Sheringham Shoal and Dudgeon Offshore Wind Farm Extension Projects

Environmental Statement

Volume 3

Appendix 6.2 - Wave Climate Assessment

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REPORT

Sheringham and Dudgeon OWF Extension

Wave Climate Assessment

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1 Introduction

1. Royal HaskoningDHV has been commissioned as Impact Assessment (IA) Contractor for Equinor New Energy Limited (the Applicant) on the proposed Dudgeon Offshore Wind Farm Extension Project (DEP) and the Sheringham Shoal Offshore Wind Farm Extension Project (SEP). Part of the impact assessment requires analysis of marine physical processes, including assessment of changes to the wave regime due to the presence of foundations. The extent of the existing wind farm sites and the proposed extensions are presented in **Figure 1-1** below.

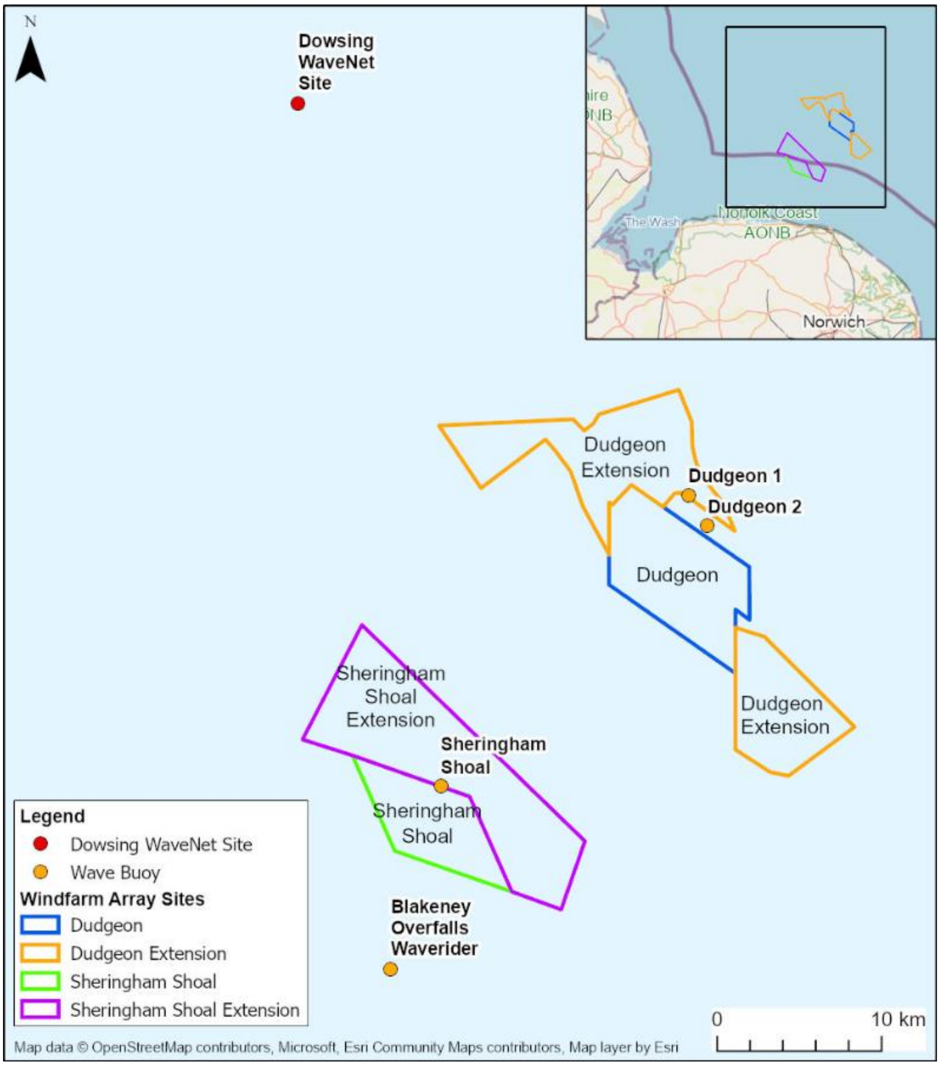

Figure 1-1: Extent of the existing Dudgeon and Sheringham Shoal OWFs and proposed extensions

2. To inform the impact assessment, wave transformation modelling has been undertaken to determine potential impacts on nearshore wave conditions caused by the proposed extension projects. This report provides details on the methodology, data collection, wave model set-up and calibration, and presents the results of the model runs.

2 Methodology

3. The approach adopted for assessing potential impact on wave climate and associated coastal processes consists of the following steps:

    1 Data collection – presented in Section 3;
    2 Data analysis and derivation of extreme wave and wind conditions – presented in Section 4;
    3 Wave model set-up – discussed in Section 18;
    4 Wave model calibration – discussed in Section 5.3;
    5 Wave model runs and scenarios – listed in Section 38;
    6 Wave model results – presented in Section 46; and
    7 Conclusions – in Section 60.

4. The wave model was set up using DHI's MIKE21-SW modelling software, which includes a new generation spectral wind-wave model based on unstructured triangular meshes. The model simulates the growth, decay and transformation of wind-generated waves and swell in offshore and coastal areas. MIKE21-SW is a state-of-the-art numerical tool for prediction and analysis of wave climates in offshore and coastal areas.

5. For this exercise the fully spectral formulation was used, which is based on the wave action conservation equation, as described in, for example, Komen et al. (1994) and Young (1999), where the directional-frequency wave action spectrum is the dependent variable.

6. The wave modelling considered a number of wave and wind directions to determine the worst-case direction, that is the direction that results in the worst-case nearshore wave conditions along the north Norfolk coast. Two return period events were assessed; the 1 in 1 year and 1 in 50 year events.

7. Results were analysed to determine changes in nearshore wave climate as a result of the proposed DEP and SEP OWFs. The cumulative impacts of the existing Dudgeon and Sheringham Shoal OWFs together with the proposed DEP and SEP extensions were also assessed.

3 Data Collation

9. All the relevant data that has been collated and used in this wave modelling exercise is listed below.

- **UK Met Office's hindcast data (WaveWatch III model):** wave hindcast frequency tables for one offshore wave point at location 53.522°N 1.529°E for the time period between 1991 to 2020. The frequency tables include analysis of wave height, wave period and wave direction.

- **Wave data** recorded by the following five wave buoys:
  - **Dowsing waverider buoy** collected by Cefas as part of the national WaveNet Programme for the time period 06/10/2003 to 02/09/2020
  - **Blakeney Overfalls waverider buoy** collected by the Channel Coastal Observatory (CCO) as part of the Anglian Coastal Monitoring Programme for the time period 09/07/2018 to 16/02/2022
  - **Dudgeon 1 waverider buoy** collected for the previous phase study of the existing Dudgeon OWF for the time period 24/04/2013 to 26/05/2014
  - **Dudgeon 2 waverider buoy** collected for the previous phase study of the existing Dudgeon OWF for the time period 11/03/2016 to 21/12/2017
  - **Sheringham Shoal waverider buoy** collected for the previous phase study of the existing Sheringham OWF for the time period 18/04/2010 to 24/01/2012

- **Bathymetric Data sets:**
  - Post construction bathymetric survey data for the **existing OWFs and cable corridors** for Sheringham (2018) and Dudgeon (2013)
  - Bathymetric survey data for the **proposed wind farm extensions and cable corridor** for SEP (2020), DEP (2020) and cable corridors (2019-2020)
  - Latest available bathymetry data (2011 to 2020) for coastal areas between Horsey in the east to Scolt Head Island in the west, downloaded from the Admiralty's Seabed Mapping Service Data Portal
  - Bathymetry EMODnet DTM (2020) downloaded from EMODnet Bathymetry Data Portal

- **Wind Data:**
  - Wind hindcast data available from previous East Anglia wind farm (East Anglia ONE North and TWO) studies for the time period between 1980 and the end of August 2017

- **Water Level Data sets:**
  - Recorded water level data for **Cromer Tide Gauge** obtained from the British Oceanography Data Centre (BODC) for the time period between 2010 to 2021. It should be noted that the data from the end of August 2017 is very patchy and has not been used.
  - Predicted water level data for **Cromer Tide Gauge** obtained using POLTIPS developed by the National Oceanography Centre (NOC) for the time period between 2019 and 2020.
  - Mean Sea Level data for **Cromer** obtained from the UK Hydrographic Office Admiralty Tide Tables (Volume I A, 2022).

4 Offshore Wave Climate

4.1 Offshore Wave Data

10. **Figure 4-1** shows the locations of the five wave buoys in relation to the existing wind farm array sites, and the proposed DEP and SEP. **Figure 4-2** to **Figure 4-7** present wave rose plots of the wave climate based on data from the Dowsing (two roses for different periods), Dudgeon 1 and 2, Sheringham Shoal and Blakeney Overfalls sites, respectively.

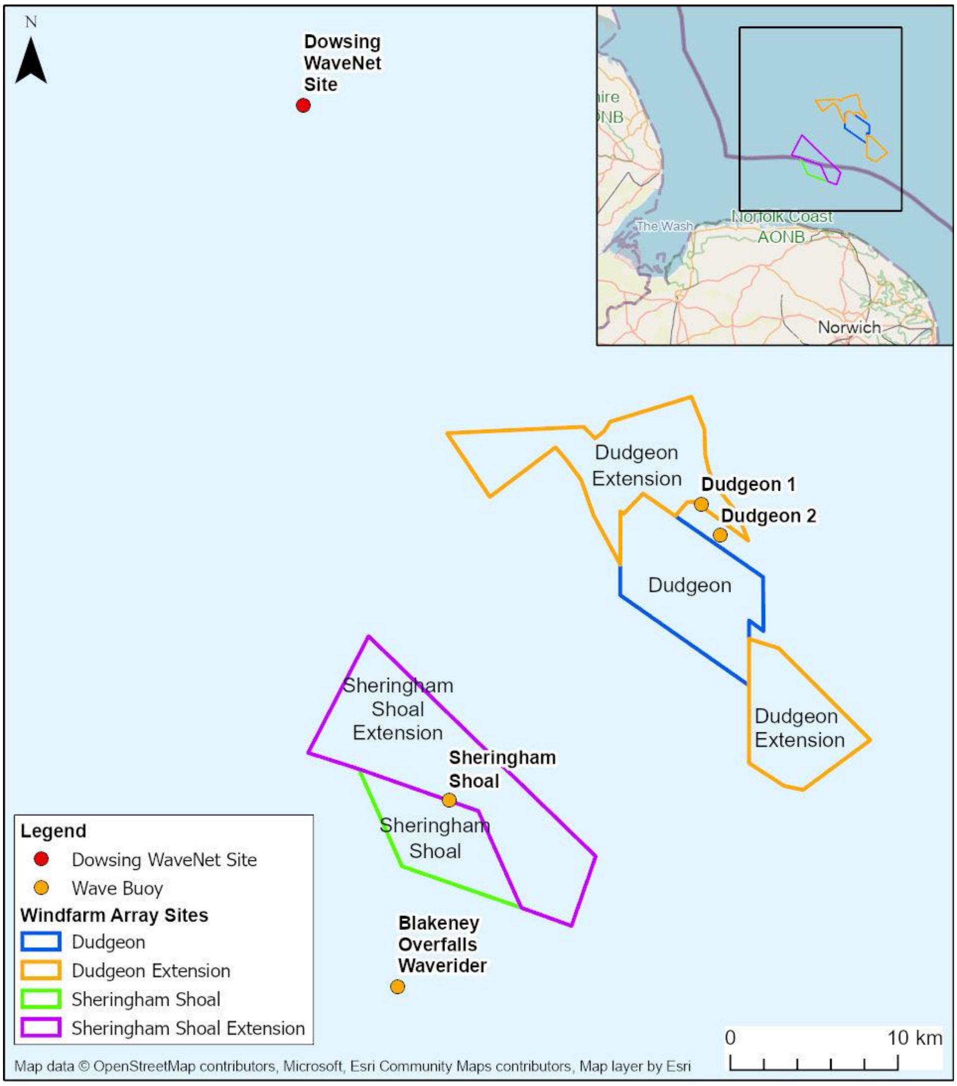

Figure 4-1: Wave buoy locations in relation to the array sites

11. **Figure 4-2** and **Figure 4-3** present the wave rose plots for the Dowsing WaveNet site covering the full period of recorded data and the calibration period (between 2010 and 2020), respectively. Both figures show that the predominant wave direction is from the north with significant wave heights mostly below 2m. Comparison of the wave roses for the full data set and the calibration period only, indicates that the highest waves (above 4.5m) have mostly been recorded in the period before 2010. Similarly, the frequency of occurrence of waves from the south-west is greater when the full dataset is considered.

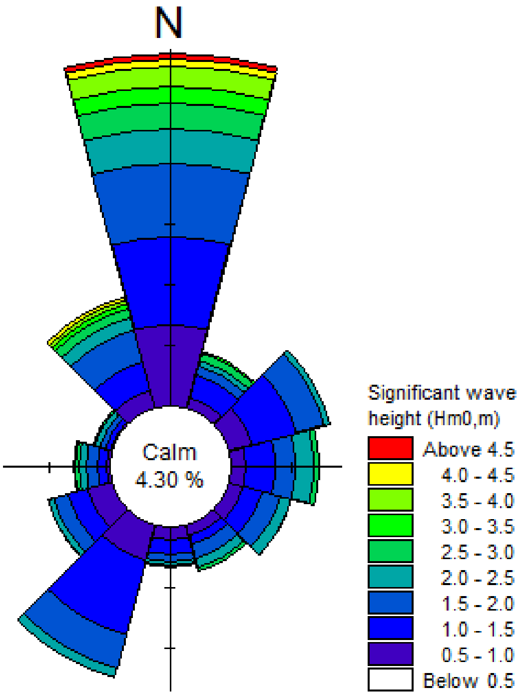

Figure 4-2: Wave rose based on recorded data at Dowsing WaveNet Site between 06/10/2003 and 02/09/2020

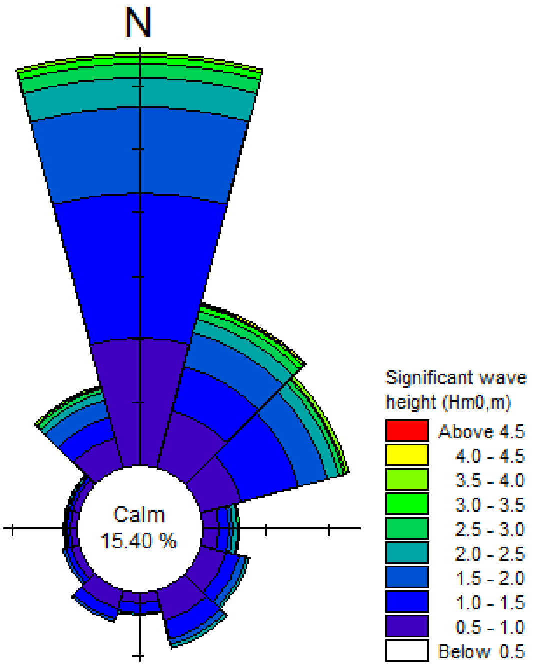

Figure 4-3: Wave rose based on recorded data at Dowsing WaveNet Site for the calibration period between 2010 and 2020

12. The wave roses in **Figure 4-4** and **Figure 4-5** below for the Dudgeon 1 and 2 sites, show that the distribution of waves at the Dudgeon 1 site is more uniform between different wave directions, whereas for the Dudgeon 2 site, the predominant wave direction is from northerly sectors.

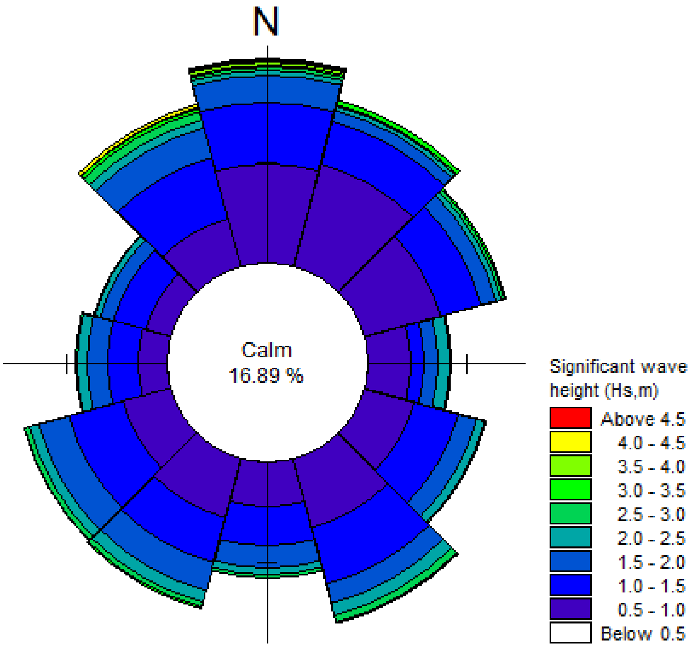

Figure 4-4: Wave rose based on recorded data at Dudgeon 1 between 24/04/2013 to 26/05/2014

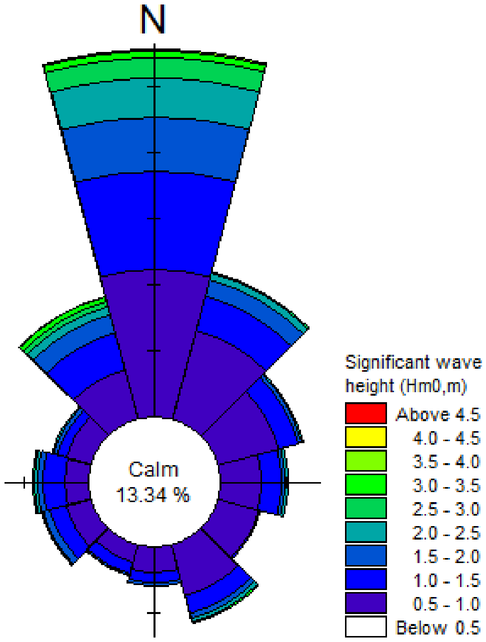

Figure 4-5: Wave rose based on recorded data at Dudgeon 2 between 11/03/2016 to 21/12/2017

13. **Figure 4-6** below shows that for the Sheringham Shoal site, the predominant wave direction is from north and north-east directions. Similarly, for the Blakeney Overfalls site, the dominant directional sectors are from the north and north-east, although the frequency of waves from westerly and easterly directions is greater than for other sites (**Figure 4-7**).

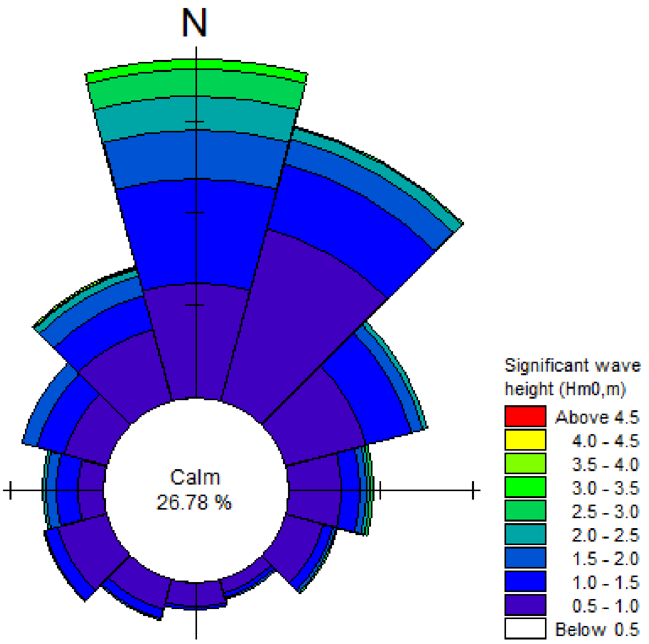

Figure 4-6: Wave rose based on recorded data at Sheringham Shoal between 18/04/2010 and 24/01/2012

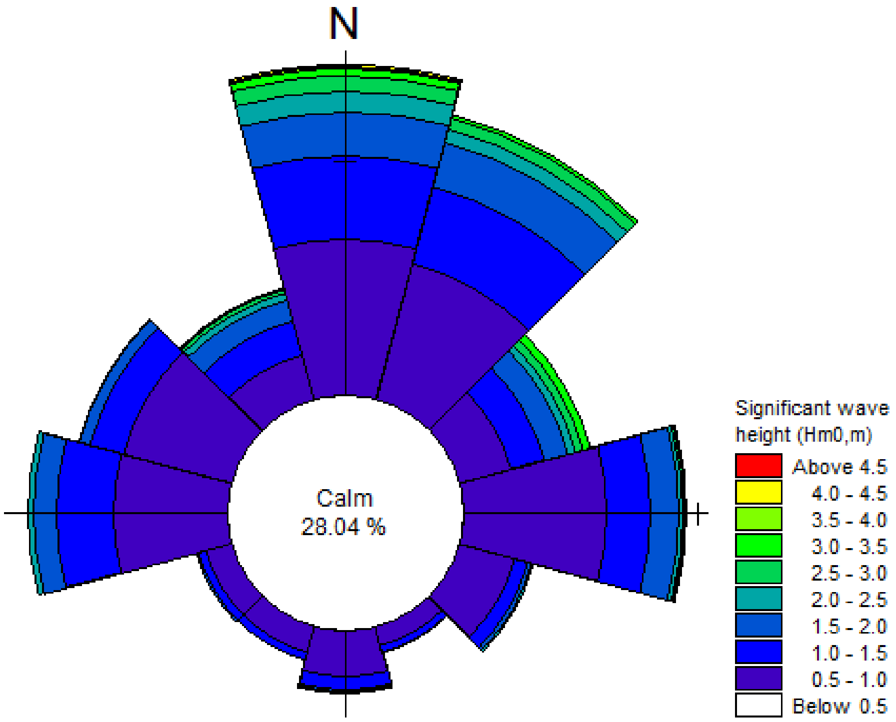

Figure 4-7: Wave rose based on recorded data at Blakeney Overfalls between 09/07/2018 and 16/02/2022

4.2 Offshore Wind Data

14. There are no measured offshore wind data available. Therefore, wind speeds 'matching' the offshore wave conditions were calculated based on the UK MetOffice hindcast wave and wind data obtained for the previous East Anglia ONE North and TWO wind farm study for the time period between 1980 and end of August 2017. **Figure 4-8** shows the relationship between the offshore wave and wind conditions. This relationship was used to derive wind speeds corresponding to offshore wave conditions applied at the wave model boundaries.

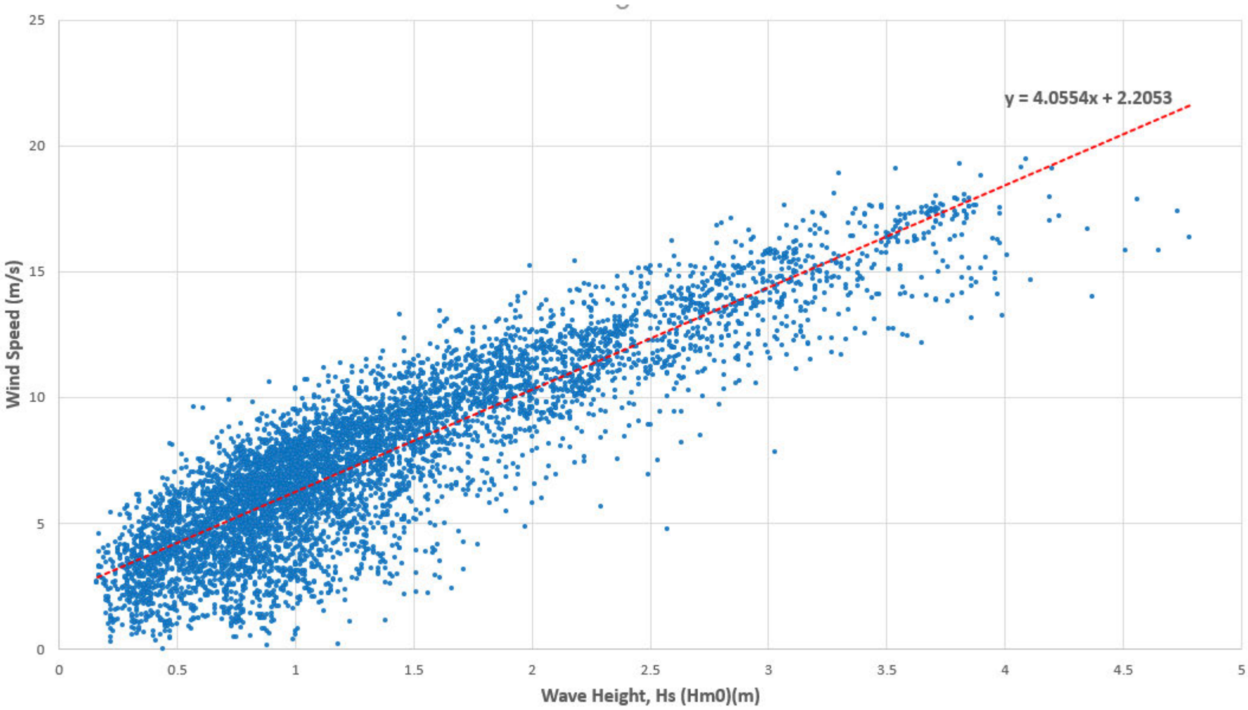

Figure 4-8: Relationship between offshore wind speed and significant wave height

4.3 Extreme Wave Analysis

15. An extreme value analysis was completed based on UK MetOffice hindcast wave data to derive extreme wave conditions at the DEP and SEP sites. The data was obtained for the period between 1991 and 2020 at 53.522ºN 1.529ºE. The data was supplied as frequency table (**Table 4-1**) and wave rose plot of the data is presented in **Figure 4-9**.

16. In-house extreme value analysis software, EXTREME, was used to derive 1 in 1 year and 1 in 50 year wave conditions for wave impact assessment. Using the EXTREME software, statistical distributions were fitted to the data using the Gumbel, Weibull and GEV distribution methods, and a preferred method was selected that provided the best statistical fit to the data.

17. **Table 4-2** presents the derived extreme wave conditions for a range of directional sectors and return period events. Corresponding peak wave periods were calculated based on wave steepness and are presented in **Table 4-3**. The derived offshore wave conditions for the 1 in 1 year and 1 in 50 year return period events were used in the wave modelling discussed in **Section 38**.

