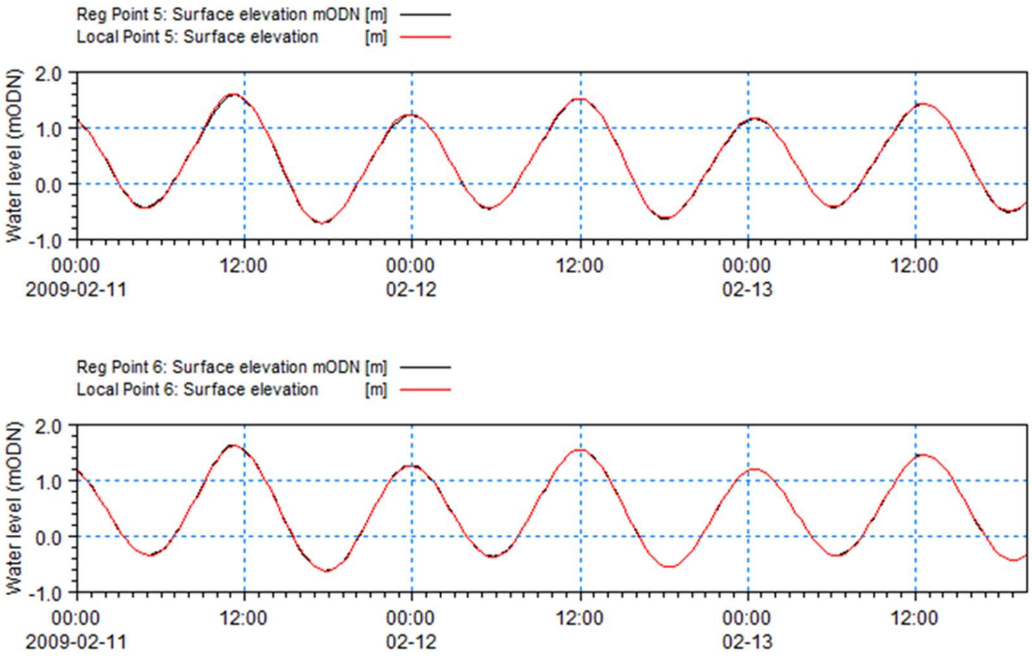
6.3.1.1 Water levels

The water level validation of the local MIKE3 FMHD model is shown in Figure 6.6 for Points 5 and 6. Additional validation plots are included in Appendix A. The results are very similar to those for the RNSM. They show that the local model represents the tide correctly over its domain and is considered to be validated.

6.3.1.2 Current speed and direction

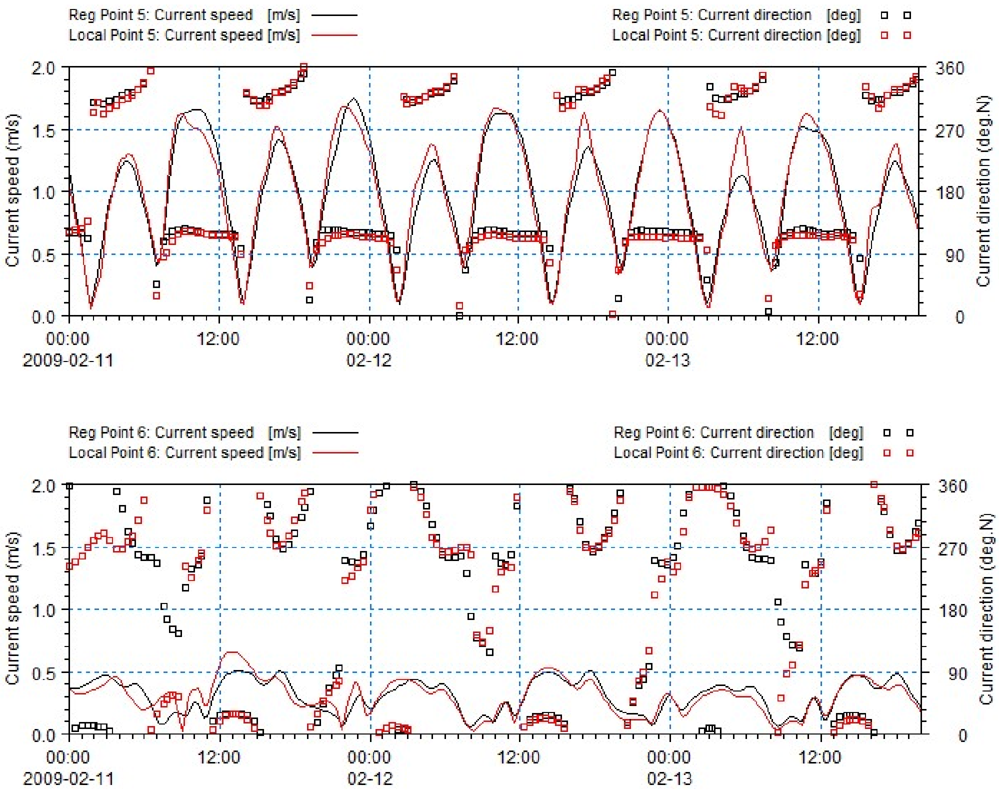
The current speed validation for the local model is shown in Figure 6.7 for Points 5 and 6. Additional validation plots are included in Appendix A. Figure 6.7 shows that the model reproduces the current speed at both sites compared to the RNSM results. The predicted currents from the local model (red) are generally slightly larger than the regional model results (black). This difference is attributed to the better resolution of bathymetry around Fair Isle in the local model.

Figure 6.6: Comparison between regional (black line) and local (red line) water levels for the validation period of the local model (Points 5 and 6).



Source: Mott MacDonald, 2023

Figure 6.7: Comparison between regional (black line) and local (red line) current speeds and direction for the validation period of the local model (Points 5 and 6).



Source: Mott MacDonald, 2023

7 Local hydrodynamic model results

7.1 Introduction

The local MIKE3 FMHD model was run for 17 days, covering a full spring-neap tidal cycle to quantify and understand the baseline hydrodynamic conditions at the study site. The model was also run for the same period with the new proposed layout included to enable the identification of potential changes brought about by the new structures.

7.1.1 Baseline conditions

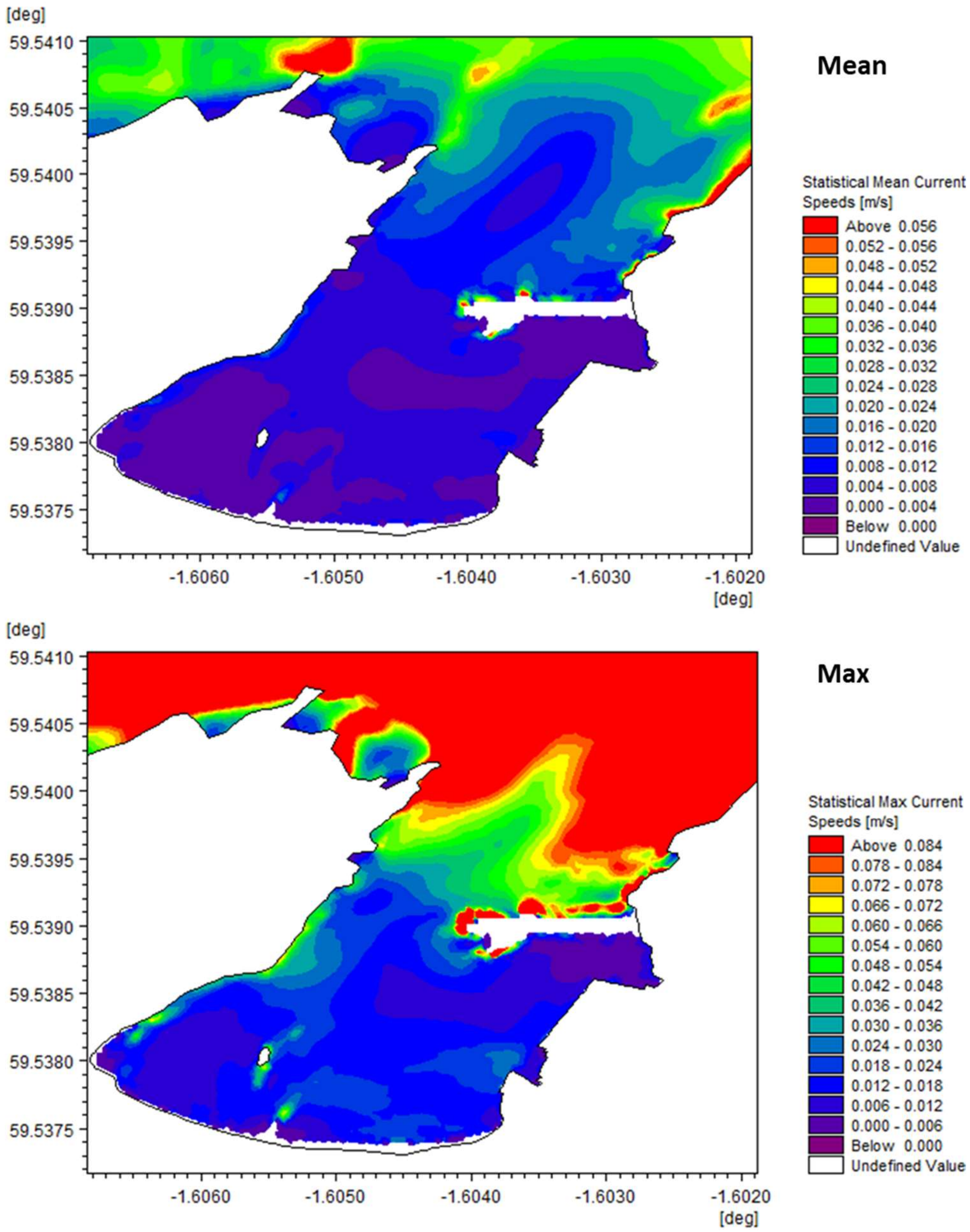
Maximum and mean current speeds during a spring-neap cycle at North Haven are shown in Figure 7.1. This figure shows that the maximum currents in the bay of 0.02 to 0.03m/s are small. Isolated locations around the existing structures in the bay show higher maximum current speeds up to 0.05 to 0.08m/s. The mean current speed inside the bay is generally very low, with velocities below 0.01m/s (Figure 7.1).

Figure 7.2 shows the spatial distribution of current speeds at the site for peak flood and ebb flows during the spring tides. Peak flood current speeds are slightly higher than ebb peak speeds. However, current speeds in the bay are generally small, with higher and more variable current speeds in the outer bay, on the northern side of the breakwater. Figure 7.2 shows that current speeds in the middle of the bay are around 0.01 to 0.015m/s during the flood tide, while during the ebb phase, peak currents do not exceed 0.01m/s.

Similarly, Figure 7.3 shows the spatial distribution of current speeds at the site for peak flood and ebb flows during the neap tides. As expected, neap tide current speeds are smaller than the spring tide case. However, this difference is more evident in the outer bay, north of the breakwater. In the inner bay area, the flood tide's current speeds are slightly larger. However, for both flood and ebb flows during neap tide conditions, current speeds do not exceed 0.01m/s.

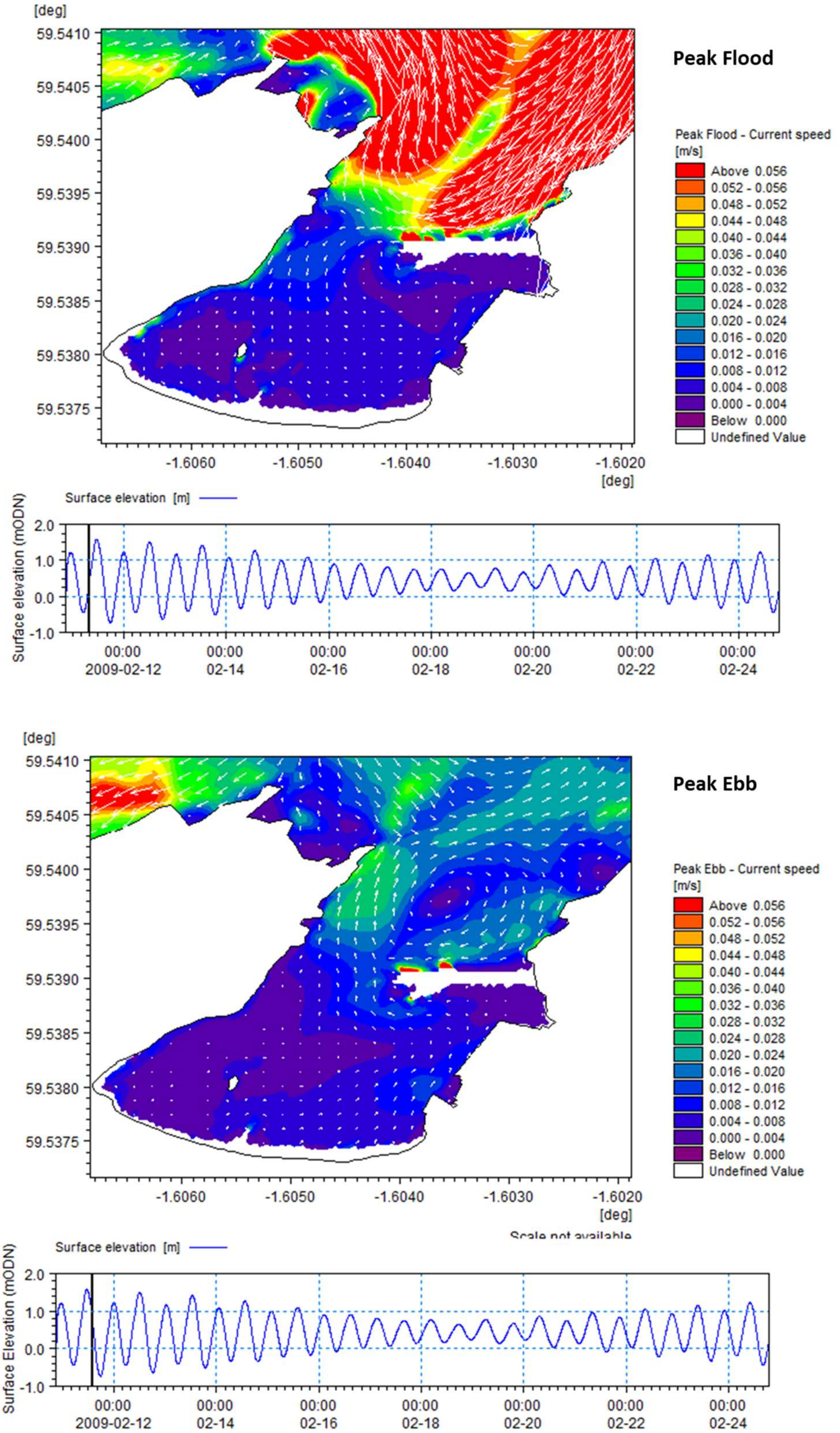
Figure 7.2 and Figure 7.3 also show how the bay tends to have a flow circulation. This circulation is attributed to the existing breakwater obstructing tidal flows entering and leaving the embayment.

Figure 7.1: Mean and maximum current over a spring-neap cycle for North Haven. Please note that the two figures do not have the same colour scale.



