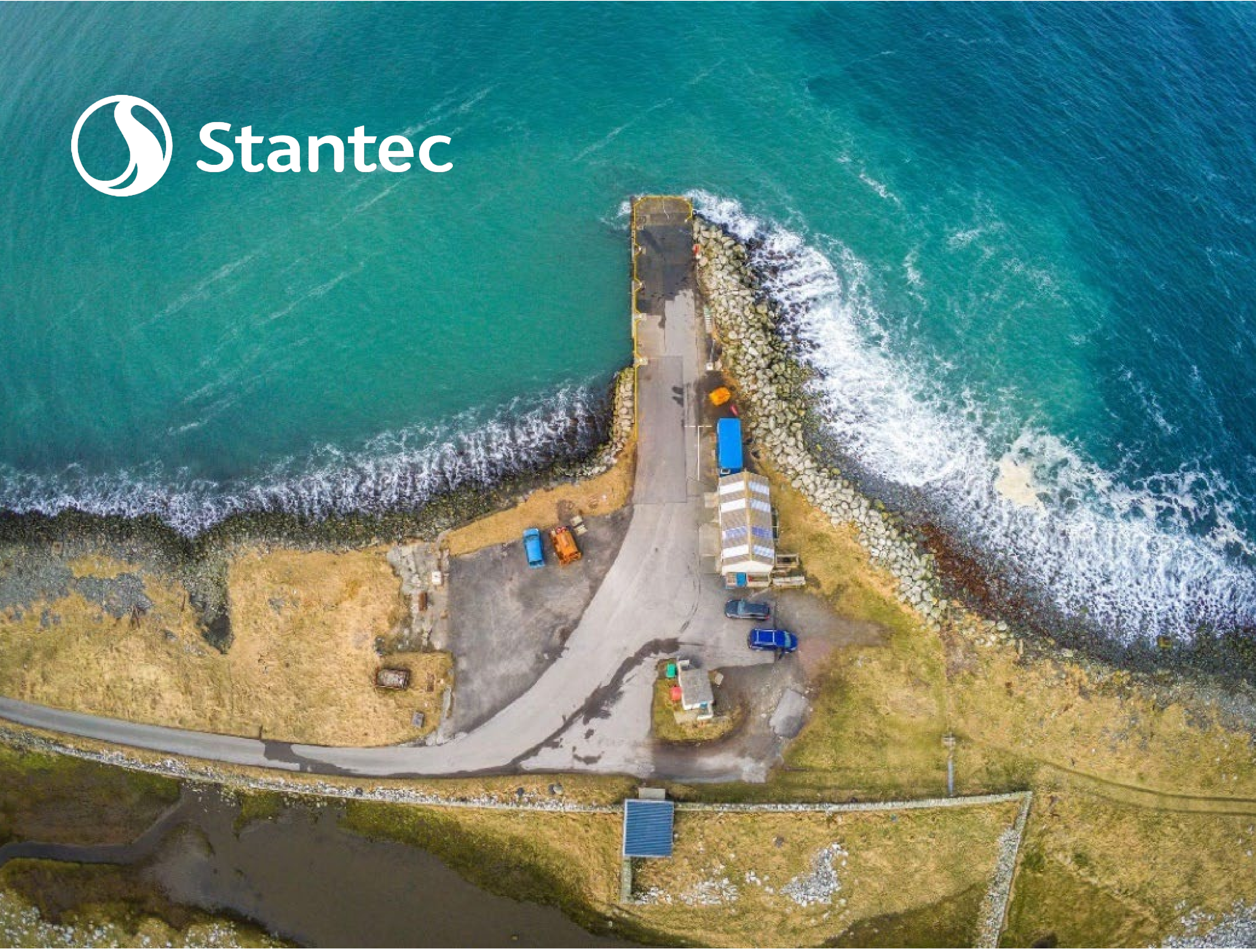

Appendix E

Wave Modelling Report

On behalf of

Shetland Islands Council

Project Ref:332511168| Rev: A | Date: March 2023

Front Cover Photograph provided by Brian Gray

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Grutness Wave Modelling

March 2023

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Grutness Wave Modelling

March 2023

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Executive summary

The Grutness ferry terminal requires upgrading to accommodate different vessels, expand access and provide improved shelter from waves. Wave modelling is required to establish the exposure to local wind-generated waves and swell from several directions.

This report first describes the development, calibration and validation of a regional-scale spectral wave model covering a wide area of Shetland Islands and all relevant coastal and offshore areas that influence the wave conditions at Grutness. The regional wave model was calibrated and validated against historical wave data at Lerwick station and conformed to robust wave model performance metrics (Williams and Esteves, 2017) during normal wave conditions and storm events. Extreme wave analysis of the regional wave model results was used to define events with Annual Exceedance Probability (AEP) values of 1,10, 50 and 100%.

Local spectral wave models of Grutness were built using bathymetric survey data commissioned for the project. These models included the existing ferry terminal layout (baseline) and two new proposed layouts (Layout 1 and Layout 2). Since the regional model showed that the highest waves occurred in 2018, the local wave model was run for that year for the baseline and proposed layouts. The local wave model was also simulated for the 1, 10, 50 and 100% AEP. Furthermore, diffraction has been included in the local wave model as the study considered breakwater options. Predicted waves were extracted and analysed to identify the differences between the layouts.

As a results, significant wave height (Hs) decreased at the extraction points behind the breakwater in Layout 1 and Layout 2 as expected due to their locations compared to the baseline layout. High peak wave period (Tp) values are also predicted at the extraction points behind the breakwater in Layout 1 and Layout 2 due to diffraction and directional spreading.

It should be noted that while the present model results provide a reasonably accurate estimation of local wave conditions, the local model was not calibrated. Therefore there will always be some uncertainty until a model calibration is performed. Additionally, the local wave conditions are better represented using a wave-resolving model (e.g. MIKE3 Wave FM), which accounts for reflections and wave-wave interactions. Correct representation of these processes in a model is required for detailed design purpose.

1 Introduction

1.1 Background

The Grutness ferry terminal requires upgrading to accommodate different vessels, expand access and provide improved shelter from wave action. As the project moves towards the design development phase, wave modelling is required to establish the exposure to local wind-generated waves and swell from several directions. By establishing a local wave model, the efficacy of the harbour designs can be assessed.

As the ferry terminal location is exposed to waves from several directions, regional and local scale MIKE21 flexible mesh (FM) spectral wave (SW) models were developed and run to understand swell and wind wave propagation from offshore to the Grutness ferry terminal. The regional model was calibrated and validated against available historical measured wave buoy data, and the outputs from the calibrated/validated regional model were then used as boundary conditions for the local wave model at Grutness. The wave model results assisted in the optimisation of two new proposed ferry terminal layouts.

1.2 Report Structure

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

- Section 2 describes the numerical modelling approach;
- Section 3 details data used to build the models, including bathymetry, waves, water level and wind;
- Section 4 describes the build, calibration and validation of the regional wave model;
- Section 5 presents an extreme value analysis (EVA) to estimate the Annual Exceedance Probability (AEP: 100%, 50%, 10% and 1%) of waves and wind;
- Section 6 describes the development of the local model and local model runs;
- Section 7 presents and discusses the local model results; and
- Section 8 summarises the work presented in this report.

2 Method

Figure 2.1 shows an overview of the methodology used in this project. The regional and local wave models were built using DHI's state-of-the-art numerical wave modelling software MIKE21 flexible mesh (FM) spectral wave (SW)[1]. The modelling and analysis methods used the best available data to deliver the study objectives. Initial stages in the model build included the acquisition of bathymetry, hindcast spatial waves and wind data from the European Centre for Medium-Range Weather Forecast (ECMWF) ERA5[2] for January 1979 to December 2020 (42 years) and water level data near the study area.

The regional wave model was calibrated and validated against historical nearshore wave data measured at Lerwick (-1.12^{0}E, 60.203^{0}N) from 3 April to 7 November 1985. The regional wave model was run from January 1979 to December 2020 (42 years), and an extreme value analysis (EVA) was performed to determine the characteristics of wave events with Annual Exceedance Probabilities (AEP) of 100%, 50%, 10% and 1%.

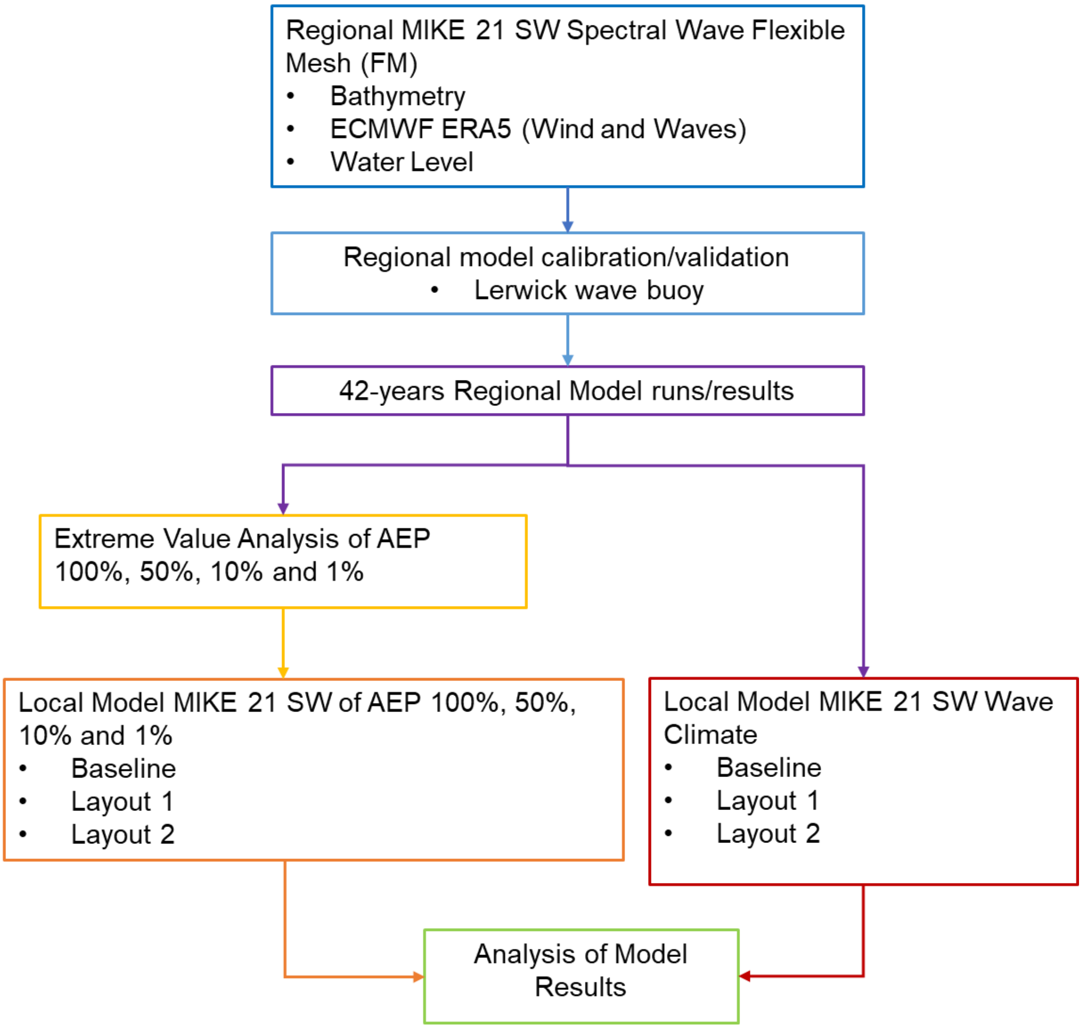
The EVA results were then supplied at the local wave model boundaries for the baseline and proposed layout runs (i.e. Layout 1 and Layout 2).

For the local wave climate runs, the local wave model boundary conditions were extracted from the regional results and used scaled ECMWF ERA5 as wind forcing in the model. The representative year for the wave climate run is 2018, as this year represents the highest significant wave height (Hs) based on the 42-years regional model results. The analysis of the local wave model results of the AEP and wave climate runs is discussed in Section 7.

[1] https://www.mikepoweredbydhi.com/products/mike-21/waves/spectral-waves

[2] H. Hersbatch et al., “Global reanalysis: goodbye ERA-Interim, hello ERA5,” ECMWF Newsl., no. 159, pp. 17-24, 2019. (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview)

Figure 2.1 Methodology



Source Mott MacDonald, 2023

3 Data

3.1 Systems and Projections

Geographical data used in this study uses the geographical coordinate (longitude/latitude) Horizontal Datum. The vertical datum was referenced to the Mean Sea level (MSL) for the regional wave model and the local ordnance (OD) datum for the local wave model.

3.2 Bathymetric data

The bathymetric data used to build wave models comprised:

- UK Hydrographic Office (UKHO)[3] datasets;
- European Marine Observation and Data Network (EMODnet, 2020)[4]; and
- A bathymetry survey[5] of Grutness.

For the regional wave model, the bathymetry datum was set to mean sea level (MSL). The local wave model datum was referenced to the local ordinance datum (OD), and priority was given to the most recent datasets with the highest spatial resolution.

3.3 Water level data

Without any measured tide data for the regional model runs, predicted water level data at Sumburgh (Figure 3.1) were extracted from Delft Dashboard[6]. Figure 3.2 shows the 42-year time series of the predicted water level from Sumburgh, close to Grutness. The tidal characteristics at Sumburgh extracted from Admiralty TotalTide[7] are shown in Table 3.1.