Table 4-1: Offshore wave frequency table for the MetOfffice hindcast data

Wave Height (m)		**Occurrence frequency (%) per directional sector (°N)**												**All classes**
Lower	**upper**	**0**	**30**	**60**	**90**	**120**	**150**	**180**	**210**	**240**	**270**	**300**	**330**	
0.0	0.5	2.5	1.6	1.3	0.8	0.7	0.8	0.5	0.3	0.3	0.3	0.4	1.3	10.7
0.5	1.0	6.6	3.9	2.8	2.2	1.5	2.5	2.0	2.0	1.9	1.5	1.7	3.2	31.7
1.0	1.5	5.2	2.3	2.0	1.6	1.1	1.8	2.0	2.5	2.7	1.9	2.0	2.9	28.0
1.5	2.0	2.8	1.0	1.0	0.8	0.5	1.0	1.3	1.9	2.0	1.2	1.2	1.8	16.5
2.0	2.5	1.4	0.4	0.4	0.5	0.2	0.4	0.6	0.9	0.8	0.5	0.6	1.1	7.8
2.5	3.0	0.7	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.1	0.3	0.6	3.1
3.0	3.5	0.3	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	1.2
3.5	4.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.6
4.0	4.5	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.3
4.5	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
5.0	5.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5.5	6.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total		**19.9**	**9.4**	**7.8**	**6.3**	**4.2**	**6.7**	**6.5**	**7.7**	**7.9**	**5.6**	**6.3**	**11.6**	**100.0**

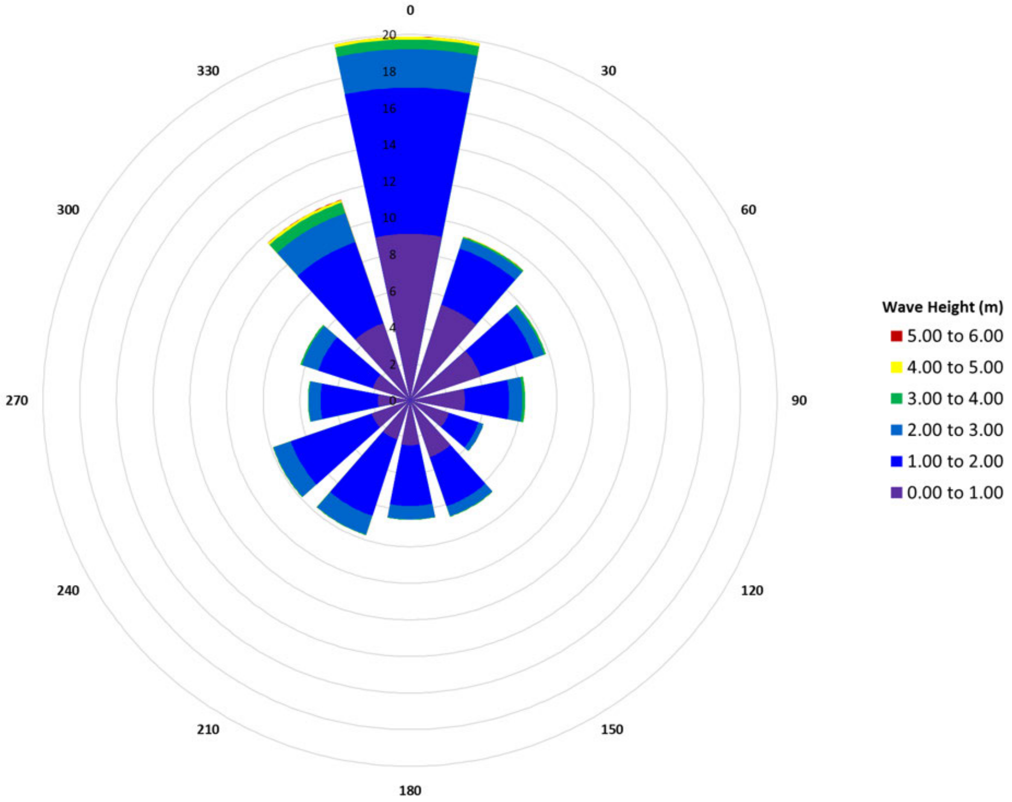

Figure 4-9: Wave rose based on MetOffice hindcast data (1991 – 2020)

Table 4-2: Derived extreme offshore wave conditions

Direction (ºN)	Extreme offshore significant wave height (Hs, m) for return period (years)							
	1	5	10	20	50	100	200	1,000
0	4.62	5.54	5.94	6.33	6.86	7.25	7.65	8.57
30	4.02	5.01	5.44	5.87	6.43	6.86	7.29	8.28
60	3.52	4.32	4.66	5.01	5.46	5.81	6.15	6.95
90	3.68	4.52	4.89	5.25	5.73	6.09	6.46	7.30
120	2.90	3.61	3.91	4.22	4.62	4.92	5.23	5.94
150	3.15	3.84	4.13	4.43	4.82	5.11	5.41	6.10
180	3.11	3.75	4.02	4.30	4.66	4.94	5.21	5.85
210	3.15	3.76	4.02	4.28	4.63	4.89	5.15	5.76
240	3.20	3.82	4.08	4.35	4.70	4.97	5.23	5.85
270	3.18	3.85	4.14	4.43	4.81	5.10	5.39	6.06
300	3.35	4.05	4.35	4.65	5.04	5.34	5.64	6.34
330	4.83	5.86	6.31	6.75	7.34	7.78	8.22	9.25

Table 4-3: Derived peak wave period corresponding to the extreme offshore wave conditions

Direction (ºN)	Wave steepness	Peak wave period (Tp, sec) for offshore waves for return period (years)							
		1	5	10	20	50	100	200	1,000
0	*0.0223*	11.5	12.6	13.1	13.5	14.0	14.4	14.8	15.7
30	*0.0266*	9.8	11.0	11.4	11.9	12.4	12.9	13.3	14.1
60	*0.0274*	9.1	10.1	10.4	10.8	11.3	11.7	12.0	12.8
90	*0.0294*	9.0	9.9	10.3	10.7	11.2	11.5	11.9	12.6
120	*0.0323*	7.6	8.5	8.8	9.2	9.6	9.9	10.2	10.9
150	*0.0323*	7.9	8.7	9.1	9.4	9.8	10.1	10.4	11.0
180	*0.0353*	7.5	8.2	8.5	8.8	9.2	9.5	9.7	10.3
210	*0.0417*	7.0	7.6	7.9	8.1	8.4	8.7	8.9	9.4
240	*0.0353*	7.6	8.3	8.6	8.9	9.2	9.5	9.7	10.3
270	*0.0417*	7.0	7.7	8.0	8.3	8.6	8.9	9.1	9.7
300	*0.0278*	8.8	9.7	10.0	10.4	10.8	11.1	11.4	12.1
330	*0.0246*	11.2	12.4	12.8	13.3	13.8	14.2	14.6	15.5

5 Wave Model Set-up

5.1 Model Extent

19. The wave model set-up for this modelling exercise covers the area between The Humber in the north-west, The Wash in the south-west and covers the North Norfolk coast between The Wash and Stalham in the east. **Figure 5-1** shows the wave model extent (red box) in relation to all the wind farm array sites (orange outlines).

20. For the model calibration, the wave model has been driven by real-time wave data recorded by the Cefas Dowsing WaveNet buoy shown in **Figure 5-1** (green point) and has been calibrated against measured wave data at four locations shown in **Figure 4-1**; Dudgeon 1, Dudgeon 2, Sheringham Shoal and Blakeney Overfalls.

21. The calibrated wave model investigates potential impacts on nearshore wave conditions caused by the proposed wind farm using the results of the extreme wave analysis as boundary conditions (see **Section 4.3**). The analysis of extreme waves was based on the UK MetOffice Hindcast model point shown in **Figure 5-1** as a yellow star.

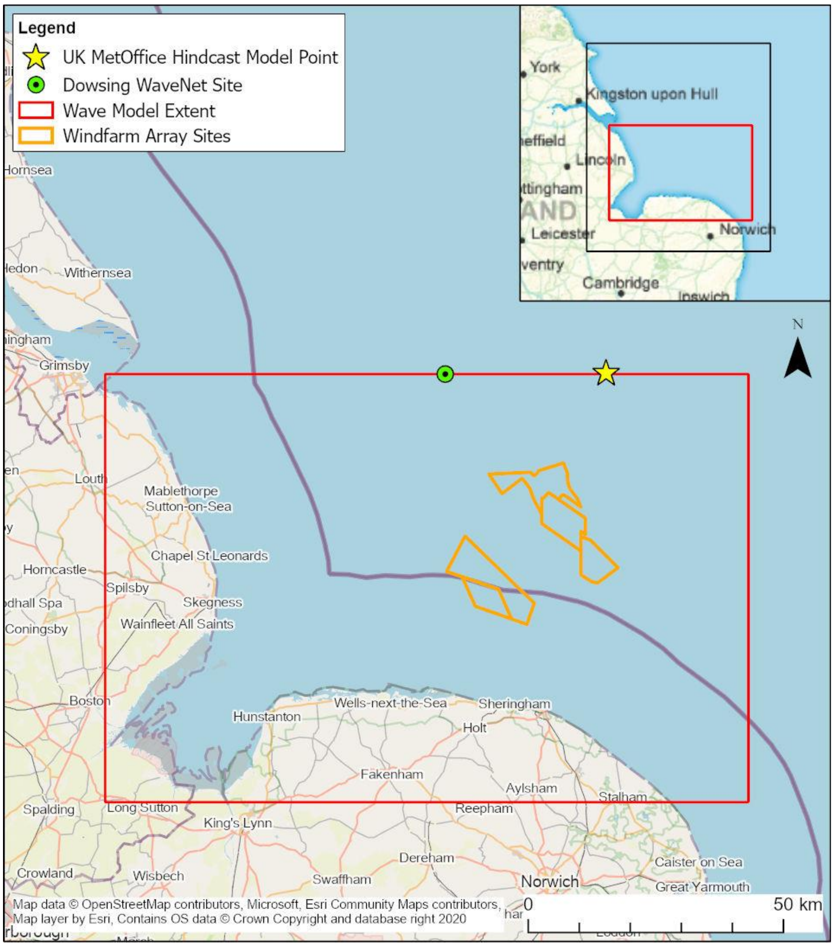

Figure 5-1: Wave model extent (red box) in relation to all the wind farm array sites (orange outlines)

5.2 Model Bathymetry

22. The wave model bathymetry was composed of three groups of data:

- The existing and proposed wind farm array sites and cable corridors (RED) are covered by detailed bathymetry provided by the client;
- the nearshore areas along the North Norfolk coast (BLACK) are also covered by detailed bathymetry sourced from the Admiralty Portal; and
- the remaining wave model area is covered by coarser EMODnet bathymetry data.

23. The coverage of each dataset is illustrated in **Figure 5-2**. Full details of all the bathymetry data used can be found in **Section 3**.

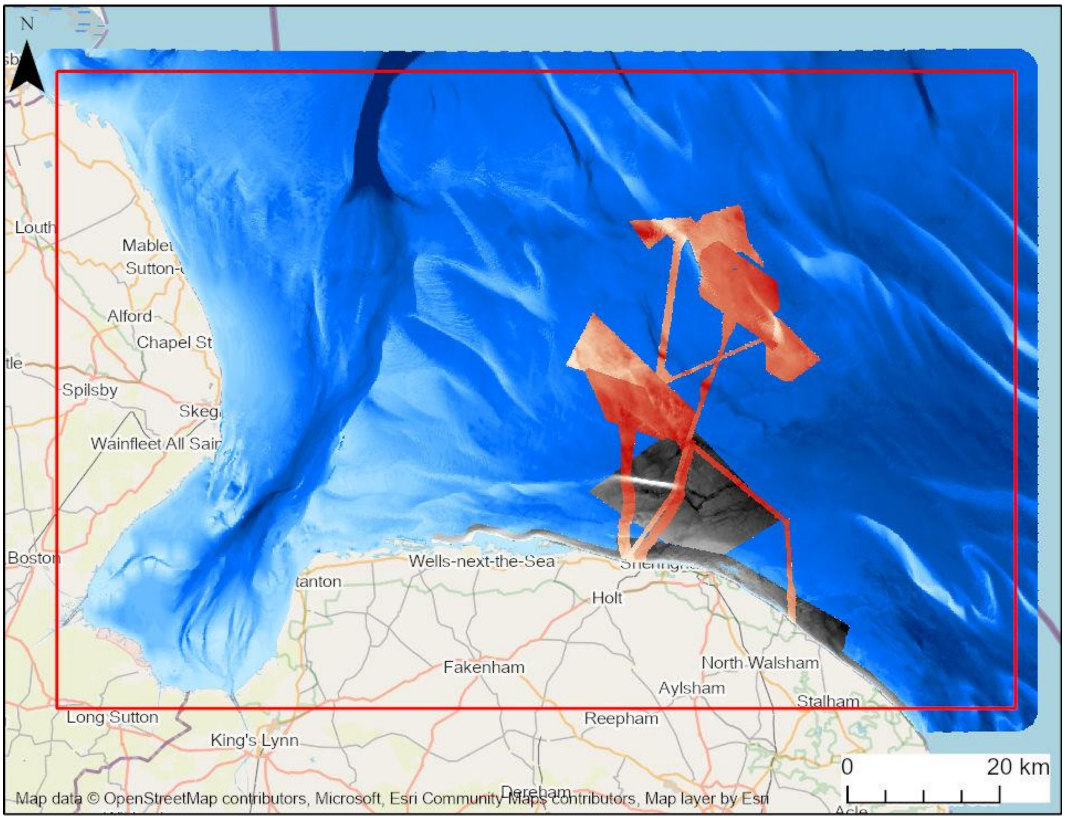

Figure 5-2: Bathymetry data coverage (RED = bathymetry of wind farm array sites and cable corridors, BLACK = Admiralty data, BLUE = EMODnet bathymetry)

5.3 Model Calibration

24. The MIKE21-SW model has been calibrated against measured data recorded at waverider buoys Dudgeon 1, Dudgeon 2, and Sheringham Shoal, which have all been collected for the previous phase study, as well as against measured data recorded at Blakeney Overfalls. Full details of all four waverider buoys used can be found in **Section 3**.

25. For three of these four waverider buoys (Dudgeon 1 and 2 and Blakeney Overfalls), the four biggest storm events have been selected for the model calibration. The worst potential impacts in terms of wave direction are considered to be waves from the north and north-east; hence two storm events for

each of these directions have been selected. The Sheringham Shoal waverider buoy has proven to be difficult to calibrate and therefore only two storm events have been included in this report; please refer to section 5.3.3 for details on the encountered issues and possible reasons for them. **Table 5-1** shows the list of selected storms for the model calibration.

Table 5-1: Storm events selected for model calibration

Waverider Location	Storm Event	Direction	Peak Wave Height (m) at waverider buoy	Storm Event Date	
Dudgeon 1	1	N	4.5	10/09/2013 12:00	11/09/2013 12:00
	2	N	3.8	23/05/2013 09:30	24/05/2013 09:30
	3	NE	4.8	10/10/2013 01:00	11/10/2013 01:00
	4	NE	3.0	29/01/2014 07:00	30/01/2014 07:00
Dudgeon 2	5	N	4.0	08/12/2017 04:30	09/12/2017 14:00
	6	N	4.0	12/11/2017 08:00	13/11/2017 08:00
	7	NE	4.9	06/11/2016 11:00	07/11/2016 11:00
	8	NE	4.1	11/02/2017 18:00	13/02/2017 01:00
Blakeney Overfalls	9	N	3.5	17/01/2019 06:00	17/01/2019 23:00
	10	N	3.1	04/02/2020 06:30	04/02/2020 22:00
	11	NE	3.6	08/01/2019 13:00	09/01/2019 13:00
	12	NE	4.0	28/03/2020 16:00	29/03/2020 16:00
Sheringham Shoal	13	N	3.6	05/01/2012 05:00	06/01/2012 10:00
	14	E	4.6	01/12/2010 10:00	02/12/2010 17:00

5.3.1 Calibration model resolution

26. The MIKE21-SW modelling software allows unstructured triangular meshes which enables the model to use a coarser grid in the offshore area and the areas further away from the proposed development site and a finer mesh in the areas of greatest interest. This approach enables higher computational efficiency whilst still maintaining sufficient accuracy of mesh coverage in areas of greatest interest in the present study. The calibration model domain was divided into three areas of different grid resolution as shown in **Figure 5-3**.

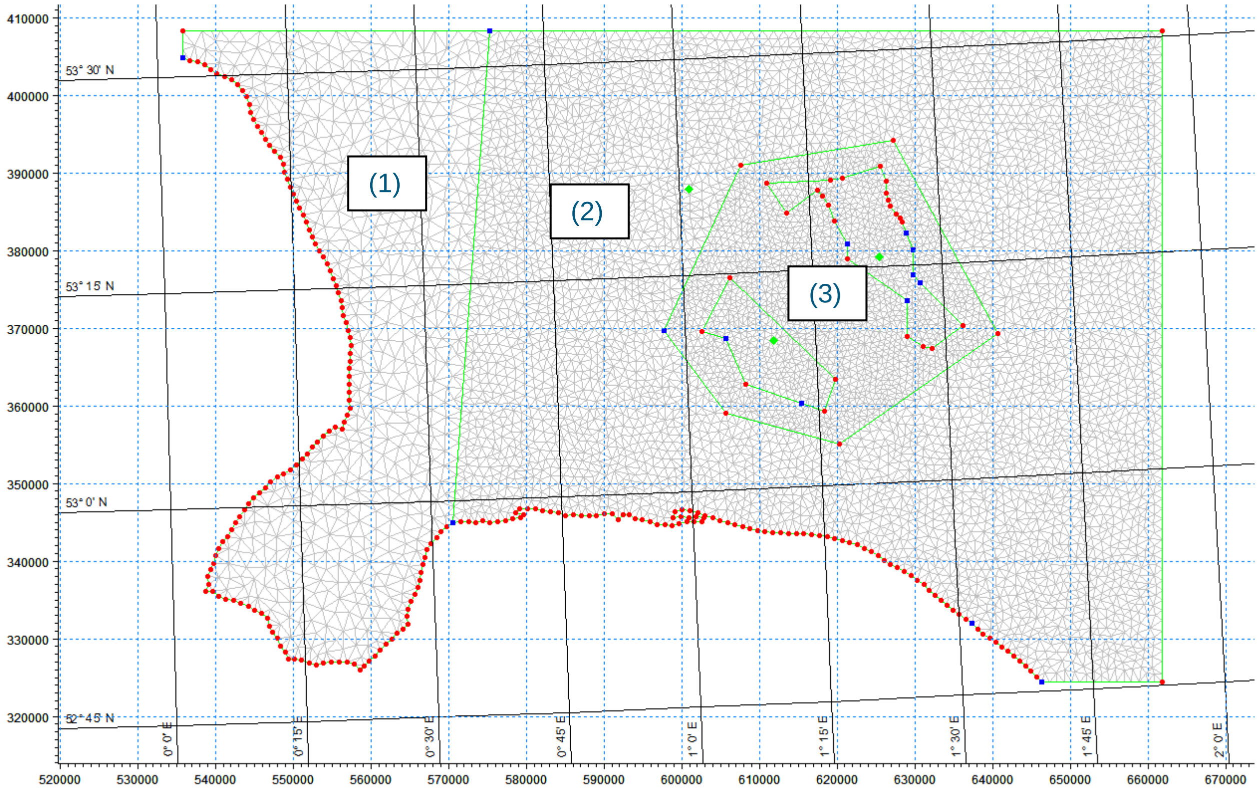

Figure 5-3: Triangular calibration model mesh resolution

27. The grid is coarser for areas at distance from the study area (1), is finer in areas adjacent to the array sites (2) and is finest in the array sites (3). The resolutions of the three mesh areas are detailed in **Table 5-2**.

Table 5-2: Calibration model mesh resolution

Mesh area	Mesh resolution (m^2)	Approximate maximum mesh size (m)
1) Lincolnshire coast and The Wash	2.5 million	1,500
2) North Norfolk coast and offshore areas	1.0 million	1,000
3) Wind farm array sites	500,000	700

5.3.2 Calibration model inputs

28. Offshore boundary of the calibration model has been driven at by real-time wave data recorded by the Cefas Dowsing WaveNet buoy shown in **Figure 5-1** (green point). The adopted model settings for the MIKE21-SW calibration model are listed in

29. **Table 5-3**.

Table 5-3: MIKE21-SW Calibration Model Settings

Description	Adopted Settings
Basic Equations	Fully spectral formulation
Directional Discretization	360 degrees rose
Water Level Conditions	Measured tide gauge data from Cromer for storm events prior to August 2017* Predicted water level data for Cromer for storm events after August 2017*
Wind Forcing	Type of air-sea interaction: Coupled Background Charnock parameter: 0.01 a) Real-time wind from previous study for storm events prior August 2017* b) Calculated wind using wind/wave relationship (y = 3.5703x + 2.3123) for storm events after August 2017*
Wave Breaking	Gamma constant 0.8
Bottom Friction	Model: Nikuradse roughness, kn Constant value: 0.04m
White Capping	Constant: 4.5 Dissipation coefficient, DELTA dis: constant 0.5
Offshore Boundary	Wave parameters: significant wave height, wave period, wave direction and wave spreading.

* See Section 3 for details on available data sets

5.3.3 Calibration model results

31. This section presents model calibration results for all the storm events selected and listed in **Table 5-1**. On all the figures the measured wave heights and wave directions are shown as crosses, whilst the modelled wave heights and wave directions are shown as continuous lines.

32. **Figure 5-4** to **Figure 5-7** show a comparison of the measured and modelled wave heights and wave directions for storm events selected for waverider buoy Dudgeon 1.

33. **Figure 5-8** to **Figure 5-11** show a comparison of the measured and modelled wave heights and wave directions for storm events selected for waverider buoy Dudgeon 2.

34. **Figure 5-12** to **Figure 5-15** show a comparison of the measured and modelled wave heights and wave directions for storm events selected for waverider buoy Blakeney Overfalls.

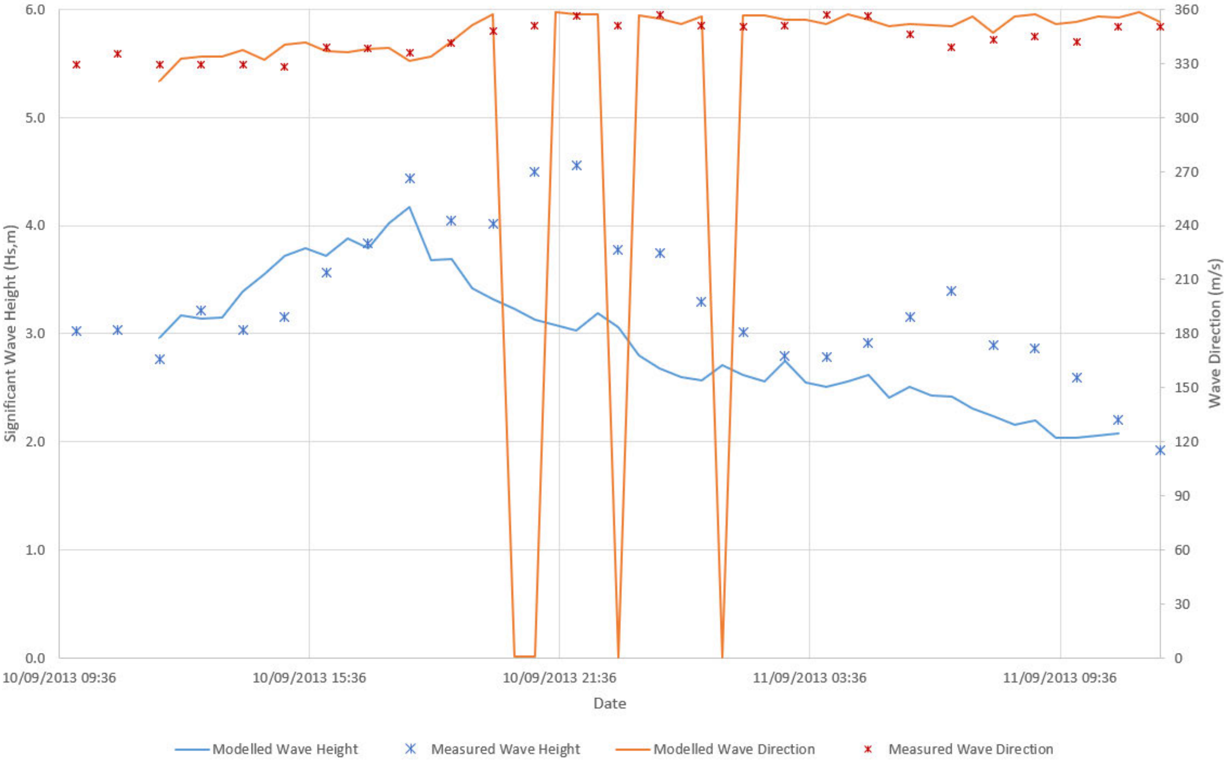

Figure 5-4: Storm Event 1 - Dudgeon 1 (waves from the north)

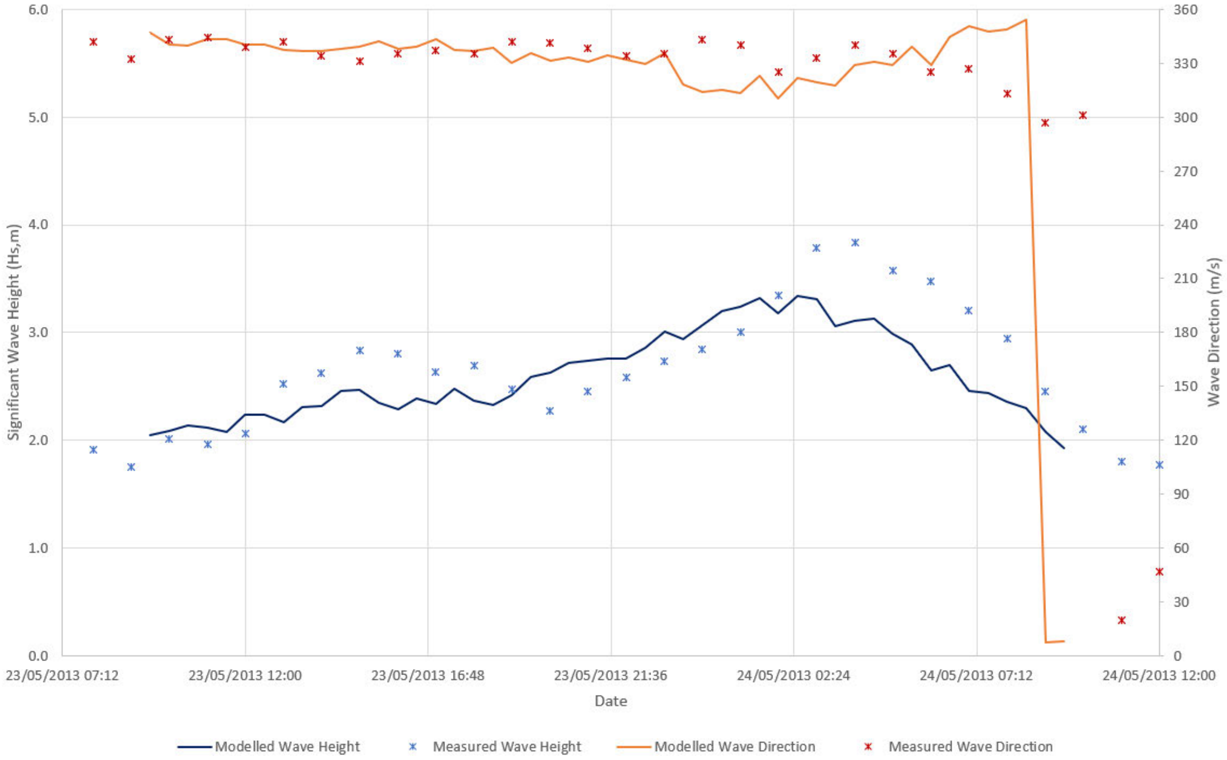

Figure 5-5: Storm Event 2 - Dudgeon 1 (waves from the north)

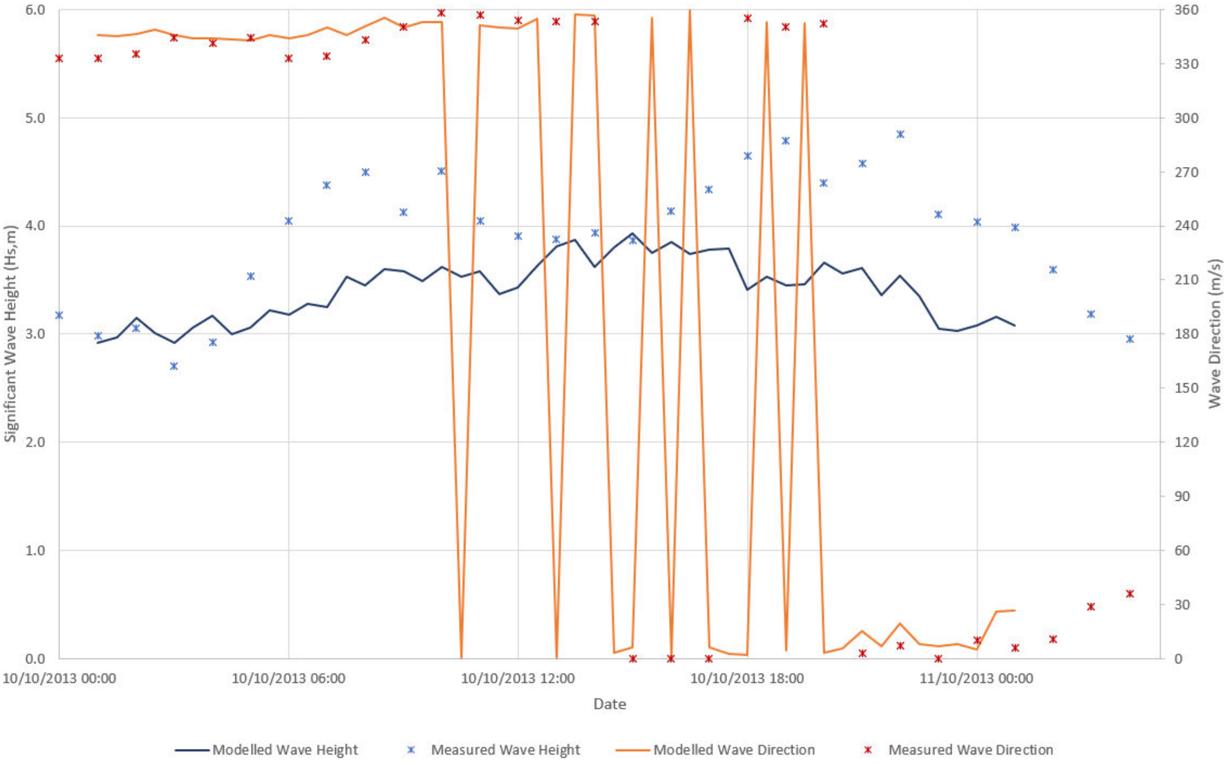

Figure 5-6: Storm Event 3 - Dudgeon 1 (waves from the north-east)