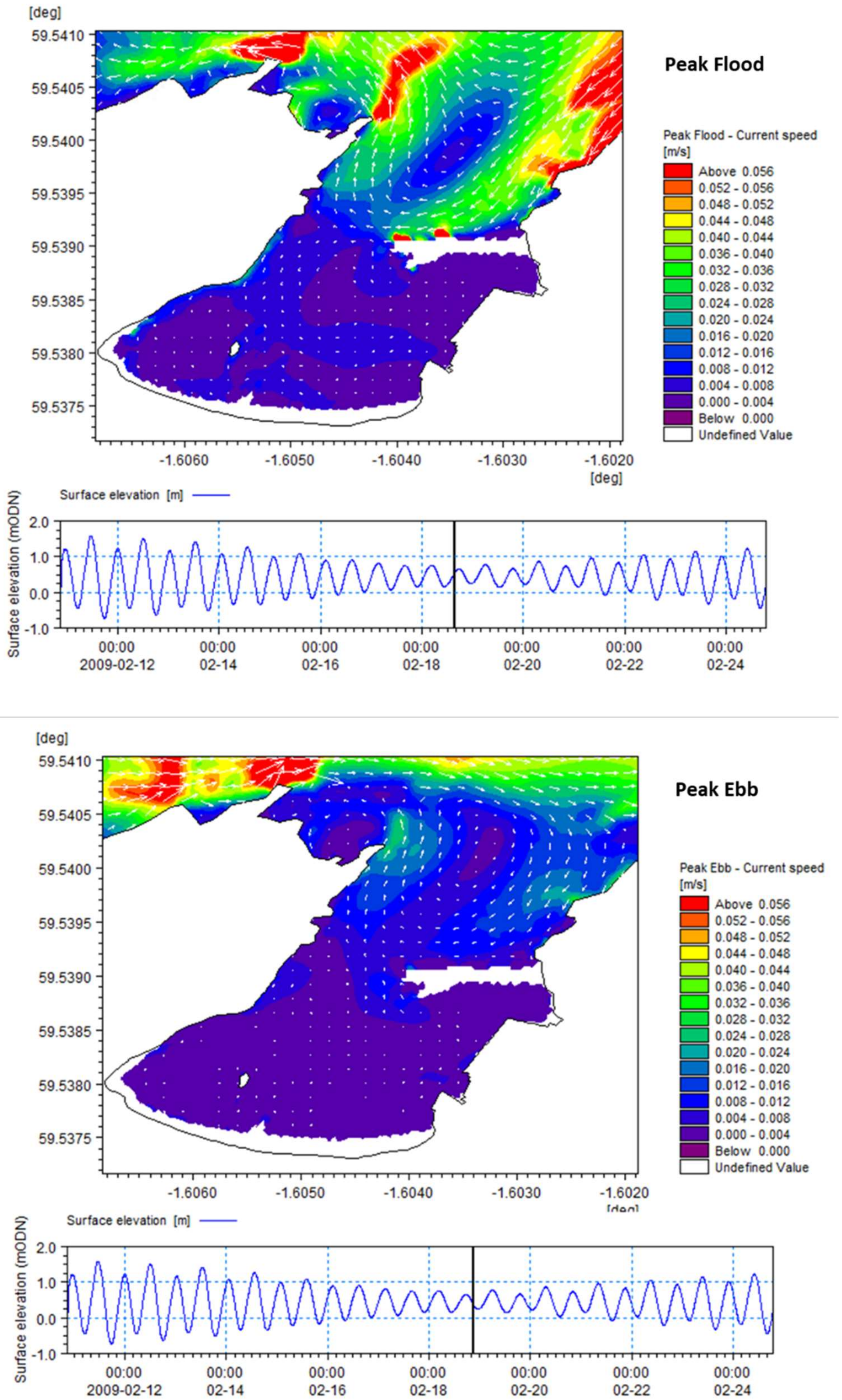
Source: Mott MacDonald, 2023

Figure 7.2: Peak flood and peak ebb depth-averaged current speeds at North Haven, Fair Isle, under spring tide conditions. The water level time series has been extracted north of the breakwater in the middle of the outer bay.



Source: Mott MacDonald, 2023

Figure 7.3: Peak flood and peak ebb depth-averaged current speeds at North Haven, Fair Isle, under neap tide conditions. The water level time series has been extracted north of the breakwater in the middle of the outer bay.



Source: Mott MacDonald, 2023

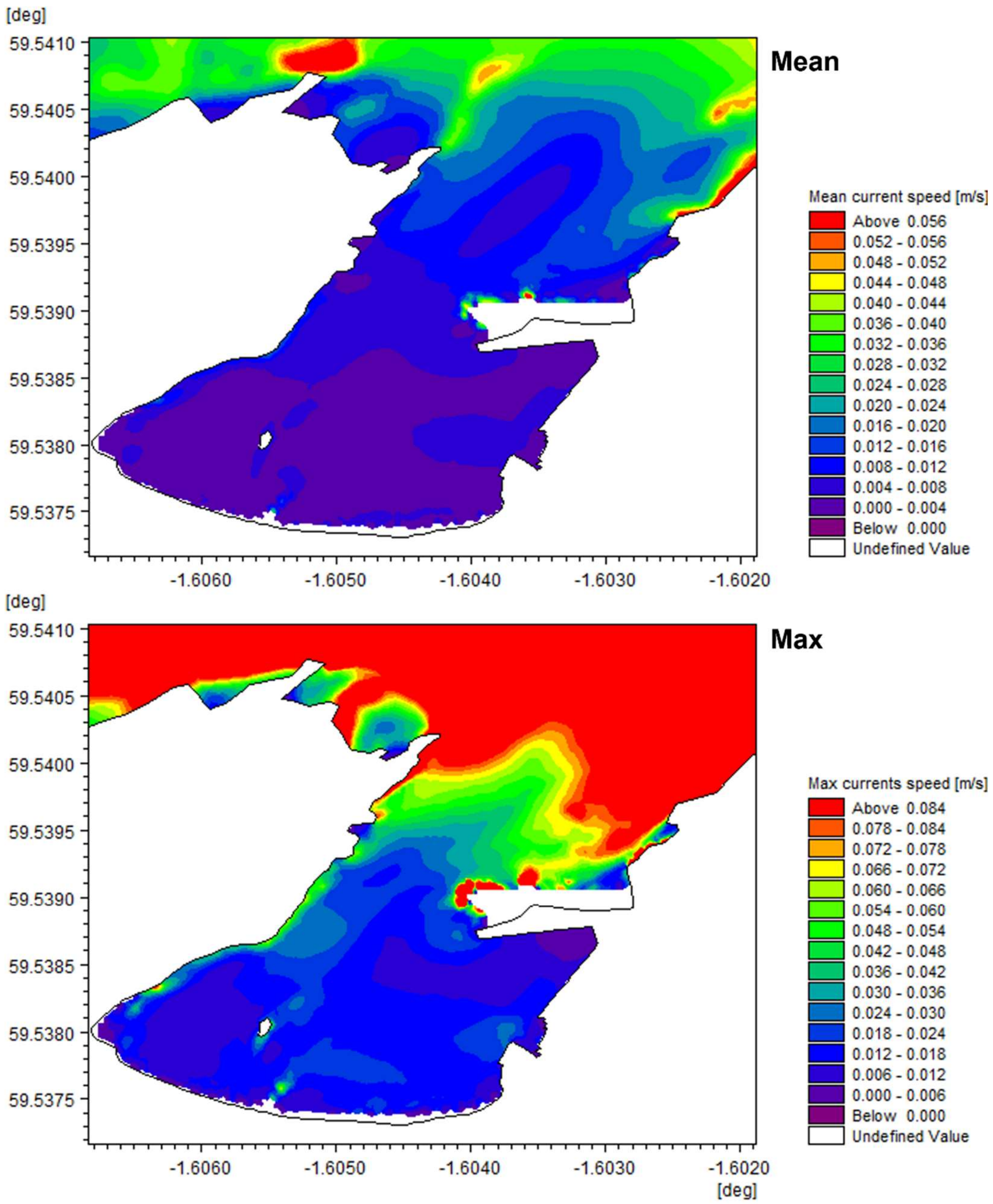
7.1.2 Proposed new layout

Maximum and mean current speeds during a spring-neap cycle at North Haven are shown in Figure 7.4. Figure 7.5 shows the spatial distribution of current speeds at the site for peak flood and ebb flows during the spring tides with the new layout. Results are visually indistinguishable from the baseline case (Figure 7.2). Peak flood currents are slightly higher than peak ebb speeds, especially in the outer bay. Figure 7.5 shows that current speeds in the middle of the bay are in the range 0.01 to 0.015 m/s during the flood tide, while during the ebb phase, peak currents do not exceed 0.01m/s.

Similarly, Figure 7.6 shows the spatial distribution of current speeds at the site for peak flood and ebb flows during the neap tides with the new layout.

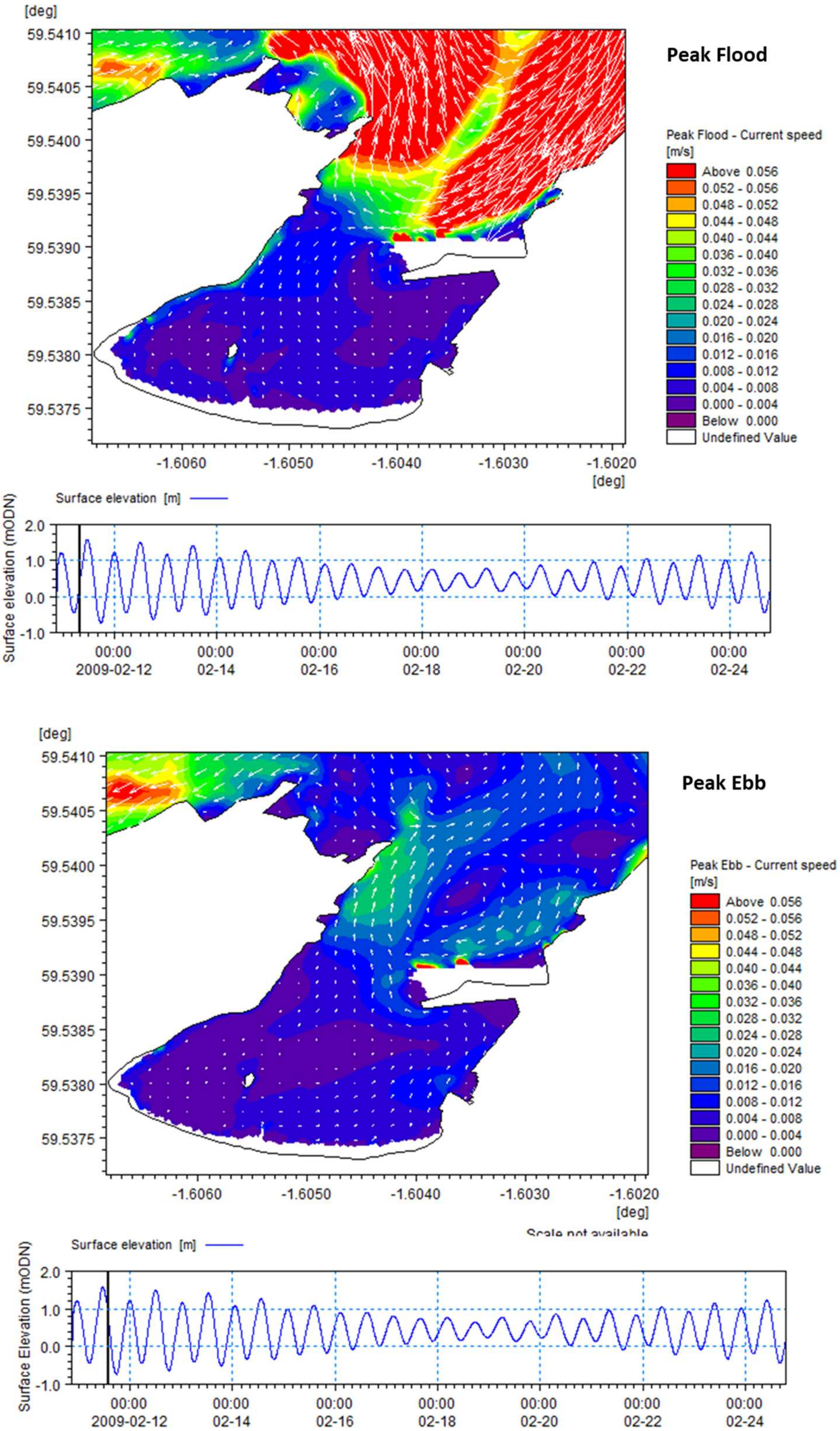
As per the baseline, Figure 7.5 and Figure 7.6 also show how the bay tends to have a current circulation due to breakwater obstructing both the entering and leaving of the flood and ebb flows and causing the flows to split.

Figure 7.4: Mean and maximum current over a spring-neap cycle for North Haven. Please note that the two figures do not have the same colour scale – Proposed layout



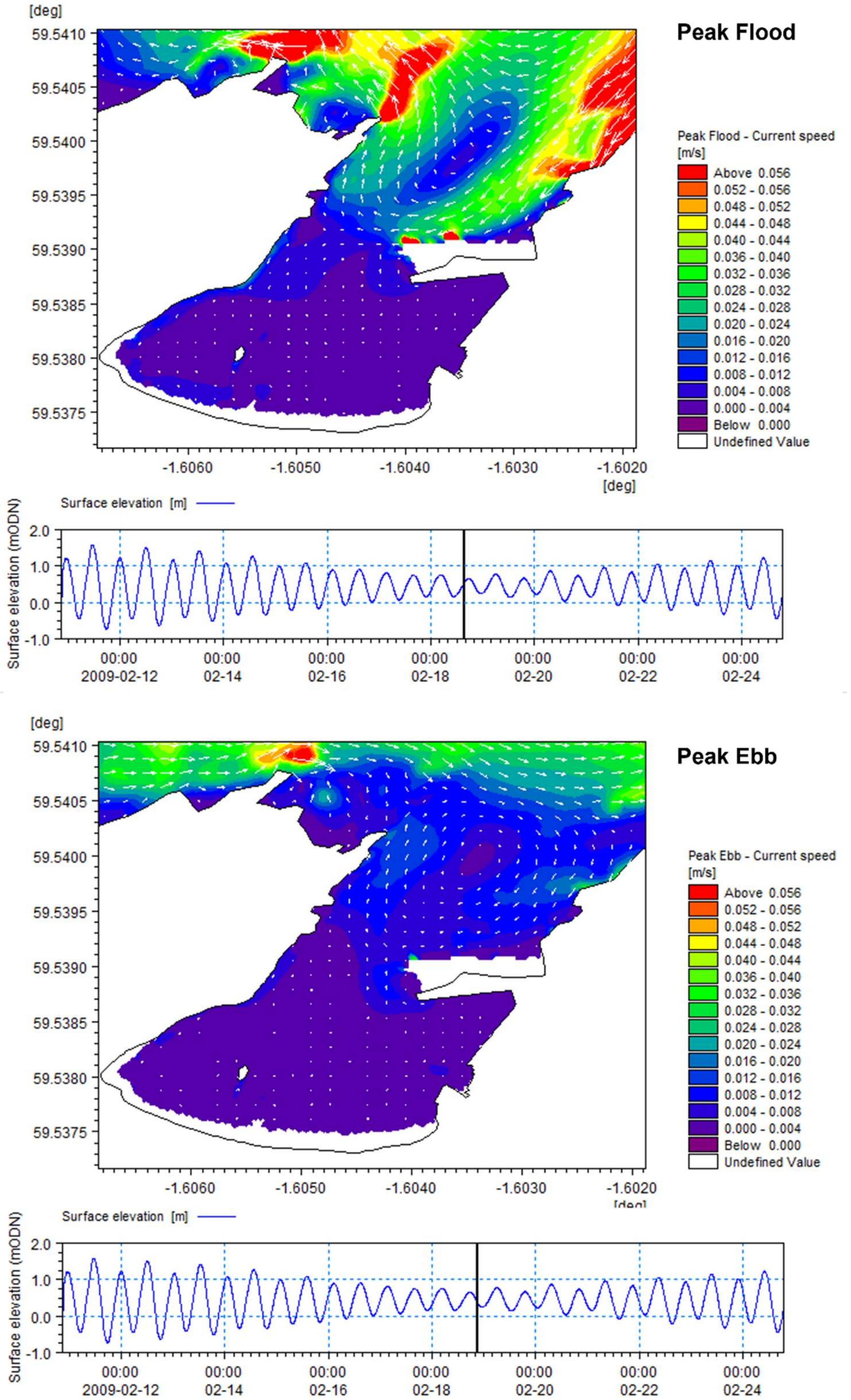
Source: Mott MacDonald, 2023

Figure 7.5: Peak flood and peak ebb depth-averaged current speeds for North Haven, Fair Isle under spring tide conditions. The water level time series has been extracted at a point north of the breakwater in the middle of the outer bay – Proposed layout



Source: Mott MacDonald, 2023

Figure 7.6: Peak flood and peak ebb depth-averaged current speeds at North Haven, Fair Isle, under neap tide conditions. The water level time series has been extracted at a point north of the breakwater in the middle of the outer bay – <u>Proposed layout</u>



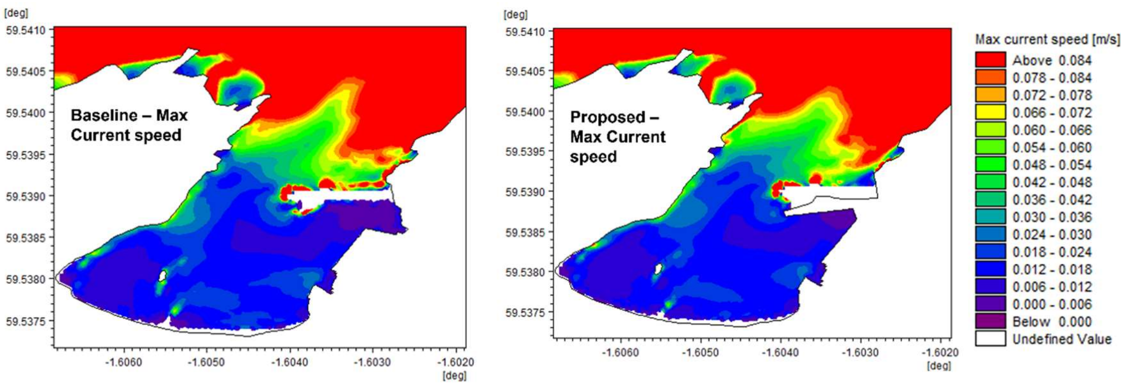
Source: Mott MacDonald, 2023

7.1.3 Changes to hydrodynamic conditions

The results of the local hydrodynamic model, for both the baseline and the proposed layout, in terms of current speeds, are shown together from Figure 7.7 to Figure 7.9. These figures aim to provide a direct comparison of the results and identify the potential impacts of the new layout.