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[3] Bathymetry data Service (admiralty.co.uk)

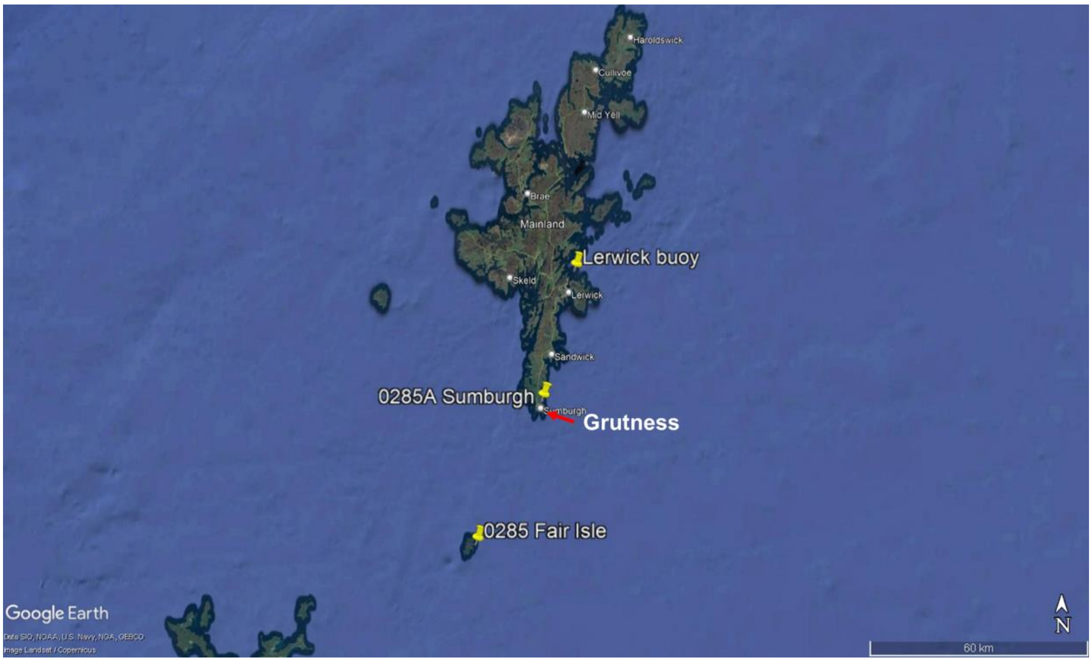
[4] https://portal.emodnet-bathymetry.eu/

[5] Undertaken by Aspect Ltd in June 2022

[6] Delft Dashboard - Delft Dashboard - Deltares Public Wiki

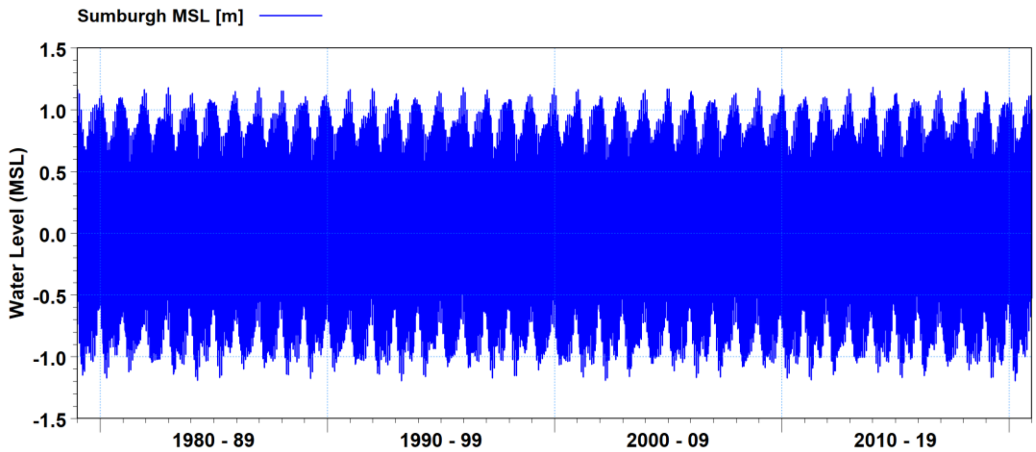
[7] https://www.admiralty.co.uk/

Figure 3.1 Location of the Sumburgh and Fair Isle tide stations and Lerwick buoy



Source Google Earth and Mott MacDonald, 2023

Figure 3.2 Time series of water level at Sumburgh (January 1979-December 2020)



Source Delft Dashboard, 2023

Table 3.1 Tidal levels at 0285A Sumburgh

Tidal level	Chart Datum (CD), m	Local Ordnance Datum (OD), m
Highest Astronomical Tide (HAT)	2.20	1.14
Mean High Water Springs (MHWS)	1.80	0.74
Mean High Water Neaps (MHWN)	1.40	0.34
Mean Sea Level (MSL)	1.06	0.00
Mean Low Water Neaps (MLWN)	0.70	-0.36

Mean Low Water Springs (MLWS)	0.40	-0.66
Lowest Astronomical Tide (LAT)	0.00	-1.06

Source: Admiralty TotalTide, 2021

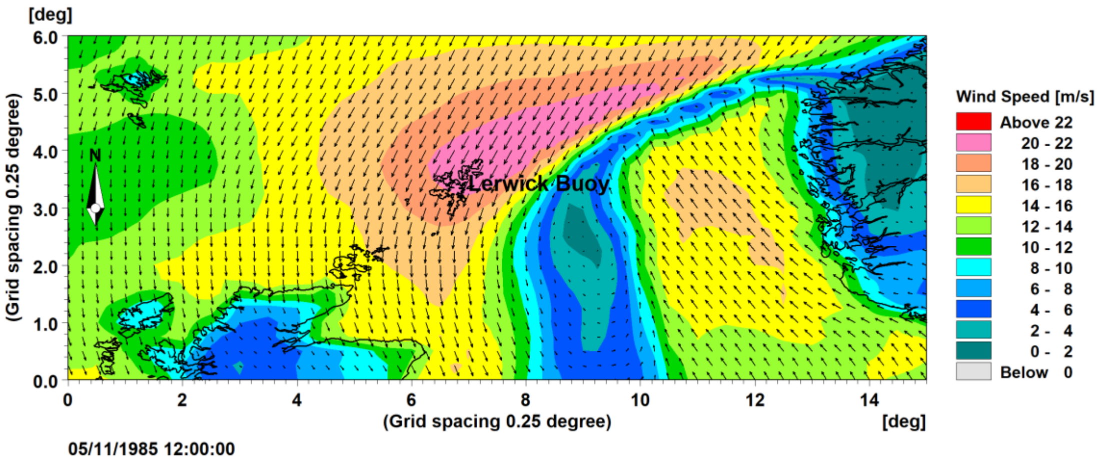
3.4 Wave data

ECMWF ERA5 hindcast spatial wave data (0.5-degree spatial resolution, 1-hr intervals) from January 1979 to December 2020 were used as offshore boundary conditions to the regional wave model. Historical measured wave data at Lerwick (Figure 3.1), quantifying significant wave height (Hs) and zero-crossing wave period (Tz), were obtained from the Cefas database[8]. Mean wave direction (MWD) at Lerwick station is not available. The Hs and Tz data were used to calibrate the regional model (Section 4.5).

3.5 Wind data

The wind is the primary forcing contribution to ocean wave formation, and thus, acquiring accurate wind data is important in wave modelling studies. The study used wind data from the ECMWF ERA5 database (0.25-degree spatial resolution, 1-hr intervals). A 42-year record of U and V wind components at an elevation of 10m was extracted from the database from January 1979 to December 2020. Figure 3.3 shows an example of a spatial wind map during the largest storm at a regional scale defined by the highest recorded Hs from the historical Lerwick wave buoy data on 5 November 1985 at 12:00 indicates that strong winds up to 22 m/s from the north-east at Lerwick.

Figure 3.3 Wind speed distribution in the 5 November 1985 storm at 12:00 UTC.



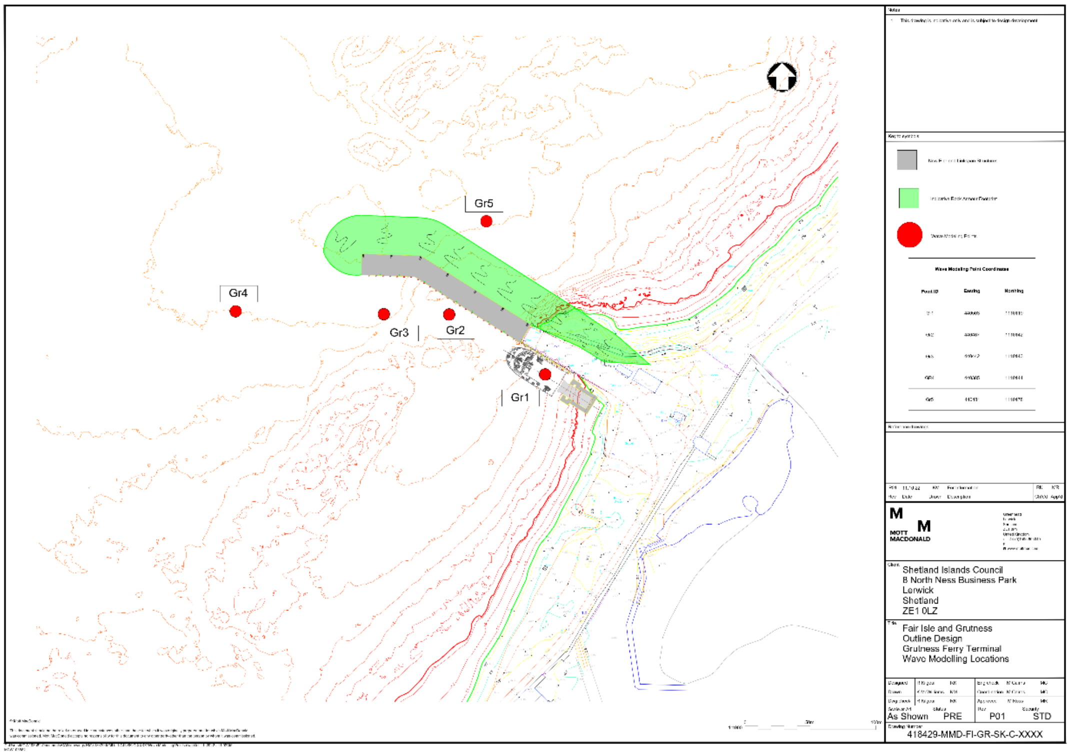
Source: ECMWF ERA5 & Mott MacDonald, 2023

3.6 Proposed Layouts

Two proposed port layouts were used in local wave models to simulate AEP events and annual wave climate (one-year period) scenarios. Layout 1 only involved extending the breakwater's length. Layout 2 involves the extension of the breakwater and dredging. The proposed Layouts 1 and 2 and the five wave data extraction points used to assess wave conditions at the project site are illustrated in Figure 3.4 and Figure 3.5, respectively.

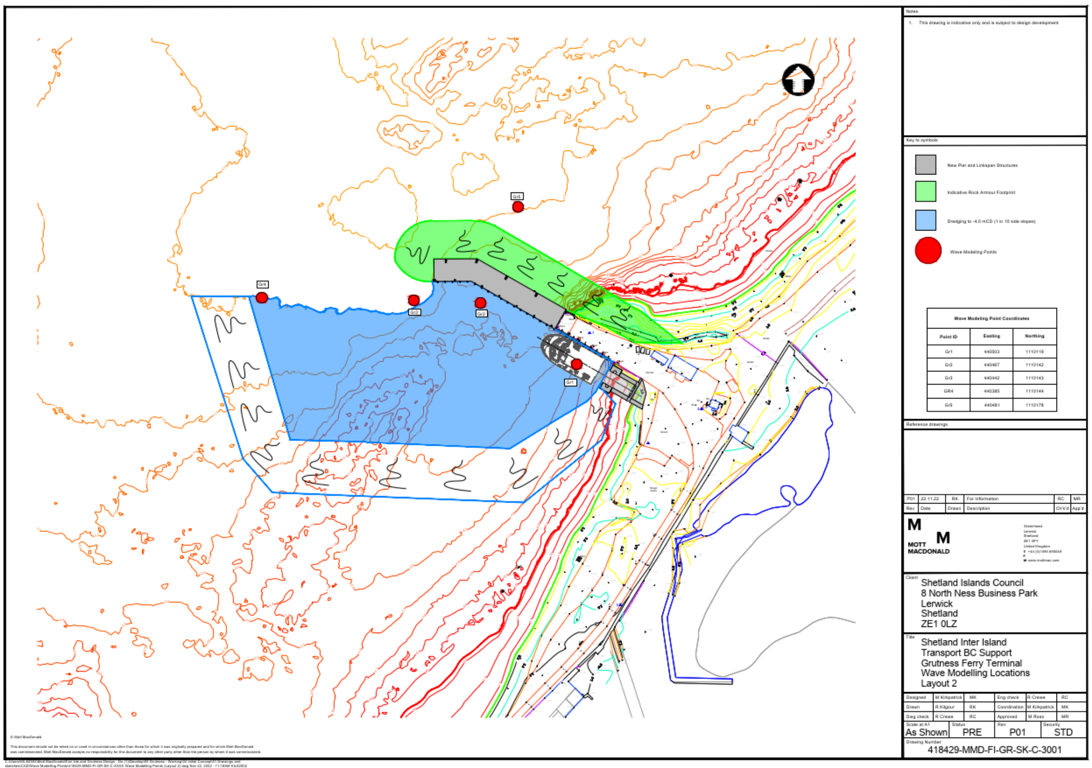
[8] http://wavenet.cefas.co.uk/Map?ZoomTo=0.4755%2C53.0582

Figure 3.4 Proposed Layout 1.



Source: Mott MacDonald, 2023

Figure 3.5 Proposed Layout 2.



Source: Mott MacDonald, 2023

4 Regional MIKE21 FMSW model

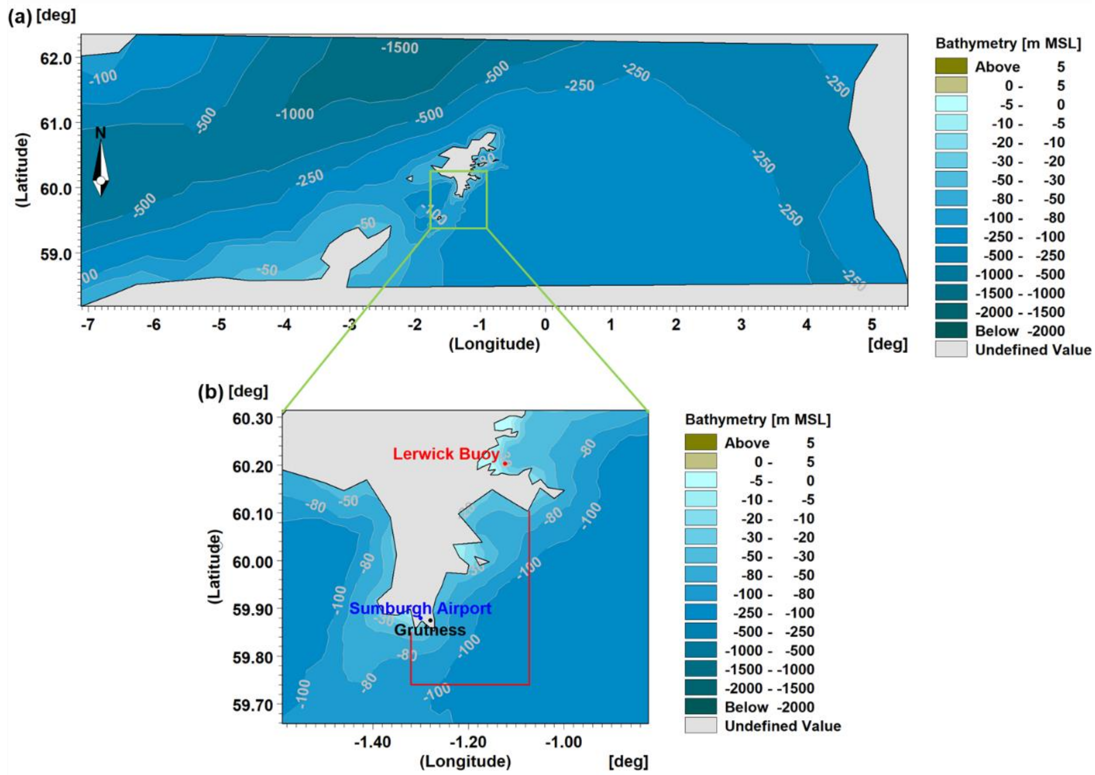
The regional MIKE21 FMSW model was built to transform ECMWF ERA5 offshore data to the inshore area and provide the wave boundary conditions for the local MIKE21 FM SW wave model. This is a third-generation spectral wind-wave model based on the finite volume method on an unstructured mesh that enables full-time domain simulations. The model simulates wind-generated waves' growth, decay and transformation and swells in offshore and coastal areas. The model includes wave growth by wind, nonlinear wave-wave interaction, dissipation due to white-capping dissipation due to bottom friction, dissipation due to depth-induced wave breaking, refraction and shoaling due to depth variations, wave-current interaction and the effect of time-varying water depth. Therefore, the model is deemed suitable to define the wave conditions in this study.