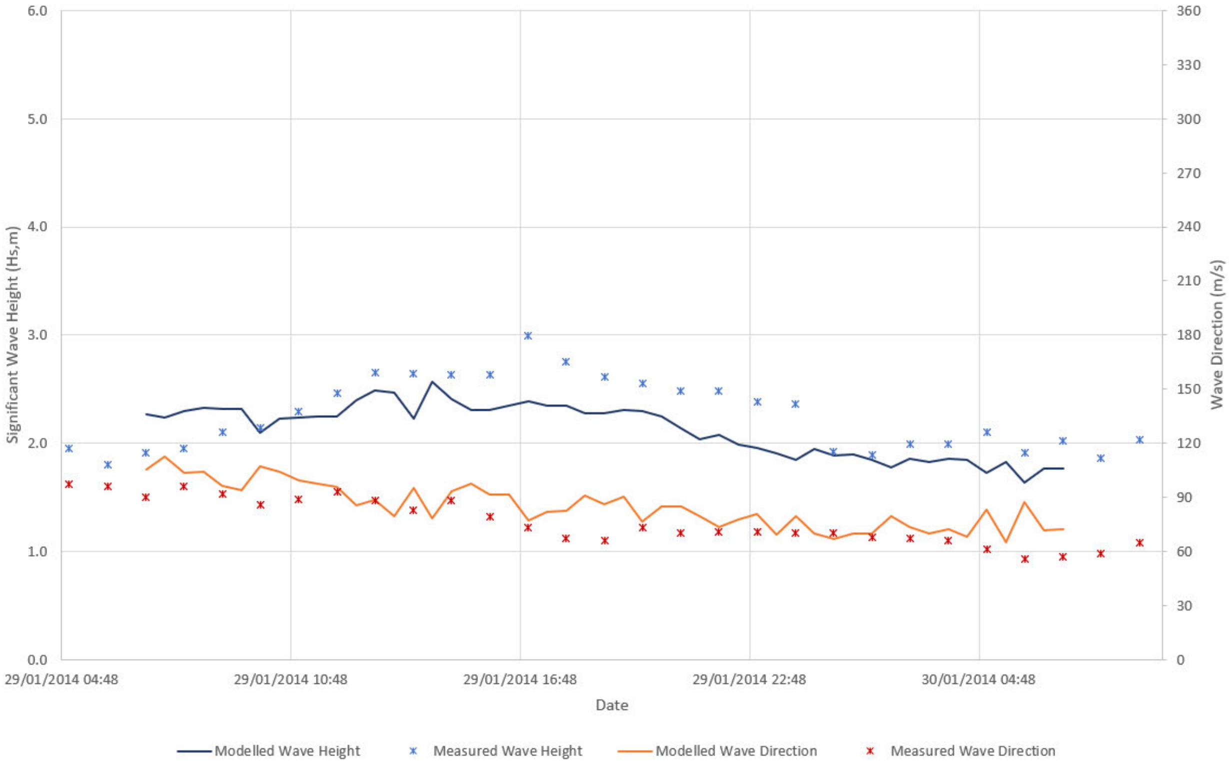

Figure 5-7: Storm Event 4 - Dudgeon 1 (waves from the north-east)

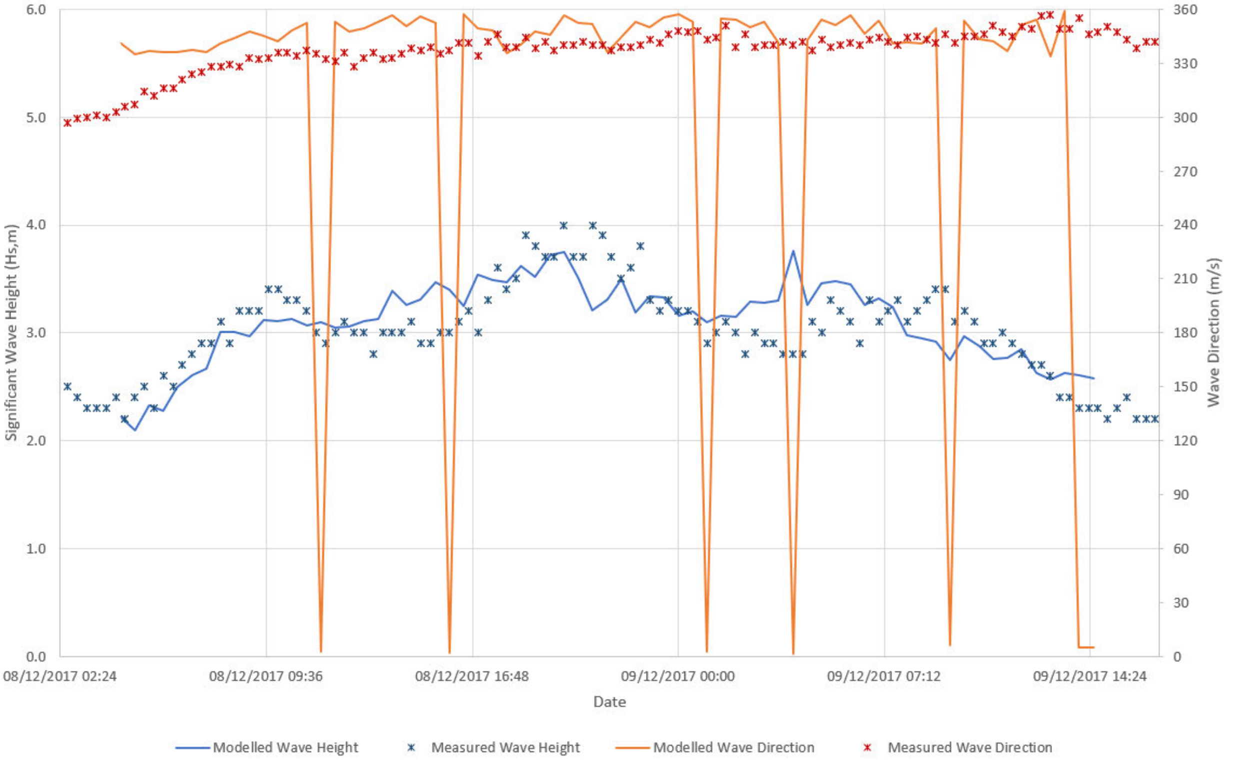

Figure 5-8: Storm Event 5 - Dudgeon 2 (waves from the north)

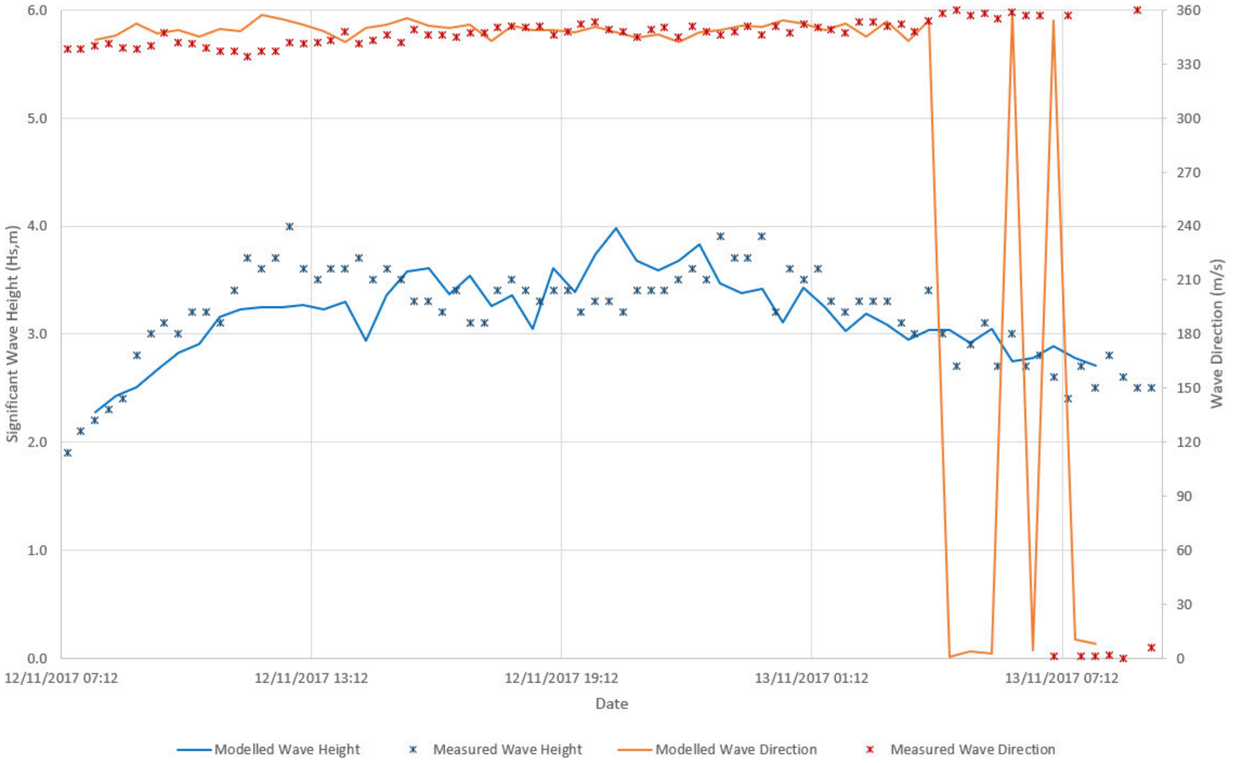

Figure 5-9: Storm Event 6 - Dudgeon 2 (waves from the north)

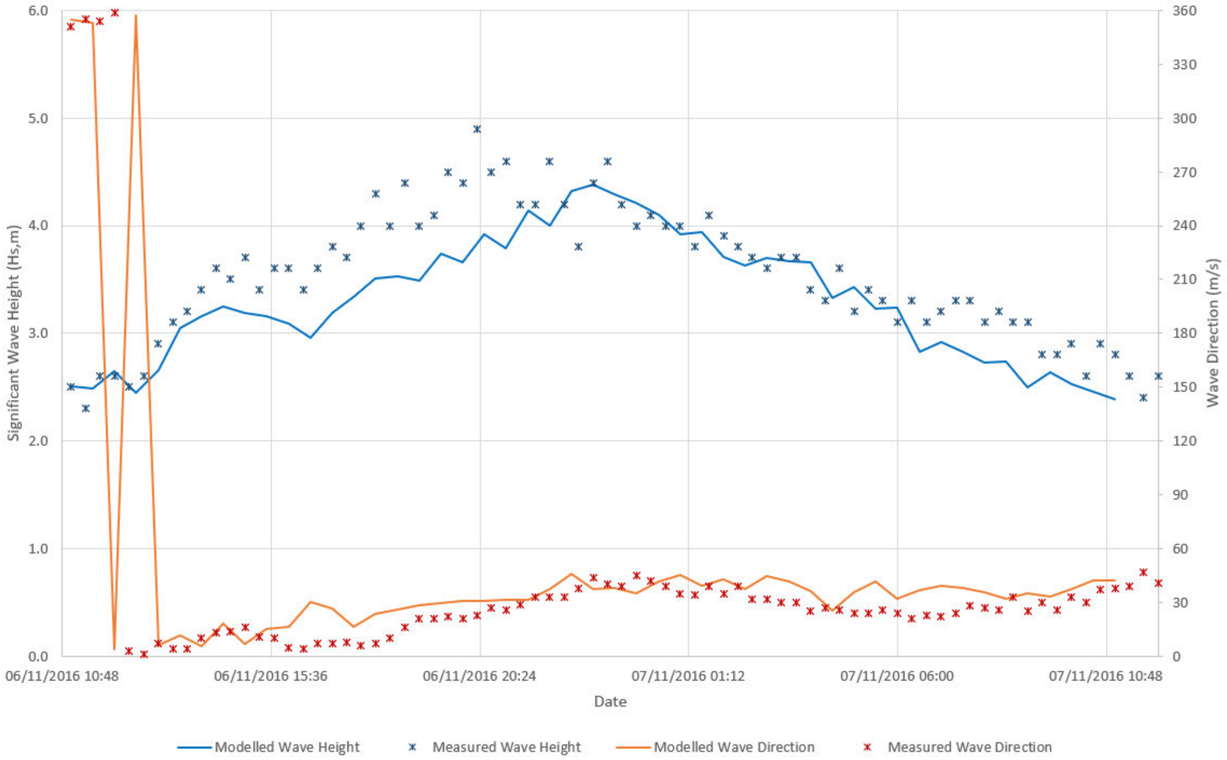

Figure 5-10: Storm Event 7 - Dudgeon 2 (waves from the north-east)

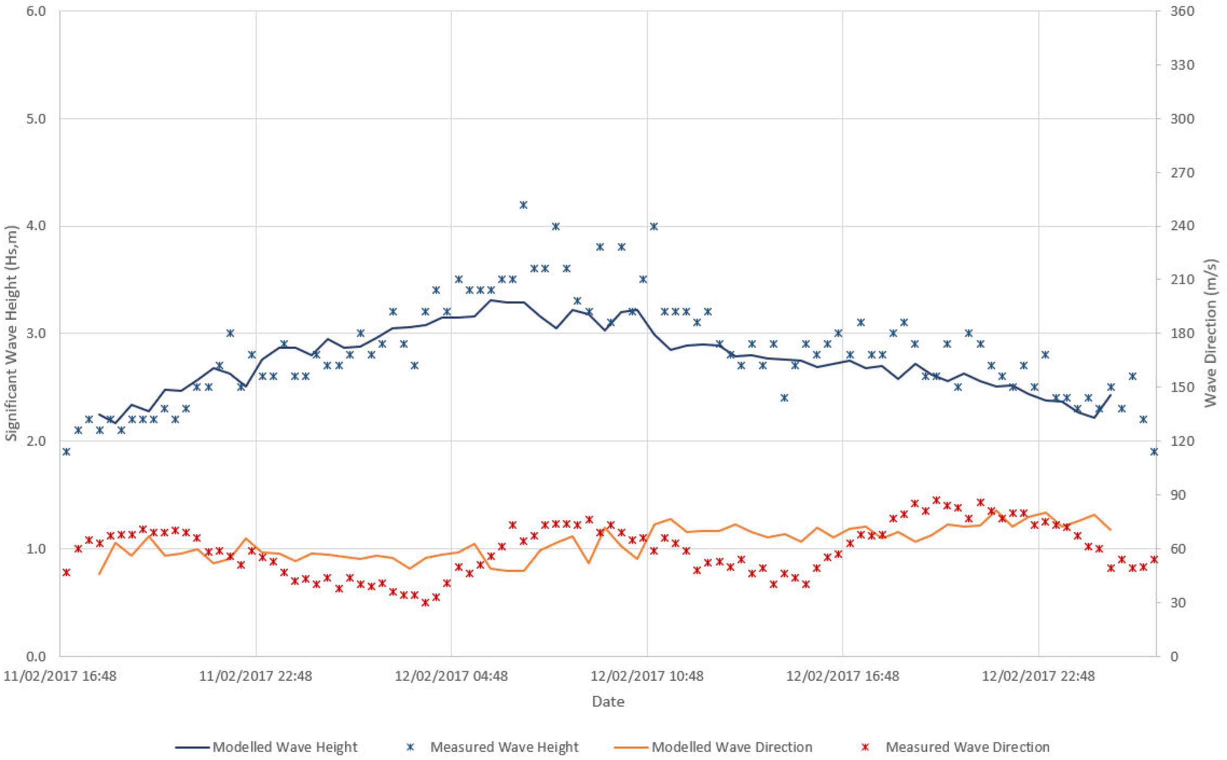

Figure 5-11: Storm Event 8 - Dudgeon 2 (waves from the north-east)

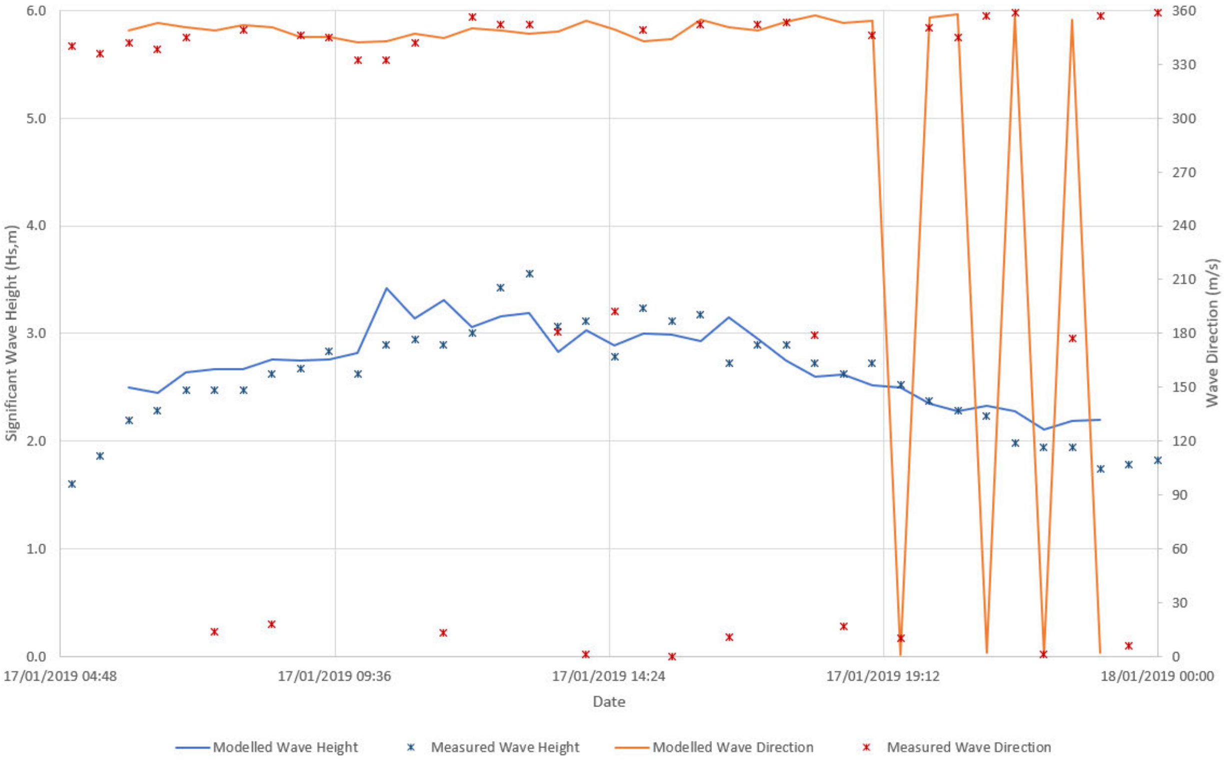

Figure 5-12: Storm Event 9 – Blakeney Overfalls (waves from the north)

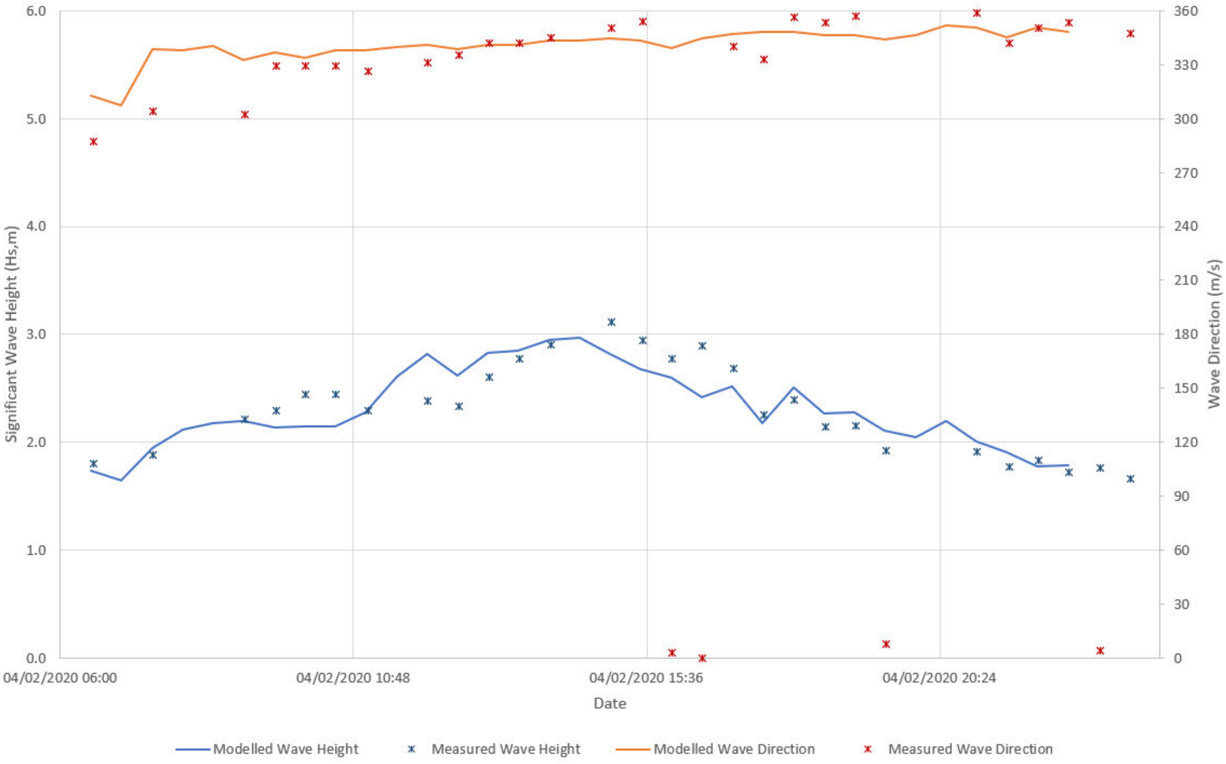

Figure 5-13: Storm Event 10 – Blakeney Overfalls (waves from the north)

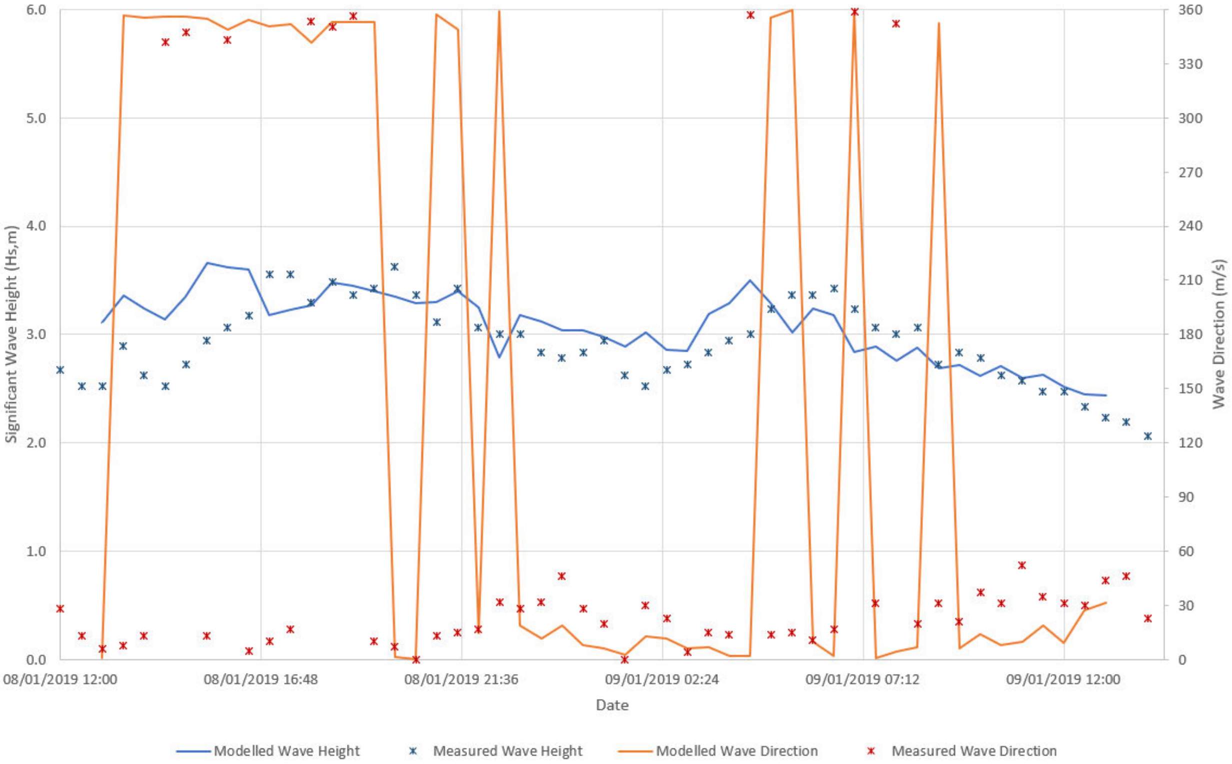

Figure 5-14: Storm Event 11 – Blakeney Overfalls (waves from the north-east)

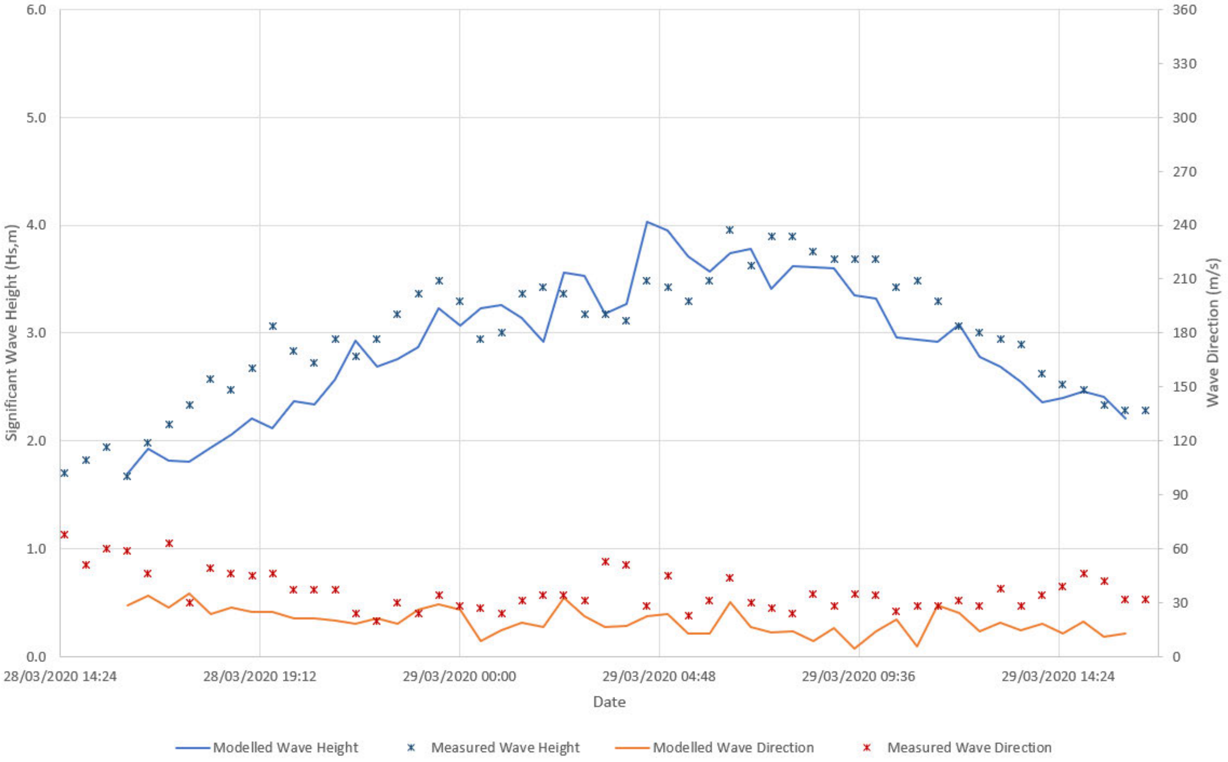

Figure 5-15: Storm Event 12 – Blakeney Overfalls (waves from the north-east)

35. The model calibration for waverider buoy Sheringham Shoal has been more difficult as was mentioned in section 5.3. The comparison of the measured and modelled wave heights and wave directions was not satisfactory and not even the "shape" of the time series curve could be matched. **Figure 5-17** and **Figure 5-19** show a comparison of the measured and modelled wave heights and wave directions for storm events selected for waverider buoy Sheringham Shoal. In order to illustrate the encountered issues, both figures also show the measured wave heights recorded at the Dowsing WaveNet Site that have been applied to the offshore model boundary for these storm events. To further support the validity of the model calibration results for storm events 13 and 14, **Figure 5-18** and **Figure 5-20** show recorded wave heights at waverider buoy Clipper for these two storm events (see **Figure 5-16** for location).