Figure 7.7 shows the change in maximum current speed between the baseline and scheme. It can be seen a very small reduction in the current speeds at the project, around 0.06m/s in some locations.

Figure 7.7: Comparison in maximum current speed for baseline and proposed layout.



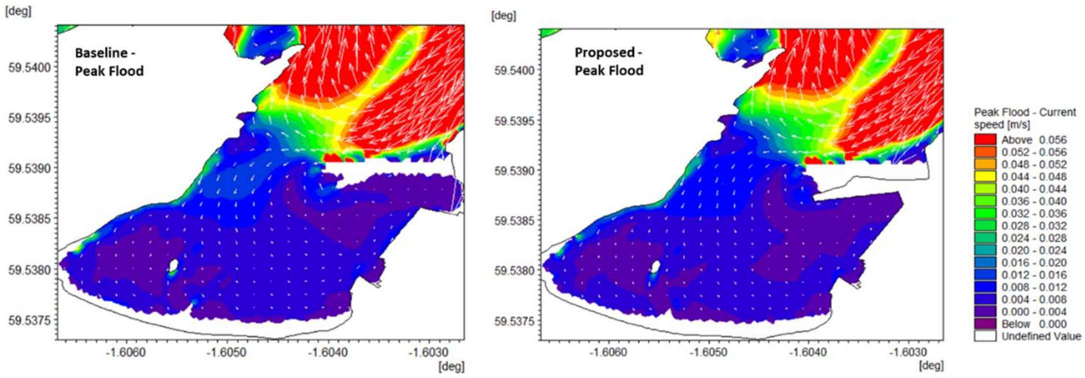
Source: Mott MacDonald, 2023

Figure 7.8 shows the peak spring tide flood current speed and direction for the baseline and the layout simulations. The figure shows that it is difficult to distinguish any differences in the peak flood current speed and direction between the baseline and the scheme. Small differences that can be seen show:

- A small change in flow velocity at the western end of the breakwater, where the flood flows tend to create a circulation; and
- A small change in the current speed in front of the new quay is attributable to the new dredged pocket.

There are no changes in peak current speeds in the inner bay and close to the shore. There is also no increase in peak flood current speeds. The impact of the new layout on the local hydrodynamic regime is therefore shown to be insignificant.

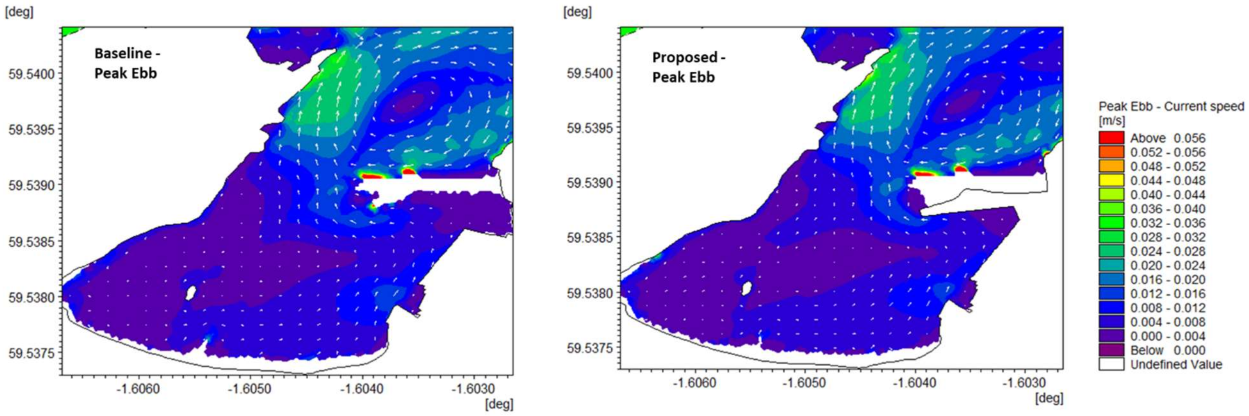
Figure 7.8: Comparison of spring tide peak flood current speed for baseline and proposed layout.



Source: Mott MacDonald, 2023

Figure 7.9 shows the spring tide peak ebb flows for the baseline and the layout simulations. The figure shows only a small change in the current distributions in the inner bay, potentially due to the new dredged pocket and the new quay. There is no detected increase in peak ebb current speeds. These results add further evidence to show that the impact of the new layout is insignificant.

Figure 7.9: Comparison of spring tide peak ebb current speed for baseline and proposed layout.



Source: Mott MacDonald, 2023

Since, as previously shown, current speeds during neap tides are very small, a comparison of neap tide peak ebb and flood conditions for the baseline and scheme cases is not presented here.

The results shown in Figure 7.7 to Figure 7.9 provide compelling evidence that the new layout has minor effects on the hydrodynamic regime in North Haven. This result is unsurprising since the scheme only involves raising the breakwater's elevation and adding a new quay to an area that is already extremely sheltered.

8 Sediment transport

8.1 Introduction

With the aim of defining further the baseline conditions for the study area and determining the impacts of the proposed development on local sediment processes, a local sand transport local model was set up for North Haven. The model comprised several dynamically linked modules, including (a) the local MIKE3 FMHD model; (b) the local MIKE21 FMSW model (Mott MacDonald, 2023); and (c) the MIKE Sand Transport (ST) module. The model was run for three days using a morphological wave approach to capture the longer-term dynamics of the bed sediments in North Haven.

8.2 Sand Transport (ST) module

The sand transport model assumed:

- Uniform medium sand with a median grain diameter (D50) of 0.275mm over most of the model domain;
- Courser sediments on the upper beach (D50 = 0.3025mm);
- The gravel on the upper beach is immobile;
- A uniform sediment grading of 1.9 over the model domain;
- The available sediment at North Haven is limited to 5m depth; and
- The model has zero sediment flux gradients at the boundaries.

8.3 Wave analysis

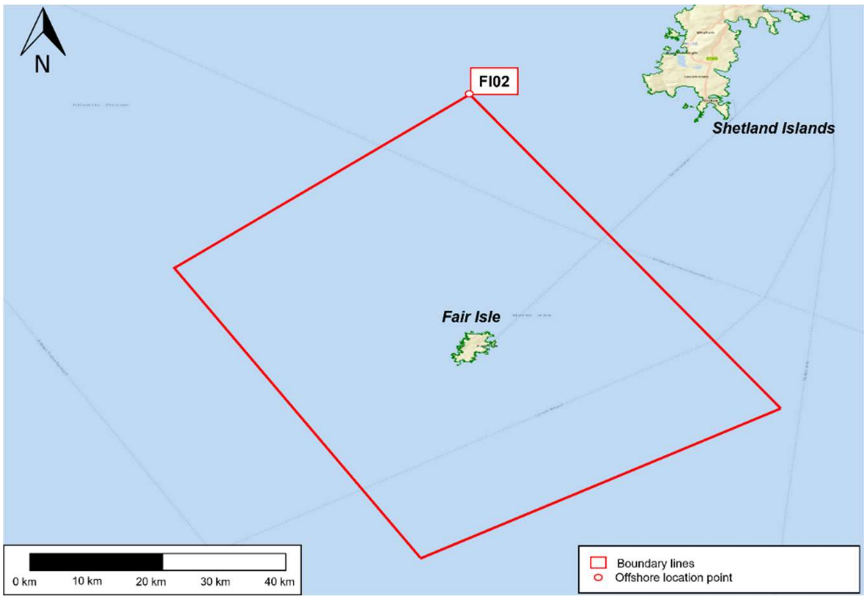
To better understand sediment mobility and how the new layout may impact sediment dynamics, the sediment model was run using a *morphological wave* and 1 in-1-year wave conditions. This approach, described below, is frequently used when considering how sea bed sediment may respond to new developments over medium to long periods.

8.3.1 Morphological waves conditions

The full wave climate (distribution of wave height, period and direction) is reduced to a set of representative (morphological) wave-wind conditions to define a morphological wave. Similar data decomposition is used to define a morphological tide. Model simulations use an appropriate number of representative wave conditions combined with a morphological tidal period. Wave-current impacts on morphology are then multiplied by a factor related to the frequency of occurrence of a given wave condition to estimate the annual sediment transport rate.

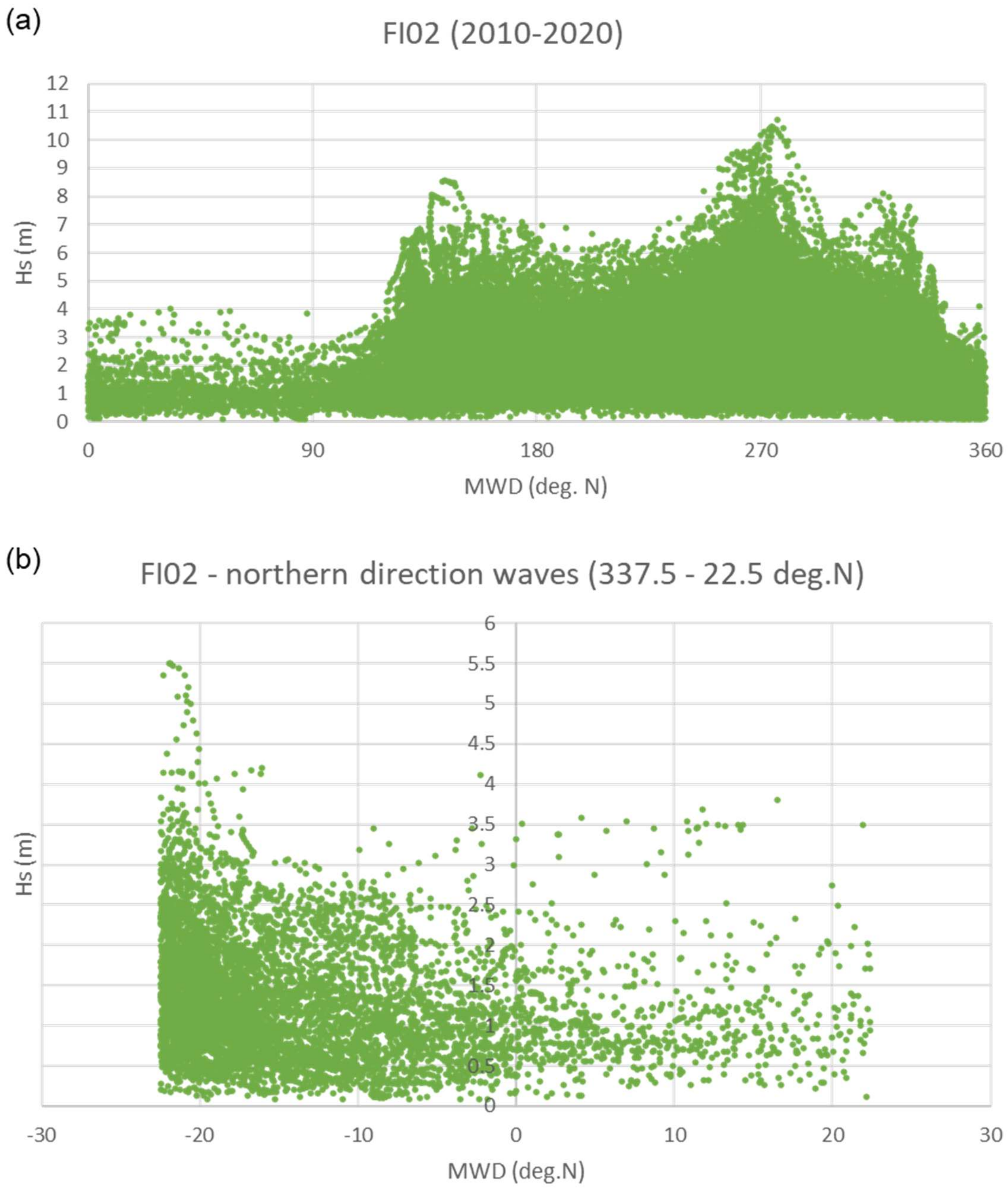
Only waves from the northern sector were considered, giving the largest extreme waves at the breakwater (Mott MacDonald, 2023). Hourly wave data were extracted from the MIKE21 FMSW model at location F102 (Figure 8.1) from 2010 to 2020. Figure 8.2 shows a scatter plot of significant wave height (Hs) against mean wave direction (MWD) for all directional sectors. An enlarged view of these data for the sector 337.5 to 22.5 deg. N is shown in Figure 8.2b.

Figure 8.1: Location of FI02



Source: Mott MacDonald, 2023

Figure 8.2: (a) Scatter plot showing modelled waves at offshore location FI02 for the significant wave height (Hs) against mean wave direction (MWD) (2010 to 2020); and (b) enlarged view of the northern sector waves.



Source: Mott MacDonald, 2023

Morphological waves were derived from the data from location F102 using the Energy Flux Method (EFM) described by Benedet *et al.* (2016). This method is based on wave energy flux concepts where the wave energy flux of each wave record from a wave time series is calculated using

$$Ef = \left(\rho g \frac{Hs^2}{8}\right) Cg \qquad \text{(Eq. 1)}$$

where ρ is the water density (1025 kg/m³), g is the acceleration due to gravity (9.81 m/s²), Hs is the significant wave height, and Cg is the group deep water wave celerity.

Using Eq. 1, the method defines directional wave bin(s) with defined wave energy. Wave heights are defined and related to wave energy. As the analysis only considers a specific wave direction sector (northern sector from 337.5 to 22.5 deg.N), a single wave directional bin was defined using the mean wave energy flux direction of the bin (Table 8.1). The wave period was defined as the mean wave period of the group, and wave height was calculated according to the mean wave energy flux of the bin (Table 8.1).

Table 8.1: Representative wave condition (morphological wave) defined by the average wave flux from the northern sector direction.