4.1 Regional model domain

The regional MIKE21 FM SW model was set up to cover a wide area of Shetland Islands and all relevant coastal and offshore areas influencing the wave conditions from the regional to local areas (Figure 4.1a). Figure 4.1b shows an enlarged view of the Grutness local model domain (indicated as the red line) and the locations of the historical Lerwick wave buoy and local wind station at Sumburgh airport. An overview of the model flexible mesh resolution for the regional models is shown in Figure 4.2a, with an enlarged view of the Grutness local model domain boundaries in Figure 4.2b. The resolution of the model mesh is coarser in the offshore region (5km to 20km). In the nearshore area around the local model boundary (Figure 4.2b), the element sides of the mesh are approximately 1500m long. The processed bathymetry data in Section 3.2 was linearly interpolated across the regional model flexible mesh using the MIKE Mesh Generator toolbox[9].

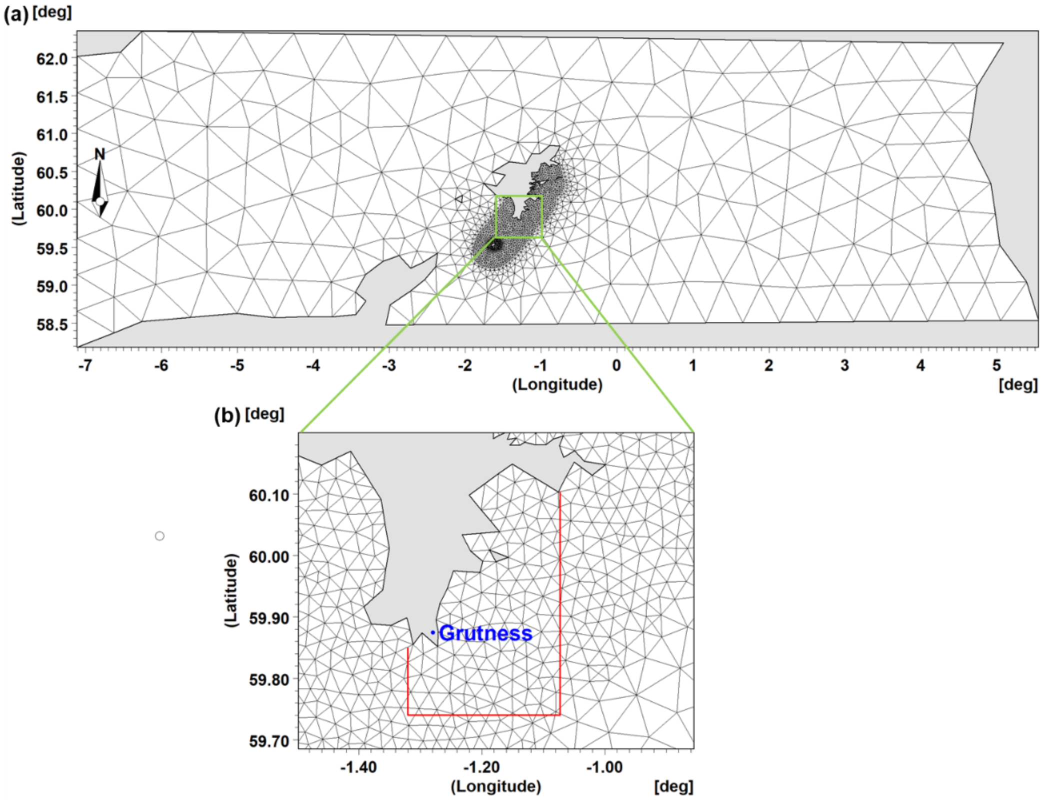
[9] https://manuals.mikepoweredbydhi.help/2017/General/Mesh_Generator_Step_by_Step.pdf accessed on 5 September 2022.

Figure 4.1 MIKE21 FMSW regional model domain and bathymetry of: (a) the whole regional model; and (b) enlarged view at the Grutness model domain boundaries indicated as the red lines.



Source Mott MacDonald, 2023

Figure 4.2 MIKE21 FM SW regional model domain mesh of: (a) the whole regional model; and (b) enlarged view at the Grutness model domain boundaries indicated as the red lines.



Source Mott MacDonald, 2023

4.2 Model forcing by wind and water levels

The main wind forcing applied as surface boundary conditions was taken from the 42-year ECMWF ERA5 hindcast data set. Water level conditions were included as time series from the predicted water level at Sumburgh station (Section 0) in the mean sea level vertical datum.

4.3 Model Boundary

The boundary conditions for the regional MIKE21 FM SW wave model were extracted from the 42-year ECMWF ERA5 hindcast data set (Section 3.4).

4.4 Regional model set-up

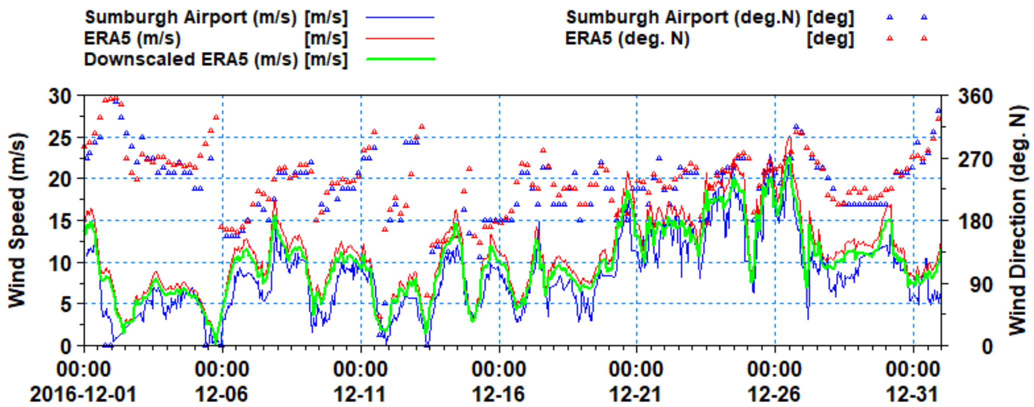
Following the standard modelling procedure, several iterative sensitivity tests were undertaken in which several wave parameters in the model were tuned to achieve the best model set-up. Appendix A summarises the key parameters used in the final regional wave model set-up for calibration.

4.5 Regional model calibration

As part of the process to calibrate the regional MIKE21 FMSW model, wind data from the ECMWF ERA5 dataset was compared with measured wind data from the closest wind station to the Lerwick wave buoy location at Sumburgh airport (Figure 4.1b). This work was undertaken to identify and, if necessary, remove undesirable ECMWF ERA5 wind speed trends against the locally measured wind data.

Figure 4.3 shows that ECMWF ERA5 wind speed is overestimated compared to the measured wind data at Sumburgh airport. Thus, for model calibration purposes, the ECMWF ERA5 data was downscaled by 10% to achieve a similar wind speed trend as Sumburgh. The downscaled ECMWF ERA5 wind speed is shown in Figure 4.3 and demonstrates good agreement with Sumburgh airport. It is noted that the downscaled ECMWF ERA5 wind speed is also higher generally and is, therefore, conservative.

Figure 4.3 Comparison between measured and hindcast wind speed and direction at Sumburgh Airport.

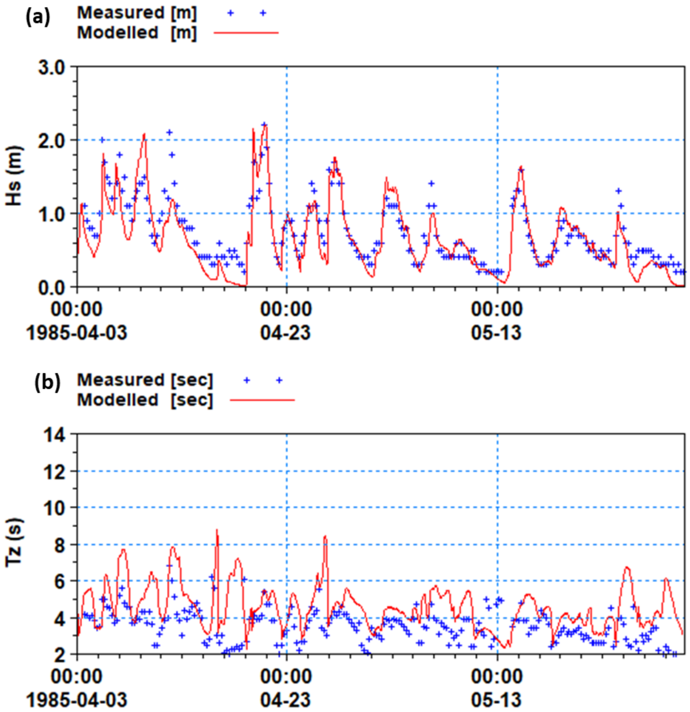


Source Mott MacDonald, 2023

By applying the downscaled ECMWF ERA5 wind data in the regional model, the results show that the model wave predictions compare well against the available historical measured wave data at Lerwick (Figure 4.4, 3 March to 31 May 1985). Model performance statistics are given in Table 4.1 for bias, root-mean-square error (RMSE) and index of agreement (IA). It is shown that the regional model can replicate measured data with high accuracy for Hs (bias = -0.08m, RMSE = 0.18m and IA = 0.93). Similarly, Tz also shows good agreement against measured data. Mean wave direction (MWD) data cannot be compared against model results. The model calibration statistics in Table 4.1 demonstrate that the regional model performance meets the model standard defined in Williams & Esteves (2017)[10].

[10] Williams, J.J. and Esteves, L.S., 2017. Guidance on Setup, Calibration, and Validation of Hydrodynamic, Wave and Sediment Models for Shelf Seas and Estuaries. Advances in Civil Engineering, 5251902, 2017

Figure 4.4 Comparisons between historical measured waves at Lerwick and regional modelled data showing: (a) significant wave height, Hs; and (b) zero-crossing wave period, Tz.



Source Mott MacDonald, 2023

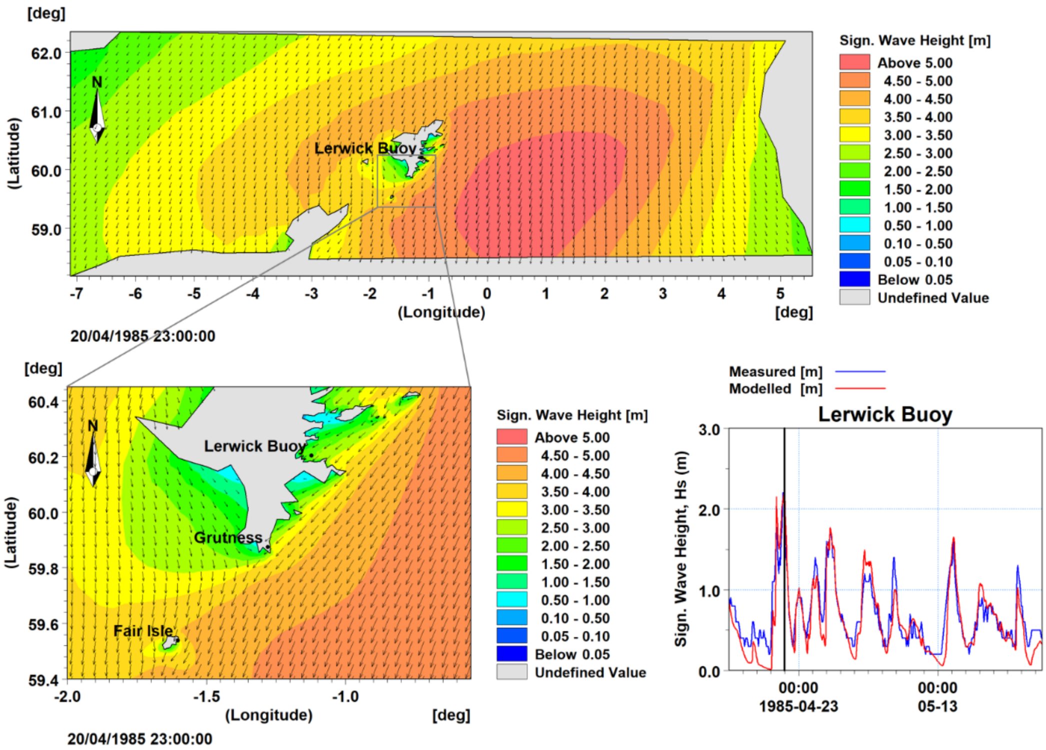
Table 4.1 Summary of the calibrated regional model performance metrics at Lerwick location

Parameter	Hs	Tz
Bias	0.08m	-1.00s
Root Mean Square Error (RMSE)	0.18m	1.73s
Index of Agreement (IA)	0.93	0.50

Source Mott MacDonald, 2023

An overview of the model results during the storm period on 20 April 1985 at 23:00UTC when the dominant wave direction was from the northeast at Lerwick is shown in Figure 4.5.