36. **Figure 5-17** shows a good agreement between the measured wave height at Dowsing WaveNet Site (model boundary data) and the modelled wave height, and the recorded wave height at waverider buoy Clipper. **Figure 5-18** shows the same magnitude of wave height of around 4.0m at the event peak. The difference to the measured wave height at waverider buoy Sheringham can only be explained by some local weather events.

37. **Figure 5-19** shows a reasonable agreement between the measured wave heights at Dowsing WaveNet Site (model boundary data) and the modelled wave heights. Whilst the modelled wave heights are slightly underpredicted, the shape of the rising and falling of the wave height is the same. The recorded wave height at waverider buoy Clipper (**Figure 5-20**) shows a significant wave height at the event peak of around 4.0m and then falls continuously down to 2.0m. The additional peak in the measured wave height at waverider buoy Sheringham can only be explained by some local weather events.

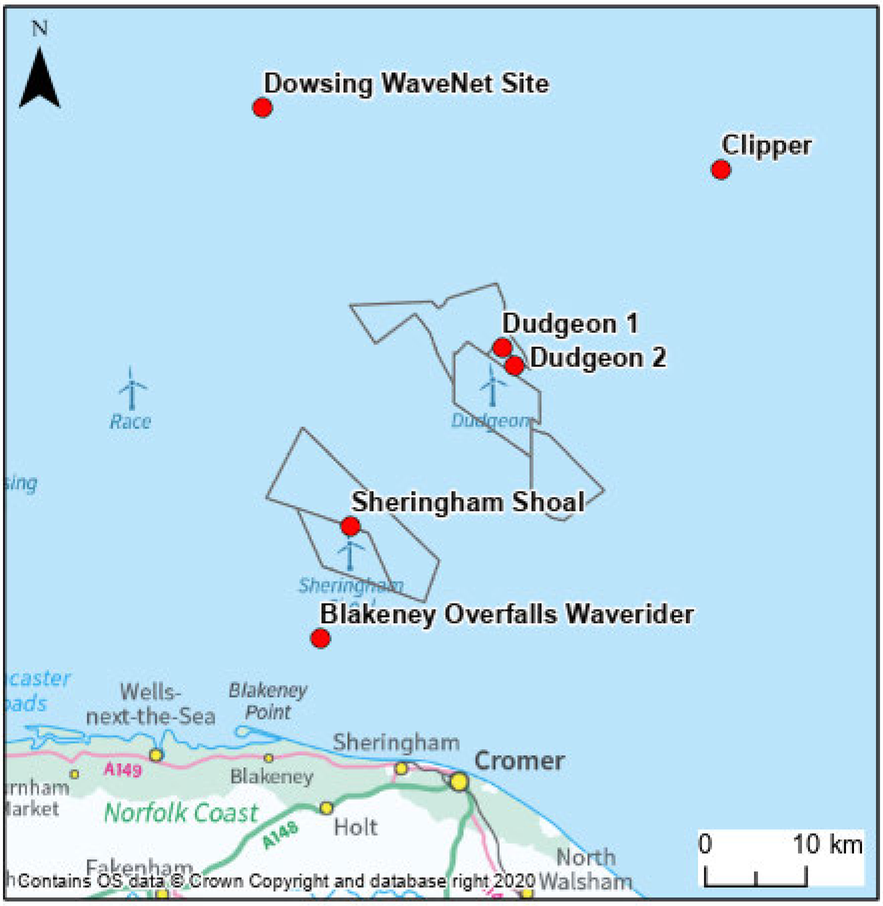

Figure 5-16: Location of waverider buoy Clipper (Cefas wavenet website)

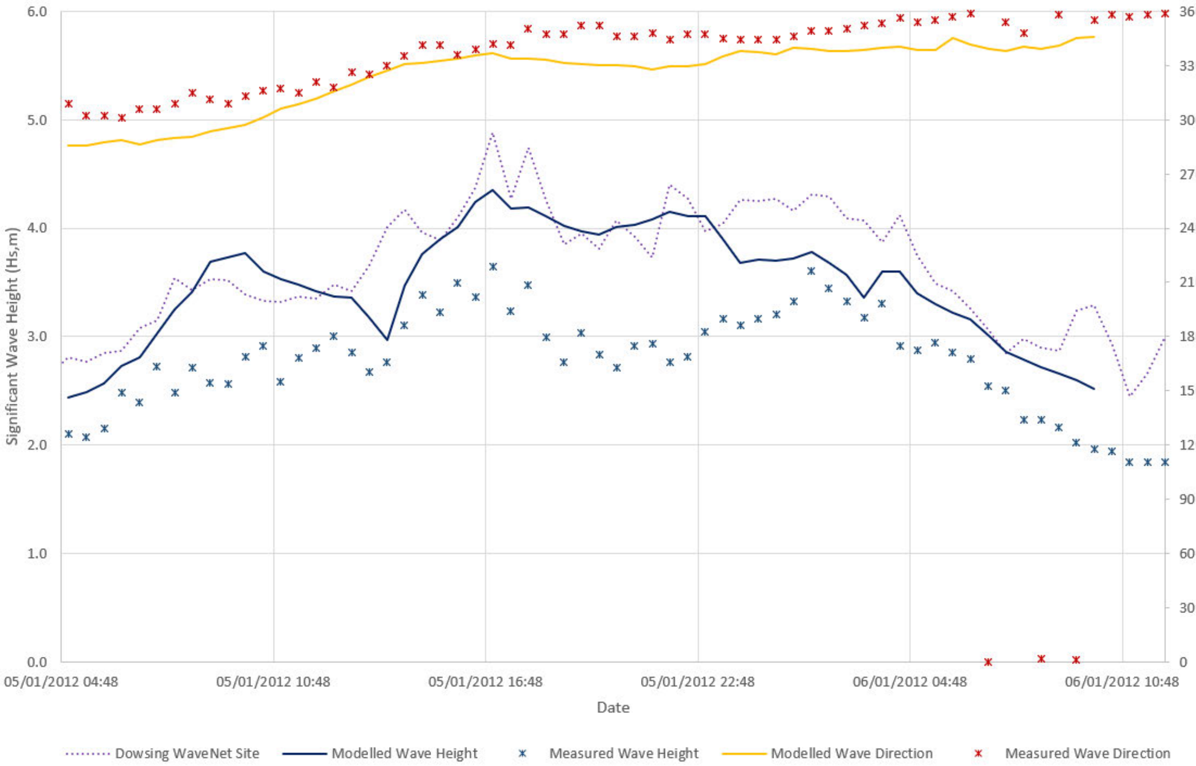

Figure 5-17: Storm Event 13 – Sheringham Shoal (waves from the north)

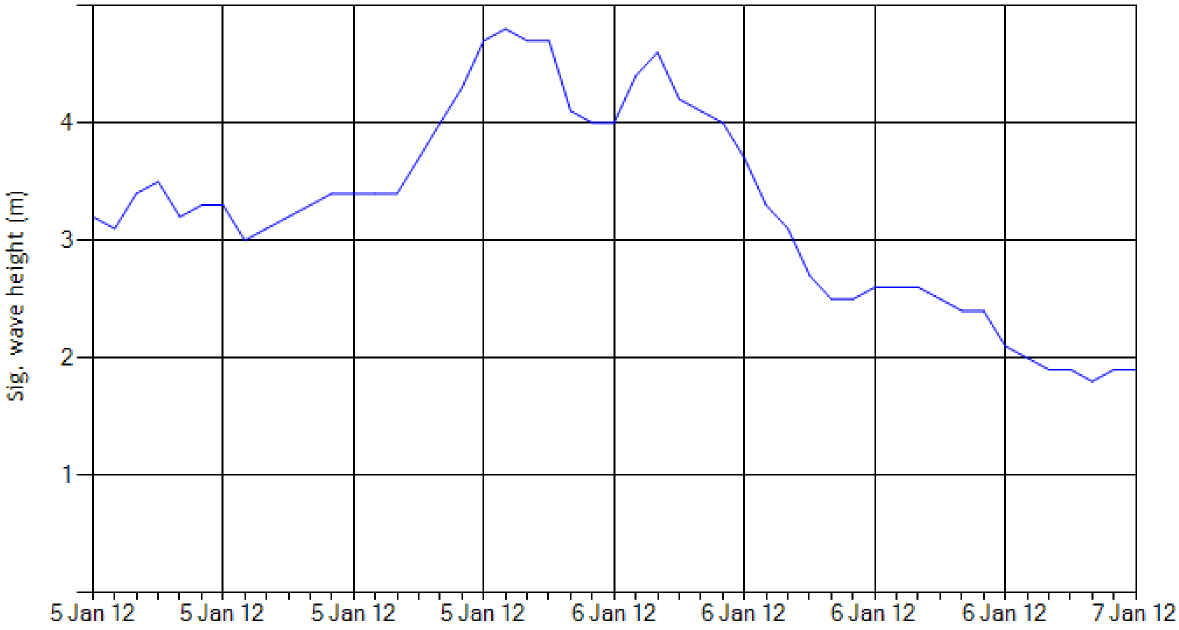

Figure 5-18: Recorded wave height at waverider buoy Clipper for Storm Event 13

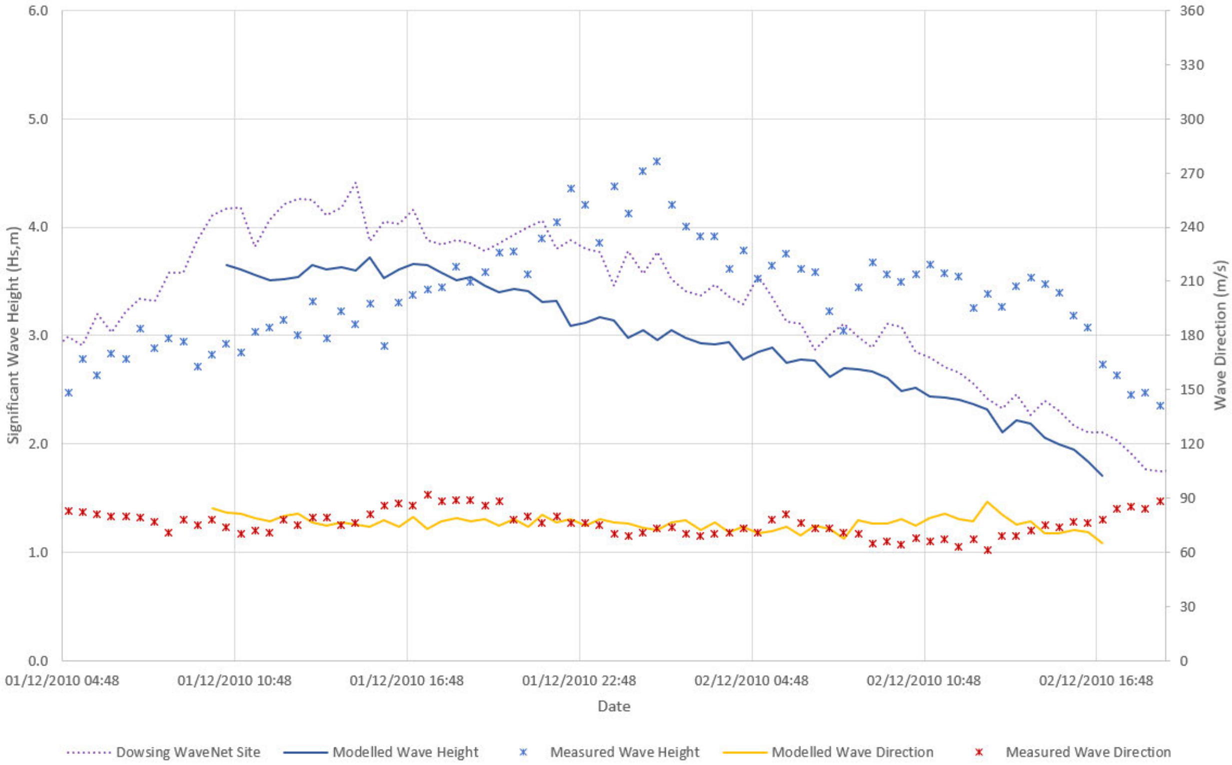

Figure 5-19: Storm Event 14 – Sheringham Shoal (waves from the east)

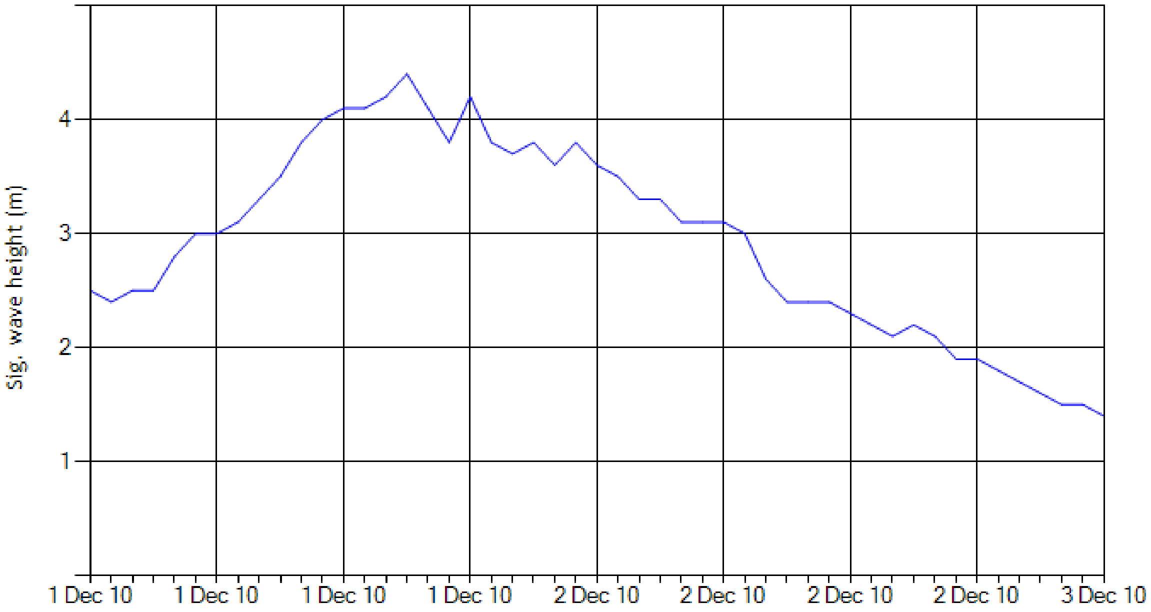

Figure 5-20: Recorded wave height at waverider buoy Clipper for Storm Event 14

38. In summary, both storm events 13 and 14 show a good agreement between the model input data recorded at the Dowsing WaveNet Site and the modelled wave heights. This is also supported by a good agreement between the recorded wave heights at waverider buoy Clipper and the modelled wave heights. Therefore, it can be concluded that some local weather events are the possible cause for the discrepancy between the recorded data at Sheringham Shoal waverider and the modelled data.

6 Wave Model Runs

6.1 Model Resolution

39. In order to best represent the wave climate of the baseline and option runs, the model domain was refined and divided into four areas of higher grid resolution compared to the calibration mesh. These improved mesh areas are shown in **Figure 6-1**. The grid is coarser for areas at distance from the array sites (1), becomes finer in the offshore areas closer to the array sites (2) and finer still in areas adjacent to the array sites (3), with the finest grid in the array sites (4). The mesh resolutions of the four areas are detailed in **Table 6-1**.

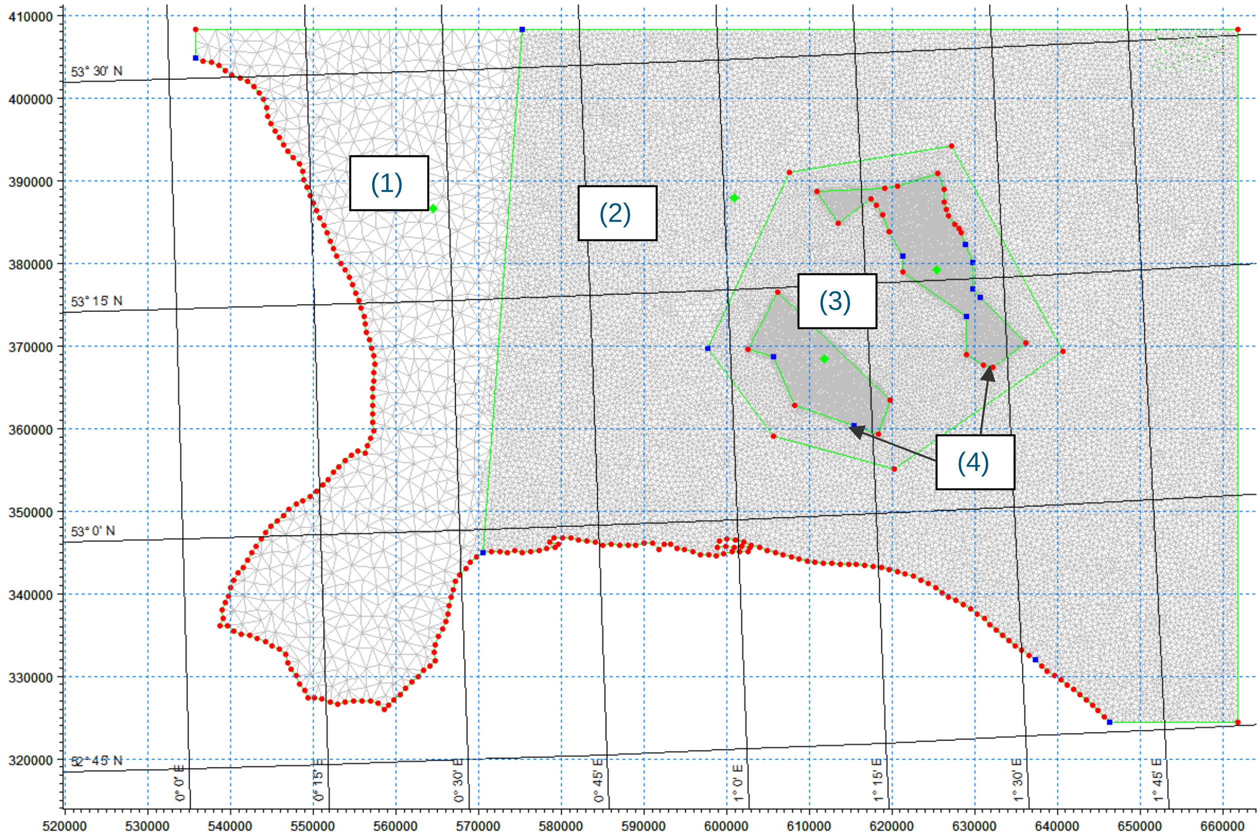

Figure 6-1: Triangular baseline model mesh resolution

Table 6-1: Baseline model mesh resolution

Mesh area	Mesh resolution (m^2)	Approximate maximum mesh size (m)
(1) Lincolnshire coast and The Wash	2.5 million	1,500
(2) North Norfolk coast and offshore areas	300,000	550

Mesh area	Mesh resolution (m^2)	Approximate maximum mesh size (m)
(3) Areas adjacent to the wind farm array sites	200,000	450
(4) Wind farm array sites	25,000	150

6.2 Wind Turbines Layout

40. The wave model has been run for the worst-case scenario in terms of turbine foundation and wind farm extent. The existing Sheringham Shoal and Dudgeon wind farm arrays have been included in the model so that the combined effects with the proposed DEP and SEP arrays can be assessed.

41. The existing wind farm turbine locations are represented in the model as circular monopiles with 5.5m diameters for the existing Sheringham Shoal array, and 7.2m diameter for the existing Dudgeon array. These were included in the ‘Baseline’ wave model scenarios (excluding the DEP and SEP turbines).

42. It is assumed that a Gravity Base Structure (GBS), illustrated in **Figure 6-2**, would represent the worst case for turbine foundations for DEP and SEP. Therefore, GBS foundations have been used to represent the turbine locations in the proposed array sites. The GBS foundations were represented in the wave model by means of a wave reflection coefficient derived specifically for these types of structures using DIFFRACT software. This follows an approach adopted in the East Anglia ONE North and TWO wind farm studies.

43. A summary of the wind turbines input into the wave model is provided in **Table 6-2**. The ‘Extensions’ wave model scenario includes the existing Sheringham Shoal and Dudgeon wind farm arrays, as well as the proposed extension arrays.

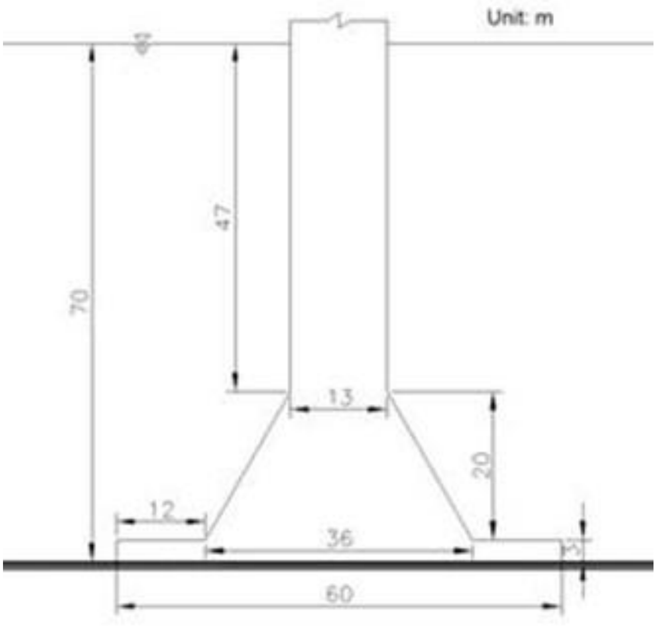

Figure 6-2: Dimensions of the GBS simulated by DIFFRACT for input into the wave model

Table 6-2: Wind turbines input into the wave model

Wind farm Site	Modelled Wind Turbine Foundation	Dimensions	Number of Wind Turbines
Existing Sheringham Shoal	Circular	Ø 5.5 m	88
Existing Dudgeon	Circular	Ø 7.2 m	67
Sheringham Shoal Extension	GBS	See **Figure 6-2**	23
Dudgeon Extension	GBS	See **Figure 6-2**	30

6.3 Model Scenarios

44. As mentioned in **Section 2**, the wave model has been run for a series of offshore wave and wind directions. These runs were to determine the direction that results in the highest nearshore wave conditions along the north Norfolk coast. Two return period events were considered; 1 in 1 year and 1 in 50 year.

45. **Table 6-3** presents a list of the wave model scenarios with a summary of their input conditions. These conditions were modelled for both the 'Baseline' scenario and the 'Extensions' scenario (a total of 28 model runs).

Table 6-3: Summary of the wave model input conditions

Run number	Return period (years)	Water Level (mCD)	Wave direction (^{o}N)	Wave height (Hs, m)	Wave period (Tp, s)	Wind speed (m/s)
1	1	2.95	300	3.35	8.8	15.8
2	1	2.95	330	4.83	11.2	21.8
3	1	2.95	0	4.62	11.5	20.9
4	1	2.95	30	4.02	9.8	18.5
5	1	2.95	60	3.52	9.1	16.5
6	1	2.95	90	3.68	9.0	17.1
7	1	2.95	120	2.90	7.6	14.0
8	50	2.95	300	5.04	10.8	22.6
9	50	2.95	330	7.34	13.8	32.0
10	50	2.95	0	6.86	14.0	30.0
11	50	2.95	30	6.43	12.4	28.3
12	50	2.95	60	5.46	11.3	24.3
13	50	2.95	90	5.73	11.2	25.4
14	50	2.95	120	4.62	9.6	20.9

46. Results from the model runs were analysed and the nearshore wave conditions along the north Norfolk coast compared to determine the worst offshore wave direction. The impact of the proposed extensions on the nearshore wave climate were also assessed.

47. Following the main model runs, two additional ‘Baseline’ scenarios without the existing Sheringham Shoal and Dudgeon arrays, were run for the 1 in 1 year and 1 in 50 year events for the identified worst-case offshore wave direction. Results from these additional runs were used to assess the cumulative impact of the existing OWFs and the proposed extensions.

7 Model Results

7.1 Baseline Model Results

49. **Figure 7-1** to **Figure 7-6** present contour plots of predicted significant wave height for the ‘Baseline’ scenarios for three directional sectors, namely 330ºN, 0ºN and 30ºN, for the 1 in 1 year and 1 in 50 year return period events, respectively. Contour plots for the other directional sectors listed in **Table 6-3** predict lower nearshore wave conditions. Contour plots for all directional sectors are provided in **Appendix A**.

50. Comparing the results in **Figure 7-1**, **Figure 7-2** and **Figure 7-3** for the 1 in 1 year return period event, the 330ºN and 0ºN offshore wave directions predict very similar nearshore wave climates, whereas for the 30ºN direction, the significant wave height is predicted to be slightly lower. This is also the case for the 1 in 50 year return period results when comparing **Figure 7-4**, **Figure 7-5** and **Figure 7-6**.

51. Based on closer analysis of the results it was determined that nearshore wave conditions along the north Norfolk coast are, overall, the worst for the 0ºN directional sector. This is consistent for both return period events.