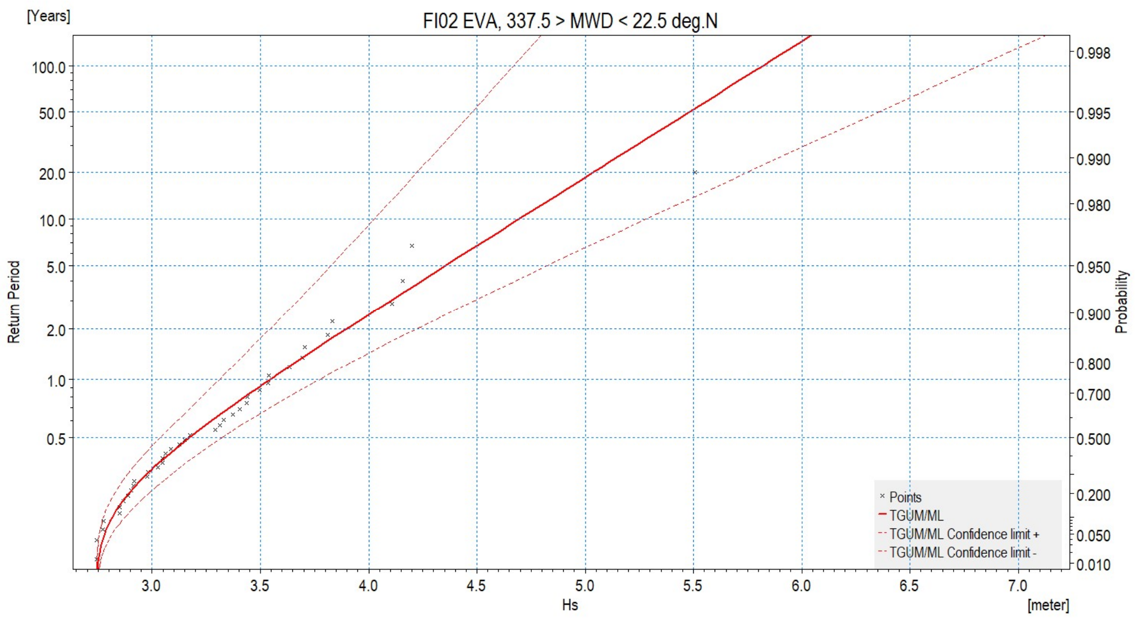
Wave height (m)	Wave Period (s)	Wave direction (deg. N)
1.6	9.5	347

Source: Mott MacDonald, 2023

8.3.2 1 in 1-year wave conditions

An extreme value analysis (EVA) of wave height data from location F102 was performed using the DHI EVA Toolbox[2] for the northern sector waves (337.5 to 22.5 deg. N). The best-fit probability distribution curve for the extreme Hs is shown in Figure 8.3, with lines showing the 95% confidence intervals. The 100% AEP (1:1 year) Hs obtained from the EVA was 3.54m. The wave period associated with a given wave height was obtained using the relationship between predicted Tp and Hs value giving a 100% AEP (1:1 year) Tp value of 13.14s. The wind speed associated with 100% AEP (1:1 year) wave height of 12.9m/s was obtained using the relationship between predicted wind speed and Hs value.

Figure 8.3: Probability distribution fit of Hs for the northern sector waves (337.5 to 22.5 deg. N)



Source: Mott MacDonald, 2023

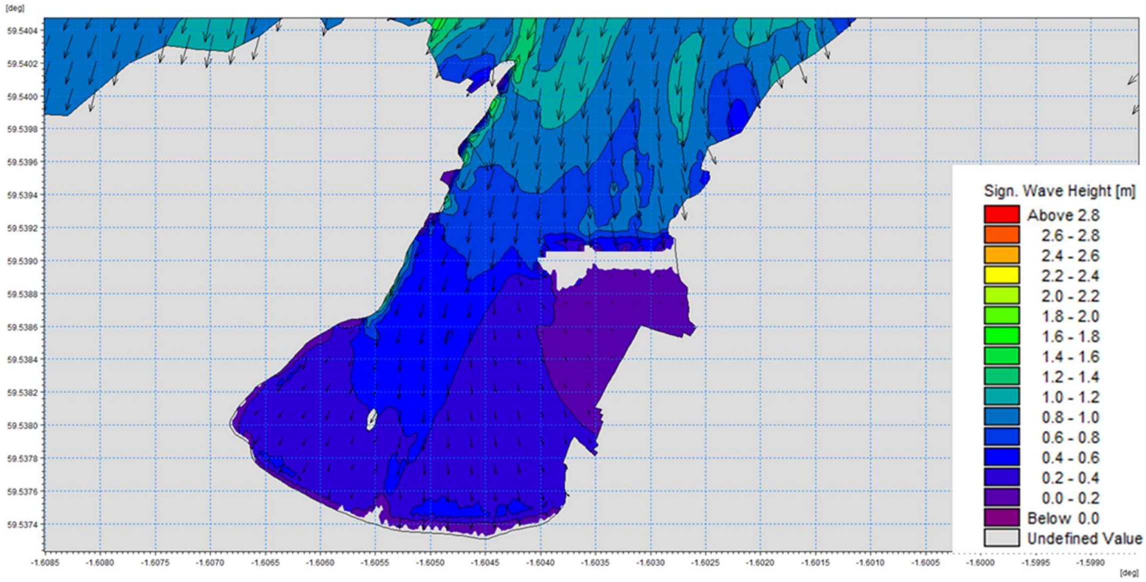
[2] https://manuals.mikepoweredbydhi.help/latest/General/EVA_SciDoc.pdf accessed April 2023.

8.4 Baseline results

8.4.1 Morphological waves conditions

The sediment transport model was run during spring tide conditions for five tides using the morphological waves (Section 8.3.1). Figure 8.4 shows the morphological wave conditions in North Haven. Waves are typically of the order of 0.5m. Figure 8.4 shows that the inner bay is sheltered, both naturally by the shape of the coast and the bathymetry, as well as by the existing breakwater. For further information regarding the way climate at North Haven, please refer to the Mott MacDonald (2023).

Figure 8.4: Wave climate at the site with morphological waves conditions



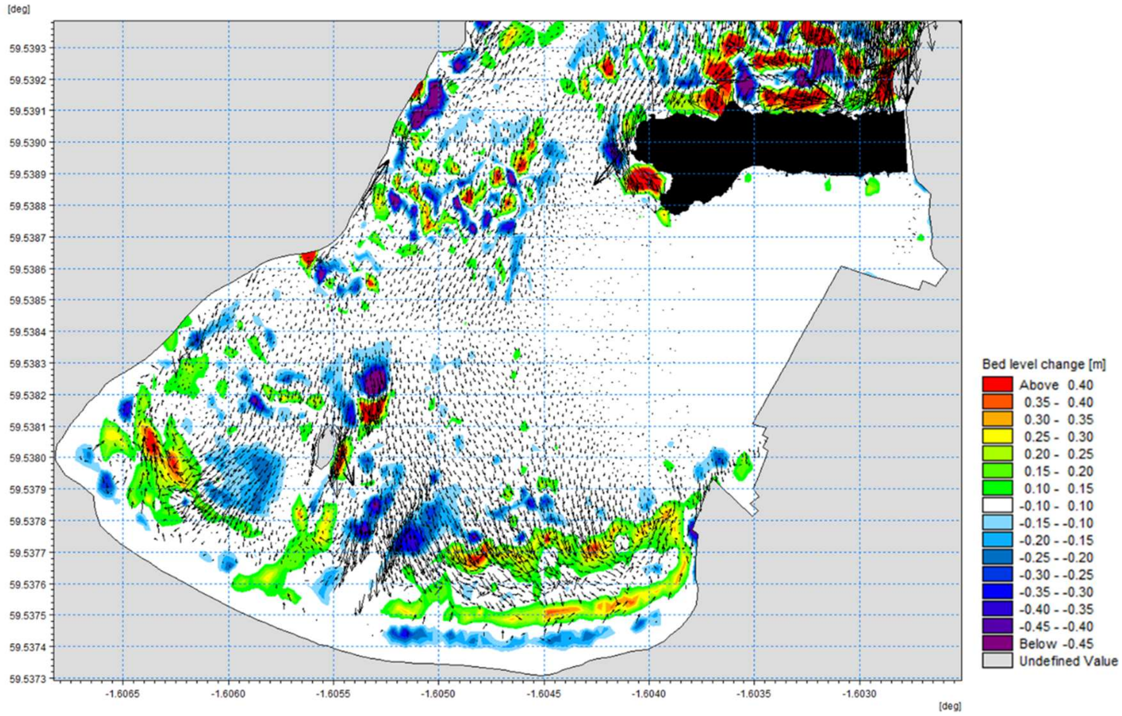
Source: Mott MacDonald, 2023

Figure 8.5 shows the predicted bed level change at the end of the sediment transport simulation using morphological waves. The vectors show the net sediment transport direction and magnitude. Green to red colours show areas of potential accretion, while blue to purple colours show erosion. The figure shows evidence of:

- Bed level changes, due to the sediment movement in North Haven, are small of the order of +/-20cm;
- Localised minor scour at the western end of the breakwater;
- Onshore (beach-building) sediment transport, especially east of the slipway; and
- Minor erosion of the upper eastern beach.

It is important to note that the upper beach at North Haven comprises coarse gravel that is not included in the model. It is considered that mobilisation of this coarser material under normal hydrodynamic and wave conditions is unlikely.

Figure 8.5: Predicted bed level attributable to morphological wave conditions. Vectors indicate net sediment transport magnitude and direction. Positive values show accretion and negative values show erosion.

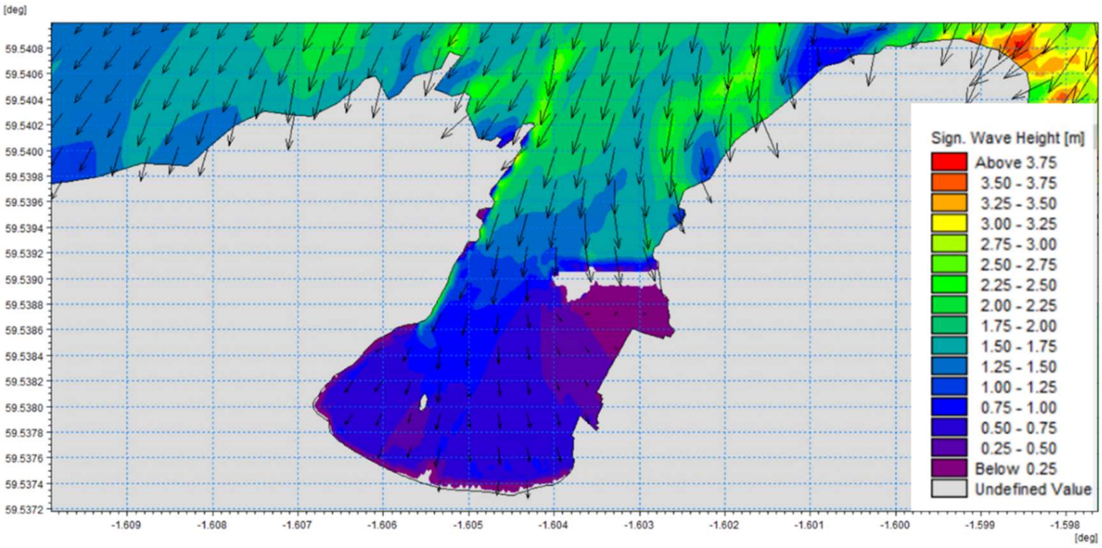


Source: Mott MacDonald, 2023

8.4.2 1:1-year wave conditions

The sediment model was run with 1:1-year wave conditions (Section 8.3.2). Figure 8.6 shows the wave climate at the bay for 1:1-year wave conditions where waves in the inner bay reach up to 1m in height.

Figure 8.6: Wave climate at the site with 1:1-year extreme waves conditions

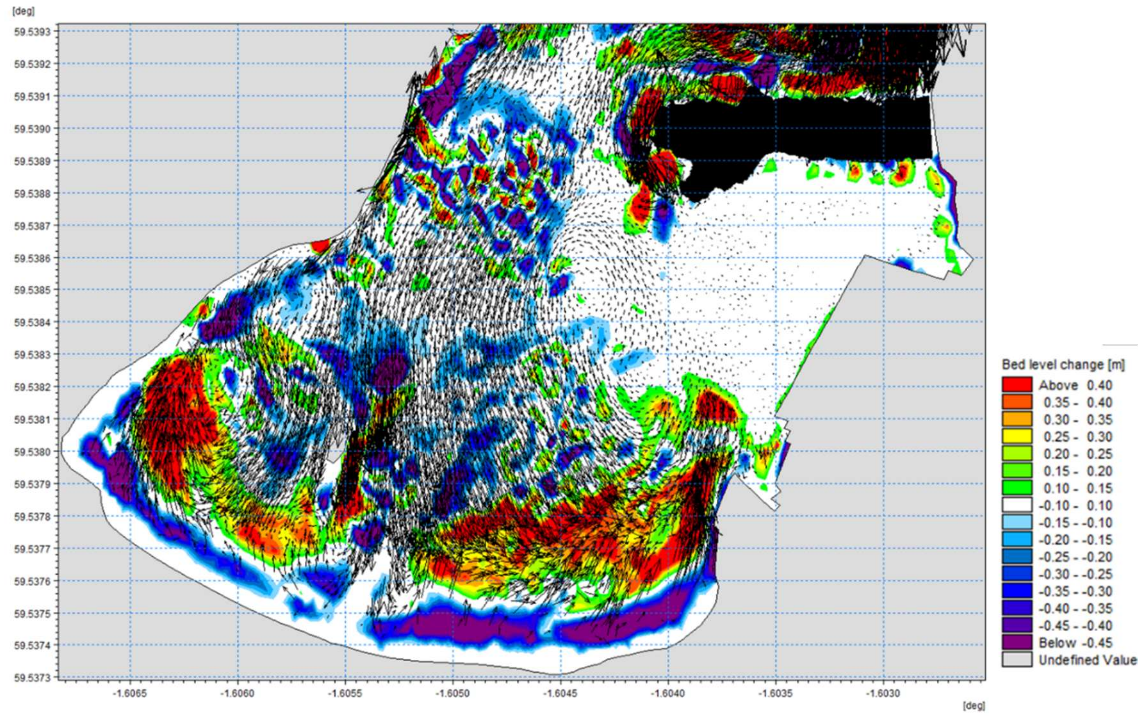


Source: Mott MacDonald, 2023

Results from the sediment transport simulation are shown in Figure 8.7. The vectors show the net sediment transport direction and magnitude, green to red colours show areas of potential accretion, and blue to purple colours show erosion. The figure shows evidence of:

- Bed level changes, due to the sediment movement, of the order of +/-40cm;
- Onshore (beach-building) transport of sediment resulting in elevated bed levels towards both ends of the beach attributable to the onshore sediment transport both to the east and west of the slipway; and
- Erosion of the upper beach, noting again the coarser nature of the sediment and related comments above.

Figure 8.7: Bed level change at the end of a five-tide period (spring tides) with 1:1-year return period wave conditions. Vectors indicate net sediment transport magnitude and direction. Positive values show accretion and negative values show erosion.



Source: Mott MacDonald, 2023

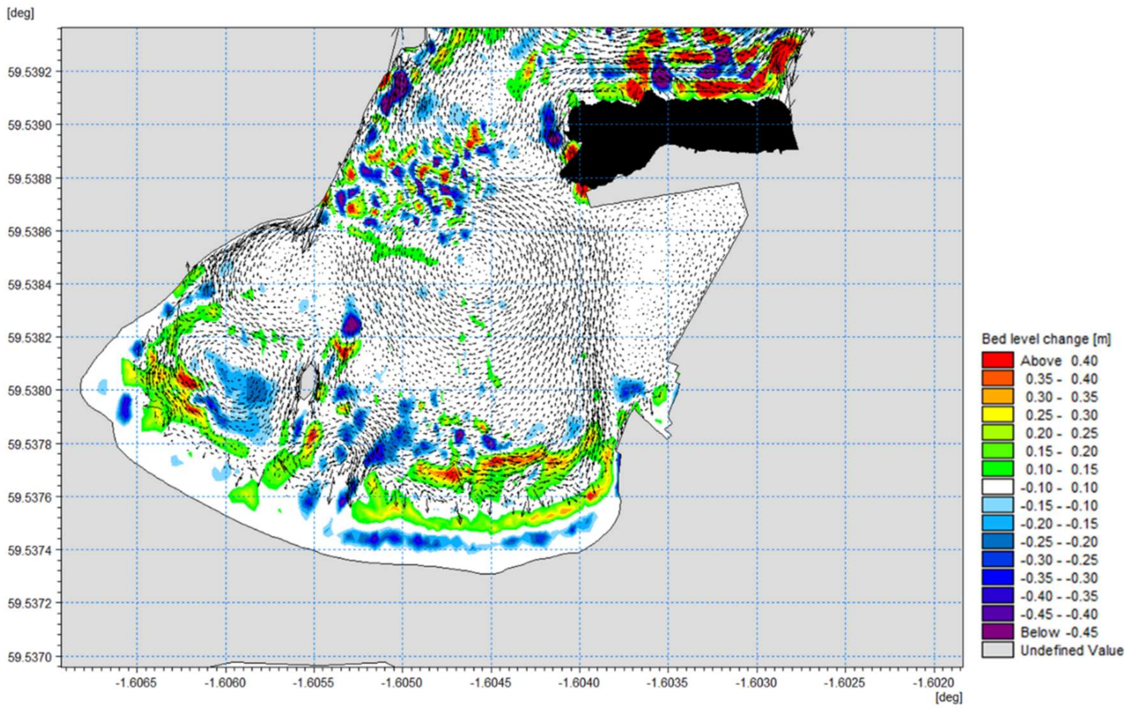
8.5 Proposed new layout results

8.5.1 Morphological waves conditions

Figure 8.8 shows bed level change predictions from the sediment transport model with the proposed new port layout included. The vectors show the net sediment transport direction and magnitude. Green to red colours show areas of potential accretion, while blue to purple colours show erosion. The following can be seen:

- Small bed levels change of the order of +/-20cm, similar to the baseline case;
- Minor scour at the western end of the elevated breakwater, closely similar to the baseline case;
- Onshore (beach-building) sediment transport; and
- Some erosion upper beach.