Figure 4.5 Significant wave height (Hs) predicted by the regional MIKE21 FMSW model during the storm period's peak on 13 April to 28 May 1985



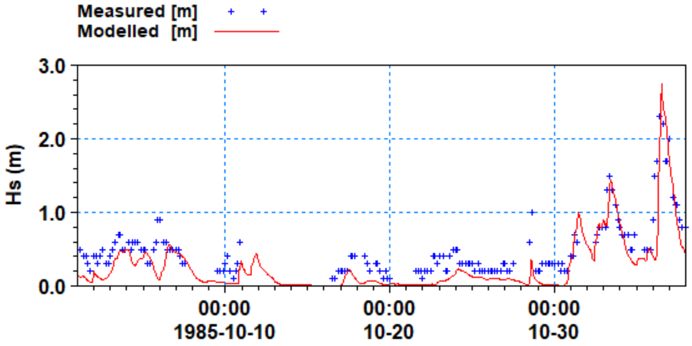
Source Mott MacDonald, 2023

4.6 Regional model validation

Validation of the regional model was undertaken by running the model for a different observational period. Figure 4.6 compares measured and modelled data at the Lerwick buoy location for Hs only, as historical measured Tz and MWD data are unavailable. The model is shown visually to replicate the observed wave conditions from 5 October to 7 November 1985.

Statistics to quantify the model performance are summarised in Table 4.2. Based on the evidence provided in Figure 4.6 and Table 4.2, it is considered that the regional model again reproduces wave conditions in this study satisfactorily and meets the model performance standard defined in Williams & Esteves (2017). Therefore, the calibrated/validated regional model is judged to be suitable to provide boundary conditions for the local models. The calibrated regional model was simulated for 42 years. The 42-year model results were then used to perform extreme value analysis (EVA, Section 5) to estimate extreme wave conditions at the local model boundaries for the 100%, 50%, 10% and 1% AEP.

Figure 4.6 Comparisons between historical measured waves at Lerwick and regional modelled data showing the significant wave height, Hs.



Source Mott MacDonald, 2023

Table 4.2 Summary of the validated regional model performance metrics at the Lerwick location

Parameter	Hs
Bias	0.16m
Root Mean Square Error (RMSE)	0.26m
Index of Agreement (IA)	0.91

Source Mott MacDonald, 2023

5 Extreme value analysis

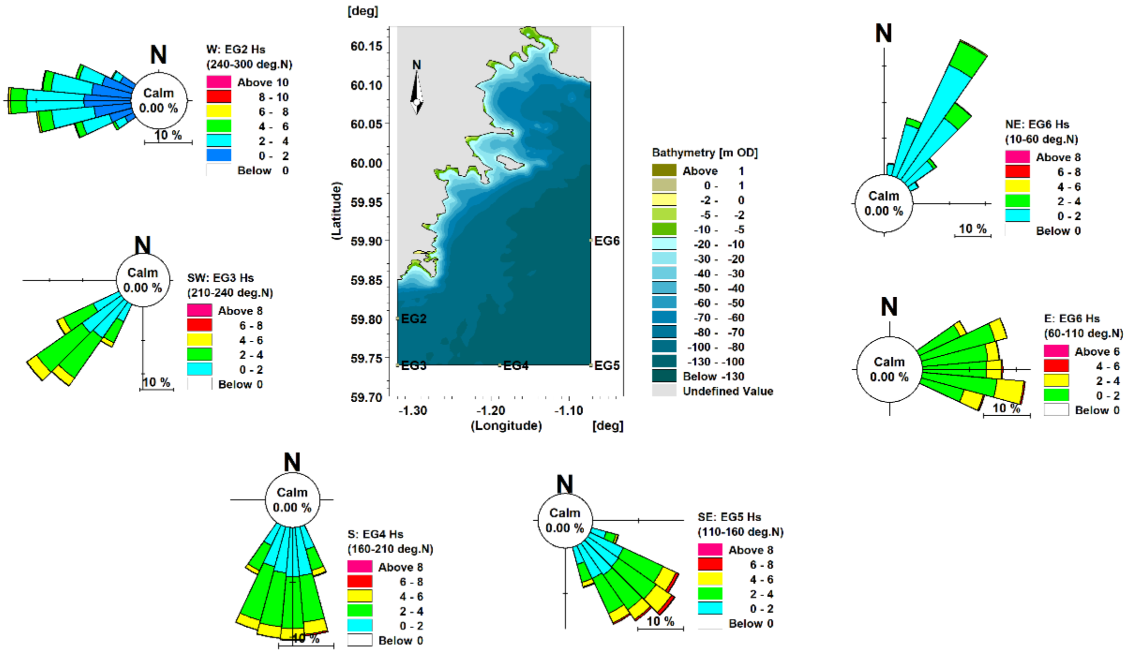
The extreme value analysis (EVA) was performed on the regional wave model results to define wave characteristics associated with 100%, 50%, 10% and 1% AEP events. These conditions were subsequently applied at the local wave model boundaries. The EVA analysis of Hs was undertaken using the DHI EVA Toolbox[11].

5.1 EVA of Hs

The EVA of Hs was conducted using data extracted from the regional wave model at the local wave model boundaries (locations EG2, EG3, EG4, EG5 and EG6, Figure 5.1). Hs values at each boundary point were also analysed for six directional wave sectors:

- West (W): EG2 (240 to 300 deg.N);
- South-West (SW): EG3 (210-240 deg.N);
- South (S): EG4 (160-210 deg.N);
- South-East (SE): EG5 (110-160 deg.N);
- East (E): EG6 (60-110 deg.N); and
- North-East (NE): EG6 (10-60 deg.N).

Figure 5.1 Location of waves data extraction at E3-EG6 with the filtered Hs rose plot based on the selected dominant directional sector.



Source Mott MacDonald, 2023

The filtered Hs dataset was used in the EVA analysis where various probability distribution and estimation methods were considered to calculate the extreme Hs of the 100%, 50%, 10% and

[11] https://manuals.mikepoweredbydhi.help/latest/General/EVA_SciDoc.pdf accessed on 13 September 2022.

1% AEP. The estimated Hs values for the 100%, 50%, 10% and 1% AEP are presented in Section 5.4, Table 5.1. The best-fitted curves to the extreme Hs data for each selected sector are shown in Figure 5.2, with lines showing the 95% confidence intervals.

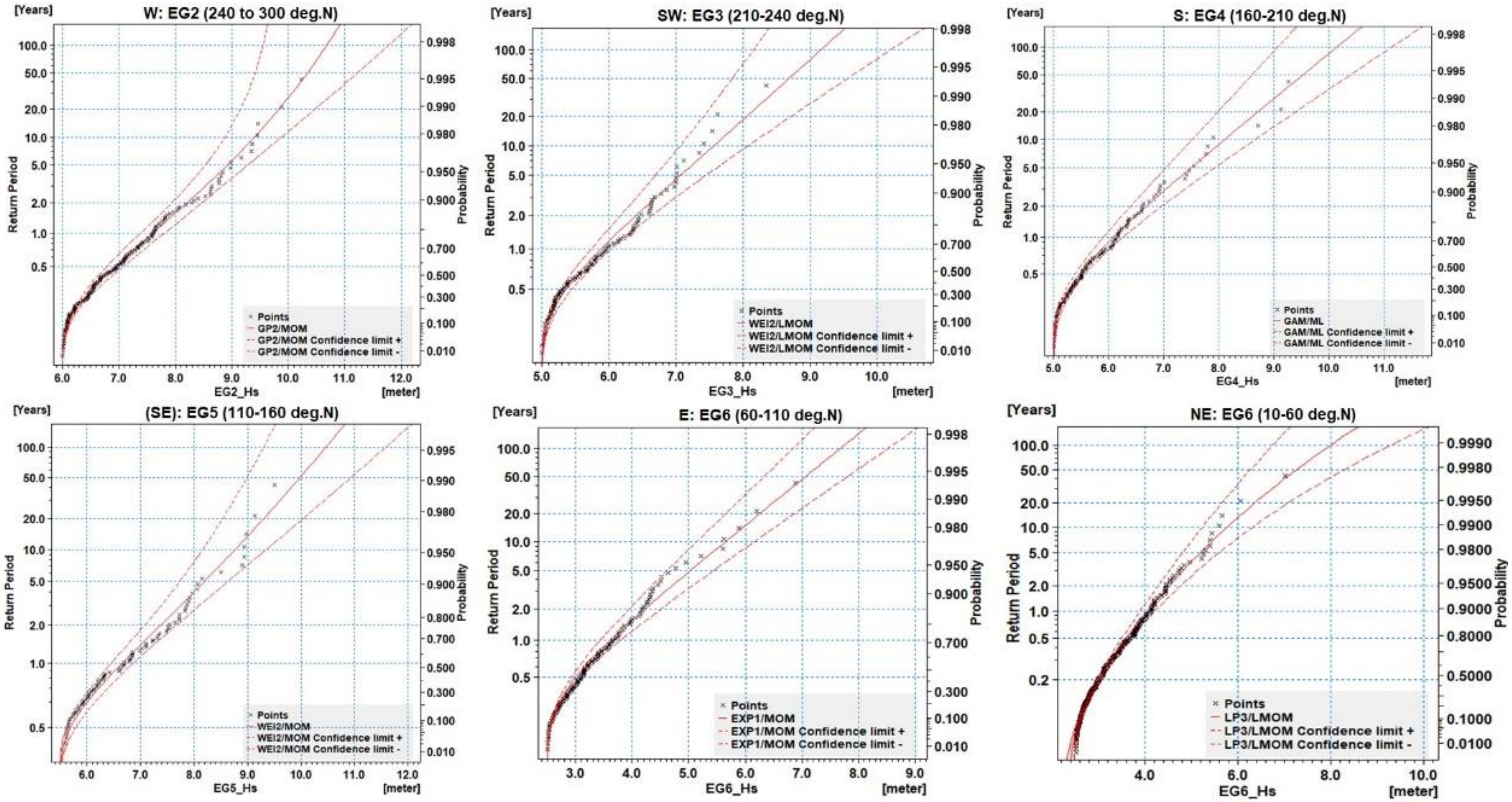
5.2 Tp and Hs relationship

Due to various environmental factors, wave periods were highly variable. Therefore, wave periods associated with given wave heights were defined by the relationship between predicted Tp and Hs values (Figure 5.3). The resulting Tp applied as boundary conditions for the AEP local wave model simulation are shown in Section 5.4, Table 5.1.

5.3 Wind Speed and Hs relationship

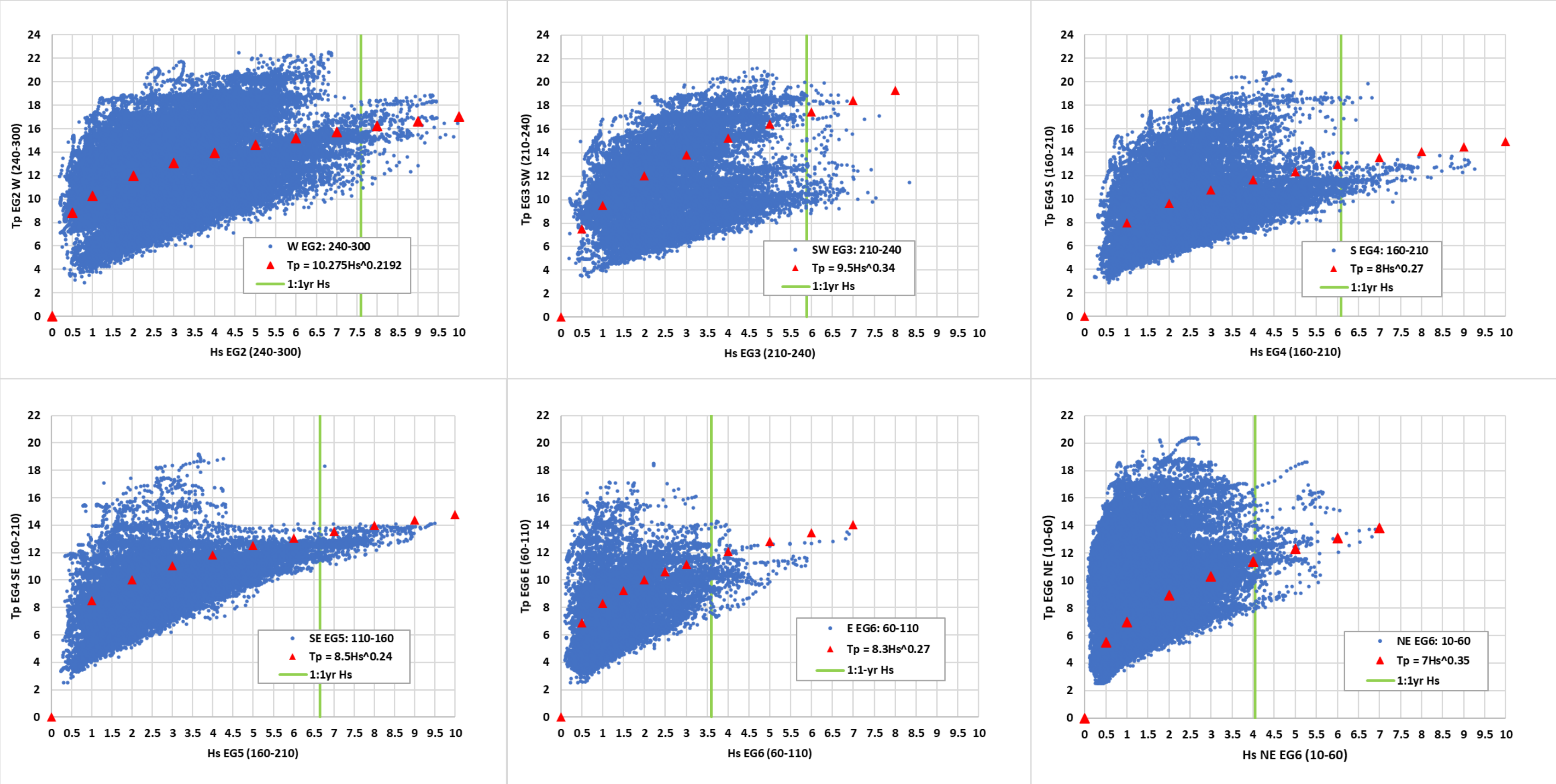
The relationship between wind and wave height was obtained for the six selected directional sectors (Figure 5.4). The resulting extreme wind speeds are tabulated in Section 5.4 (Table 5.1).

Figure 5.2 Probability distribution fit of Hs at the six selected dominant directional sectors (W, SW, S, SE, E and NE).