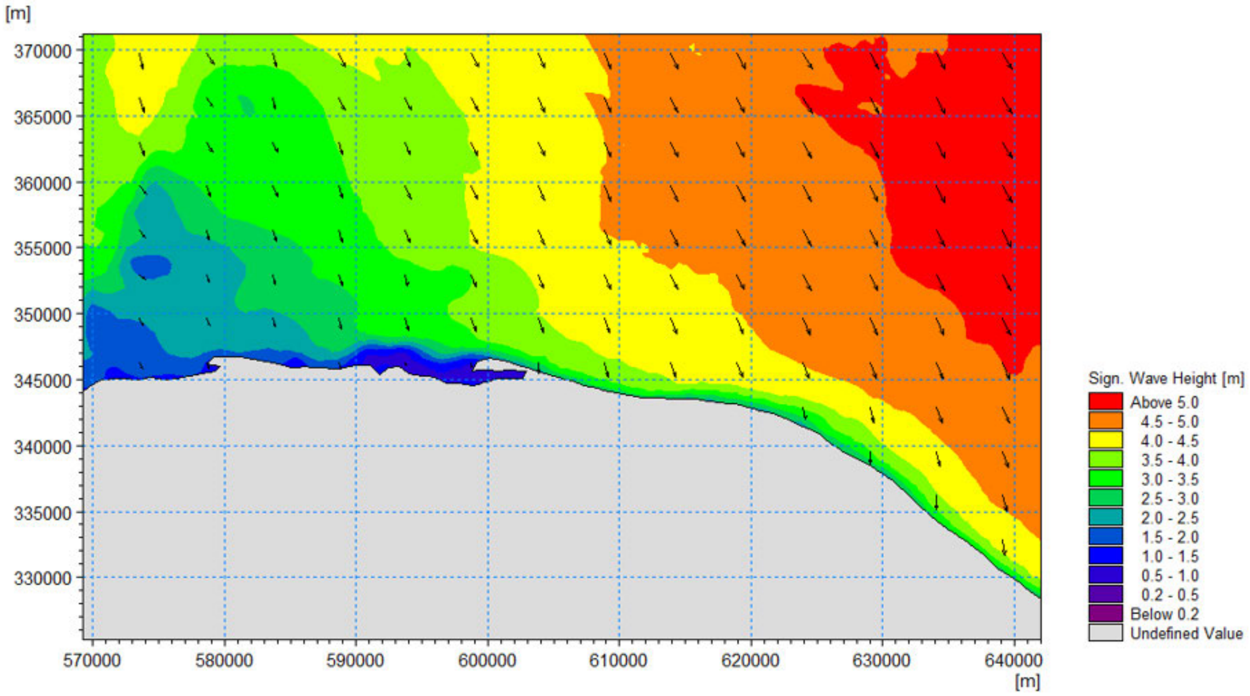

Figure 7-1: Significant wave height for the 1 in 1 year return period event ‘Baseline’ scenario – 330ºN offshore wave direction

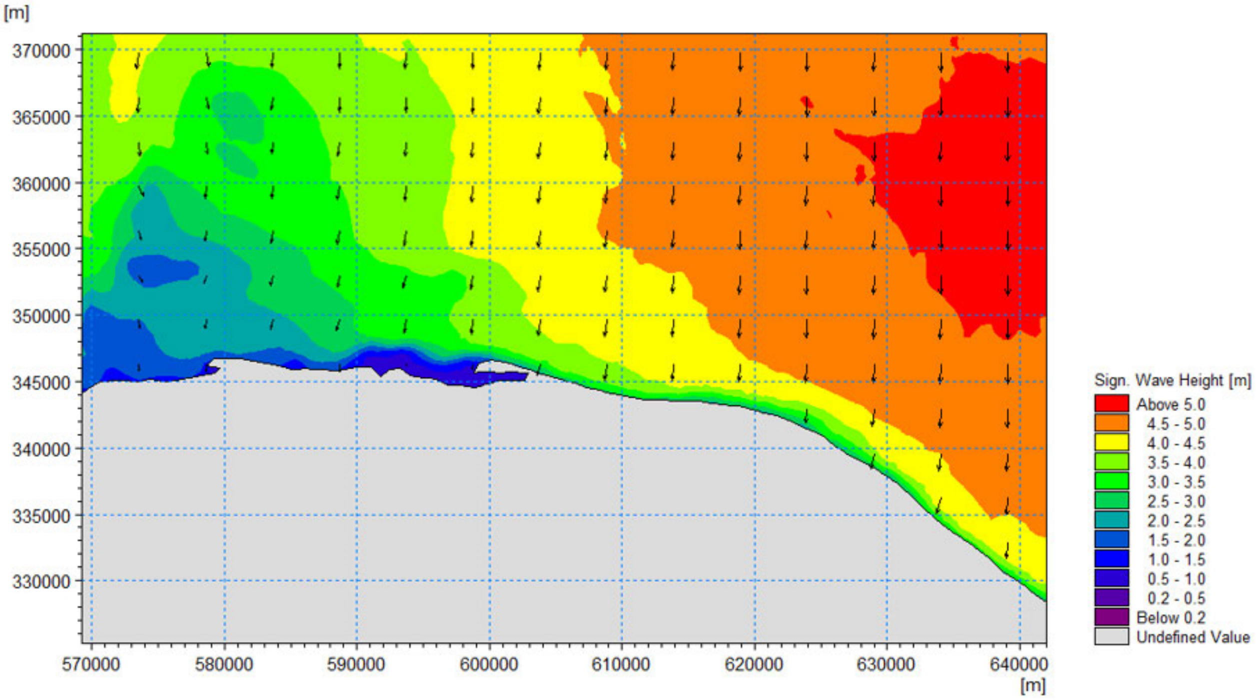

Figure 7-2: Significant wave height for the 1 in 1 year return period event 'Baseline' scenario – 0ºN offshore wave direction

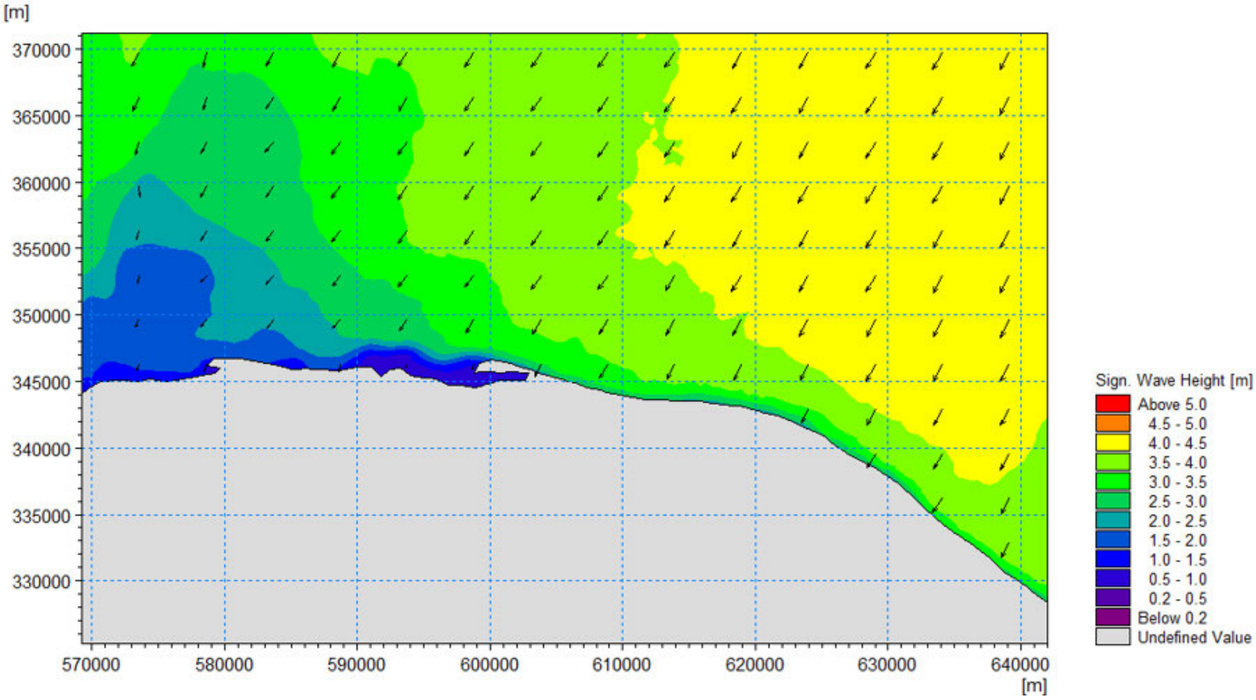

Figure 7-3: Significant wave height for the 1 in 1 year return period event 'Baseline' scenario – 30ºN offshore wave direction

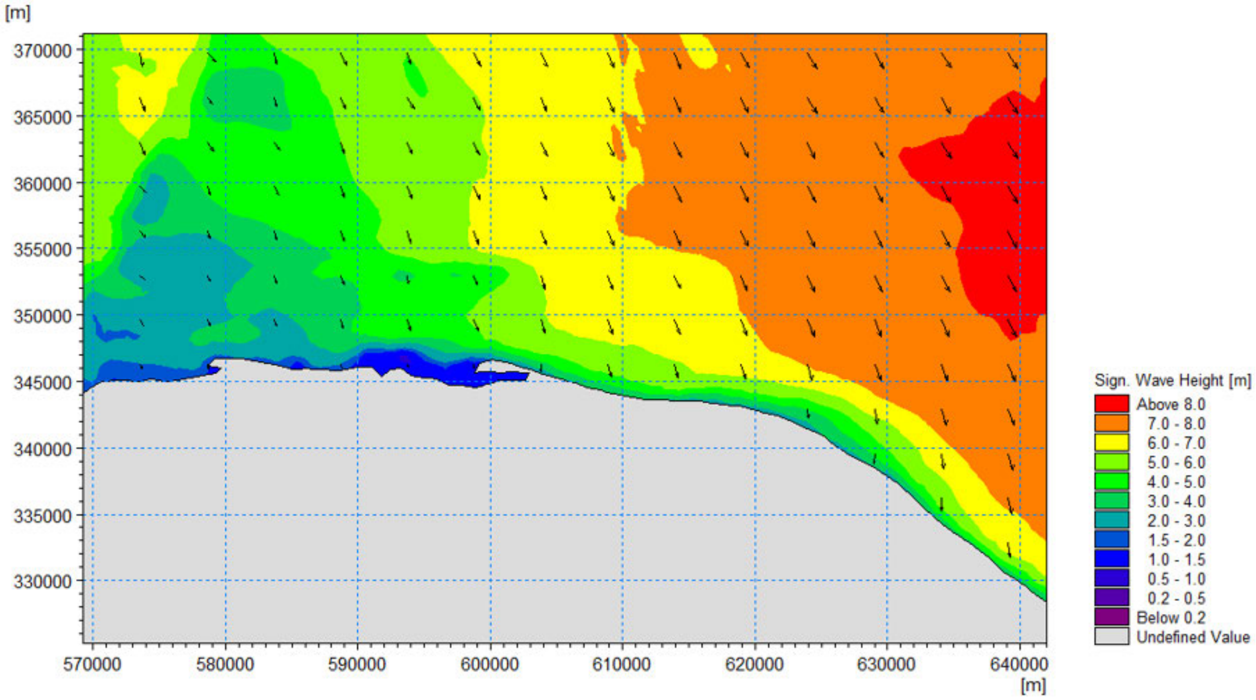

Figure 7-4: Significant wave height for the 1 in 50 year return period event 'Baseline' scenario – 330°N offshore wave direction

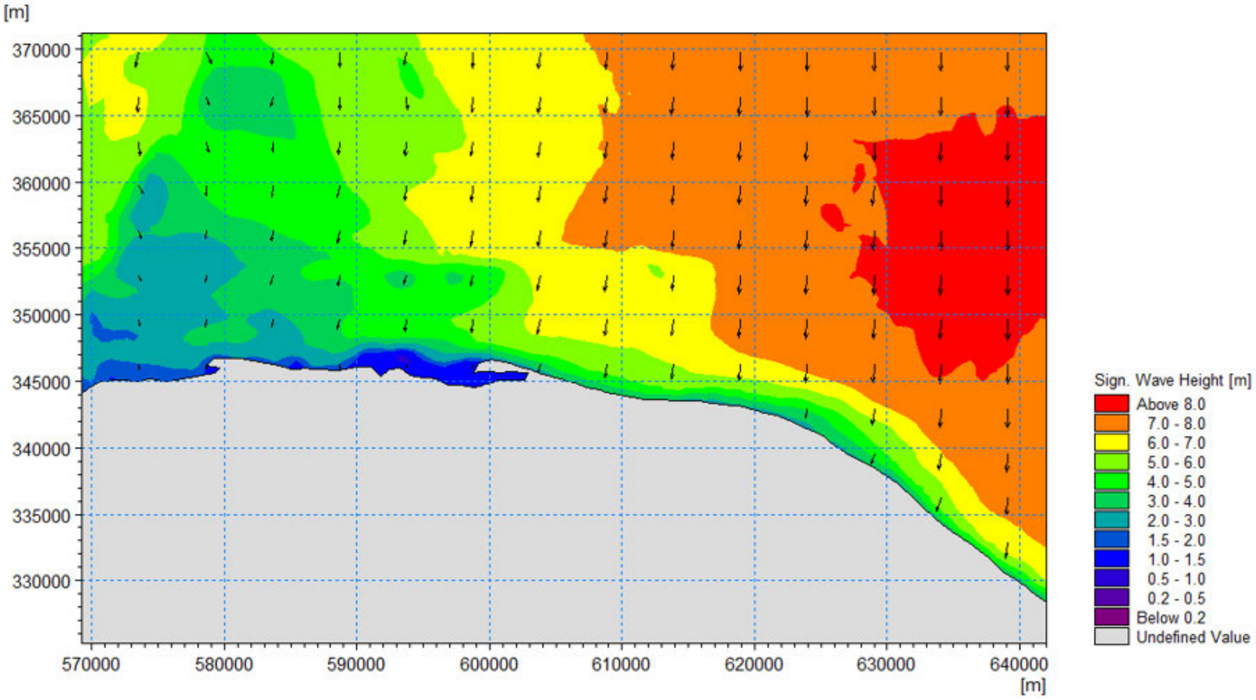

Figure 7-5: Significant wave height for the 1 in 50 year return period event 'Baseline' scenario – 0°N offshore wave direction

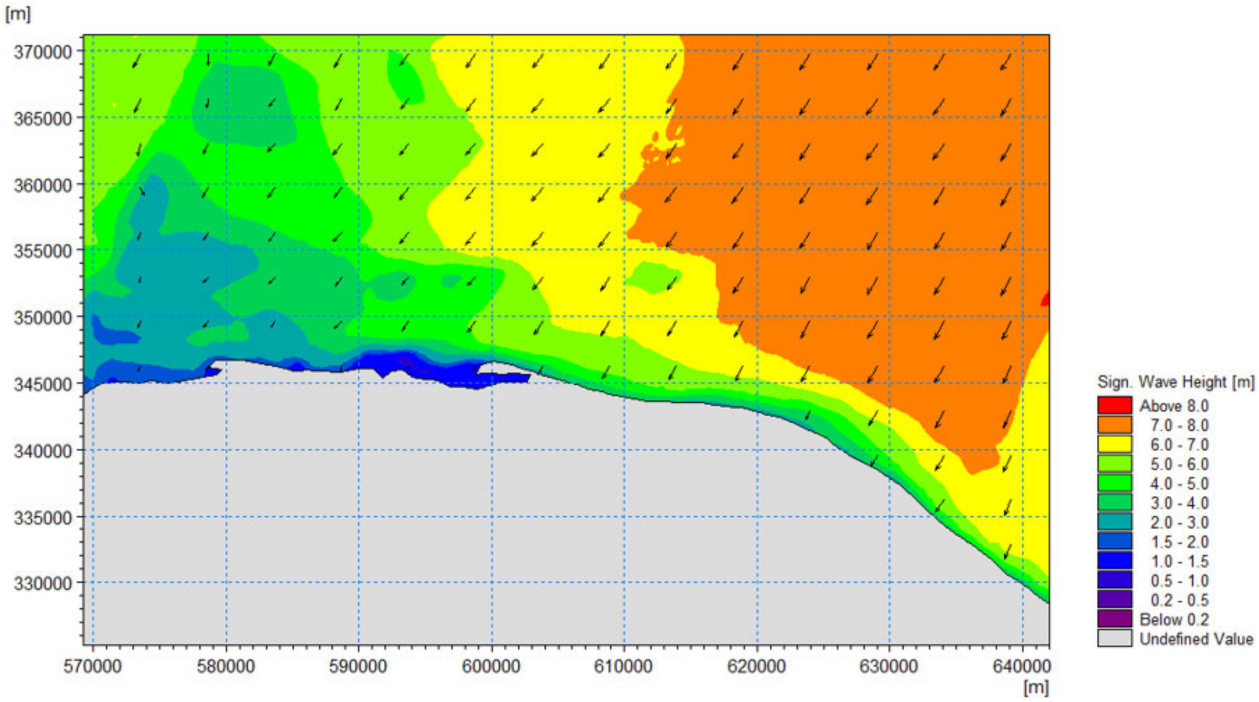

Figure 7-6: Significant wave height for the 1 in 50 year return period event 'Baseline' scenario – 30°N offshore wave direction

7.2 Extensions Model Results

52. **Figure 7-7** to **Figure 7-12** present contour plots of significant wave height for the 'Extensions' scenarios for three directional sectors; 330°N, 0°N and 30°N, for the 1 in 1 year and 1 in 50 year return period events, respectively. Contour plots for the other directional sectors listed in **Table 6-3** predict lower nearshore wave conditions. Contour plots for all directional sectors are provided in **Appendix B**.

53. As for the 'Baseline' scenarios, comparing the results in **Figure 7-7**, **Figure 7-8** and **Figure 7-9** for the 1 in 1 year return period event, the 330°N and 0°N offshore wave directions predict very similar nearshore wave climates, whereas for the 30°N direction, the significant wave height is predicted to be slightly lower. This is also the case for the 1 in 50 year return period results when comparing **Figure 7-10**, **Figure 7-11** and **Figure 7-12**.

54. Similarly, it was predicted that the nearshore wave conditions along the north Norfolk coast are, overall, the worst for the 0°N directional sector. This is consistent for both return period events.

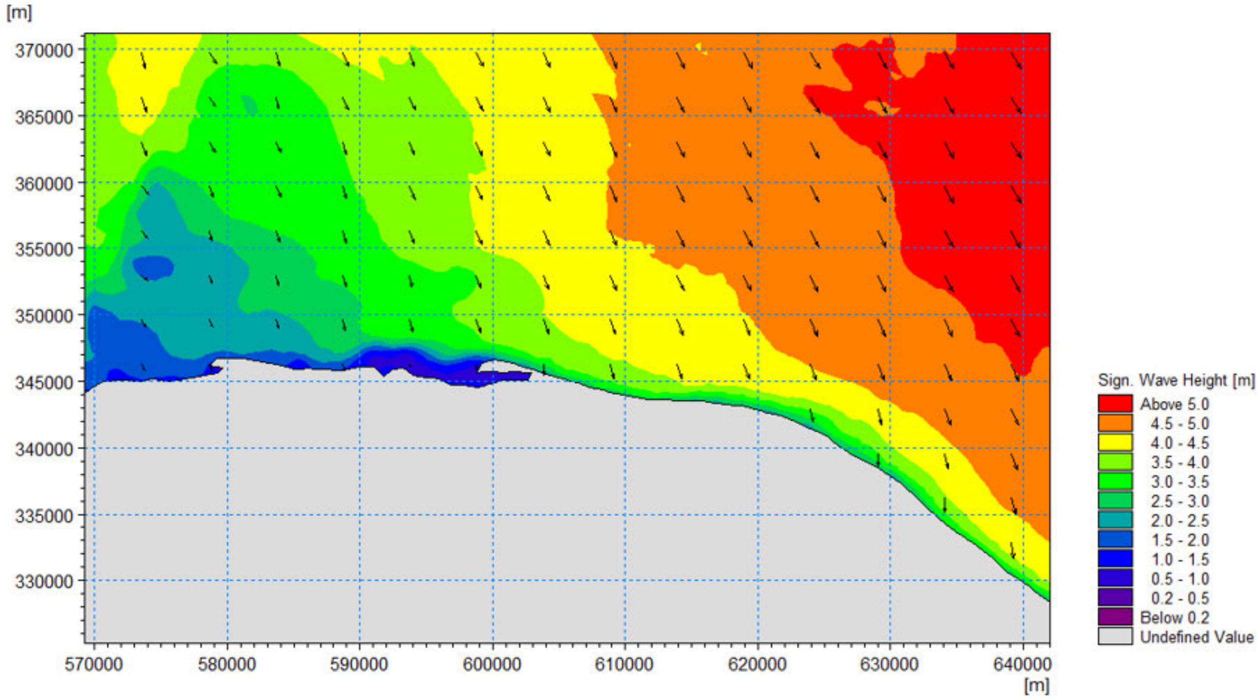

Figure 7-7: Significant wave height for the 1 in 1 year return period event 'Extensions' scenario – 330ºN offshore wave direction

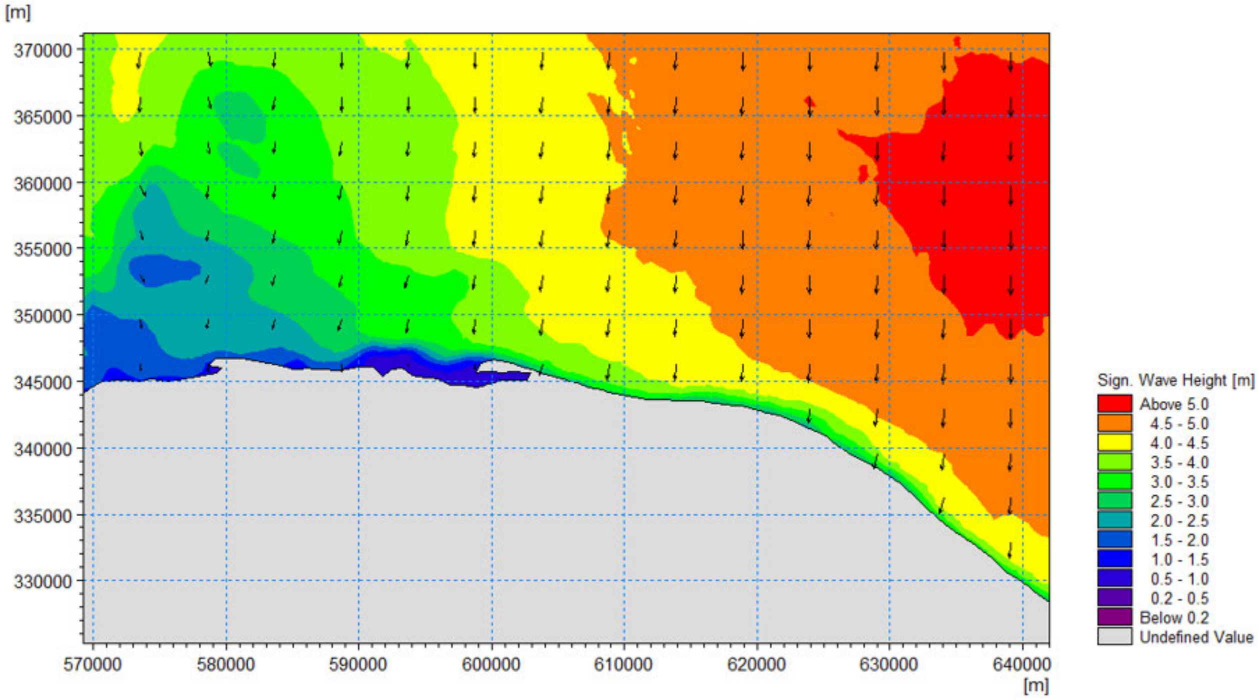

Figure 7-8: Significant wave height for the 1 in 1 year return period event 'Extensions' scenario – 0ºN offshore wave direction

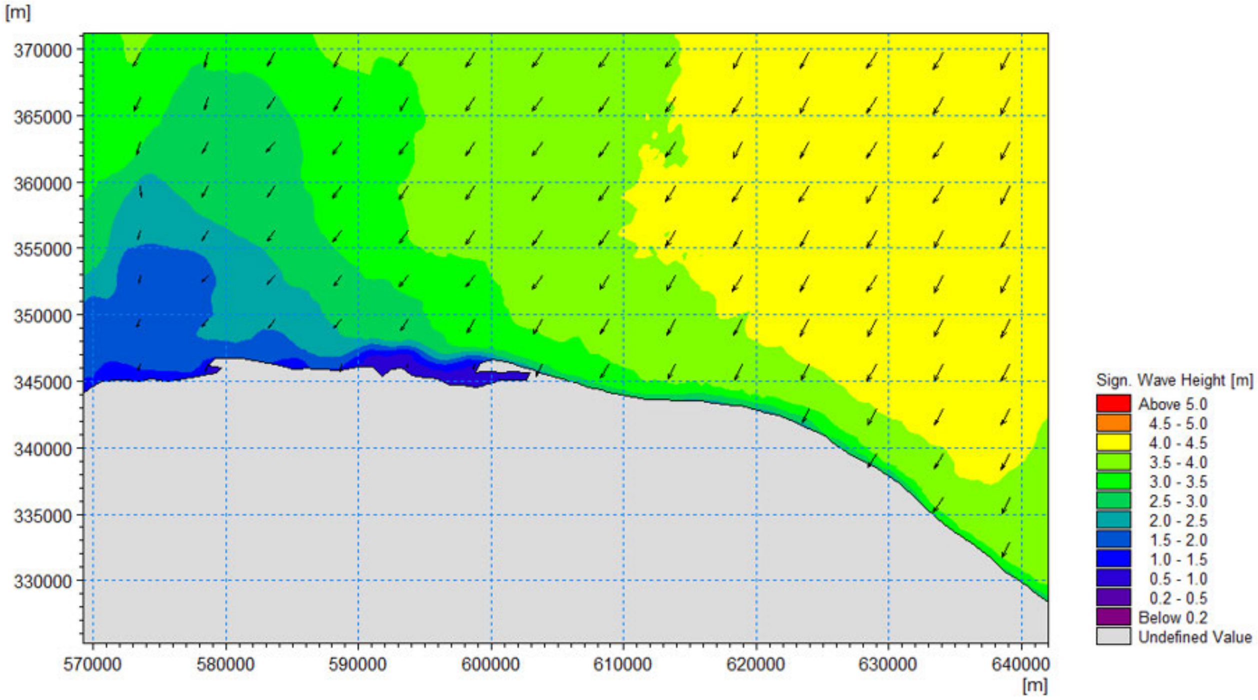

Figure 7-9: Significant wave height for the 1 in 1 year return period event 'Extensions' scenario – 30ºN offshore wave direction

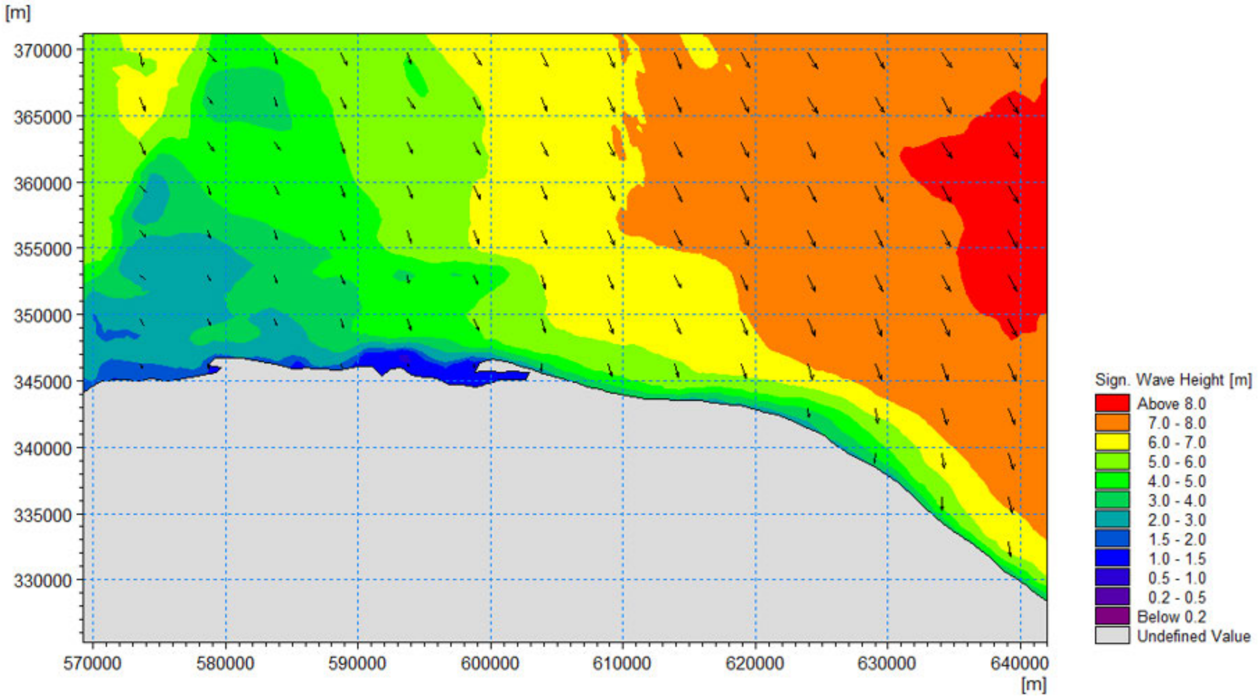

Figure 7-10: Significant wave height for the 1 in 50 year return period event 'Extensions' scenario – 330ºN offshore wave direction