Figure 8.8: Bed level change at the end of a five-tide period (spring tides) with morphological wave conditions and proposed layout. Vectors indicate net sediment transport magnitude and direction. Positive values show accretion and negative values show erosion.



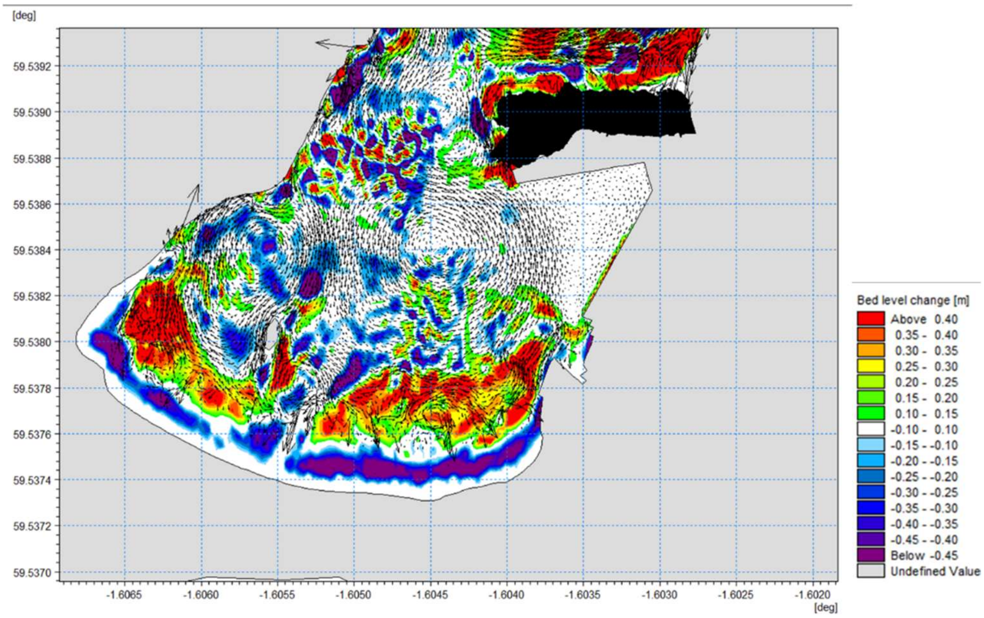
Source: Mott MacDonald, 2023

8.5.2 1:1-year wave conditions

Sediment modelling results for the extreme 1:1-year wave conditions with the new port layout included are shown in Figure 8.9. The patterns of bed level change are very similar to those observed in the baseline case (Figure 8.5). It is observed that:

- Bed level changes, due to the sediment movement, are of the order of +/-40cm; and
- There is a clear onshore (beach-building) sediment transport, increasing bed levels towards either end of the beach. This result is very similar to the baseline case.

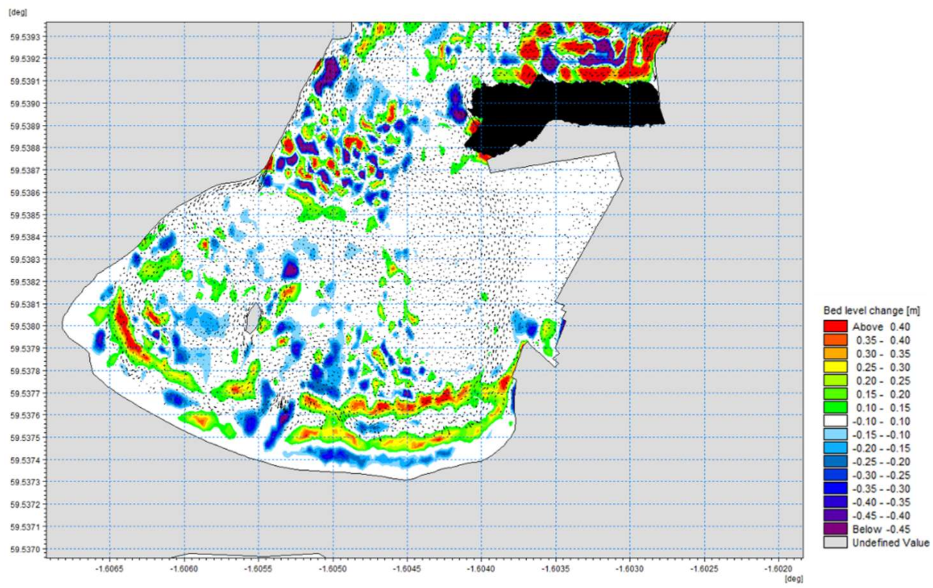
Figure 8.9: Bed level change at the end of a five-tide period (spring tides) with 1:1-year return period wave conditions and proposed layout. Vectors indicate net sediment transport magnitude and direction. Positive values show accretion and negative values show erosion.



Source: Mott MacDonald, 2023

Sediment modelling results for the extreme 1:1-year wave conditions with the new port layout and climate change (2072) included are shown in Figure 8.10. Vectors are used to indicate net sediment transport magnitude and direction. Positive values show accretion and negative values show erosion.

Figure 8.10: Bed level change at the end of a five-tide period (spring tides) with morphological wave conditions, the proposed layout and climate change (2072). Vectors indicate net sediment transport magnitude and direction. Positive values show accretion and negative values show erosion.

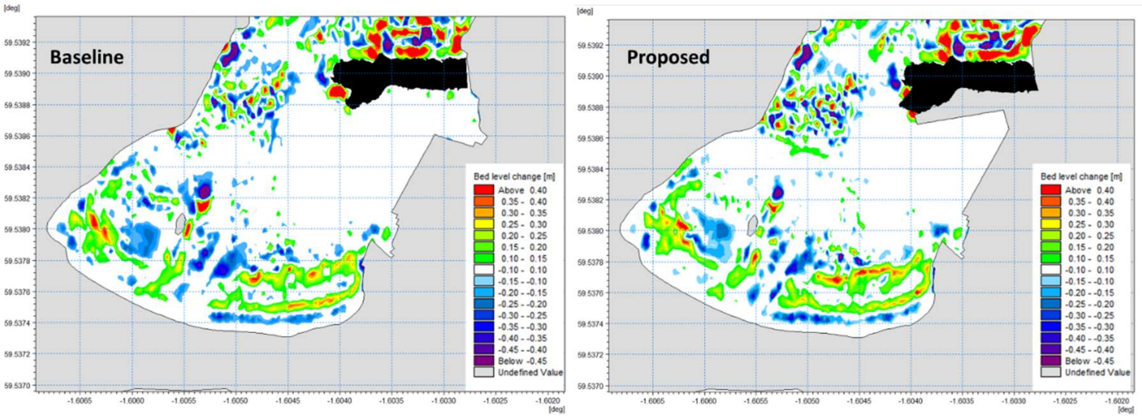


Source: Mott MacDonald, 2023

To aid visual intercomparisons between the baseline and scheme results, Figure 8.11 shows baseline and scheme results for a five-tide period (spring tides) with morphological wave conditions. Figure 8.12 shows baseline and scheme results for the extreme 1:1-year return period wave conditions. In these figures, vectors have been removed for clarity.

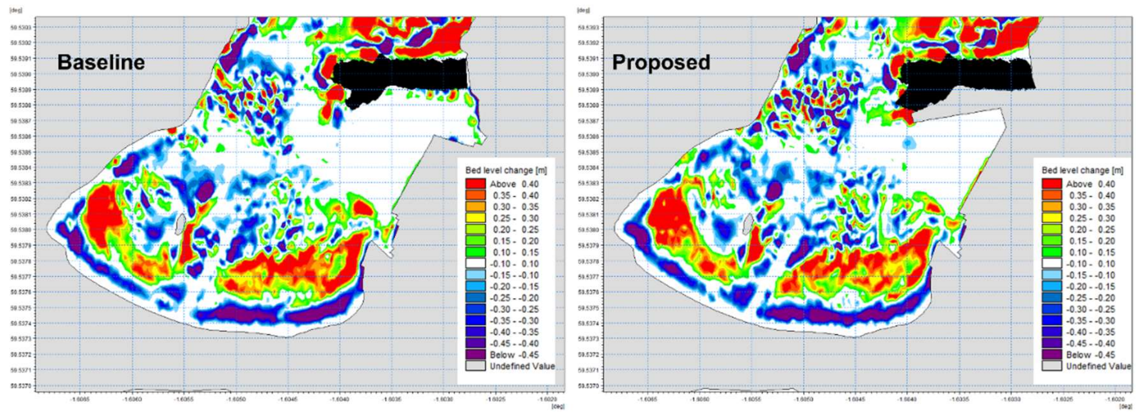
Figure 8.12 shows that, during normal conditions, sediments accrete and erode in the same areas and with the same magnitude for the baseline and the proposed layout. The impact of the layout on the sediment patterns in North Haven is judged to be insignificant, and no changes to the coastal processes in the bay are expected. Similarly, the sediment transport for both baseline and proposed under extreme 1 in 1-year wave conditions shown in Figure 8.12 are almost identical, demonstrating that the effect of the new layout is extremely small and is considered to be insignificant.

Figure 8.11: Comparison of bed level change at the end of a five-tide period (spring tides) with morphological wave conditions for the <u>baseline</u> and <u>proposed layout</u>. Positive values show accretion and negative values show erosion.



Source: Mott MacDonald, 2023

Figure 8.12: Comparison of bed level change for 1:1-year return period wave conditions for the baseline and proposed layout. Positive values show accretion and negative values show erosion.



Source: Mott MacDonald, 2023

8.5.3 Climate change considerations

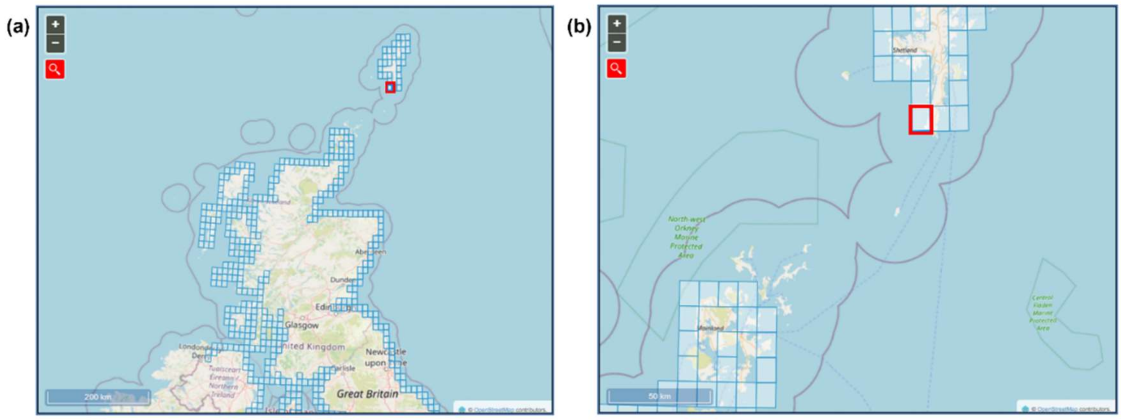
Account needs to be taken of climate change impacts concerning water levels, waves and the wind is required for the 50-year design life of the new port facilities (2072). The present study has followed climate change guidance from the Scottish Environment Protection Agency (SEPA) guidance for flood risk assessment[3], which states that:

- Sea level rise (SLR) should be calculated using UKCP18 RCP 8.5 95th percentile;
- Offshore significant wave heights change is uncertain but is expected to have a much smaller effect on coastal flood risk than sea level rise; and
- No information regarding the effect of climate change on the winds is provided. However, a conservative approach has been undertaken, as described below.

8.5.3.1 Sea level rise (SLR)

Sea level rise (SLR) projections are guided in this study by the UKCP18[4] Representative Concentration Pathway, RCP8.5, at the 95th percentile as recommended by SEPA. Figure 8.13 shows the nearest UKCP18 data extraction location to Fair Isle. Cumulative SLR was calculated from 2023 (baseline) to 2072. The total cumulative SLR for RCP8.5 for the 95th percentile is 0.52m.

Figure 8.13: Sea level rise data extracted from UKCP18 database: (a) grid location; (b) grid location detail



Source: Met Office UKCP18, 2018.

8.5.3.2 Waves

SEPA guidance recommends model sensitivity tests using a 10 to 20% increase in extreme offshore wave heights. For Fair Isle, a moderately conservative 10% increase in offshore wave height has been applied.

8.5.3.3 Wind

The local wind primarily influences the waves in Fair Isle. While it's uncertain how the wind conditions will change, some global atmospheric models suggest that near-surface wind speeds over the UK will increase during winter in the latter half of the 21st century. However, predictions regarding future wind speed increases are inconclusive according to the UKCP18 Land Report, and there's significant variability depending on the chosen model. The present study assumes a

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[3] SEPA, 2023. Climate change allowances for flood risk assessment in land use planning.

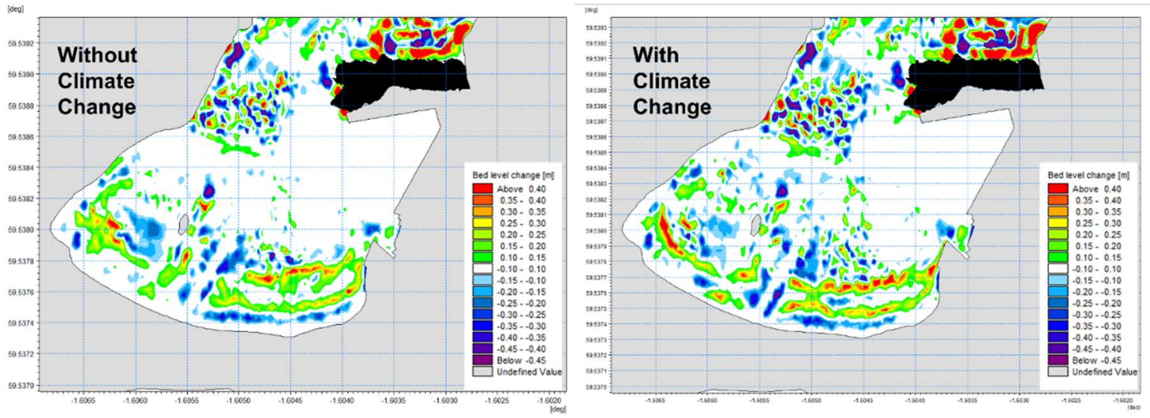
[4] UK Climate Projections (UKCP) - Met Office

conservative approach by increasing the wind speed by 10% in future climate scenario simulations. This increase is in line with the predictions of multiple atmospheric models.

8.5.4 Sediment responses to climate change

Figure 8.14 compares bed level changes at the end of a five-tide period (spring tides) with morphological wave conditions for the proposed layout and with and without climate change allowances defined in Section 8.5.3. While some minor differences between the two cases can be seen, they are judged insignificant and undetectable within the range of natural variability through time.