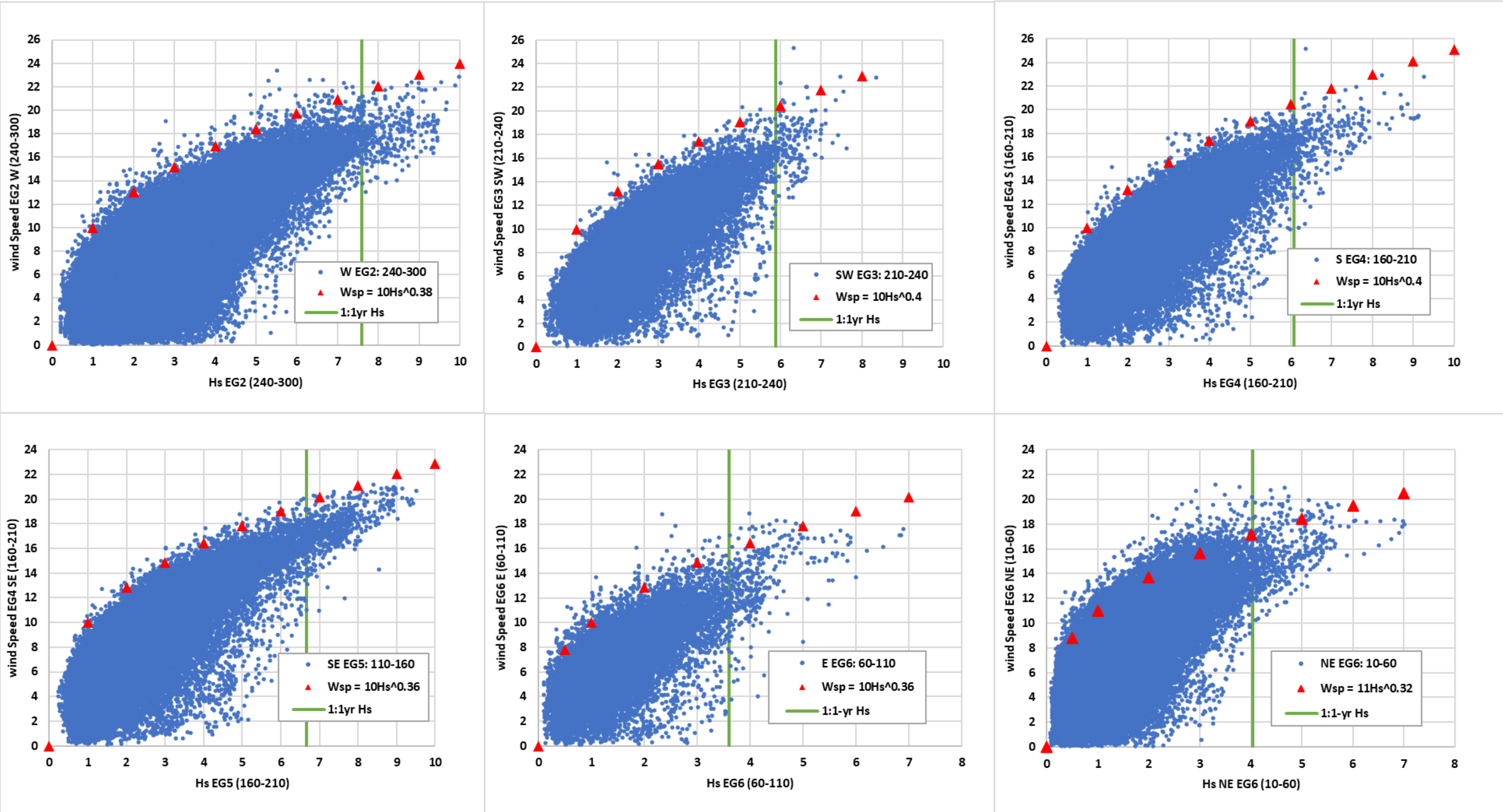
Source Mott MacDonald, 2023

Figure 5.3 Relationship between Tp and Hs at the six selected dominant directional sectors (W, SW, S, SE, E and NE) with the 100%AEP (1:1-yr RP) of Hs.



Source Mott MacDonald, 2023

Figure 5.4 Relationship between Wind Speed and Hs at the six selected dominant directional sectors (W, SW, S, SE, E and NE).



Source Mott MacDonald, 2023

5.4 AEP extreme conditions

Table 5.1 summarises extreme Hs, Tp and wind speed for the 100%, 50%, 10% and 1% AEPs. The water level condition at HAT from the Sumburgh station was selected as the extreme water level in the AEP's wave model runs. The MWD and wind direction used the six selected directional sectors (W, SW, S, SE, E, NE) at 10 degrees intervals.

Table 5.1 Summary of the wave and wind conditions for the AEP local wave model simulations.

		AEP (%)			
Sector	Item	100	50	10	1
W (240-300 deg.N)	Hs (m)	7.59	8.20	9.40	10.68
	Tp (s)	16	16	17	17
	Wind Speed (m/s)	22	22	23	25
SW (210-240 deg.N)	Hs (m)	5.89	6.41	7.56	9.16
	Tp (s)	17	18	19	20
	Wind Speed (m/s)	20.3	21	22.5	24.3
S (160-210 deg.N)	Hs (m)	6.08	6.68	8.1	10.14
	Tp (s)	13	13	14	15
	Wind Speed (m/s)	20.6	21.4	23.1	25.3
SE (110-160 deg.N)	Hs (m)	6.66	7.37	8.76	10.46
	Tp (s)	13	14	14	15
	Wind Speed (m/s)	19.8	20.5	21.8	23.3
E (60-110 deg.N)	Hs (m)	3.6	4.22	5.64	8.07
	Tp (s)	12	12	13	15
	Wind Speed (m/s)	15.9	16.8	18.6	21.2
NE (10-60 deg.N)	Hs (m)	4.04	4.52	5.76	7.99
	Tp (s)	11	12	13	15
	Wind Speed (m/s)	17.2	17.8	19.3	21.4

Source Mott MacDonald, 2023

6 Local MIKE21 FMSW model

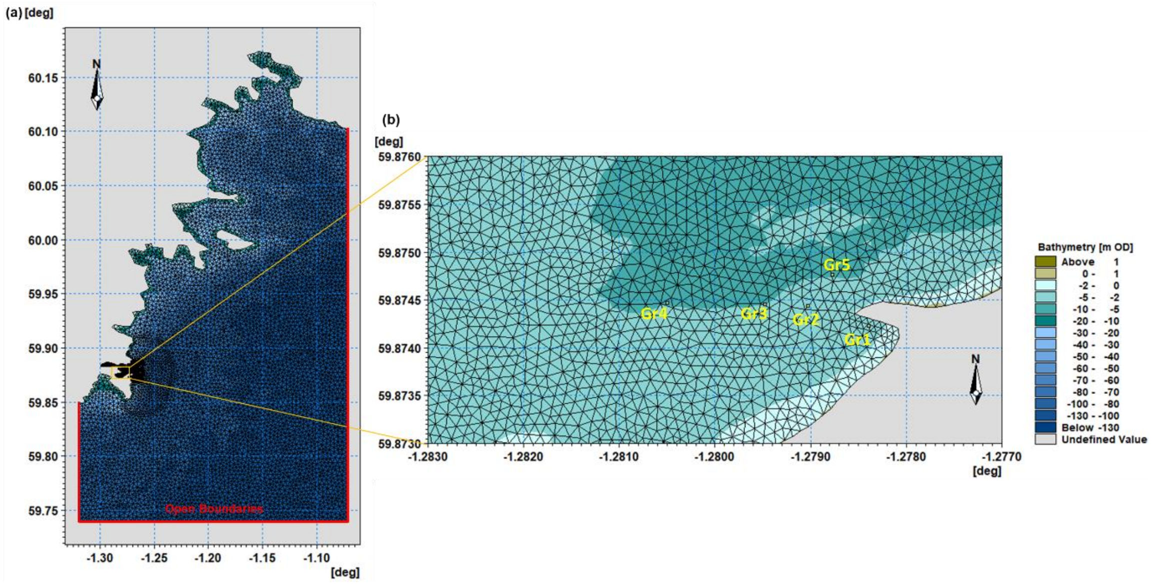
Based on the calibrated regional model results, the local MIKE21 FMSW model of Grutness was built to transform offshore wave conditions to the study area and to simulate 100%, 50%, 10% and 1% AEP wave events (Section 5). It should be noted that calibration of the local model was not conducted as this was not part of the project's scope and no suitable wave measurements were available.

6.1.1 Grutness local model domain

The local wave model was set up to cover a large offshore area. This approach ensured accurate wave propagation to the study area. Figure 6.1a shows an overview of the model's flexible mesh resolution, open boundary locations and model bathymetry for the whole local model. In contrast, the enlarged view at the project site is shown in Figure 6.1b. Similar to the regional model, the processed bathymetry data in Section 3.2 was linearly interpolated across the local model flexible mesh using the Mesh Generator toolbox. The horizontal datum of the model domain is set as geographical coordinate (longitude/latitude), while the vertical bathymetry datum is in local ordnance datum (OD).

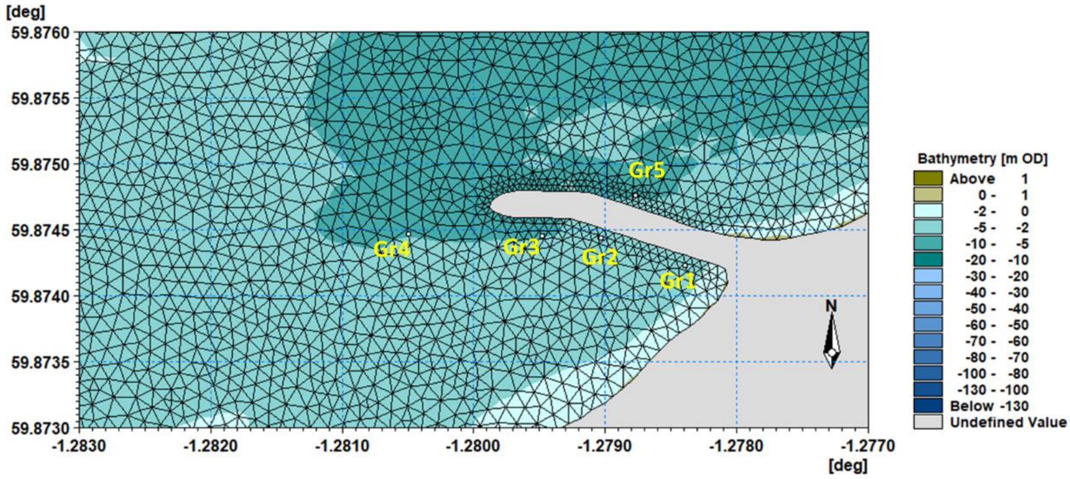
The model domain shown in Figure 6.1 is defined as the baseline layout. The resolution of the outer model domain varies between approximately 20m and 400m. In the nearshore areas within the baseline layout, the mesh resolution varies between approximately 5m and 10m. By keeping the same local model domain extent and resolution, the proposed Layouts 1 and 2 were incorporated into the local model. An enlarged view of the local model mesh and bathymetry of the two proposed layouts (Layout 1 and Layout 2) are shown in Figure 6.2 and Figure 6.3, respectively. These three model domains were used in the annual wave climate and AEP scenario simulations. The five wave data extraction points (Gr1 to Gr5) are also shown in all local model domains (Figure 6.1b, Figure 6.2 and Figure 6.3).

Figure 6.1 Local model bathymetry and mesh of (a) the whole local model domain with open boundary locations indicated as the red lines and (b) an enlarged view of the baseline layout at the project site with five extraction points (Gr1-Gr5) to assess wave conditions.



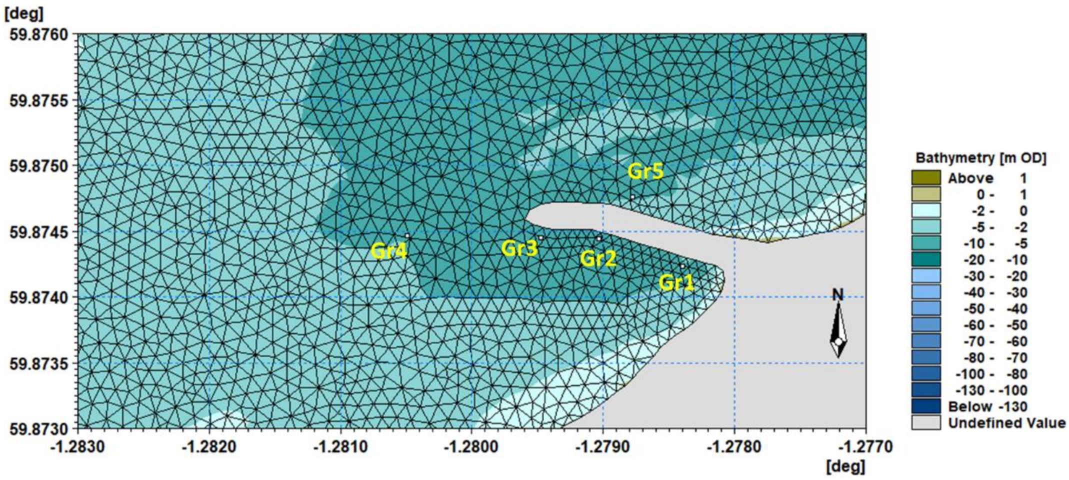
Source Mott MacDonald, 2023

Figure 6.2 Enlarged view of the mesh and bathymetry of the proposed Layout 1 with five extraction points (Gr1-Gr5) to assess wave conditions.



Source Mott MacDonald, 2023

Figure 6.3 Local model bathymetry and mesh: Proposed layout 2 with five extraction points (Gr1-Gr5) to assess wave conditions.



Source Mott MacDonald, 2023

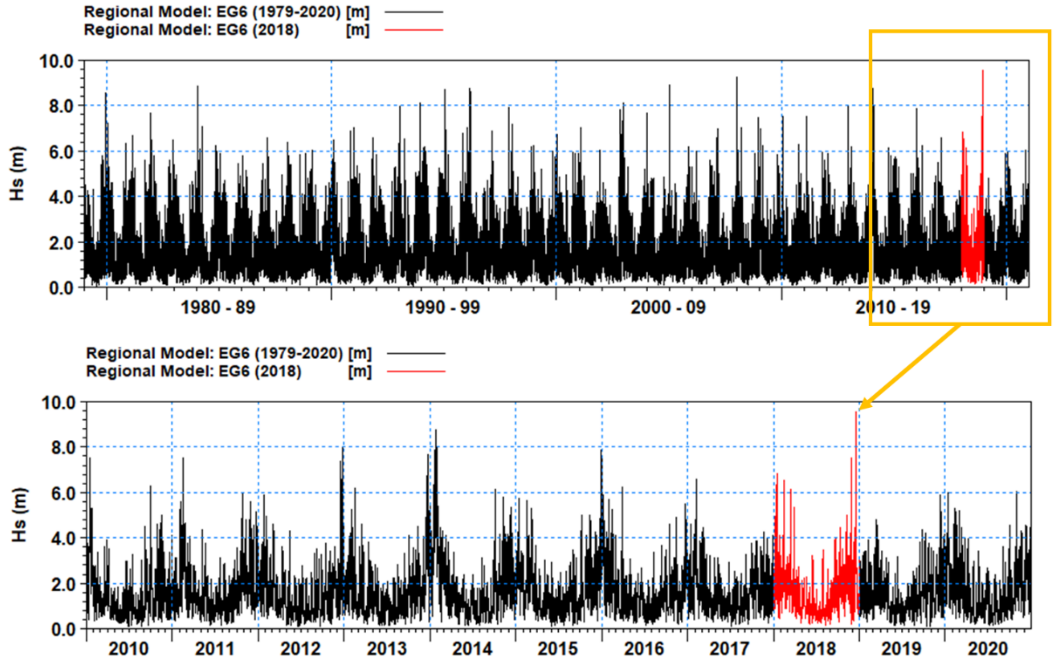
6.1.2 Grutness model set up

Following the standard modelling practice, several iterative sensitivity tests were undertaken in which several wave parameters in the model set up were tuned to achieve the best model set up. Appendix B summarises the key parameters used in the local wave model set up. Since the study is considering breakwater options, diffraction has also been included in the model.