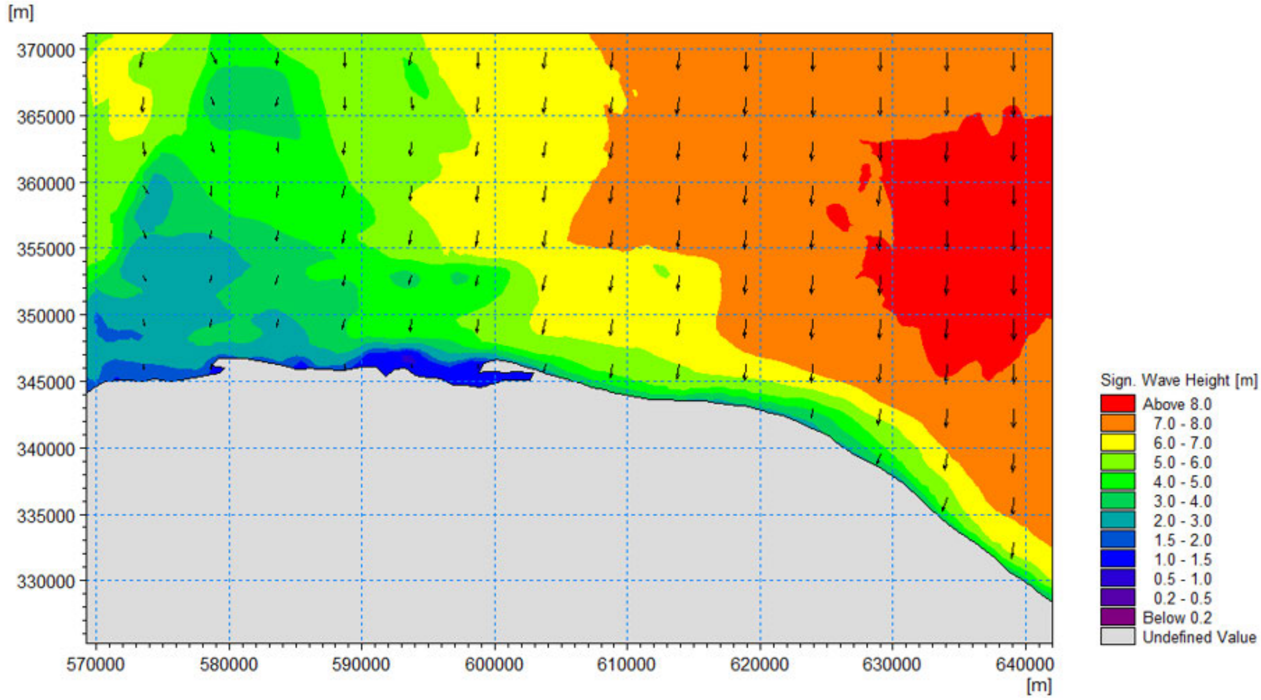

Figure 7-11: Significant wave height for the 1 in 50 year return period event 'Extensions' scenario – 0ºN offshore wave direction

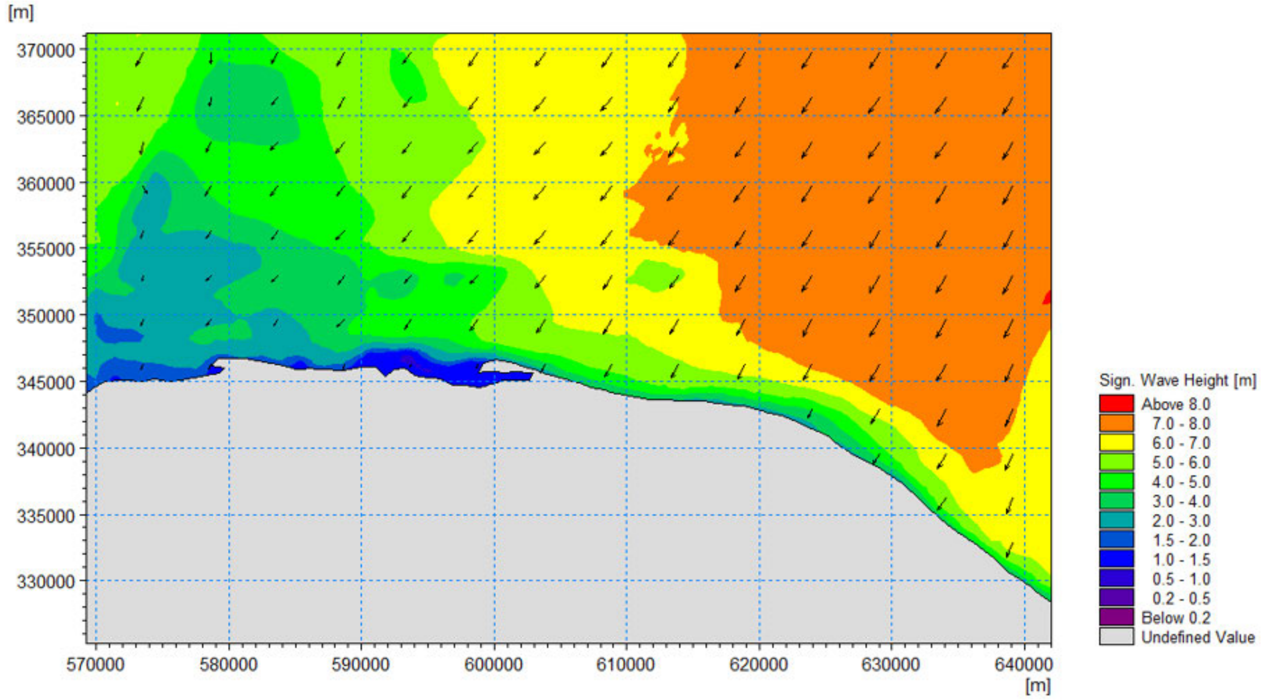

Figure 7-12: Significant wave height for the 1 in 50 year return period event 'Extensions' scenario – 30ºN offshore wave direction

7.3 Impact on Wave Climate

55. The impact on the nearshore wave climate along the north Norfolk coast was assessed as a change in wave conditions as a result of the proposed DEP and SEP arrays. The impact was only assessed for

the offshore wave direction identified as resulting in the worst nearshore wave conditions; the 0ºN direction. **Figure 7-13** and **Figure 7-14** present contour plots showing the predicted difference in significant wave height between the 'Extensions' scenario and the 'Baseline' scenario for the 1 in 1 year and 1 in 50 year return period events, respectively.

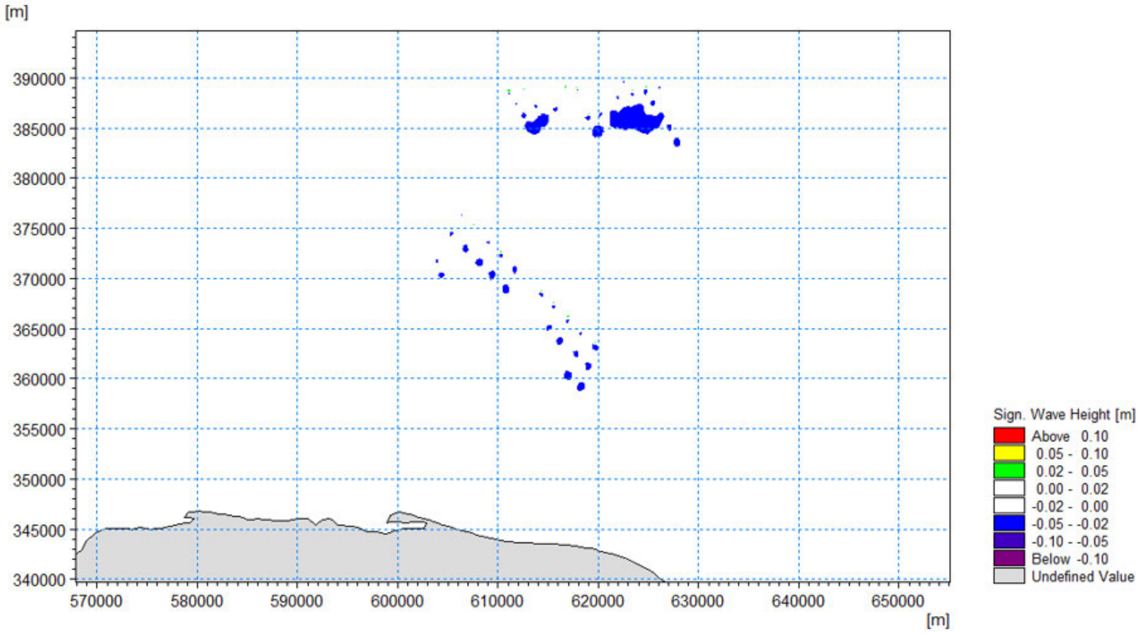

Figure 7-13: Difference in significant wave height for the 1 in 1 year return period event ('Extensions' minus 'Baseline' scenario) – 0ºN offshore wave direction

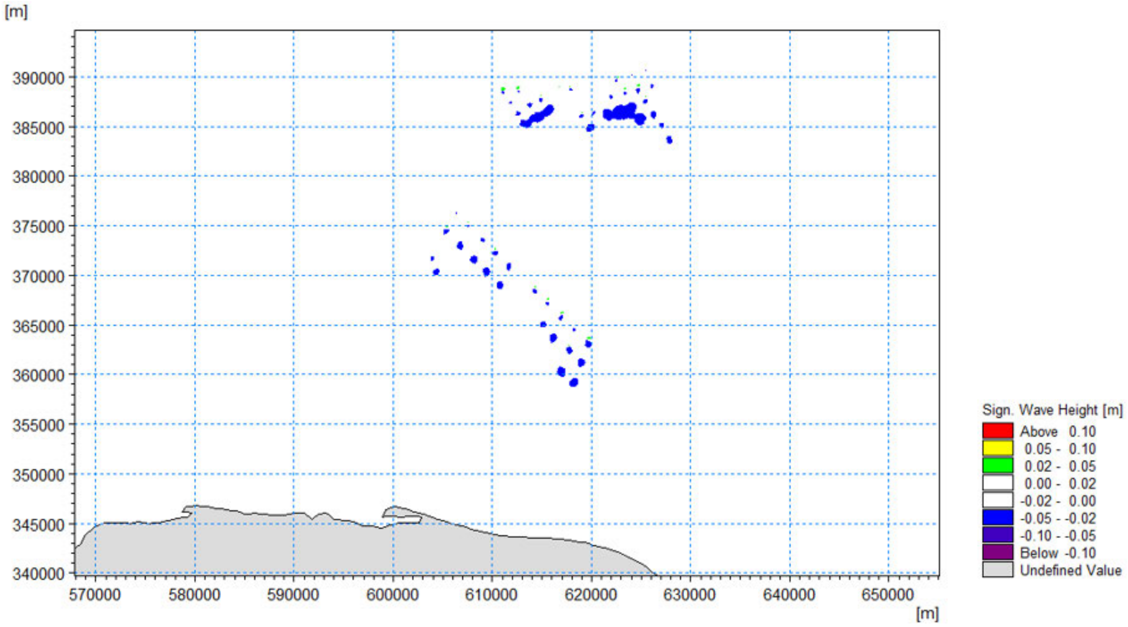

Figure 7-14: Difference in significant wave height for the 1 in 50 year return period event ('Extensions' minus 'Baseline' scenario) – 0ºN offshore wave direction

56. **Figure 7-13** and **Figure 7-14** predict that the proposed DEP and SEP arrays have only a localised impact on wave climate, where reflection from the wind turbines results in a slight reduction in wave

conditions, up to 0.05m significant wave height. There is no impact on the nearshore wave conditions along the north Norfolk coast.

57. The overall impact is relatively insignificant. This is likely due to the number of wind turbines and their spacing within the extension arrays, where each turbine has an individual impact, with little interaction between adjacent turbines.

58. The cumulative impact of the existing and proposed wind turbines was assessed by comparing the results of the 'Extensions' scenario and the 'Baseline' scenario run without the exiting arrays. **Figure 7-15** and **Figure 7-16** present the predicted differences in significant wave height for the 1 in 1 year and 1 in 50 year return period events, respectively.

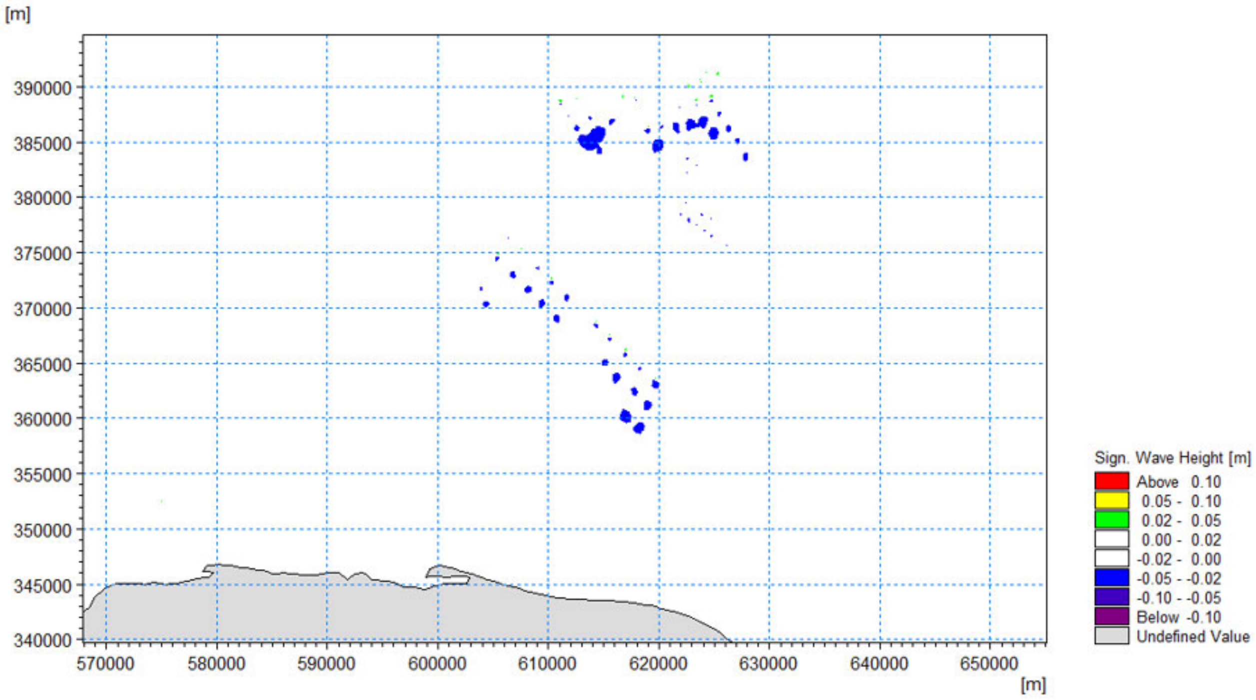

Figure 7-15: Difference in significant wave height for the 1 in 1 year return period event ('Extensions' minus 'Baseline' without existing arrays scenario) – 0ºN offshore wave direction

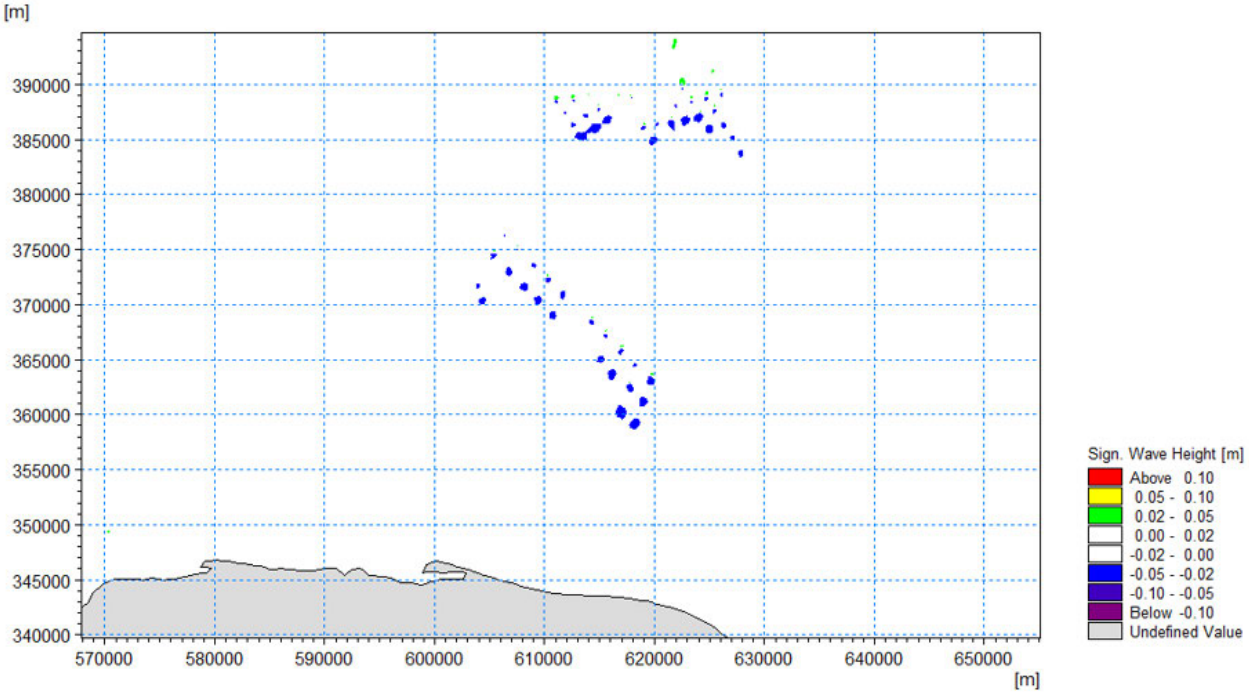

Figure 7-16: Difference in significant wave height for the 1 in 50 year return period event ('Extensions' minus 'Baseline' without existing arrays scenario) – 0ºN offshore wave direction

59. **Figure 7-15** and **Figure 7-16** predict that the cumulative impact of the existing and proposed extensions arrays is very limited, and is localised around the wind turbines. When compared with the impact of the DEP and SEP arrays only (**Figure 7-13** and **Figure 7-14**), the cumulative impact is very similar. This means that the existing arrays do not significantly impact the wave conditions. This is likely due to the fact that the wind turbines within the existing arrays have much smaller diameters than the proposed arrays (7.2m and 5.5m, whereas the GBS have diameters of 13m with 30m wide bases). Therefore, wave reflection from the existing arrays is much smaller than the reflection from the proposed GBS structures.

8 Conclusion

61. Extreme wave analysis and wave transformation modelling were undertaken to assess impacts of the proposed Dudgeon Extension Project (DEP) and the Sheringham Shoal Extension Project (SEP) on nearshore wave climate along the north Norfolk coast.

62. Wave conditions were derived for a number of directional sectors and return period events. For the purpose of the impact assessment, 1 in 1 year and 1 in 50 year return period events were considered. Analysis of offshore wave conditions showed that the worst-case wave directions are from the north-west, north and north-east.

63. A wave transformation model was set-up and calibrated against measured wave data. The model was then used to derive wave conditions for a number of offshore wave directions and the two considered return period events. Results showed that the offshore wave direction resulting in the worst nearshore wave conditions is from north (0ºN).

64. The assessment of impact of the wind turbines on the nearshore wave climate was carried out for the identified worst offshore wave direction only. Results predict that the proposed DEP and SEP arrays would have only limited localised impact on wave climate, where reflection from the wind turbines results in a slight reduction in wave conditions. There is no impact on nearshore wave conditions along the north Norfolk coast.

65. The cumulative impact of the existing and proposed arrays was assessed against a ‘Baseline’ scenario without any wind turbines in place. Results show that the cumulative impact of the existing and proposed extensions arrays is also very limited, mostly localised around the proposed wind turbines. The cumulative impact is mostly concentrated around the proposed arrays with little contribution from the exiting arrays. This is likely due to the smaller diameter of the wind turbines within the existing arrays compared to the proposed arrays (GBS structures).

66. The predicted overall impact of the proposed DEP and SEP arrays is insignificant. This is likely due to the number and spacing between the wind turbines within the arrays, where each turbine has an individual impact, with little interaction between adjacent turbines.

Appendix A – Wave Model Results: 'Baseline' Scenarios

68. **Figure A- 1** to **Figure A- 14** present contour plots of significant wave height for the 'Baseline' scenarios for three direction sectors, namely 300ºN, 330ºN, 0ºN and 30ºN, 60ºN, 90ºN and 120ºN, for the 1 in 1 year and 1 in 50 year return period events, respectively.

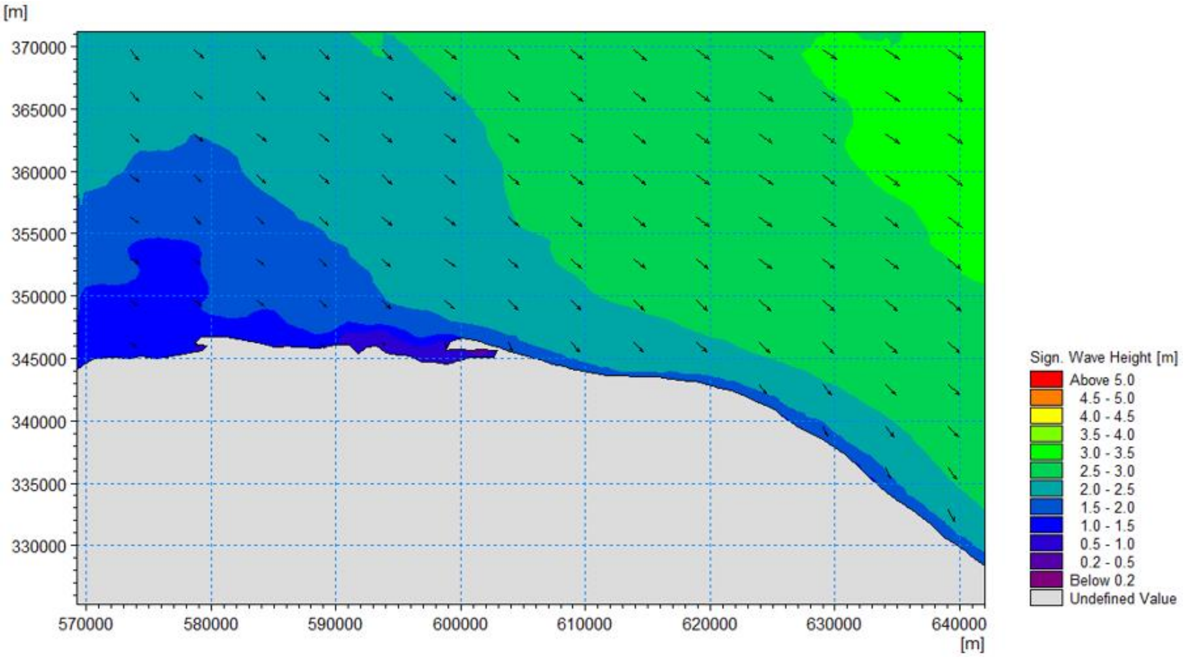

Figure A- 1: Significant wave height for the 1 in 1 year return period event 'Baseline' scenario – 300ºN offshore wave direction

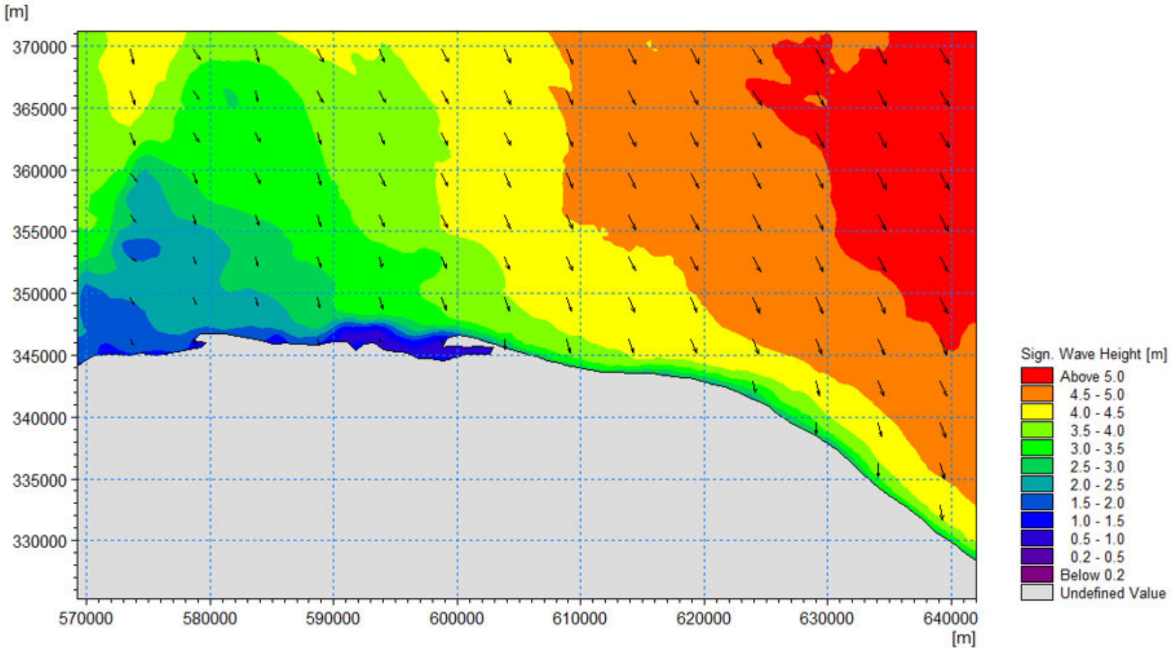

Figure A- 2: Significant wave height for the 1 in 1 year return period event 'Baseline' scenario – 330ºN offshore wave direction

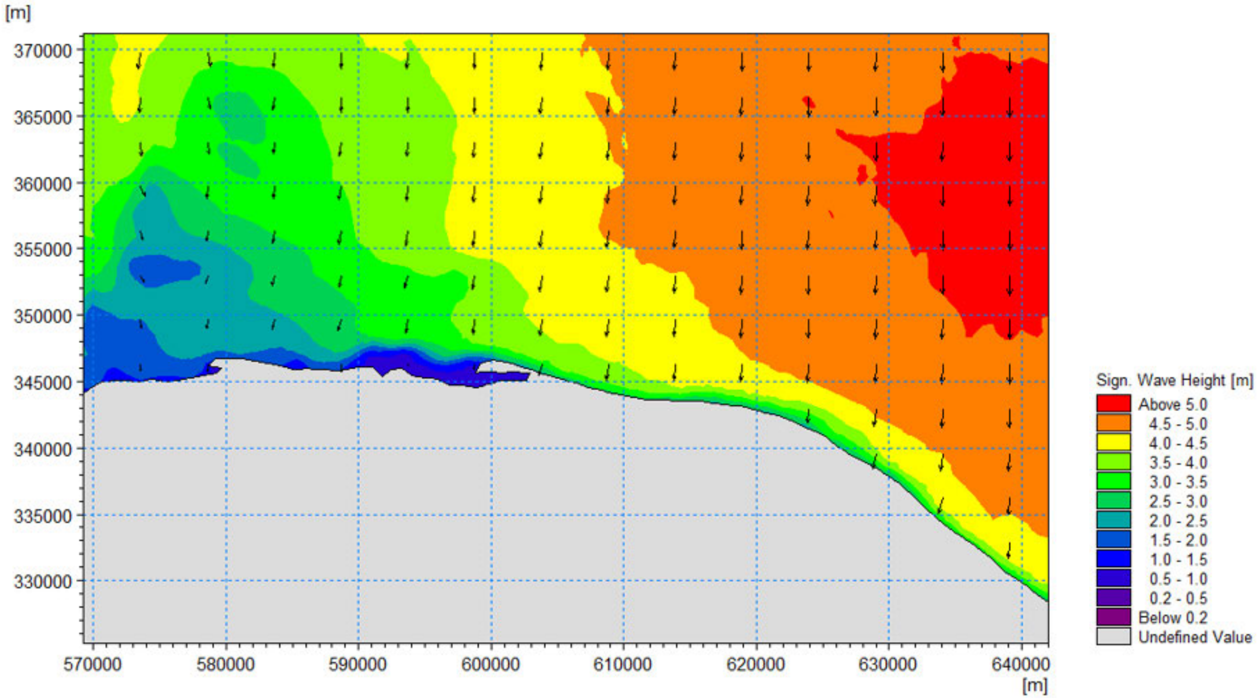

Figure A- 3: Significant wave height for the 1 in 1 year return period event 'Baseline' scenario – 0ºN offshore wave direction