Figure 8.14: Comparison of bed level change at the end of a five-tide period (spring tides) with morphological wave conditions for the proposed layout and with and without climate change. Positive values show accretion and negative values show erosion.



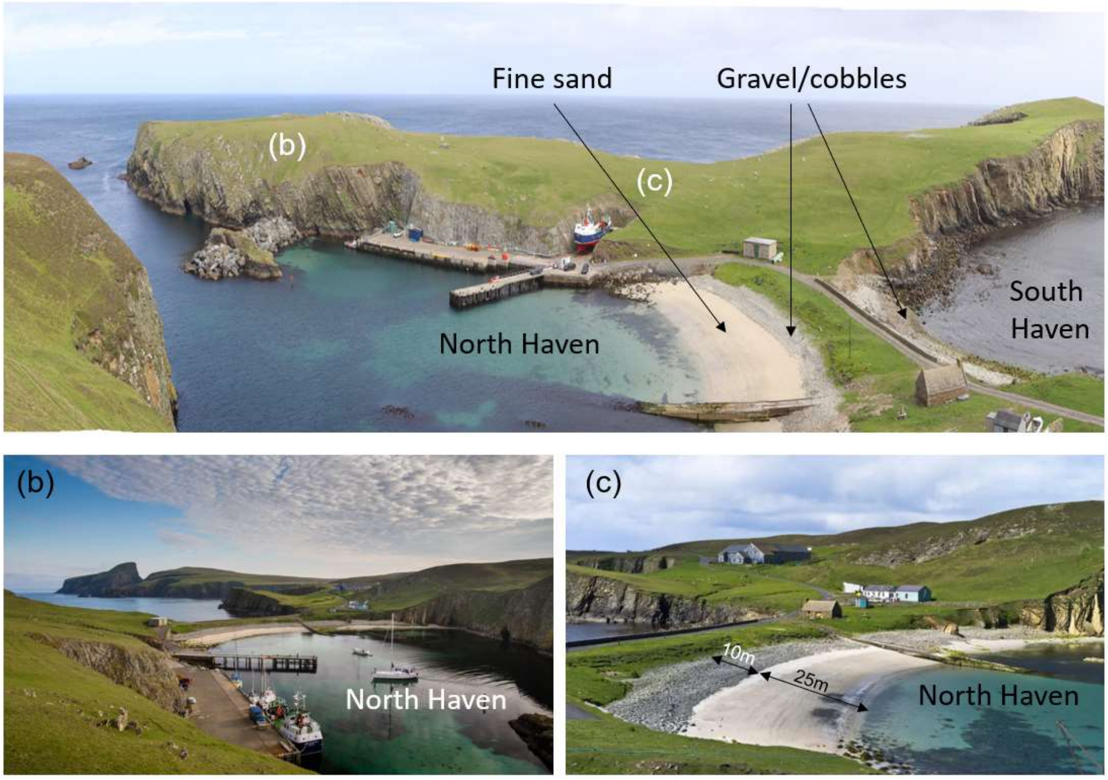
Source: Mott MacDonald, 2023

8.6 Beach morphology

An important element of the modelling contribution to the environmental impact assessment of the proposed port developments concerns North Haven Beach (Figure 8.15). The lower sandy portion of the beach is a popular spot for swimming, picnicking, and sunbathing in summer. In contrast, South Haven Beach is essentially devoid of sand. This section links with the above evidence to assess if the development will harm this valued beach.

The lower and upper beach of North Haven (Figure 8.15) is composed of fine sand (cross-shore extent of approximately 25m) and gravel (cross-shore extent of approximately 10m), respectively (ABPmer, 2023). It exhibits classical evidence of hydraulic sediment sorting during energetic wave conditions that leave the coarse gravel component on the upper part of the beach profiles and the finer sand in the intertidal area.

Figure 8.15: The upper panel shows a view of the Fair Isle port and tombolo looking east with beach composition indicated. The location from where photographs (b) and (c) were taken is also shown.



Source: Highland Tourist Board

8.6.1 Geology and origin

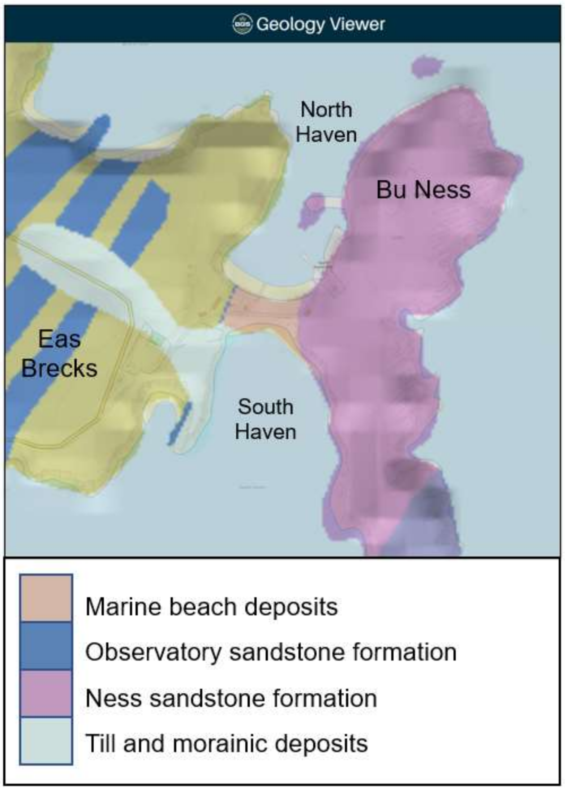
The local geology is shown in Figure 8.16. It shows the sandstone rocks of Bu Ness separated from the Fair Isle 'mainland' by a tombola composed of marine sediments (BGS, 2023[5]). Given no evidence of any geological control, this low feature is most likely the result of wave refraction around Bu Ness, causing waves to converge along the north and south shores of the tombola.

While undoubtedly maintained in its present morphological state by the current wave climate, sea level rise probably contributed to forming the feature in the past. The raised beaches on either side of the tombola and other locations on Fair Isle provide evidence of past eustatic and non-eustatic changes in mean sea level. Sediment sources for the tombolo are less clear, with till and moraine only observed on the western shore of South Haven.

The evidence of wave convergence in Figure 8.17 comes from the Mott MacDonald local MIKE21 FMSW model (Mott MacDonald, 2023, Fig. 4.1). This figure shows the dominant wave directions around Fair Isle Port favour tombolo formation at this location. The present-day geomorphology indicates that the tombola is a resilient stable landform in dynamic equilibrium with the prevailing wave climate.

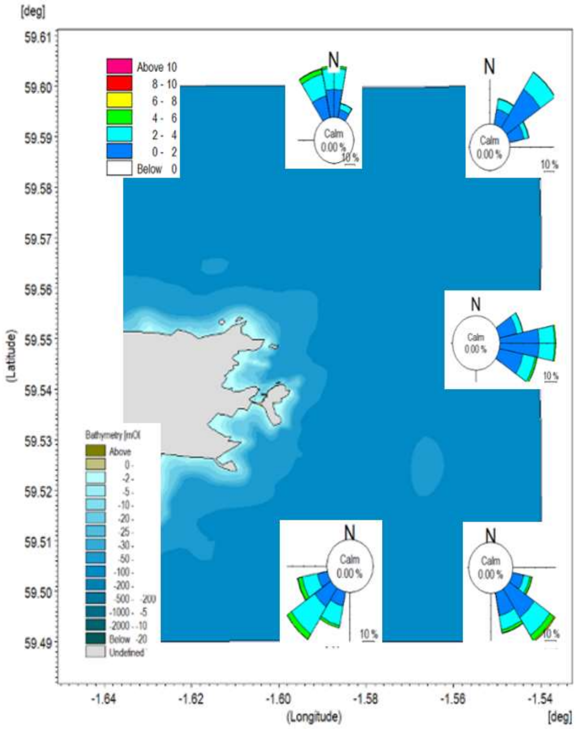
[5] https://geologyviewer.bgs.ac.uk

Figure 8.16: Solid and drift geology of the study site



Source: https://geologyviewer.bgs.ac.uk

Figure 8.17: Roses showing dominant wave directions at locations around the study site



Source: Mott MacDonald (2023)

8.6.2 Beach morphodynamics

Based on visual characteristics, North Haven Beach can be divided into a western and eastern sector on either side of the old slipway. To the west of the old slipway, the cross-shore width of the gravel and sand fractions beach does not vary until it reaches the higher land where the beach is absent. To the east of the old slipway, the cross-shore gravel width is uniform alongshore and marginally wider than on the western side of the beach. Here the cross-shore extent of fine sand is significantly wider and merges into a rocky area on the eastern side near the port structures. The beach is considered swash aligned, and there is no morphological indication of beach rotation attributable to a long-term net alongshore transport vector.

The evidence presented above shows that the proposed port development has little effect on the North Haven embayment's wave climate or sediment transport. Therefore, changes to the present morphology or sediment characteristics of the beach are unlikely and are probably undetectably within the natural envelope of morphological response associated with the spring-neap tidal cycle and storm events. If anything, the increase in breakwater height and the reduction in porosity would reduce overtopping and wave transmission through the structure during extreme events and increase wave protection to the beach's eastern section used for recreational purposes.

9 Dredge plume modelling

9.1 Introduction

Installing a new quay on the south side of the harbour breakwater will require dredging. During dredging, sediments will be released into the water column, potentially causing an increase in the suspended sediment concentrations and sediment deposition over the seabed. Due to the sensitive nature of local habitats in Fair Isle, dredge plume dispersion modelling has been carried out to inform the Environmental Impact Assessment (EIA).

To simulate the mobilisation, transport, and accretion of the dredged fine sediments at North Haven, a MIKE3 FM Mud Transport (MT) module was used. The model is driven by the validated local MIKE3 FMHD model (Section 6) and includes descriptions of bed sediment strength, sediment entrainment and deposition thresholds and suspended sediment settling velocities and accounts for flocculation and hindered settling (Winterwerp*,* 2002).

Limited data availability related to bed sediments made it necessary to make several conservative assumptions regarding the nature of the dredged material. These assumptions are based on experience gained in past studies and the skill and knowledge of the modelling team. They have been tested in a series of sensitivity analyses reported below.

9.2 Sediment plume and dredging

In dredge modelling, it is necessary to conceptualise operations while ensuring that the dredge timings and release rates assumed in the model are realistic and based on the available information. This approach ensures the numerical model's best representation of dredging. During dredging operations, sediments will be released into the water column, which may impact the receiving environment. Under the UK legislation, all dredging license applications are subject to environmental impact assessment that includes the potential impact arising from the sediment plumes including: (a) investigating the environmental effect associated with the sediment plume while it is in the water column; and (b) its subsequent deposition. The sources of sediment plumes are essentially the losses, deliberate or otherwise, that occur during a dredging operation. There are three primary influences on the generation of sediment plumes: (a) the dredging operation; (b) the material; and (c) the hydrodynamic conditions (CIRIA, 2008).

9.2.1 The dredging operation

The dredging operation and method define the location where the plume forms. The mechanical disturbance applied to the sediment and the locations associated with the dredging plan determines where the losses (accidental or deliberate) can occur and their magnitude (CIRIA, 2008).

Backhoe dredgers are used for dredging cohesive and non-cohesive sediments in confined seabed areas. Backhoe dredgers are similar to land-based excavators but located on a barge. The main causes of sediment release during backhoe dredging are:

- Impact of the bucket on the bed;
- Disturbance of the bed during initial removal of the bucket;
- The material spilt from the bucket;
- The material washed from the outer surface of the bucket;
- Leakage and dripping during slewing;
- Washing of residual adhering material during lowering;

- Disturbance of gas in the sediments, which may enhance resuspension; and
- Spilling, splashing, overflow from the barge.

The resuspension caused by backhoe dredging depends on operator skill and can be reduced using experienced operators. The reduction can also be achieved using a silt screen or a visor grab (similar to a closed grab) (CIRIA, 2008).

9.2.2 The sediment

The properties of the sediment and rock to be dredged influence the amount and size distribution of the sediment released into suspension. The source strength, measured in terms of concentration by weight, is highly dependent on the type of sediment being dredged, particularly its particle size distribution and the degree to which it disaggregates when disturbed (CIRIA, 2008).

9.2.3 The hydrodynamic conditions

The hydrodynamic environment affects how the dredging operation is carried out and, therefore, the rate of sediment loss. The losses will generally be higher if operating conditions are difficult, e.g. waves, high current speeds, etc. (CIRIA, 2008).

9.3 Measurement of sediment losses

Fine and coarse sediments can be lost to the surrounding water during dredging. The coarse sediment disturbed from the bed or lost during other phases of the dredging operation falls rapidly back to the seabed, close to the point of dredging. The fine sediment fractions stay in suspension longer, forming a sediment plume. The plume's behaviour is governed by the hydrodynamic environment, mainly the strength and direction of the currents, and by the dynamic behaviour of sediment particles within the plume.

According to CIRIA (2008), sediment losses will increase as:

- Sediment concentration increases;
- The rate of release of sediments into the water column per unit of time increases; and
- The total mass of sediment put into suspension, relative to the quantity of dredged material – known as the "S-factor" increases.

Each of these losses is described in CIRIA, 2008. Table 9.1 has been extracted from CIRIA (2008) and summarises the increased suspended sediment concentrations arising from different dredging activities and places. The table also indicates the release rate of sediments per unit time (kg/s). It also shows great variability in the increase of suspended sediments and the release of sediments over time, even for the same type of operation. This variability reflects the differences between the site conditions and the methods used to derive this information.

Table 9.1: Example values for the sediment mass resuspended and lost during dredging.

Dredging operation	Suspended sediment concentration increases (mg/l)	Fine sediment losses (kg/s)
TSHD (Owers bank, UK)	29–209 (silt) 611–2117 (sand)	
TSHD (Great Yarmouth, UK)		20
TSHD (Hastings, UK)		14
TSHD (Hong Kong)		280*
TSHD (Rotterdam, the Netherlands)	150–450	
TSHD (Delfzijl)	10–20	
TSHD (Grays Harbor)	Up to 700	
TSHD (Mare Island)	Up to 1100	
TSHD (Richmond Harbor)	20–200	
TSHD (Alameda Naval Air Station)	40–190	
Grab (Merwdehaven)	35	
Grab (Hollandsche IJssel)	2–100	
Grab (Zierikzee)	90–105	
Grab (Black Rock)	720–1100	1.68
Grab (Duwamish Waterway)	70–160	
Grab (Calumet River)	30–130	0.24
Grab (Alameda Naval Air Station)	29–214	
Grab (Ketelmeer)	up to 5 (depth-avg)	
CSD (Land in Mott McDonald, 1991)		1.33
CSD (Hong Kong)		0.9–1.6
CSD (Calumet Harbur)	2–5	
CSD (James River)	42–86	
CSD (Ketelmeer)	7 (depth-avg)	
Bucket ladder (Barnard, 1978)	Up to 500+, 100 average	
Bucket ladder (Noordzeekanaal, Rotterdam)	110	
Bucket ladder (SATURN)		4
Bucket ladder (Aalschover)		0.33
Bucket ladder (Ketelmeer)	30 (depth-avg)	
Scoop (Standaert *et al*, 1993)	2–5	

* The magnitude of this loss figure reflects the type of dredged material and operation and is not considered to be exceptional under these circumstances.

Source: CIRIA, 2008. TSHD – Trailing suction hopper dredging; CSD – Cutter suction dredging

Table 9.2, also extracted from CIRIA (2008), summarises losses of fine sediment from different types of dredging operations in muddy sediments. It shows that the losses resulting from digging-type methods are significantly higher than those for the suction-type methods.

Table 9.2: Indicative values for the mass of sediments resuspended per m^3 of dredged material.