6.1.3 Local model runs

The local wave model simulated the AEP scenarios and a selected one-year period to provide annual wave conditions at the project site for the baseline case and each new layout. Having the highest recorded Hs in the 42-year wave record, 2018 was selected for the one-year run. A 42-year time series of predicted Hs from the regional model at EG6 is shown in Figure 6.4. As this plot shows that the highest Hs was predicted in 2018, the one-year model run was undertaken for this year. The results of the AEP scenarios and wave climate simulations of the baseline and two proposed layouts are given in Section 7.

Figure 6.4 Time series of Hs based on the regional model results (1979-2020) at EG6.



Source Mott MacDonald, 2023

7 Results

7.1 AEP results

Table 7.1 shows the highest predicted Hs values with the associated Tp and MWD for each AEP scenario for the baseline, Layout 1 and Layout 2 conditions. Table 7.1 shows that, as expected due to their locations (i.e. sheltered behind the breakwater), Hs decreased at Gr1, Gr2 and Gr3 (Figure 6.2) for Layout 1 and Layout 2.

Table 7.2 shows the highest predicted Tp values with the associated Hs and MWD at Gr1, Gr2 and Gr3 for each AEP scenario of the baseline, Layout 1 and Layout 2. Table 7.2 shows that due to diffraction and directional spreading, high Tp values are predicted at Gr1, Gr2 and Gr3 (Figure 6.2) in layouts 1 and 2.

Table 7.1 AEP results at Gr1 to Gr5 for the baseline, Layout 1 and Layout 2 for the high Hs.

Point	AEP	Baseline			Layout 1			Layout 2		
		Highest Hs (m)	Associated Tp (s)	Associated MWD (deg.N)	Highest Hs (m)	Associated Tp (s)	Associated MWD (deg.N)	Highest Hs (m)	Associated Tp (s)	Associated MWD (deg.N)
Gr1	AEP 100%	0.3	13	309	0.2	3	292	0.3	3	292
	AEP 50%	0.3	14	309	0.3	3	292	0.2	3	291
	AEP 10%	0.4	14	307	0.3	3	292	0.3	3	290
	AEP 1%	0.5	15	305	0.3	3	290	0.3	3	289
Gr2	AEP 100%	1.2	13	16	0.2	3	290	0.2	3	293
	AEP 50%	1.2	13	17	0.2	3	290	0.2	3	292
	AEP 10%	1.3	14	14	0.2	3	289	0.2	3	291
	AEP 1%	1.5	15	14	0.2	3	288	0.2	3	290
Gr3	AEP 100%	1.1	13	21	0.3	3	298	0.3	3	301
	AEP 50%	1.1	13	21	0.3	3	298	0.3	3	301
	AEP 10%	1.3	14	18	0.3	3	297	0.3	3	300
	AEP 1%	1.5	15	16	0.3	3	297	0.3	3	300
Gr4	AEP 100%	1.0	13	35	0.7	13	35	0.9	13	40
	AEP 50%	1.0	13	35	0.8	13	33	1.0	13	40
	AEP 10%	1.2	14	33	0.9	14	29	1.2	14	38
	AEP 1%	1.4	15	32	1.2	15	25	1.4	15	32
Gr5	AEP 100%	1.1	13	22	1.1	13	19	1.1	13	21
	AEP 50%	1.2	14	21	1.2	13	19	1.2	13	17
	AEP 10%	1.5	14	15	1.4	14	18	1.3	14	19
	AEP 1%	1.7	15	13	1.7	15	12	1.5	15	15

Source Mott MacDonald, 2023

Table 7.2 AEP results at Gr1. Gr1 and Gr3 (extraction points behind the layout) for the baseline, Layout 1 and Layout 2 for the high Tp.

Point	AEP	Baseline			Layout 1			Layout 2		
		Associated Hs (m)	Highest Tp (s)	Associated MWD (deg.N)	Associated Hs (m)	Highest Tp (s)	Associated MWD (deg.N)	Associated Hs (m)	Highest Tp (s)	Associated MWD (deg.N)
Gr1	AEP 100%	0.3	13	309	0.1	12	288	0.1	13	292
	AEP 50%	0.3	14	309	0.1	12	290	0.1	13	293
	AEP 10%	0.3	15	305	0.1	13	288	0.1	14	292
	AEP 1%	0.3	16	304	0.1	15	285	0.2	15	293
Gr2	AEP 100%	0.9	14	22	0.1	12	286	0.2	13	288
	AEP 50%	0.8	15	22	0.1	12	288	0.2	13	294
	AEP 10%	0.7	16	23	0.1	13	285	0.2	14	293
	AEP 1%	0.8	18	16	0.2	15	284	0.2	15	291
Gr3	AEP 100%	0.9	14	26	0.1	12	304	0.3	13	309
	AEP 50%	0.7	15	27	0.2	12	305	0.3	13	314
	AEP 10%	0.8	16	23	0.2	13	302	0.3	14	312
	AEP 1%	0.8	17	21	0.3	15	300	0.4	15	315

Source Mott MacDonald, 2023

7.2 Wave climate results

The mean statistics of Hs, Tp and MWD at the five extraction points for the baseline, Layout 1 and Layout 2 are shown in Table 7.3. Table 7.4 shows the results of the high Hs with the associated Tp and MWD for each AEP scenario of the baseline, Layout 1 and Layout 2 conditions. Table 7.4 shows that Hs decreased at Gr1, Gr2 and Gr3 for Layout 1 and Layout 2 as expected due to their locations (i.e. sheltered behind the breakwater). Table 7.5 shows the results of the highest Tp with the associated Hs and MWD at Gr1, Gr2 and Gr3 (the extraction points behind the layouts) for each AEP scenario of the baseline, Layout 1 and Layout 2. It is predicted that high Tp's exist in the Layout 1 and Layout 2 results at Gr1, Gr2 and Gr3 due to diffraction and directional spreading (Table 7.5).

Table 7.3 Annual mean wave conditions at the five extraction points of the baseline, Layout 1 and Layout 2.

Point	Baseline			Layout 1			Layout 2		
	Mean Hs (m)	Mean Tp (s)	Mean MWD (deg.N)	Mean Hs (m)	Mean Tp (s)	Mean MWD (deg.N)	Mean Hs (m)	Mean Tp (s)	Mean MWD (deg.N)
Gr1	0.1	10	311	0.02	10	287	0.03	10	291
Gr2	0.4	10	016	0.03	10	285	0.04	10	291
Gr3	0.3	10	019	0.04	10	303	0.10	10	316
Gr4	0.3	10	037	0.20	10	037	0.30	10	039
Gr5	0.3	10	021	0.30	10	021	0.30	10	020

Source Mott MacDonald, 2023

Table 7.4 High Hs conditions at the five extraction points of the baseline, Layout 1 and Layout 2.

Point	Baseline			Layout 1			Layout 2		
	Highest Hs (m)	Associated Tp (s)	Associated MWD (deg.N)	Highest Hs (m)	Associated Tp (s)	Associated MWD (deg.N)	Highest Hs (m)	Associated Tp (s)	Associated MWD (deg.N)
Gr1	0.4	13	312	0.2	3	238	0.2	3	236
Gr2	1.1	13	015	0.2	3	233	0.2	3	229
Gr3	1.0	13	019	0.2	3	229	0.2	3	228
Gr4	0.9	13	036	0.7	13	035	0.8	13	040
Gr5	1.0	13	019	1.0	13	020	1.0	13	017

Source Mott MacDonald, 2023

Table 7.5 High Tp conditions at Gr1, Gr2 and Gr3 of the baseline, Layout 1 and Layout 2.

Point	Baseline			Layout 1			Layout 2		
	Associated Hs (m)	Highest Tp (s)	Associated MWD (deg.N)	Associated Hs (m)	Highest Tp (s)	Associated MWD (deg.N)	Associated Hs (m)	Highest Tp (s)	Associated MWD (deg.N)
Gr1	0.1	17	303	0.04	16	292	0.03	16	287
Gr2	0.3	16	019	0.05	16	293	0.04	16	287
Gr3	0.3	16	021	0.06	16	305	0.07	17	312

Source Mott MacDonald, 2023

An example of the annual wave occurrences of Hs and Tp for the baseline, Layout 1 and Layout 2 at Gr3 are given in Table 7.6**Error! Reference source not found.**, Table 7.7 and Table 7.8, respectively. As described previously for Layout 1 and Layout 2, Hs decreased at Gr3 as it is sheltered behind the breakwater, while high Tp's also exist at Gr3 due to diffraction and directional spreading. The annual wave occurrences of Hs and Tp at Gr1, Gr2, Gr4 and Gr5 for the baseline, Layout 1 and Layout 2 are presented in Appendix C.

Table 7.6 Annual wave occurrence of Hs (m) against Tp (s) at Gr3 for the baseline.

Hs (m) | Tp (s)	0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1	Total	Total (%)
0-2	0	0	0	0	0	0	0	0	0	0	0	0
2-4	0	0	5	0	0	0	0	0	0	0	5	0.1
4-6	14	0	1	2	0	0	0	0	0	0	17	0.2
6-8	315	321	305	142	65	25	0	0	0	0	1173	13.4
8-10	567	512	793	383	370	263	164	39	0	0	3091	35.2
10-12	451	377	520	329	281	344	319	214	77	0	2912	33.1
12-14	10	247	300	149	73	114	74	44	45	41	1097	12.5
14-16	0	69	199	49	16	80	11	16	34	0	474	5.4
16-18	0	0	16	0	0	0	0	0	0	0	16	0.2
18-20	0	0	0	0	0	0	0	0	0	0	0	0
20-22	0	0	0	0	0	0	0	0	0	0	0	0
Total	1357	1526	2139	1054	805	826	568	313	156	41	8785	
Total (%)	15.4	17.4	24.3	12.0	9.2	9.4	6.5	3.6	1.8	0.5		100

Source Mott MacDonald, 2023

Table 7.7 Annual wave occurrence of Hs (m) against Tp (s) at Gr3 for the Layout 1.

Hs (m) | Tp (s)	0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1	1-1.1	Total	Total (%)
0-2	0	0	0	0	0	0	0	0	0	0	0	0	0
2-4	2	25	5	0	0	0	0	0	0	0	0	32	0.4
4-6	23	0	0	0	0	0	0	0	0	0	0	23	0.3
6-8	828	0	0	0	0	0	0	0	0	0	0	828	10.4
8-10	3020	0	0	0	0	0	0	0	0	0	0	3020	38.1
10-12	2728	14	0	0	0	0	0	0	0	0	0	2742	34.6
12-14	908	87	0	0	0	0	0	0	0	0	0	995	12.6
14-16	261	20	0	0	0	0	0	0	0	0	0	281	3.5
16-18	3	0	0	0	0	0	0	0	0	0	0	3	0.04
18-20	0	0	0	0	0	0	0	0	0	0	0	0	0
20-22	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	7773	146	5	0	0	0	0	0	0	0	0	7924	
Total (%)	98.1	1.8	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		100

Source Mott MacDonald, 2023

Table 7.8 Annual wave occurrence of Hs (m) against Tp (s) at Gr3 for the Layout 2.

Hs (m) | Tp (s)	0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1	1-1.1	Total	Total (%)
0-2	0	0	0	0	0	0	0	0	0	0	0	0	0
2-4	0	18	6	0	0	0	0	0	0	0	0	24	0.3

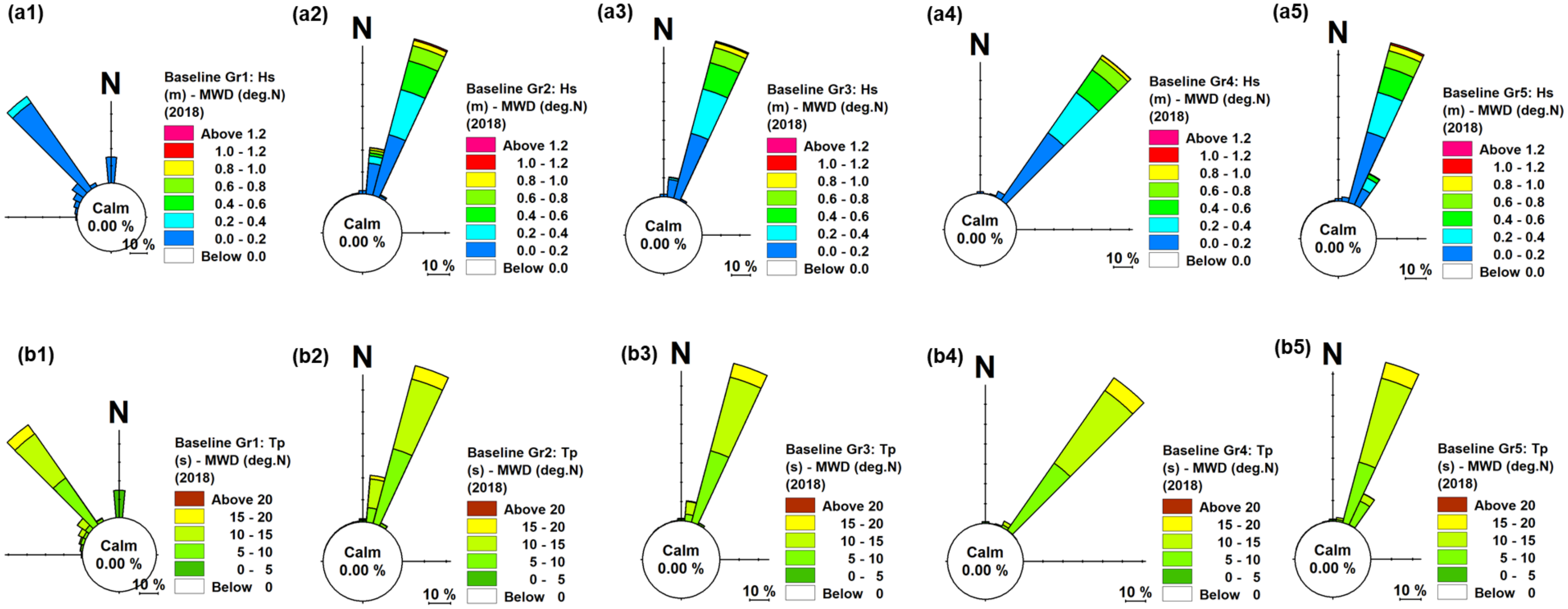
4-6	0	9	0	0	0	0	0	0	0	0	0	9	0.1
6-8	1119	19	0	0	0	0	0	0	0	0	0	1138	13.4
8-10	2673	599	0	0	0	0	0	0	0	0	0	3272	38.6
10-12	1719	973	22	0	0	0	0	0	0	0	0	2714	32.0
12-14	672	243	60	0	0	0	0	0	0	0	0	975	11.5
14-16	197	121	17	0	0	0	0	0	0	0	0	335	4.0
16-18	12	0	0	0	0	0	0	0	0	0	0	12	0.1
18-20	0	0	0	0	0	0	0	0	0	0	0	0	0
20-22	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	6392	1982	105	0	0	0	0	0	0	0	0	8479	
Total (%)	75.4	23.4	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		100