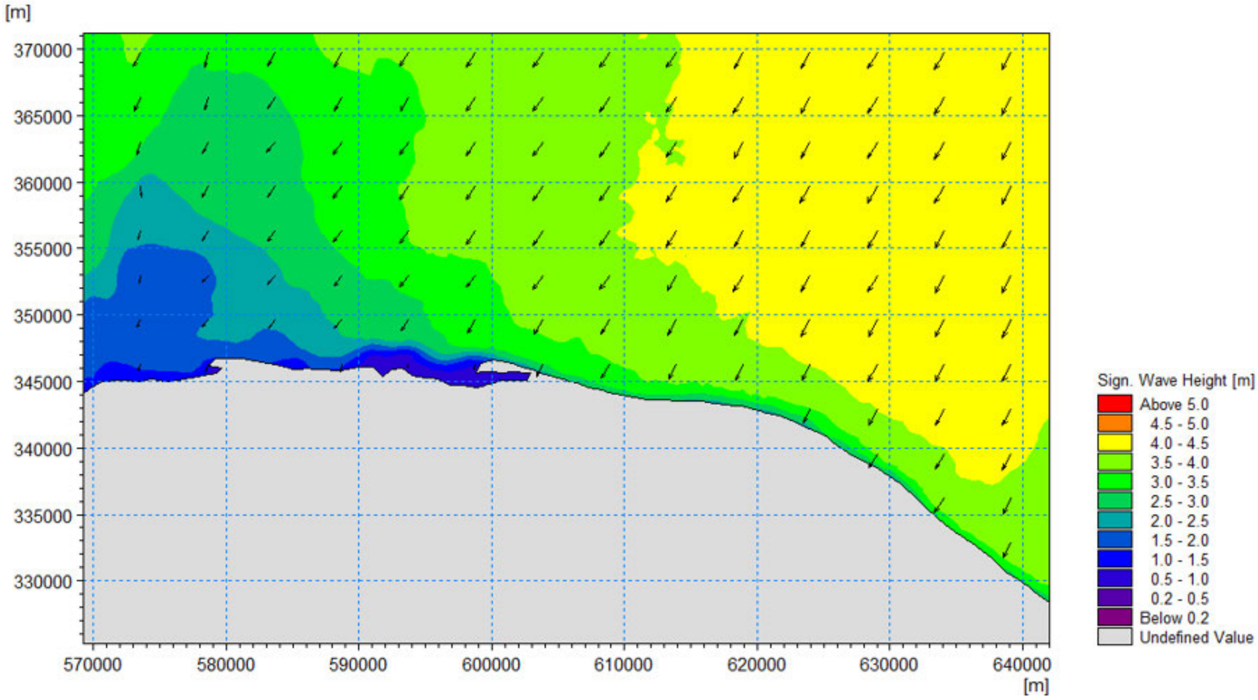

Figure A- 4: Significant wave height for the 1 in 1 year return period event 'Baseline' scenario – 30ºN offshore wave direction

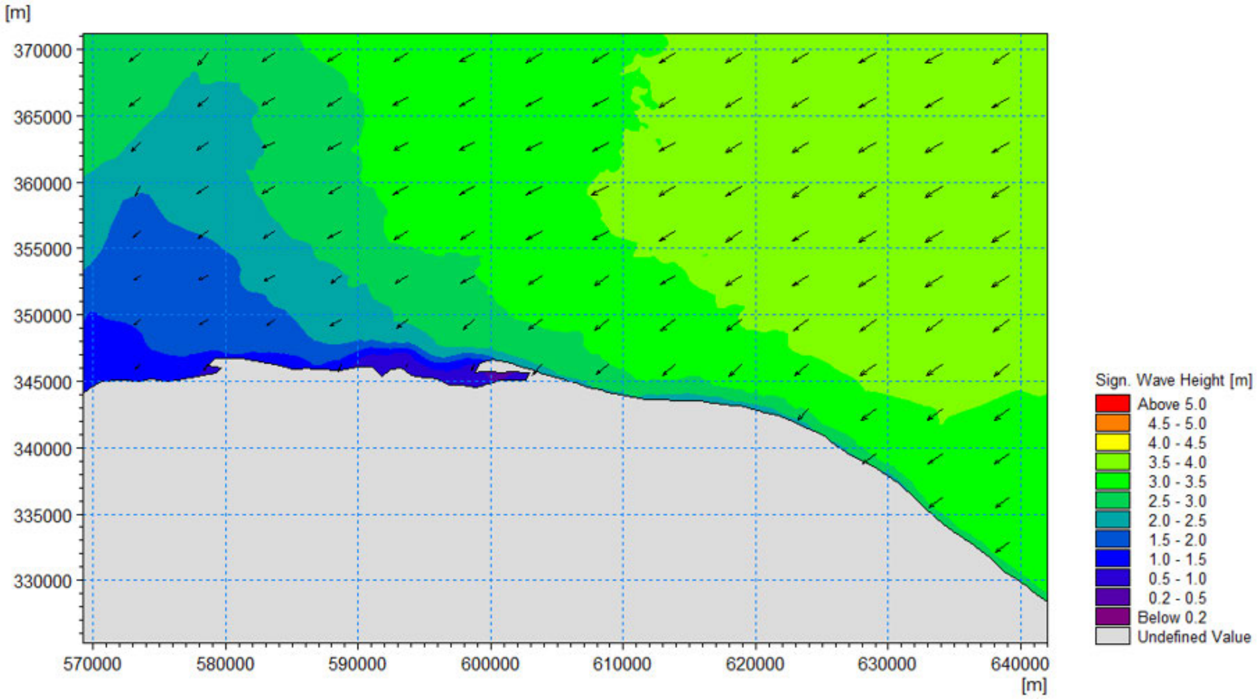

Figure A- 5: Significant wave height for the 1 in 1 year return period event 'Baseline' scenario – 60^{o}N offshore wave direction

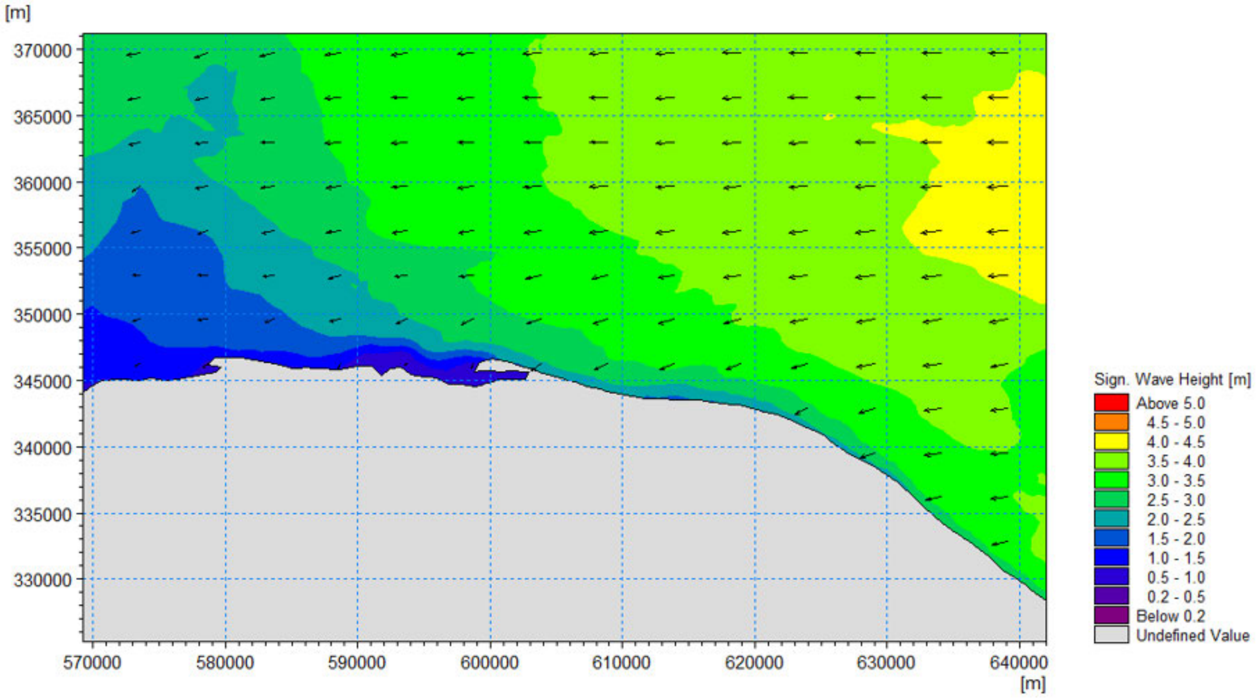

Figure A- 6: Significant wave height for the 1 in 1 year return period event 'Baseline' scenario – 90^{o}N offshore wave direction

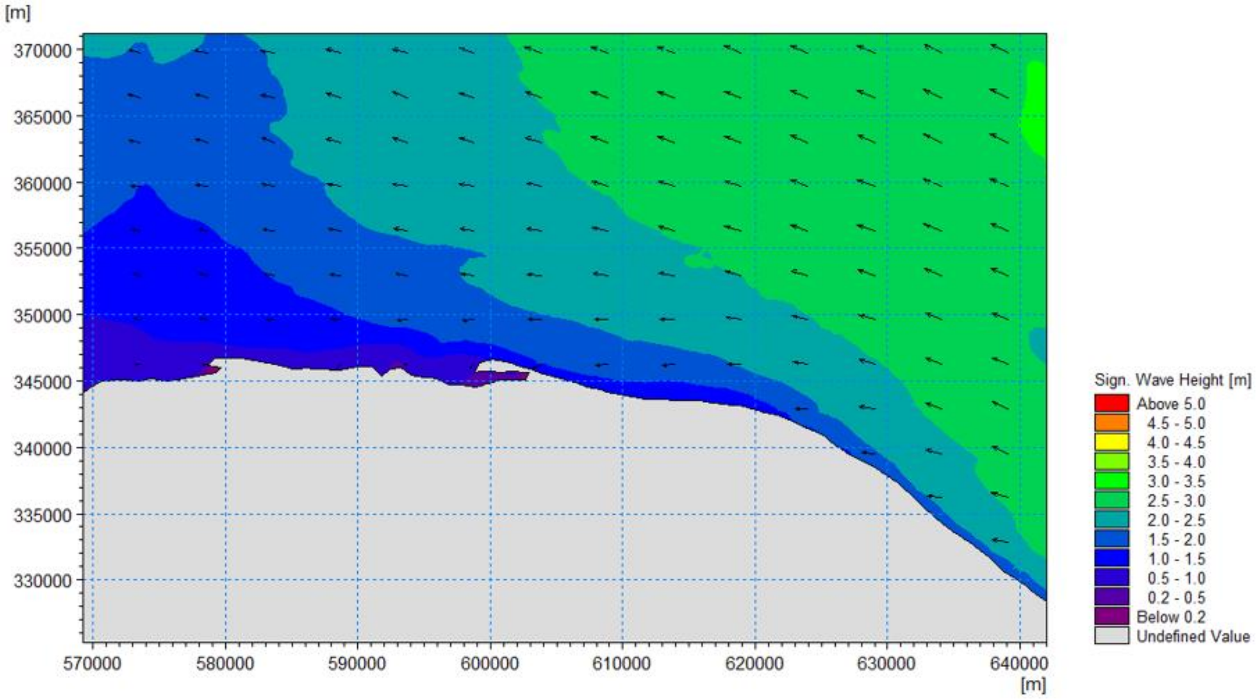

Figure A- 7: Significant wave height for the 1 in 1 year return period event 'Baseline' scenario – 120°N offshore wave direction

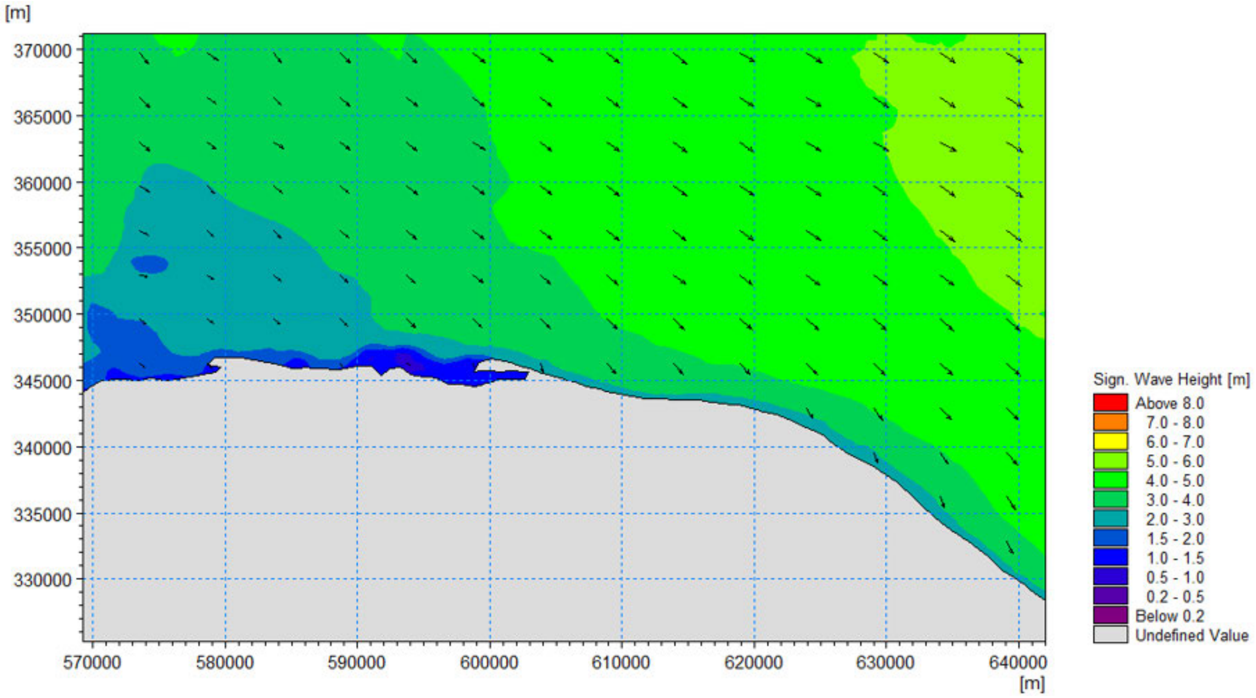

Figure A- 8: Significant wave height for the 1 in 50 year return period event 'Baseline' scenario – 300°N offshore wave direction

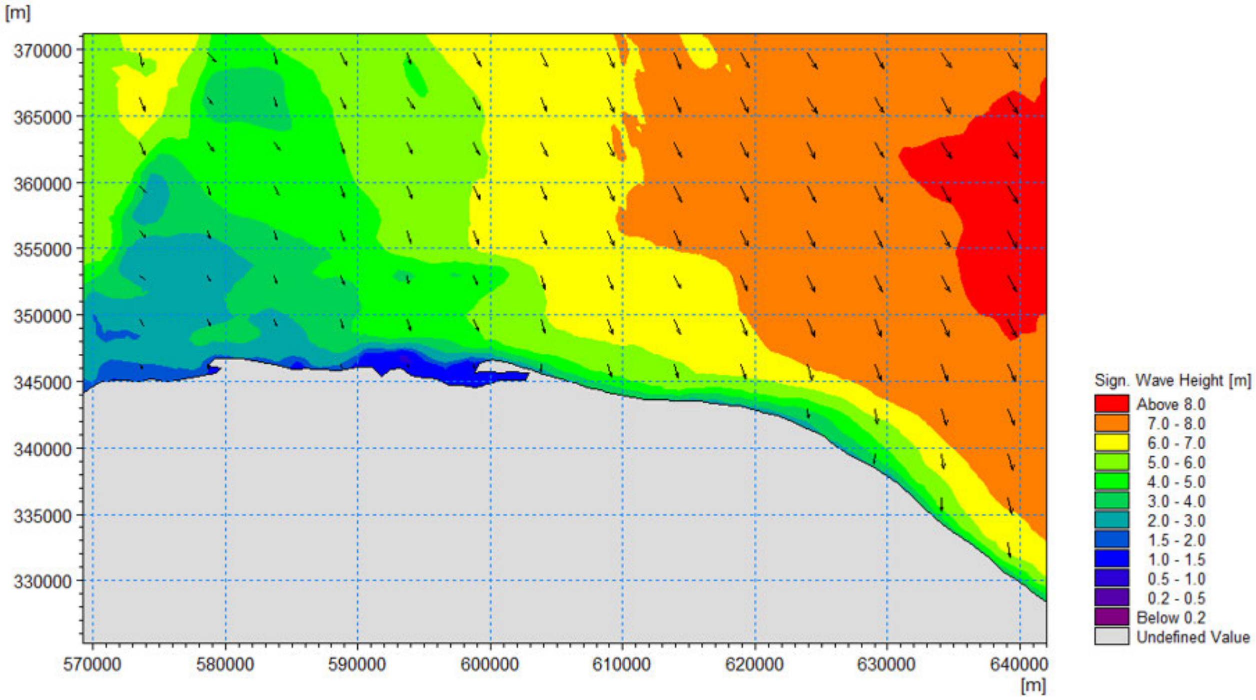

Figure A- 9: Significant wave height for the 1 in 50 year return period event 'Baseline' scenario – 330ºN offshore wave direction

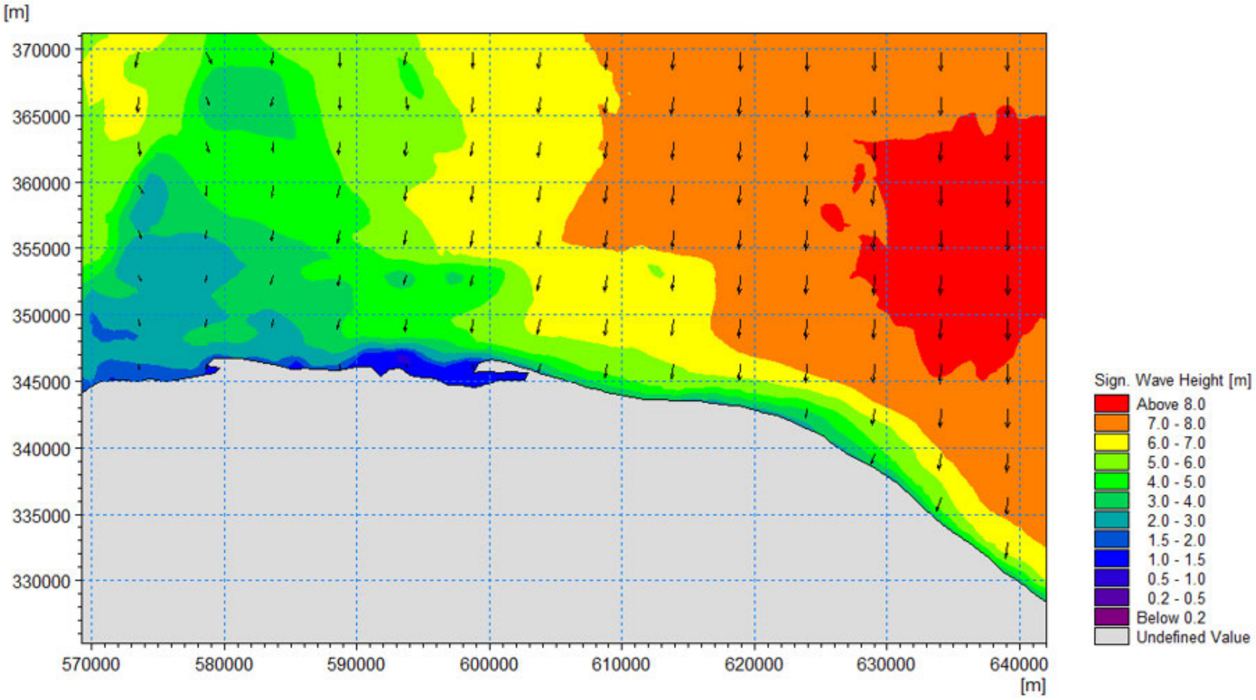

Figure A- 10: Significant wave height for the 1 in 50 year return period event 'Baseline' scenario – 0ºN offshore wave direction

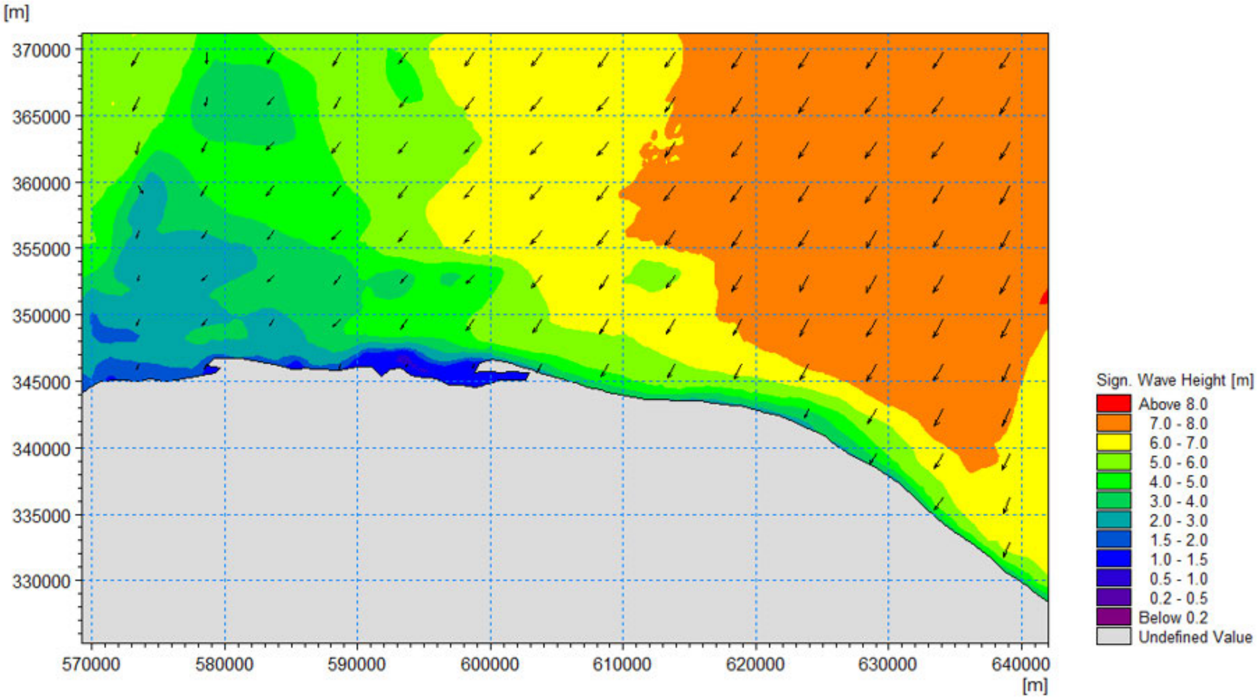

Figure A- 11: Significant wave height for the 1 in 50 year return period event 'Baseline' scenario – 30ºN offshore wave direction

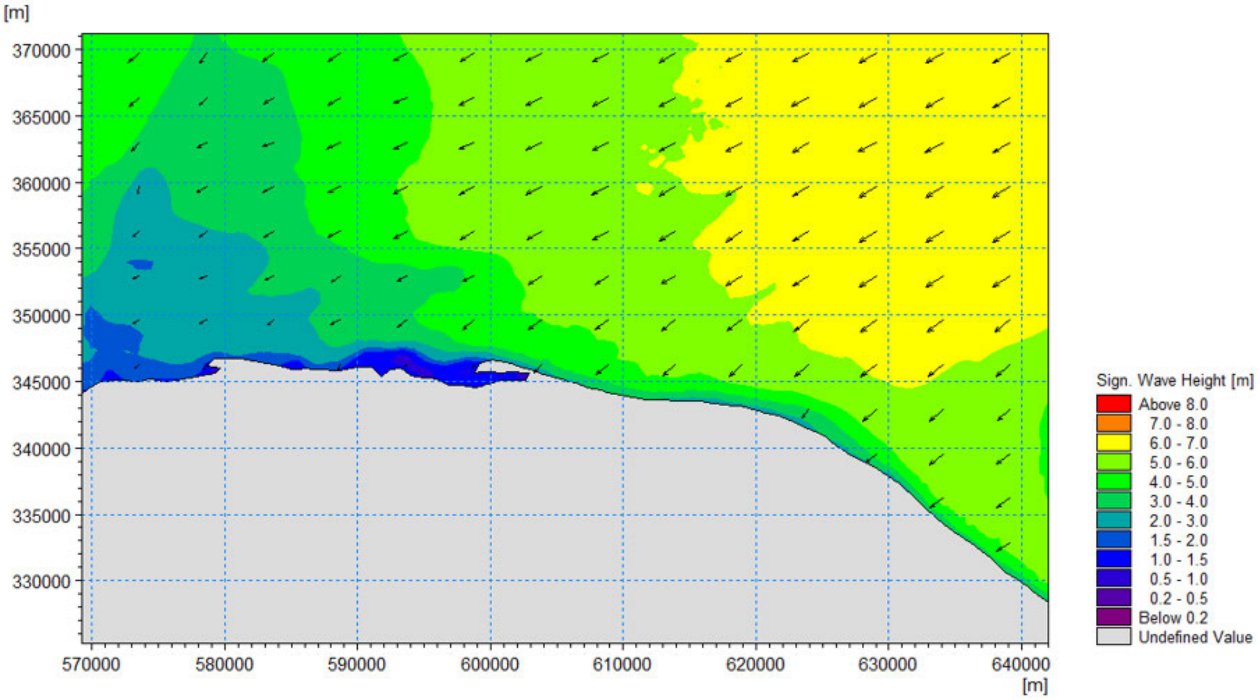

Figure A- 12: Significant wave height for the 1 in 50 year return period event 'Baseline' scenario – 60ºN offshore wave direction

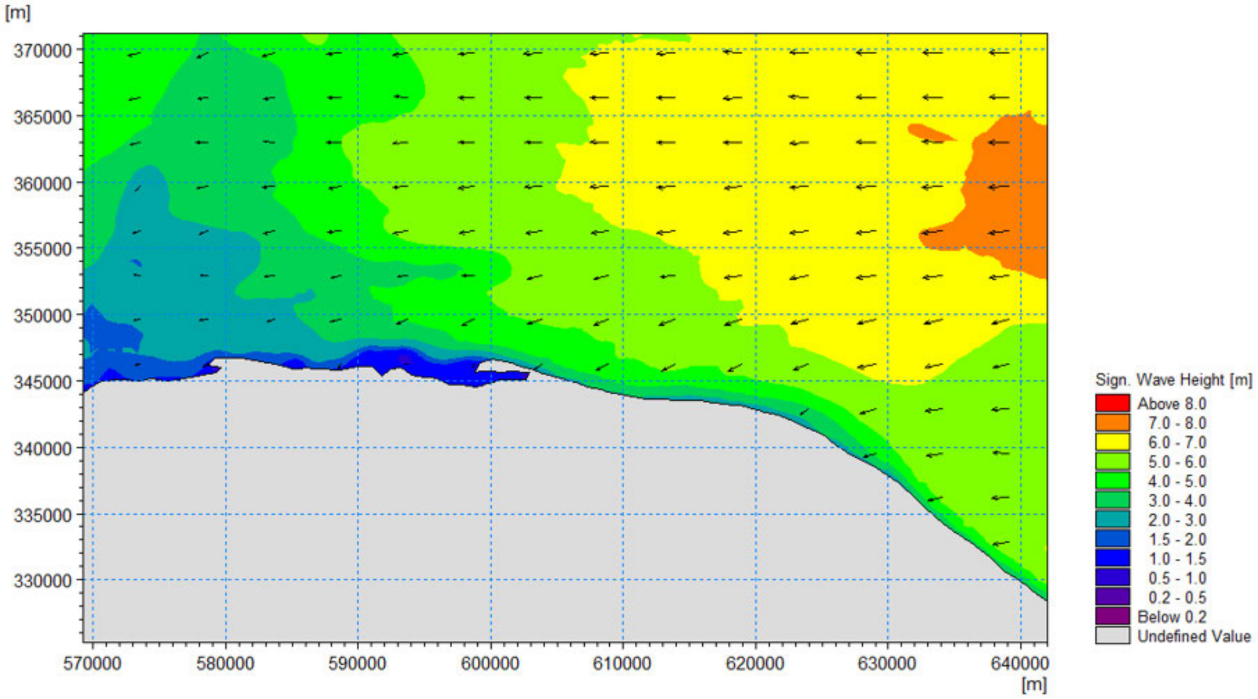

Figure A- 13: Significant wave height for the 1 in 50 year return period event 'Baseline' scenario – 90ºN offshore wave direction

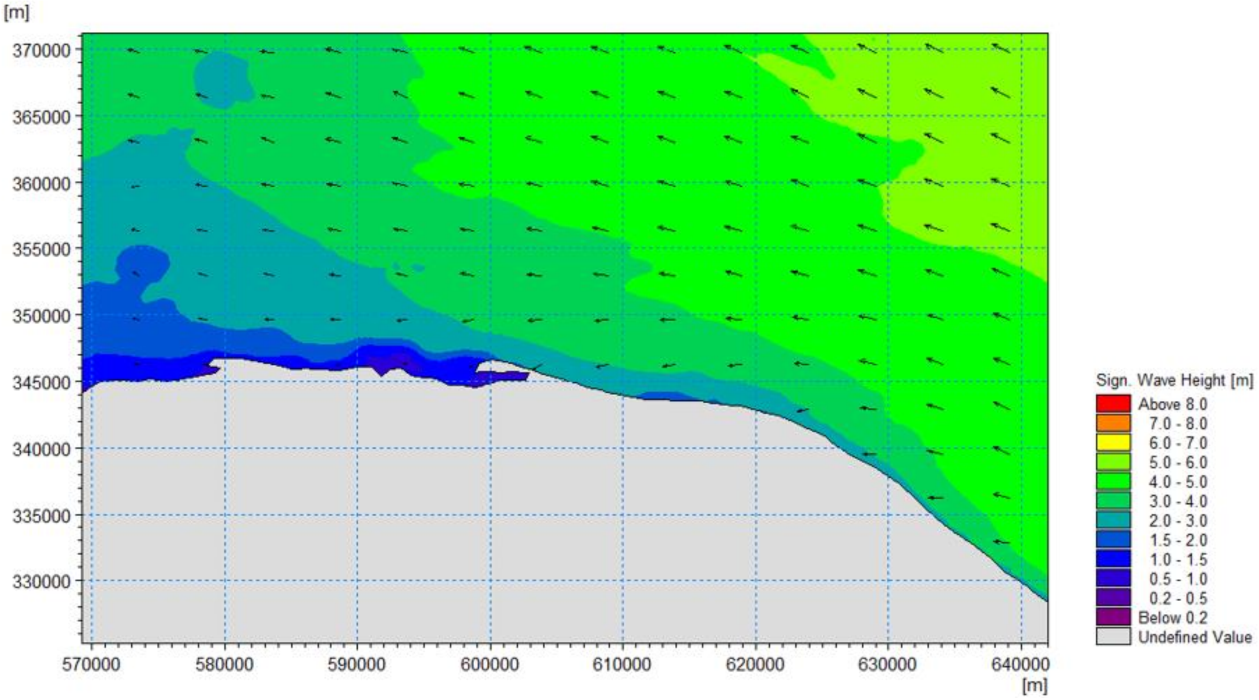

Figure A- 14: Significant wave height for the 1 in 50 year return period event 'Baseline' scenario – 120ºN offshore wave direction

Appendix B – Wave Model Results: ‘Extensions’ Scenarios

70. **Figure B- 1** to **Figure B- 14** present contour plots of significant wave height for the ‘Extensions’ scenarios for three direction sectors, namely 300ºN, 330ºN, 0ºN and 30ºN, 60ºN, 90ºN and 120ºN, for the 1 in 1 year and 1 in 50 year return period events, respectively.