Dredger type	S-factor (kgm^{-3})
TSHD (no overflow)	typically 7
TSHD (no overflow or LMOB)	typically 3–4
Grab (open, no silt screen)	12–25*
Grab (closed, no silt screen)	11–20*
Grab (closed, with silt screen)	2–5*
Bucket ladder	15–30*
CSD	approximately 6
CSD (reduced swing and rotation speeds)	approximately 3
Dustpan	approximately 4
Backhoe (no silt screen)	12–25*
Backhoe (with silt screen)	5–10*
Auger**	5
Auger (reduced rate of advance)**	3

* depending on the size of grab or bucket – the smaller the grab/bucket, the greater the re-suspension

** these auger dredgers were not designed as environmental dredgers

Source: CIRIA, 2008. TSHD – Trailing suction hopper dredging; CSD – Cutter suction dredging

A summary of spillage from dippers and backhoe dredging was derived as part of the Oresund Link project (CIRIA, 2008). The study results are presented in the extracted table of Table 9.3. They are relevant to the current project, referring to one of the proposed selected dredging methods (backhoe).

Table 9.3: Summary of the spillage from dipper and backhoe dredging

Dredging operation	Location	Material type	Spillage %
Dipper and backhoe	large open areas	clay till	1–4
Dipper and backhoe	narrow channels	clay till	2–5
Dipper and backhoe	bridge pier foundation pits	clay till	4–6

Source: CIRIA, 2008.

9.4 Mud Transport (MT) model setup

The local MIKE3 HD model was coupled with the Mud Transport (MT) module to simulate the capital dredging activities and associated sediment losses. This model captures physical sediment processes allowing the simulation of the suspended sediment plume and any subsequent deposition. The erosion, transport, and accretion of sediments in the MT module are defined by hydrodynamic conditions simulated using the HD model and the physical properties of the sediments. The bottom sediments are described using two vertical layers, each with a defined sediment thickness, a dry density value, threshold erosion/accretion properties, and erosion rates. The bed layers are organised so that the "weakest" layer (typically fluid mud or newly deposited sediment) is the uppermost layer. Layers beneath this have increasing dry density and shear strength to reflect cohesive sediments' natural consolidation and compaction.

Please note that it is assumed that there is no mud in the bed at North Haven for the modelling exercise; therefore, the only sediment deposited and suspended is due to the dredging operation. The thickness of layer 1 is set to 0m. However, some sediment needs to be "*available*" for the model to work, and therefore, layer 2 was defined with a 10m thickness and an unrealistically high critical shear stress of erosion (Table 9.4). Layer 2 parameters allow the model to run but do not allow any erosion of this layer and therefore do not add to suspended sediment concentrations.

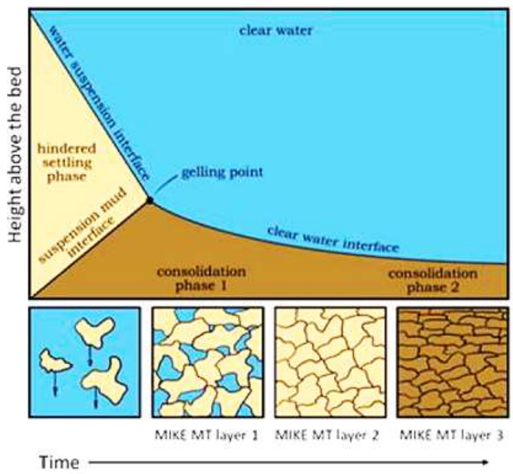
Table 9.4: MT model bed parameter setting

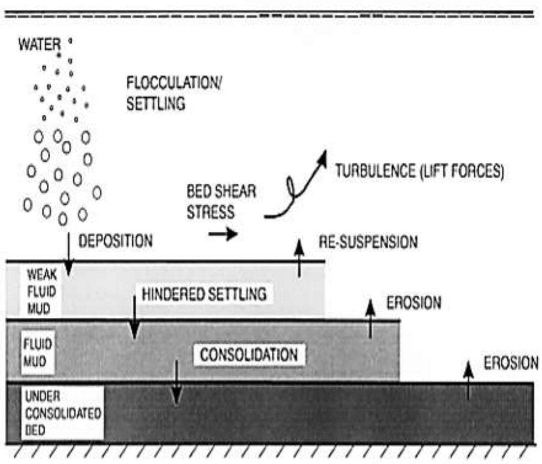
Layers	Layer Thickness (m)	Erosion coefficient (kg/m²/s)	Critical shear stress of erosion (N/m²)	Critical shear stress of deposition (N/m²)	Dry density (kg/m³)
Layer 1	0	0.0003	0.2	0.07	300
Layer 2	10 (only inside the bay)	0.0003	10	0.07	1500

Source: Mott MacDonald, 2023

Different critical bed shear stress values in the MT model define when the suspended sediment starts to erode or accrete. The MT module assumes a constant sediment settling velocity based on the grain size. No enhanced settling due to flocculation of the suspended sediment particles or hindered settling when particle concentrations are sufficiently high were included. The only sediments added to the water column during the model runs were from the dredging operation. Please refer to the next section for the details and assumptions regarding the dredging module. No suspended sediments were introduced at the model boundary. Illustrations showing how the mud transport model parameters are defined, and the main processes are shown in Figure 9.1.

Figure 9.1: Mud transport model parameters and process





Source: DHI, 2017

9.4.1 Sediment assumptions

As sediment with D50 greater than 0.1 mm will fall out of suspension close to the dredger, the dredging simulations only consider sediment sizes smaller than fine sand. Four sediment fractions corresponding to medium/fine sand, coarse/medium silt, medium/fine silt and fine silt/clay were included in the MT model (Table 9.5). This table also shows the settling velocity values defined for each sediment fraction.

Table 9.5: Percentage of sediment assumed to be comprised of fines. The total percentage of fines considered in the MIKE3 MT model is 11%.

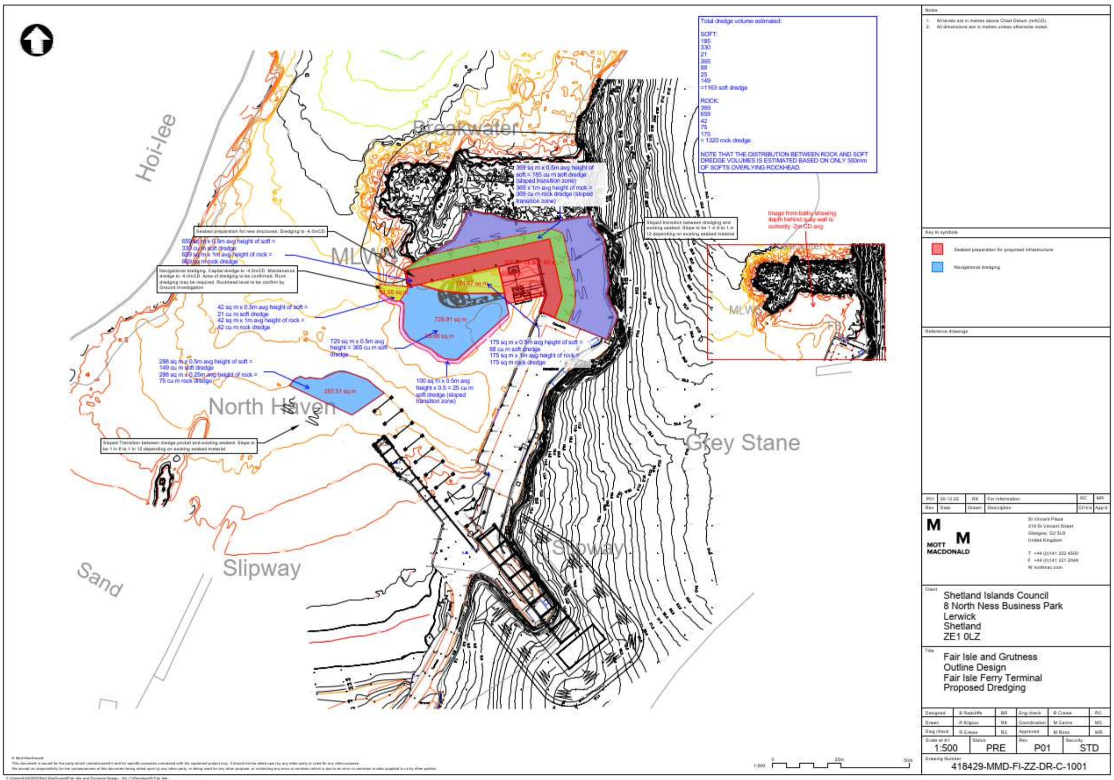
Description	Median grain diameter (mm)	% passing	% of total	Settling velocity (mm/s)
Medium/ Fine sand	0.106	11.6	38.2	3
Coarse/ Medium Silt	0.051	7.1	37.4	1.2
Medium/Fine Silt	0.016	2.8	6.1	0.2
Fine Silt/ Clay	0.001	2.1	18.3	0.05

Source: Mott MacDonald, 2023

9.4.2 Backhoe Dredger (BHD) assumptions

Backhoe dredging (BHD) is expected to occur at North Haven. Figure 9.2 and Table 9.6 show the proposed dredging areas and the volume of sediments to be dredged and modelled. The approximate dredged volume required for the proposed development is around 1,163 m^3. To be conservative, an increase of 10% of the overall sediment volume has been applied in the model (total of 1,279 m^3).

Figure 9.2: Proposed dredging plan showing the proposed dredging areas and the volume of sediment and rock.



Source: Mott MacDonald, 2023

Table 9.6: Volume of sediment to be dredged

Dredge Area	Material	Volume (m^3)	Volume to model (+10%) (m^3)
Dredge pocket 1 (-4mCD)			
	Sediment	**149**	**164**
Dredged pocket 2 (-4mCD)			
	Sediment	**499**	**548.9**
New Structure			
	Sediment	**515**	**566.5**
Total		**1,163**	**1,279**

Source: Mott MacDonald, 2023

The MT module was coupled to the local MIKE3 FMHD model and used to simulate sediment dispersion from the dredging operation. It has been assumed that:

- From the total volume to be dredged (1,279m^3), only the fine fractions of Table 9.5 are included in the model, corresponding to 11% of the total volume;
- The dredging operation will start at Dredge Pocket 1 and will move to the east towards the area (Dredge Pocket 2) next to the existing breakwater;
- A backhoe dredger (BHD) will be used;
- The BHD will use a 2.5 m^3 bucket;
- The BHD will dredge continuously (worst case);
- Each bucket load will dredge 1.75 m^3 of sediment (*in-situ* volume), assuming an average bucket efficiency of 70%, and the BHD works at a rate of 25 bucket loads per hour[6]. The BHD will therefore have a production rate of approximately 43.75 m^3 (*in-situ* volume) per hour;
- The modelled dredging will start at spring tide when tidal range and current speeds are at their highest; and
- Dredging will start at high water.

Based on the above assumptions, dredging would be completed in 29.2 hours. In reality, downtime resulting from weather, vessel movements and/or plant maintenance will result in a longer dredge period. The above assumptions provide a worst-case assessment, yielding a high release intensity and the greatest potential for higher plume concentrations.

Local flow characteristics determine how sediment suspended during dredging will disperse in the marine environment. The tidal flows in the region of the dredge are relatively low, and winds may have a notable influence on the local flow conditions. At present, the model assumes no wind (only tidal conditions). Further tests with time-varying mean wind will be provided.

This dredging operation described above was implemented in the MIKE3 FM HD/MT model using the dredging option in the model setup. The model requires time series describing the dredging operation in terms of dredger location over time, dredging rate (mass per time) and percentage of material spilt over the time of the simulation. It has been assumed that:

- The dredging material has a dry density of 1050 kg/m^3;
- The spill rate is 5% (conservative); and
- Dredging occurs over 17 days to cover a full spring-neap cycle.

[6] as specified in the productivity rates provided in the Technical Guidelines for Environmental Dredging of Contaminated Sediments (US Army Corps ERDC/EL TR-08-29).

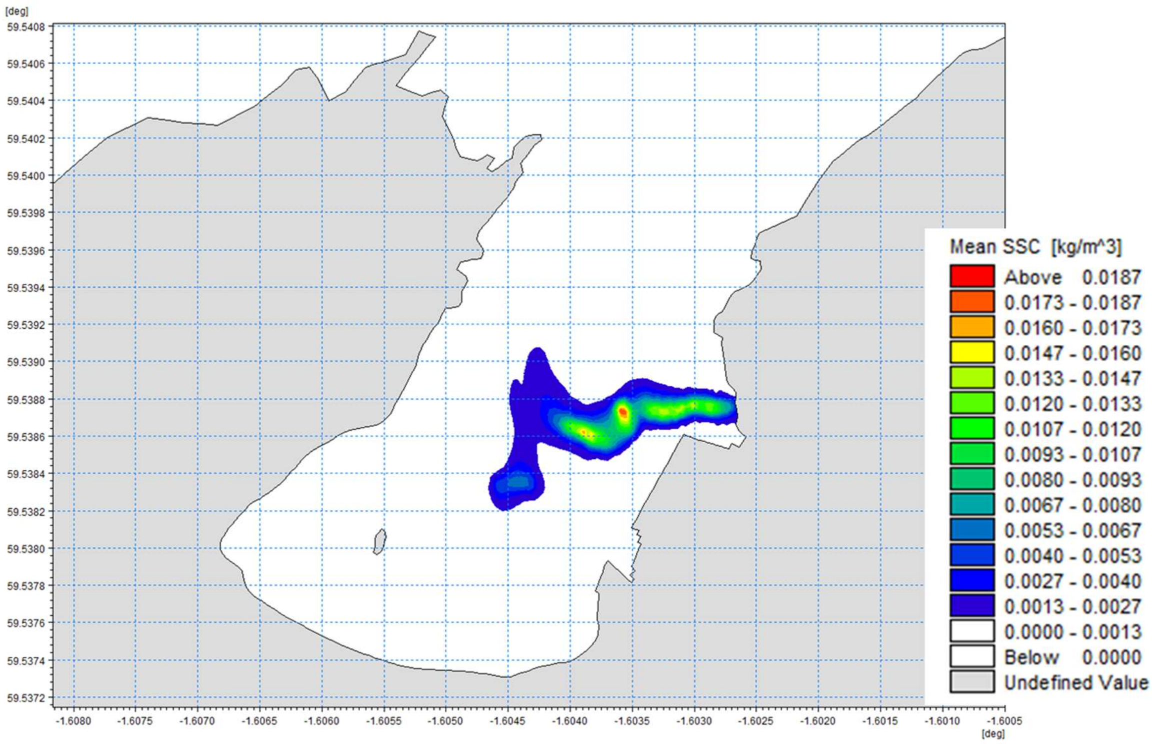
9.5 Model results

9.5.1 Suspended sediment concentration (SSC)

Figure 9.3 and Figure 9.4 show the mean and the maximum depth average suspended sediment concentration (SSC) during the simulation period. Since the model was run without any background concentrations, these figures show the spatial distribution of the suspended sediment attributable only to the BHD losses (assumed 5% of the dredged volume).