Source Mott MacDonald, 2023

A wave rose plot of Hs against MWD at five extraction points (Gr1 to Gr5) is shown in Figure 7.1(a1) to Figure 7.1(a5), respectively. A rose plot of Tp vs MWD at Gr1 to Gr5 is shown in Figure 7.1(b1) to Figure 7.1(b5), respectively, for the baseline. It is observed that, as expected, the dominant wave direction is from NE at Gr2 to Gr5 for the baseline layout, as a breakwater does not shelter these extraction points. For Gr1 located behind the existing breakwater, the dominant direction is from NW due to diffraction and directional spreading.

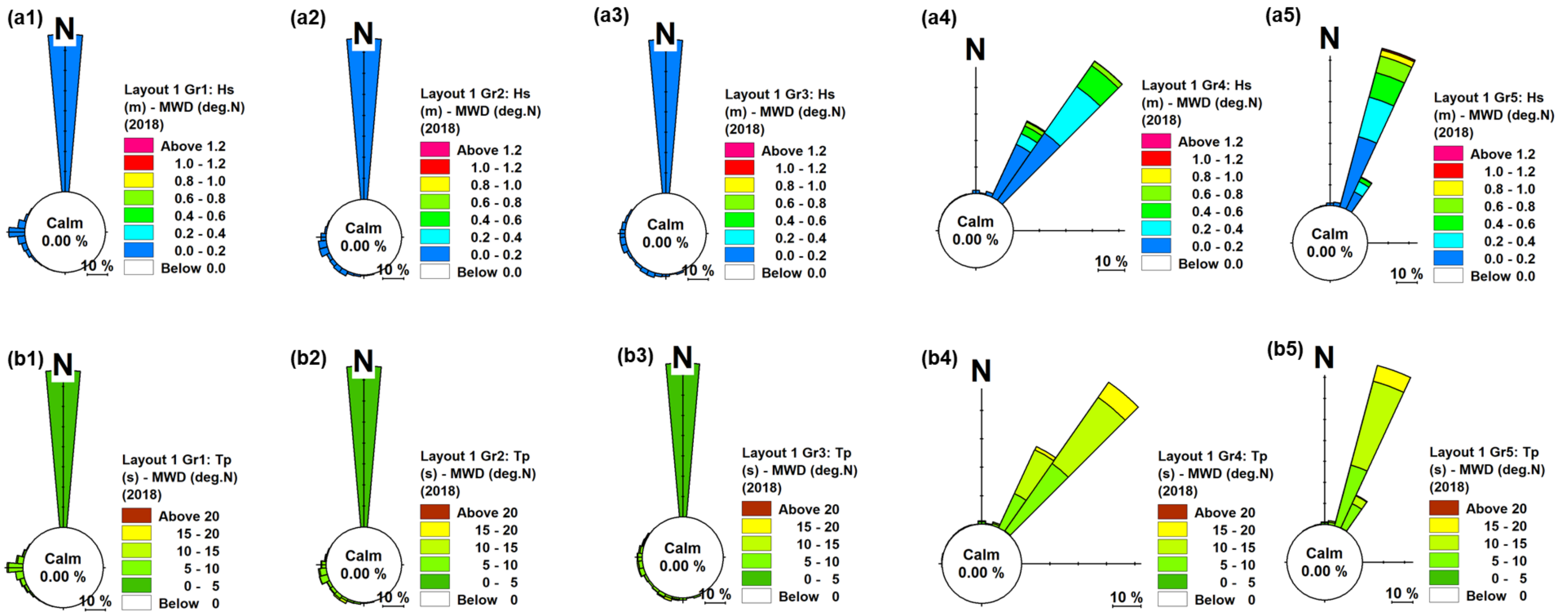
The wave rose of Hs vs MWD and Tp vs MWD at Gr1 to Gr5 for Layout 1 is shown in Figure 7.2(a1) to Figure 7.2(a5) and Figure 7.2(b1) to Figure 7.2(b5), respectively. For Layout 2, Hs vs MWD at Gr1 to Gr5 is shown in Figure 7.3(a1) to Figure 7.3(a5), respectively, while Tp vs MWD is presented in Figure 7.3(b1) to Figure 7.3(b5), respectively. Based on Figure 7.2 and Figure 7.3, it is observed that dominant MWD changes at Gr1 to Gr3 (the extraction points behind the breakwater) in Layout 1 and Layout 2, respectively, due to diffraction and directional spreading as well as dredged bathymetry (i.e. Layout 2).

Figure 7.1 Wave rose plot at Gr1 to Gr5 for Hs (m) against MWD deg.N) (a1-a5) and Tp (s) against MWD (deg.N) (b1-b5) for the baseline.



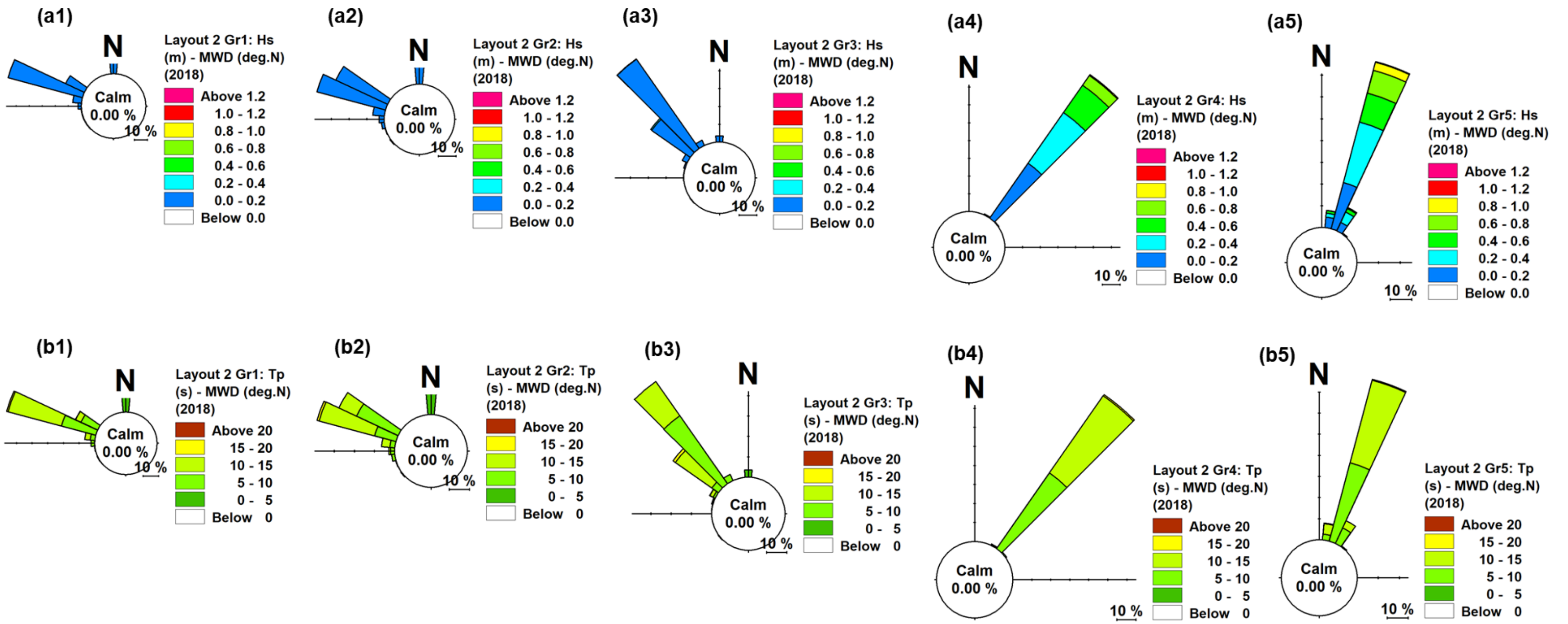
Source Mott MacDonald, 2023

Figure 7.2 Wave rose plot at Gr1 to Gr5 for Hs (m) against MWD deg.N) (a1-a5) and Tp (s) against MWD (deg.N) (b1-b5) for the proposed Layout 1.



Source Mott MacDonald, 2023

Figure 7.3 Wave rose plot at Gr1 to Gr5 for Hs (m) against MWD deg.N) (a1-a5) and Tp (s) against MWD (deg.N) (b1-b5) for the proposed Layout 2.



Source Mott MacDonald, 2023

8 Summary

This report details the development, calibration/validation of regional and local wave models to assess wave conditions of the existing layout and two proposed layouts (Layout 1 and Layout 2) for a concept design development.

- Suitable bathymetric, wave, water level and wind data datasets were identified, quality assured and used to build, calibrate and validate a regional-scale and local MIKE21 FMSW model;
- To represent wave propagation correctly from offshore to nearshore areas around Grutness, the regional MIKE21 FMSW model covers a wide area of Shetland Islands and all relevant coastal and offshore areas that influence the wave conditions;
- The regional MIKE21 FMSW model was calibrated and validated against historical wave data at Lerwick station. The model calibration and validation conformed to robust model performance metrics (Williams and Esteves, 2017) during normal wave conditions and storm events. The regional model was judged suitable for defining offshore boundary conditions for the local wave model. The model was run to transform 42 years of offshore wave data to the project site;
- The extreme wave analysis was performed on the 42-year regional model results to provide boundary conditions for the local wave model simulations of 100%, 50%, 10% and 1% AEP events;
- Annual wave climate conditions were simulated for 2018, where the highest wave height was predicted in the 42-year wave record;
- Diffraction has been included in the local wave model as the study considered breakwater options;
- Wave conditions were assessed using AEP and annual wave results from the local wave model at five wave data extraction points (Gr1 to Gr5) for the baseline, Layout 1 and Layout 2;
- Hs decreased at Gr1, Gr2 and Gr3 for Layout 1 and Layout 2 as expected due to their locations (i.e. sheltered behind the breakwater);
- High Tp values are predicted at Gr1, Gr2 and Gr3 in Layout 1 and Layout 2 due to diffraction and directional spreading;
- The dominant wave direction is from NE at Gr2 to Gr5, as expected for the baseline layout, as a breakwater does not shelter these extraction points. For Gr1, located behind the existing breakwater, the dominant direction is from NW due to diffraction and directional spreading;
- The dominant MWD changes at Gr1 to Gr3 (the extraction points behind the breakwater) in Layout 1 and Layout 2, respectively, due to diffraction and directional spreading as well as dredged bathymetry (i.e. Layout 2);
- It should be noted that the local wave model was not calibrated locally, and therefore there will always be some uncertainty until model calibration is performed. The wave conditions could be better simulated using a model like MIKE3 Wave FM where reflections and wave-wave interactions can be investigated appropriately, particularly for a detailed design purpose.

A. Regional Model Setup

Table A.1: Summary of the MIKE21 FM SW regional model setup

	Parameters	Description
Equation		Fully Spectral, Instationary formulation
Frequency Discretisation	No. of frequency	25
	Min. Frequency	0.055 Hz
	Frequency factor	1.1
	Number of direction	360 degree rose (36 directions)
Solution		Instationary formulation
Technique	Geographical space discretisation	Low order, fast algorithm
	Max. no of levels in transport calculation	32
	No of steps in source calculation	1
	Min. time step	0.01 sec
	Max. time step	30 sec
	Water Level Conditions	Varying in time, constant in domain. Measured and Predicted levels at Sumburgh.
Wind Forcing	Wind data	Varying in time and domain used downscaled wind data ECMWF ERA5 (downscaled by 10% wind velocities at 10m elevation)
	Type of air-sea	Coupled
	Background Charnock parameter	0.01
Energy Transfer		Include quadruplet-wave interaction
Wave Breaking	Model	Wave breaking
	Type of gamma	Specified gamma
	Gamma data	Constant: 0.5
	Alpha	Constant:1
White Capping	Model	White Capping Included
	Dissipation Coefficient, C dis	Constant: 4.5
	Dissipation Coefficient, DELTA dis	Constant: 0.5
Initial Conditions		Spectra from empirical formula from JONSWAP fetch growth expression
Boundary Conditions		Wave parameters from ECMWF ERA5

Source Mott MacDonald, 2023

B. Local Model Setup

Table B.2: Summary of the MIKE21 FM SW local model setup

Parameters		Description
Equation		Directional-Decoupled, Quasi-stationary
Solution		Quasi-stationary
Quasi-stationary formulation	Geographical space discretisation	Low order, fast algorithm
	Method	New-Raphson Iteration
	Max. number of iterations	100
	Tolerance (RMS-norm of residual)	0.0001
	Tolerance (Max-norm of change in sig. wave height)	0.01
	Relaxation Factor	0.1
Water Level Conditions		• Predicted Water level at Sumburgh in local OD for the wave climate simulation. • HAT for the AEP simulations.
Wind Forcing	Wind data	• Varying in time and domain used downscaled wind data ECMWF ERA5 (downscaled by 10% wind velocities at 10m elevation) for the wave climate simulation. • Wind speed and direction from the EVA results for the AEP simulations.
	Wind Generation Formula	SPM84
Diffraction	Smoothing factor	0.5
	Number of smoothing steps	10
Wave Breaking	Model	Wave breaking
	Type of gamma	Specified gamma
	Gamma data	0.5
	Alpha	1
	Gamma (wave steepness)	5
Initial Conditions		Spectra from empirical formula from JONSWAP fetch growth expression
Boundary Conditions		• Wave parameters extracted from the calibrated regional model results for wave climate simulation. • Wave parameters from the EVA results for the AEP simulations.

Source Mott MacDonald, 2023

C. Wave Occurrence

C.1 Existing Layout

Table C.3: Annual wave occurrence of Hs (m) against Tp (s) at Gr1 for the baseline.

Hs (m) | Tp (s)	0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1	1-1.1	Total	Total (%)
0-2	0	0	0	0	0	0	0	0	0	0	0	0	0
2-4	0	16	1	0	0	0	0	0	0	0	0	17	0.2
4-6	10	9	0	0	0	0	0	0	0	0	0	19	0.2
6-8	946	197	0	0	0	0	0	0	0	0	0	1143	13.2
8-10	1868	975	165	0	0	0	0	0	0	0	0	3008	34.7
10-12	1309	954	642	38	0	0	0	0	0	0	0	2943	33.9
12-14	520	320	213	65	0	0	0	0	0	0	0	1118	12.9
14-16	189	128	77	23	0	0	0	0	0	0	0	417	4.8
16-18	15	1	0	0	0	0	0	0	0	0	0	16	0.2
18-20	0	0	0	0	0	0	0	0	0	0	0	0	0
20-22	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	4857	2600	1098	126	0	0	0	0	0	0	0	8681	
Total (%)	55.9	30.0	12.6	1.5	0	0	0	0	0	0	0		100

Source Mott MacDonald, 2023

Table C.4: Annual wave occurrence of Hs (m) against Tp (s) at Gr2 for the baseline.

Hs (m) | Tp (s)	0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1	1-1.1	1.1-1.2	Total	Total (%)
0-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2-4	0	0	5	0	0	0	0	0	0	0	0	0	5	0.1
4-6	12	0	2	1	0	0	0	0	0	0	0	0	15	0.2
6-8	275	296	260	148	106	30	3	0	0	0	0	0	1118	12.7
8-10	496	441	760	438	328	284	251	112	24	0	0	0	3134	35.7
10-12	353	404	462	442	193	290	319	273	158	73	16	0	2983	34.0
12-14	1	191	262	192	91	65	86	60	55	31	52	4	1090	12.4
14-16	0	53	118	93	17	37	44	13	15	22	12	0	424	4.8
16-18	0	0	16	0	0	0	0	0	0	0	0	0	16	0.2
18-20	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20-22	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	1137	1385	1885	1314	735	706	703	458	252	126	80	4	8785	
Total (%)	12.9	15.8	21.5	15.0	8.4	8.0	8.0	5.2	2.9	1.4	0.9	0.0		100

Source Mott MacDonald, 2023

Table C.5: Annual wave occurrence of Hs (m) against Tp (s) at Gr4 for the baseline.

Hs (m) | Tp (s)	0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1	1-1.1	Total	Total (%)
0-2	0	0	0	0	0	0	0	0	0	0	0	0	0
2-4	0	0	7	0	0	0	0	0	0	0	0	7	0.1
4-6	13	0	11	0	0	0	0	0	0	0	0	24	0.3
6-8	355	351	247	36	7	0	0	0	0	0	0	996	11.3
8-10	784	1076	593	411	329	34	0	0	0	0	0	3227	36.7
10-12	608	764	454	425	501	226	47	0	0	0	0	3025	34.4
12-14	99	391	234	118	122	82	64	0	0	0	0	1110	12.6
14-16	13	174	51	91	18	49	0	0	0	0	0	396	4.5
16-18	0	0	0	0	0	0	0	0	0	0	0	0	0
18-20	0	0	0	0	0	0	0	0	0	0	0	0	0
20-22	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	1872	2756	1597	1081	977	391	111	0	0	0	0	8785	
Total (%)	21.3	31.4	18.2	12.3	11.1	4.5	1.3	0.0	0.0	0.0	0.0		100

Source Mott MacDonald, 2023

Table C.6: Annual wave occurrence of Hs (m) against Tp (s) at Gr5 for the baseline.

Hs (m) | Tp (s)	0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1	1-1.1	Total	Total (%)
0-2	0	0	0	0	0	0	0	0	0	0	0	0	0
2-4	0	0	4	0	0	0	0	0	0	0	0	4	0.05
4-6	15	0	0	4	0	0	0	0	0	0	0	19	0.2
6-8	280	309	277	147	78	28	0	0	0	0	0	1119	12.7
8-10	533	486	811	375	345	318	205	88	0	0	0	3161	36.0
10-12	377	425	480	417	230	319	326	244	115	35	0	2968	33.8
12-14	6	181	297	183	57	74	116	23	54	45	33	1069	12.2
14-16	0	58	127	76	21	64	27	9	18	31	0	431	4.9
16-18	0	0	14	0	0	0	0	0	0	0	0	14	0.2
18-20	0	0	0	0	0	0	0	0	0	0	0	0	0
20-22	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	1211	1459	2010	1202	731	803	674	364	187	111	33	8785	
Total (%)	13.8	16.6	22.9	13.7	8.3	9.1	7.7	4.1	2.1	1.3	0.4		100

Source Mott MacDonald, 2023

C.2 Layout 1

Table C.7: Annual wave occurrence of Hs (m) against Tp (s) at Gr1 for the Layout 1.

Hs (m) | Tp (s)	0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1	1-1.1	Total	Total (%)
0-2	0	0	0	0	0	0	0	0	0	0	0	0	0
2-4	28	19	1	0	0	0	0	0	0	0	0	48	1
4-6	22	0	0	0	0	0	0	0	0	0	0	22	0.3
6-8	486	0	0	0	0	0	0	0	0	0	0	486	6.6
8-10	3058	0	0	0	0	0	0	0	0	0	0	3058	41.7
10-12	2622	0	0	0	0	0	0	0	0	0	0	2622	35.7
12-14	918	0	0	0	0	0	0	0	0	0	0	918	12.5
14-16	186	0	0	0	0	0	0	0	0	0	0	186	2.5
16-18	0	0	0	0	0	0	0	0	0	0	0	0	0
18-20	0	0	0	0	0	0	0	0	0	0	0	0	0
20-22	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	7320	19	1	0	0	0	0	0	0	0	0	7340	
Total (%)	99.7	0.3	0.0	0.0	0	0	0	0	0	0	0		100

Source Mott MacDonald, 2023

Table C.8: Annual wave occurrence of Hs (m) against Tp (s) at Gr2 for the Layout 1.

Hs (m) | Tp (s)	0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1	1-1.1	1.1-1.2	Total	Total (%)
0-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2-4	16	24	5	0	0	0	0	0	0	0	0	0	45	1
4-6	24	0	0	0	0	0	0	0	0	0	0	0	24	0.3
6-8	572	0	0	0	0	0	0	0	0	0	0	0	572	7.5
8-10	3132	0	0	0	0	0	0	0	0	0	0	0	3132	41.3
10-12	2662	0	0	0	0	0	0	0	0	0	0	0	2662	35.1
12-14	934	0	0	0	0	0	0	0	0	0	0	0	934	12.3
14-16	219	0	0	0	0	0	0	0	0	0	0	0	219	2.9
16-18	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18-20	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20-22	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	7559	24	5	0	0	0	0	0	0	0	0	0	7588	
Total (%)	99.6	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		100

Source Mott MacDonald, 2023

Table C.9: Annual wave occurrence of Hs (m) against Tp (s) at Gr4 for the Layout 1.

Hs (m) | Tp (s)	0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1	1-1.1	Total	Total (%)
0-2	0	0	0	0	0	0	0	0	0	0	0	0	0
2-4	0	0	7	0	0	0	0	0	0	0	0	7	0.1
4-6	13	0	11	0	0	0	0	0	0	0	0	24	0.3
6-8	355	351	247	36	7	0	0	0	0	0	0	996	11.3
8-10	784	1076	593	411	329	34	0	0	0	0	0	3227	36.7
10-12	608	764	454	425	501	226	47	0	0	0	0	3025	34.4
12-14	99	391	234	118	122	82	64	0	0	0	0	1110	12.6
14-16	13	174	51	91	18	49	0	0	0	0	0	396	4.5
16-18	0	0	0	0	0	0	0	0	0	0	0	0	0
18-20	0	0	0	0	0	0	0	0	0	0	0	0	0
20-22	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	1872	2756	1597	1081	977	391	111	0	0	0	0	8785	
Total (%)	21.3	31.4	18.2	12.3	11.1	4.5	1.3	0.0	0.0	0.0	0.0		100

Source Mott MacDonald, 2023

Table C.10: Annual wave occurrence of Hs (m) against Tp (s) at Gr5 for the Layout 1.

Hs (m) | Tp (s)	0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1	1-1.1	Total	Total (%)
0-2	0	0	0	0	0	0	0	0	0	0	0	0	0
2-4	0	0	4	0	0	0	0	0	0	0	0	4	0.05
4-6	22	0	4	0	0	0	0	0	0	0	0	26	0.3
6-8	238	304	278	136	64	30	0	0	0	0	0	1050	12.0
8-10	523	550	834	420	287	305	199	90	0	0	0	3208	36.5
10-12	351	447	552	351	269	263	381	235	126	42	0	3017	34.3
12-14	4	160	270	192	86	65	107	30	58	51	37	1060	12.1
14-16	0	63	142	50	20	52	26	30	31	6	0	420	4.8
16-18	0	0	0	0	0	0	0	0	0	0	0	0	0
18-20	0	0	0	0	0	0	0	0	0	0	0	0	0
20-22	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	1138	1524	2084	1149	726	715	713	385	215	99	37	8785	
Total (%)	13.0	17.3	23.7	13.1	8.3	8.1	8.1	4.4	2.4	1.1	0.4		100

Source Mott MacDonald, 2023

C.3 Layout 2

Table C.11: Annual wave occurrence of Hs (m) against Tp (s) at Gr1 for the Layout 2.

Hs (m) | Tp (s)	0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1	1-1.1	Total	Total (%)
0-2	0	0	0	0	0	0	0	0	0	0	0	0	0
2-4	16	18	2	0	0	0	0	0	0	0	0	36	0.5
4-6	14	0	0	0	0	0	0	0	0	0	0	14	0.2
6-8	463	0	0	0	0	0	0	0	0	0	0	463	6.2
8-10	3023	0	0	0	0	0	0	0	0	0	0	3023	40.7
10-12	2658	1	0	0	0	0	0	0	0	0	0	2659	35.8
12-14	903	34	0	0	0	0	0	0	0	0	0	937	12.6
14-16	276	4	0	0	0	0	0	0	0	0	0	280	3.8
16-18	7	0	0	0	0	0	0	0	0	0	0	7	0.1
18-20	0	0	0	0	0	0	0	0	0	0	0	0	0
20-22	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	7360	57	2	0	0	0	0	0	0	0	0	7419	
Total (%)	99.2	0.8	0.03	0.0	0	0	0	0	0	0	0		100

Source Mott MacDonald, 2023

Table C.12: Annual wave occurrence of Hs (m) against Tp (s) at Gr2 for the Layout 2.

Hs (m) | Tp (s)	0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1	1-1.1	1.1-1.2	Total	Total (%)
0-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2-4	10	20	5	0	0	0	0	0	0	0	0	0	35	0.5
4-6	12	0	0	0	0	0	0	0	0	0	0	0	12	0.2
6-8	444	0	0	0	0	0	0	0	0	0	0	0	444	5.9
8-10	3091	0	0	0	0	0	0	0	0	0	0	0	3091	41.3
10-12	2575	46	0	0	0	0	0	0	0	0	0	0	2621	35.1
12-14	853	121	0	0	0	0	0	0	0	0	0	0	974	13.0
14-16	231	56	0	0	0	0	0	0	0	0	0	0	287	3.8
16-18	13	0	0	0	0	0	0	0	0	0	0	0	13	0.2
18-20	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20-22	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	7229	243	5	0	0	0	0	0	0	0	0	0	7477	
Total (%)	96.7	3.2	0.1	0	0	0	0	0	0	0	0	0		100

Source Mott MacDonald, 2023

Table C.13: Annual wave occurrence of Hs (m) against Tp (s) at Gr4 for the Layout 2.

Hs (m) | Tp (s)	0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1	1-1.1	Total	Total (%)
0-2	0	0	0	0	0	0	0	0	0	0	0	0	0
2-4	0	0	5	0	0	0	0	0	0	0	0	5	0.1
4-6	7	0	4	0	0	0	0	0	0	0	0	11	0.1
6-8	289	295	257	152	31	7	0	0	0	0	0	1031	11.7
8-10	677	716	790	403	327	268	74	0	0	0	0	3255	37.1
10-12	469	483	566	286	326	421	256	109	0	0	0	2916	33.2
12-14	17	386	350	117	72	114	45	60	48	0	0	1209	13.8
14-16	0	30	130	25	62	37	19	37	10	0	0	350	4.0
16-18	0	0	8	0	0	0	0	0	0	0	0	8	0.1
18-20	0	0	0	0	0	0	0	0	0	0	0	0	0
20-22	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	1459	1910	2110	983	818	847	394	206	58	0	0	8785	
Total (%)	16.6	21.7	24.0	11.2	9.3	9.6	4.5	2.3	0.7	0	0		100

Source Mott MacDonald, 2023

Table C.14: Annual wave occurrence of Hs (m) against Tp (s) at Gr5 for the Layout 2.

Hs (m) | Tp (s)	0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1	1-1.1	Total	Total (%)
0-2	0	0	0	0	0	0	0	0	0	0	0	0	0
2-4	0	0	2	0	0	0	0	0	0	0	0	2	0.02
4-6	25	0	5	0	0	0	0	0	0	0	0	30	0.3
6-8	247	312	292	147	76	35	1	0	0	0	0	1110	12.6
8-10	572	581	793	389	301	302	213	84	2	0	0	3237	36.8
10-12	356	428	525	318	261	271	332	208	147	34	0	2880	32.8
12-14	5	250	333	177	70	70	103	9	69	52	23	1161	13.2
14-16	0	27	111	37	32	58	26	13	26	18	7	355	4.0
16-18	0	0	10	0	0	0	0	0	0	0	0	10	0.1
18-20	0	0	0	0	0	0	0	0	0	0	0	0	0
20-22	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	1205	1598	2071	1068	740	736	675	314	244	104	30	8785	
Total (%)	13.7	18.2	23.6	12.2	8.4	8.4	7.7	3.6	2.8	1.2	0.3		100

Source Mott MacDonald, 2023

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