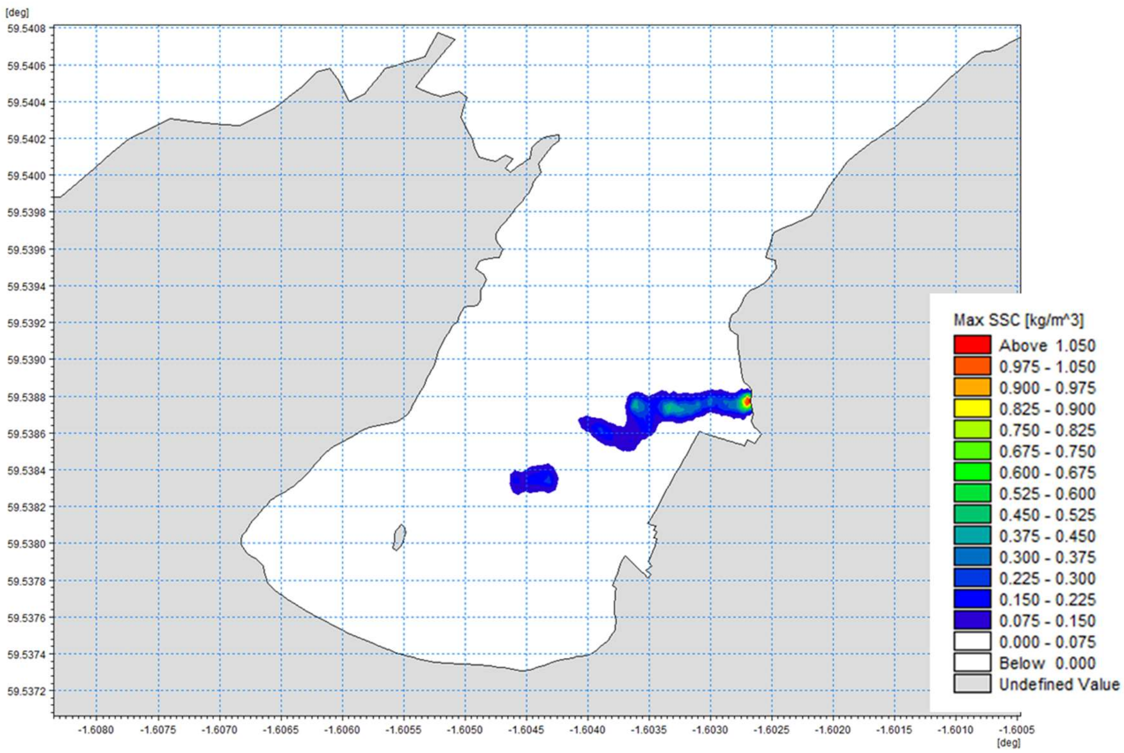
In both figures, it is clear that the effect of the spilt sediment is limited, and the SSC values are generally low. The highest SSC values of approximately 1.05 kg/m^3 (1050 mg/l) are observed close to the shore, behind the existing breakwater (Figure 9.4). SSC values decrease rapidly to less than 0.3 kg/m^3 (300 mg/l) at 30m from the dredger.

Figure 9.3: Mean modelled SSC over a spring-neap cycle. Please note that the model SSC is expressed in kg/m^3 instead of mg/l (0.1 kg/m^3 equals 100 mg/l).



Source: Mott MacDonald, 2023

Figure 9.4: Maximum modelled SSC over a spring-neap cycle. Please note that the model SSC is expressed in kg/m³ instead of mg/l (0.1 kg/m³ equals 100 mg/l).



Source: Mott MacDonald, 2023

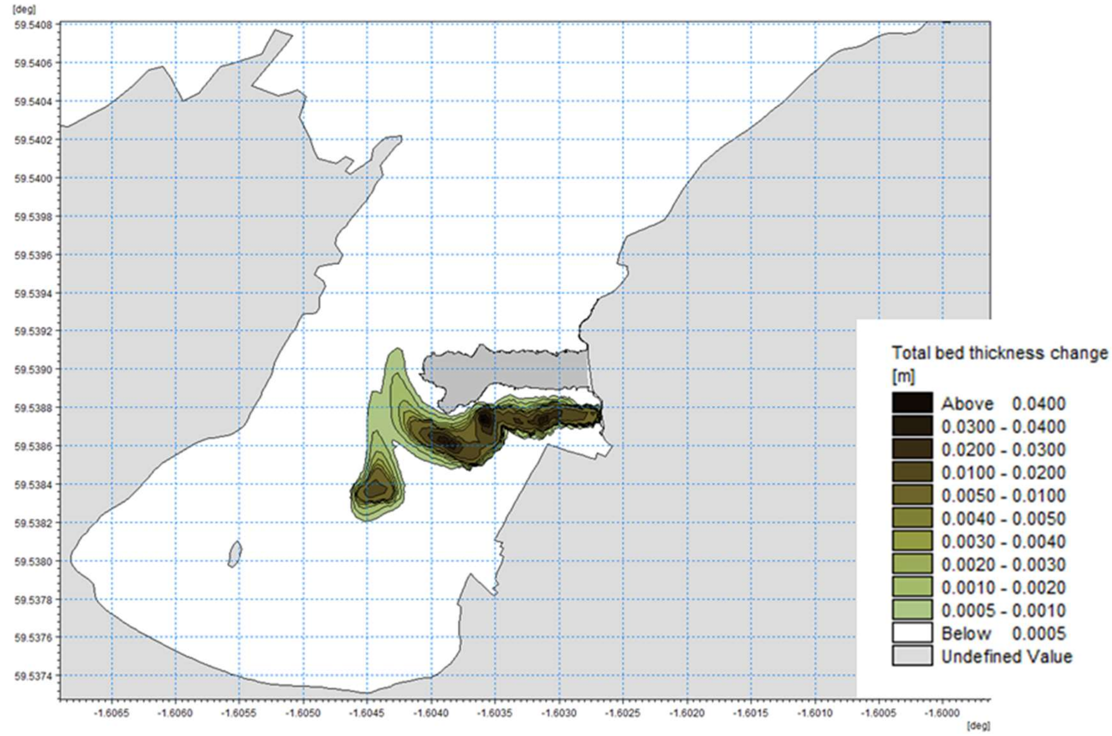
9.5.2 Sediment deposition

The predicted deposition resulting from the sediment split by the dredging is shown in Figure 9.5. Deposition of more than 0.04 m is predicted only to occur close to the dredge footprint.

The plot shows the following:

- The sedimentation is predicted to deposit very localised under the dredge footprint and adjacent areas;
- Sedimentation of more than 0.04 m is predicted to occur within the dredge footprint predominantly. It is, therefore, likely that much of this will be re-dredged throughout the dredging campaign; and
- Sedimentation of 0.001 m (1 mm) extends only up to approximately 50 m from the dredge footprint.

Figure 9.5: Excess deposition over 17-day model simulation. The deposition is estimated using a dry density of 300 kg/m^3, assuming 5% of the dredged volume was spilt during the operation.



Source: Mott MacDonald, 2023

10 Summary and conclusions

The Fair Isle Ferry Replacement Project aims to modernise the existing ferry terminal in North Haven, Fair Isle, 24 miles off the southern tip of the Shetland Islands, Scotland. To accommodate new vessels and provide better protection against wave action, MML, in collaboration with Shetland Island Council (SIC) and ZetTrans, is developing an Outline Business Case (OBC) for upgrading the Fair Isle Ferry Terminal. However, this involves dredging approximately 1,163 m^3 of sediment, which requires analysing the present hydrodynamic and sediment transport conditions to establish a baseline for North Haven and identify potential impacts on the bay's processes.

MML has utilised a calibrated MIKE3 by DHI Flexible Mesh (FM) regional North Sea hydrodynamic (HD) model of the Scottish west coast (RNSM) to simulate tidal flows around Fair Isle. A more detailed local HD model was then set up using boundary conditions from the RNSM. Together with outputs from an existing MIKE21 spectral wave (SW) model, this detailed HD model drove sand transport (ST) and mud transport (MT) modules. The ST model simulated wave-current sand transport in North Haven under normal and extreme conditions. The MT module simulated the dispersion of cohesive sediments (silt and mud) disturbed during dredging. These modelling studies provide compelling evidence demonstrating that:

- Changes to the wave-current driven sand transport in North Haven attributable to the Project are small and will have a virtually undetectable impact on the present data processes or coastal morphology;
- An assumed 5% sediment loss during dredging would release around 147 m^3 of fine-grained sediments in short-lived plumes confined to a few hundred metres from dredging operations. Consequently, impacts will be small;
- The maximum suspended sediment concentration (SSC) reaches approximately 1.5 kg/m^3 (1050 mg/l) and is short-lived and confined to an area between the existing quay and the breakwater. Consequently, impacts will be small;
- Further from the dredging source, modelling shows that SSC values rapidly decrease as sediment quickly settles to the bed;
- The maximum accretion depth attributed to dredging is predicted to be only 0.04 m and is confined to an area defined approximately by the dredging footprint. Some of this deposited sediment will be removed during the dredging process; and
- Based on current observations, it is unlikely that there will be significant changes to the morphology or sediment characteristics of the beach. Any changes that do occur are likely to fall within the natural range of response associated with the spring-neap tidal cycle and storm events and may not be detectable;
- The increase in breakwater height and the reduction in porosity will reduce overtopping and wave transmission through the structure during extreme events and increase wave protection to the beach's eastern section used for recreational purposes; and
- Following SEPA guidance, climate change assessments included an allowance for a cumulative SLR for RCP8.5 for the 95th percentile of 0.52m and increases in offshore wave height and wind speed of 10%. Differences between sediment transport with the proposed scheme in situ without and with climate change allowances are judged insignificant and probably undetectable from within the range of natural variability. The impact of the climate change conditions on the sediment patterns is therefore considered negligible.

11 References

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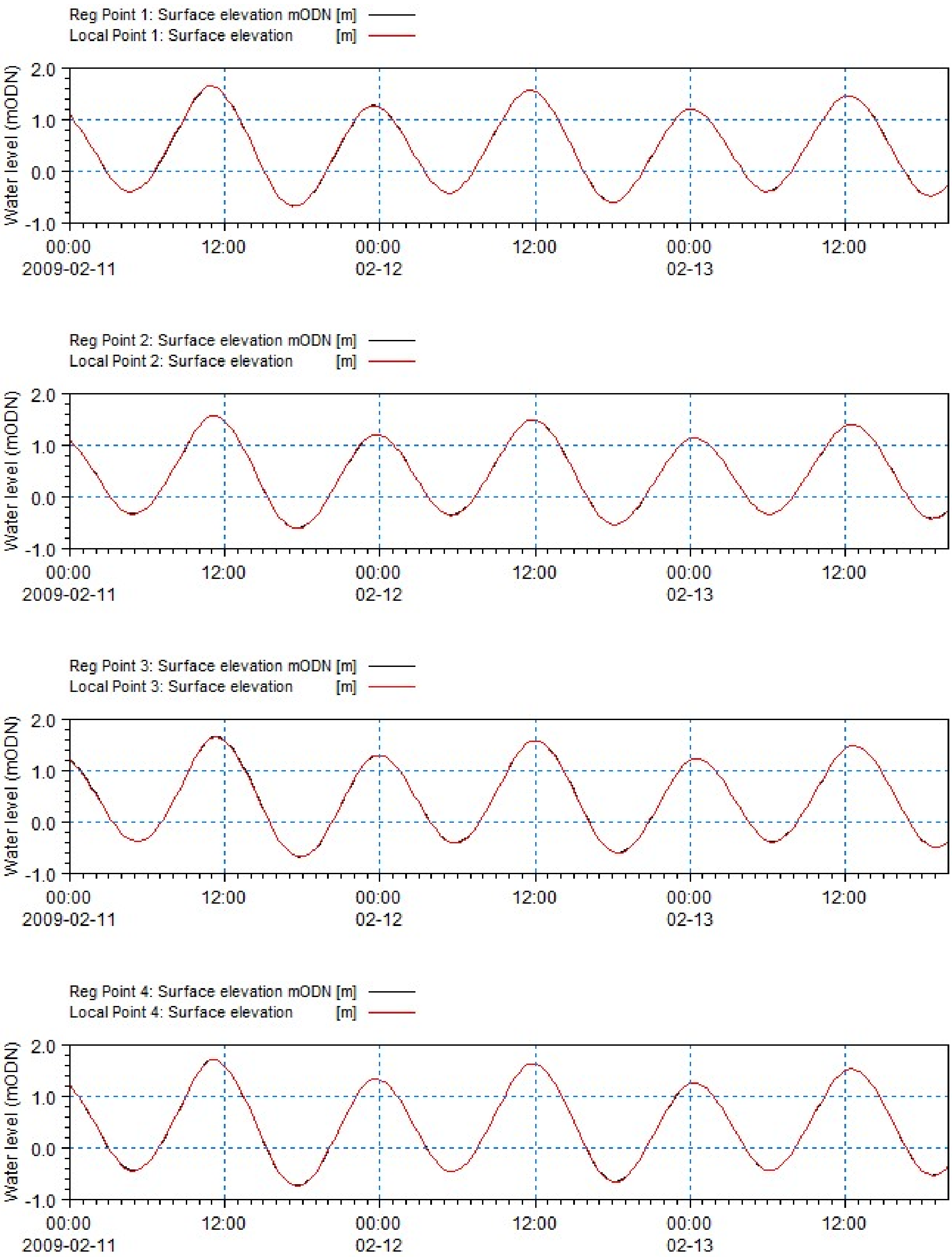
Appendices

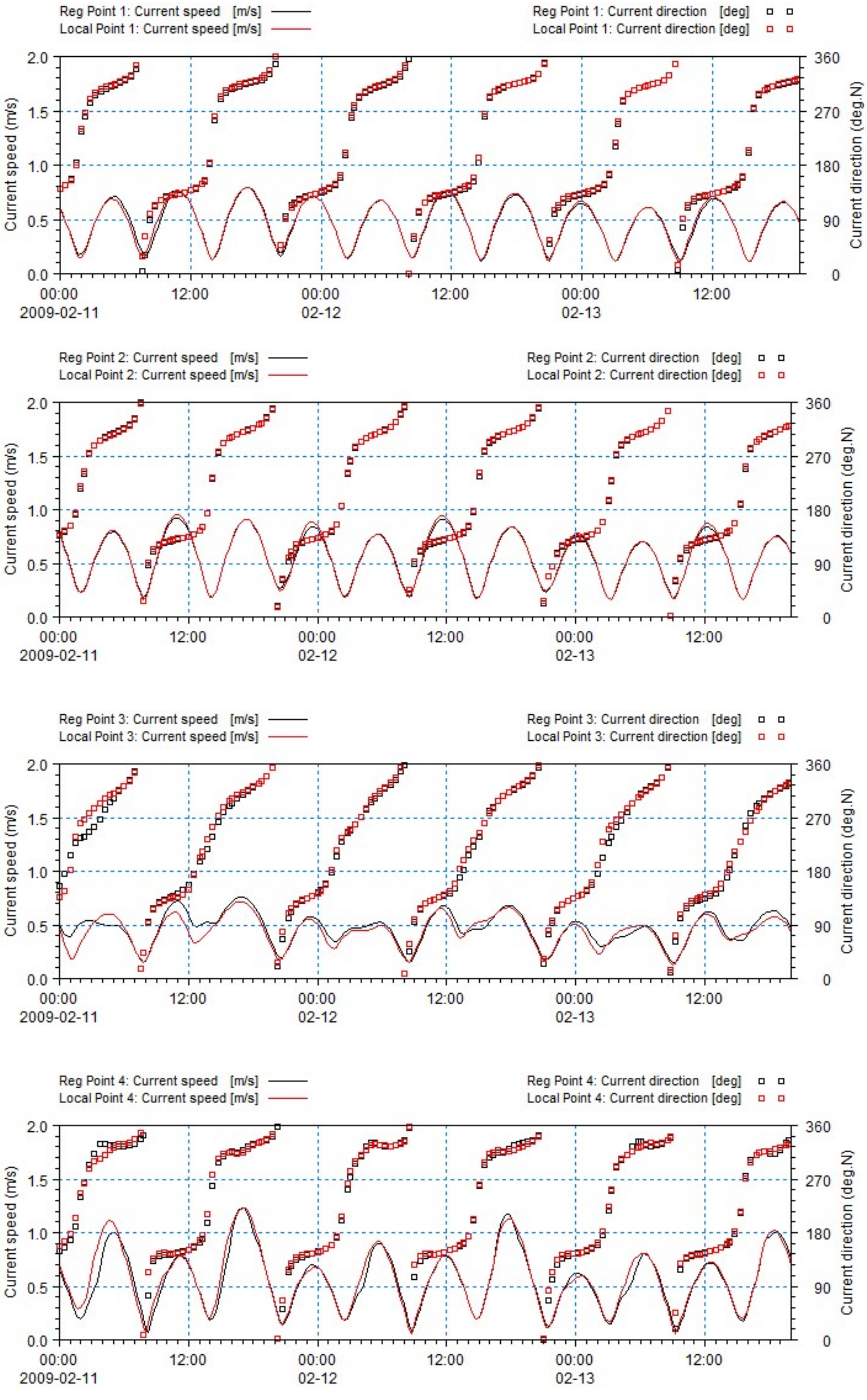
A. Validation plots

Figure A.1: Comparison between regional (black line) and local (red line) water levels for the validation period of the local model – Poitns 1 to 4



Source: Mott MacDonald, 2023

Figure 11.1: Comparison between regional (black line) and local (red line) current speeds and direction for the validation period of the local model – Poitns 1 to 4



Source: Mott MacDonald, 2023

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