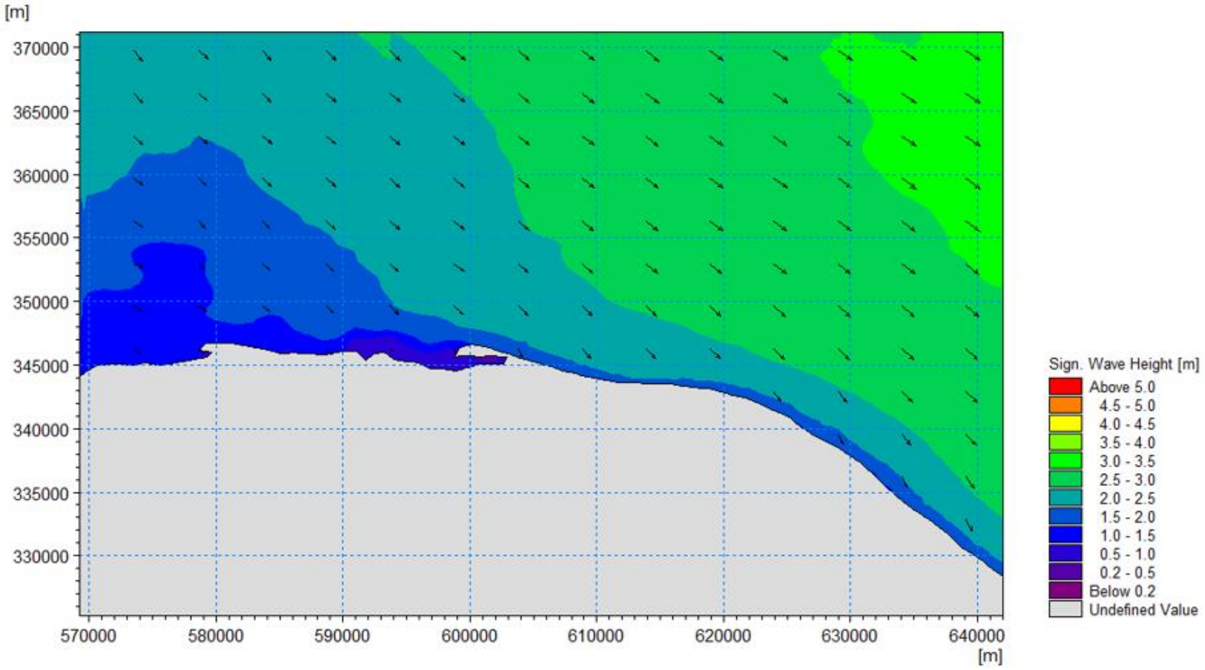

Figure B- 1: Significant wave height for the 1 in 1 year return period event ‘Extensions’ scenario – 300ºN offshore wave direction

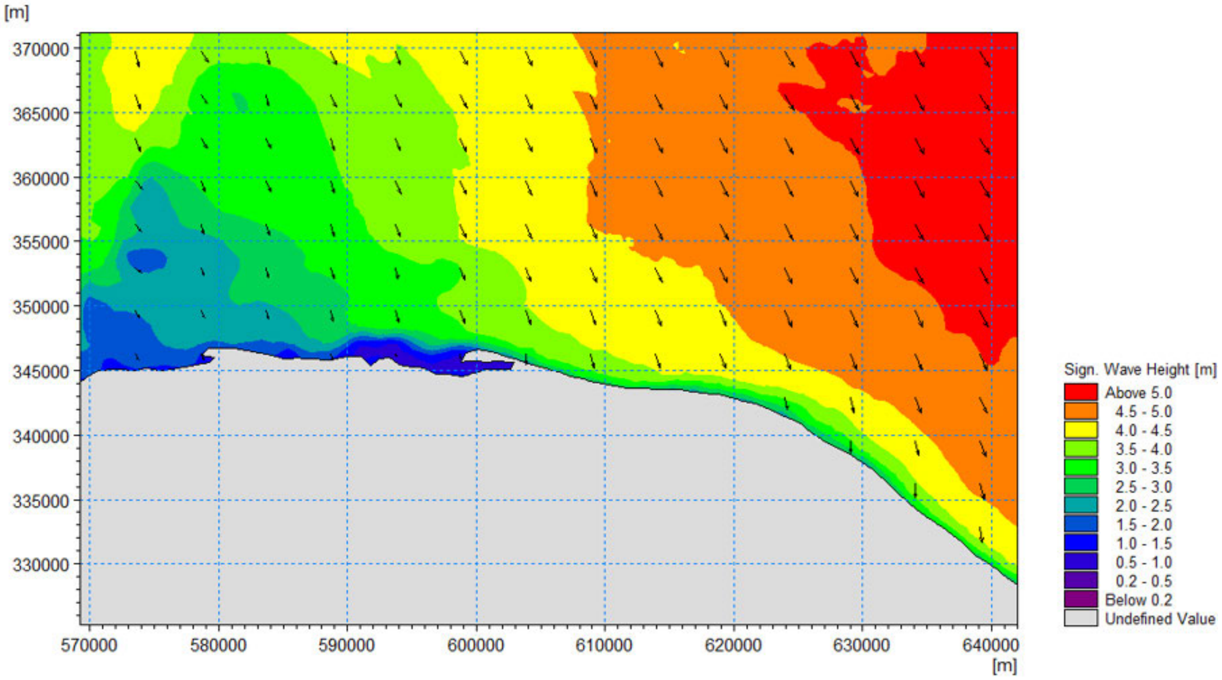

Figure B- 2: Significant wave height for the 1 in 1 year return period event ‘Extensions’ scenario – 330ºN offshore wave direction

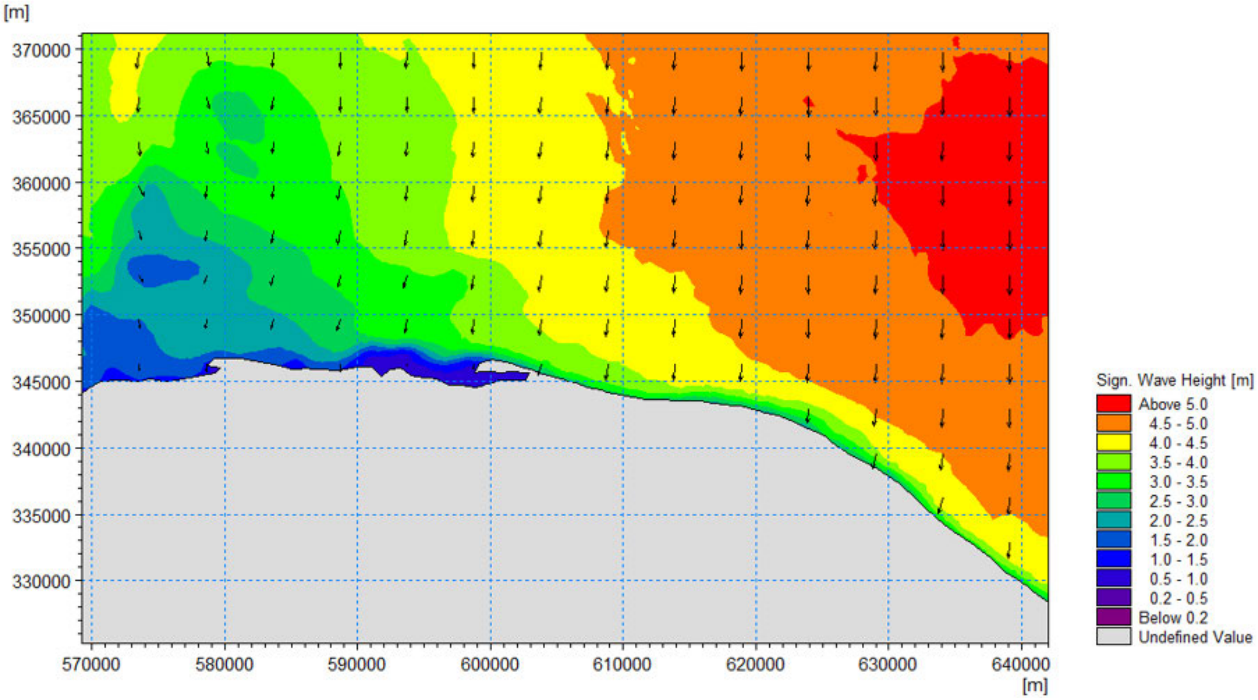

Figure B- 3: Significant wave height for the 1 in 1 year return period event 'Extensions' scenario – 0ºN offshore wave direction

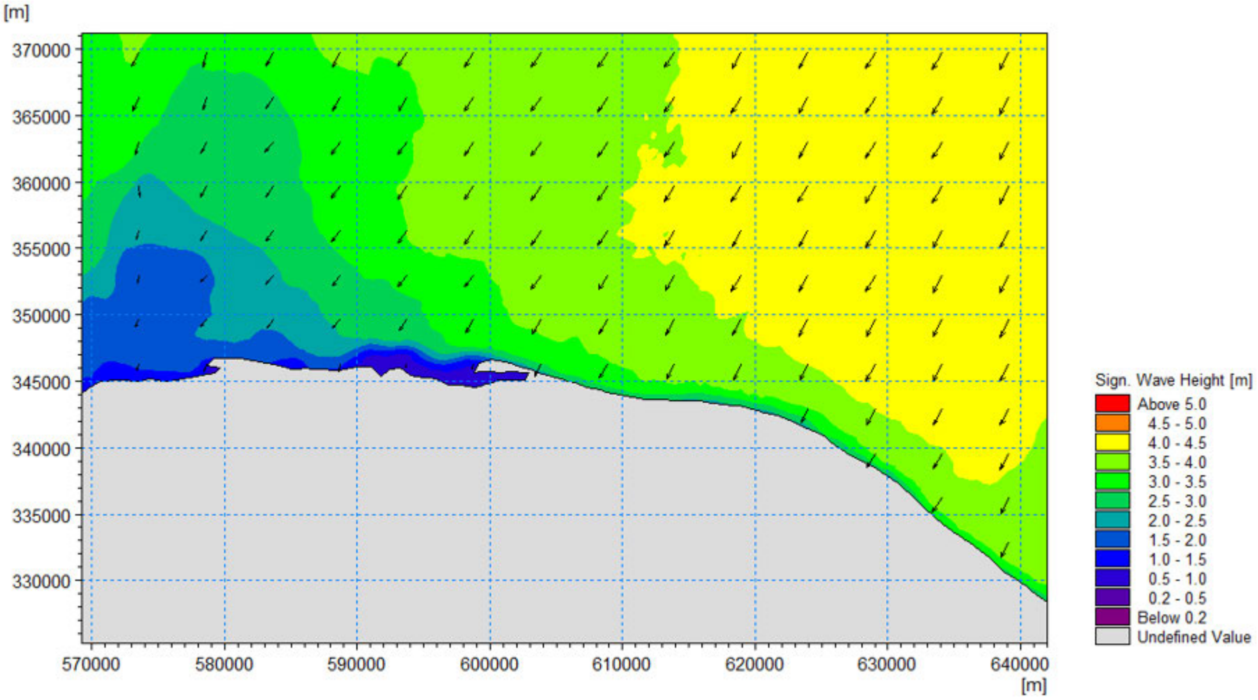

Figure B- 4: Significant wave height for the 1 in 1 year return period event 'Extensions' scenario – 30ºN offshore wave direction

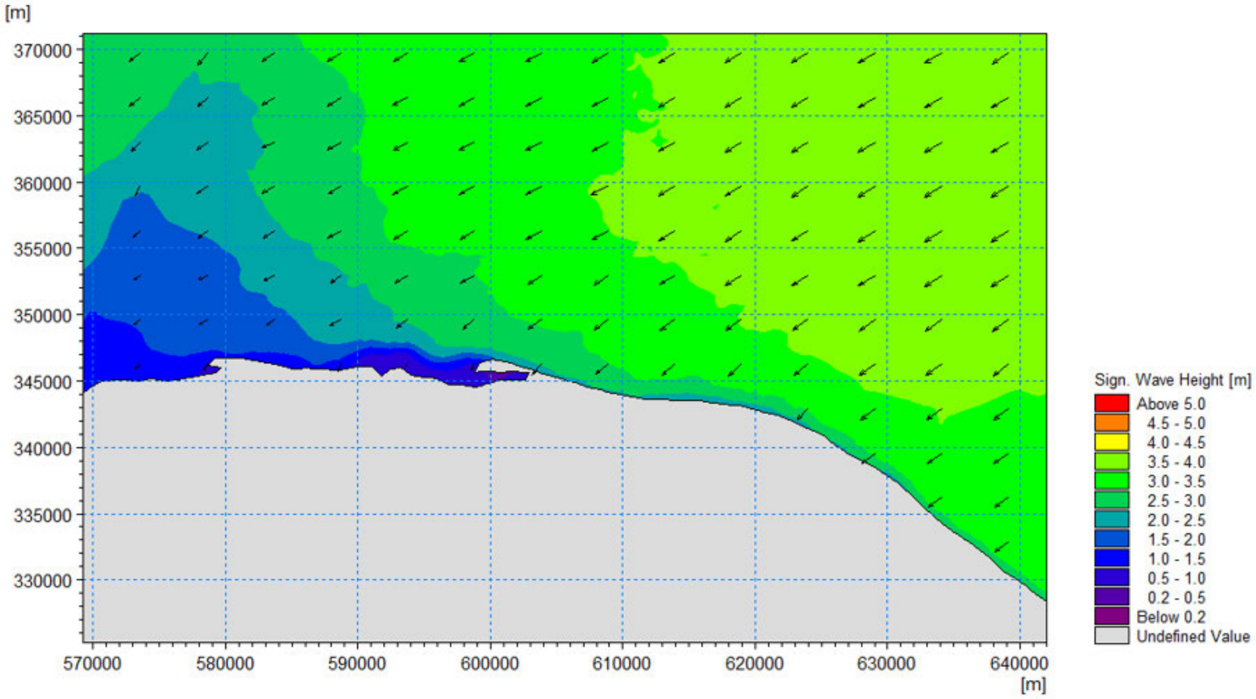

Figure B- 5: Significant wave height for the 1 in 1 year return period event 'Extensions' scenario – 60ºN offshore wave direction

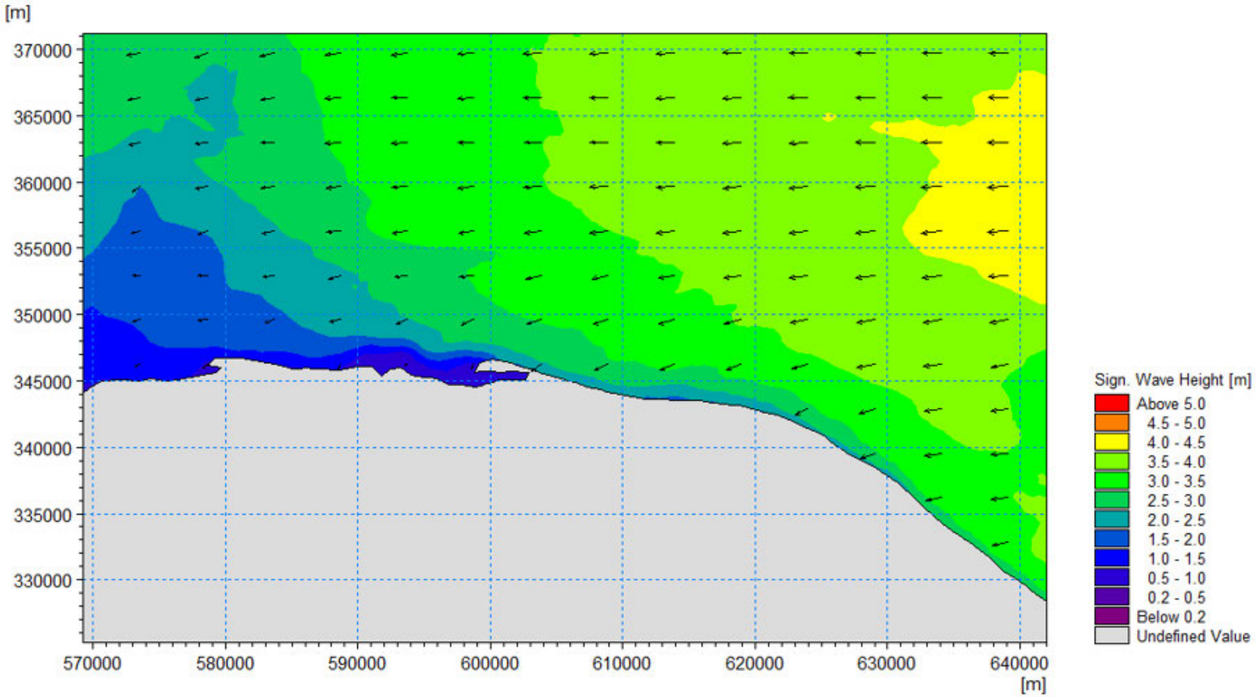

Figure B- 6: Significant wave height for the 1 in 1 year return period event 'Extensions' scenario – 90ºN offshore wave direction

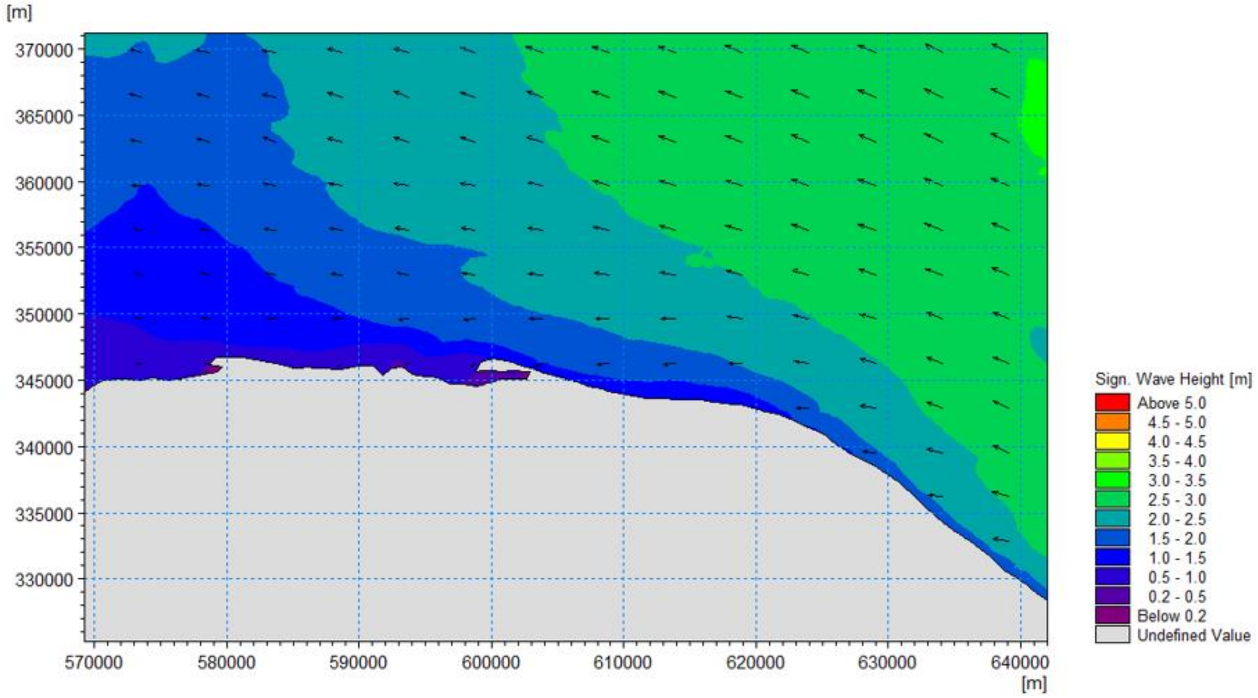

Figure B- 7: Significant wave height for the 1 in 1 year return period event 'Extensions' scenario – 120ºN offshore wave direction

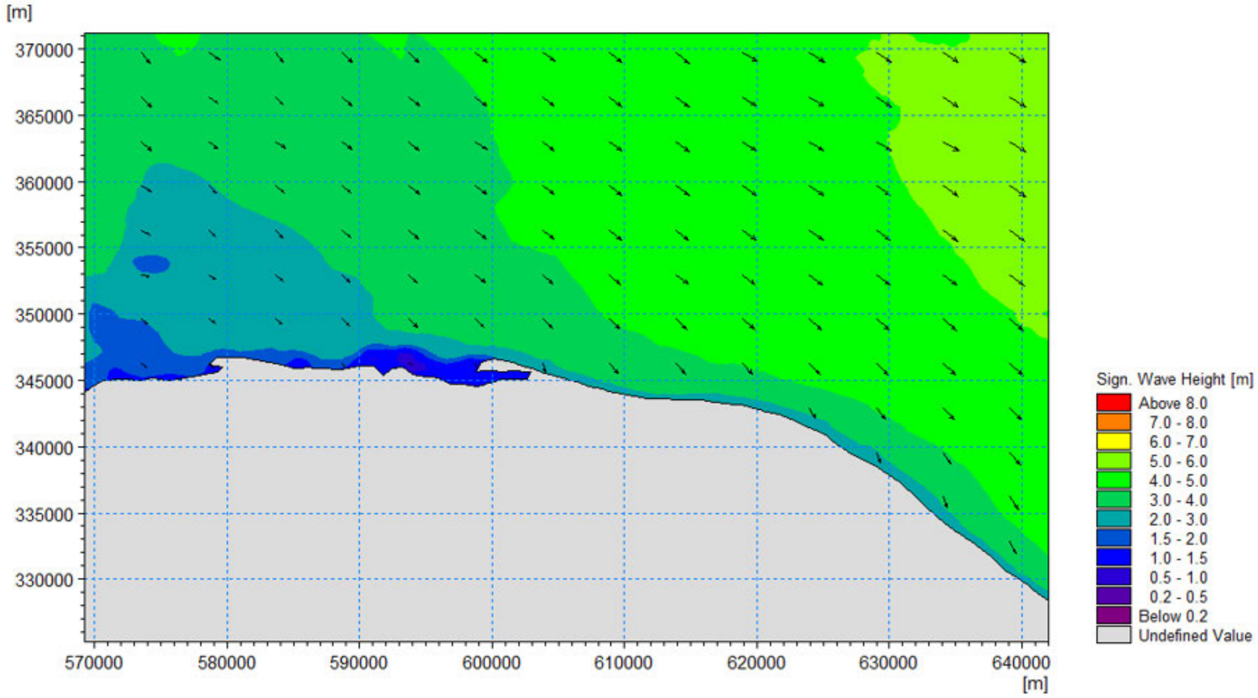

Figure B- 8: Significant wave height for the 1 in 50 year return period event 'Extensions' scenario – 300ºN offshore wave direction

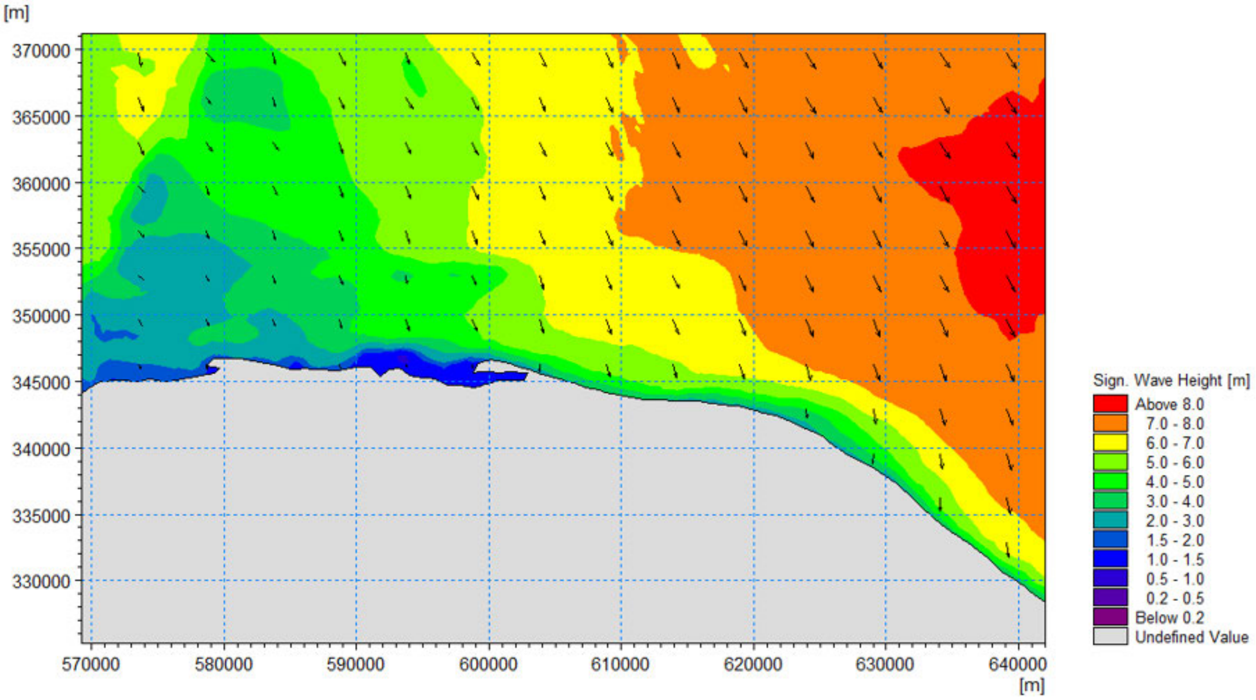

Figure B- 9: Significant wave height for the 1 in 50 year return period event 'Extensions' scenario – 330ºN offshore wave direction

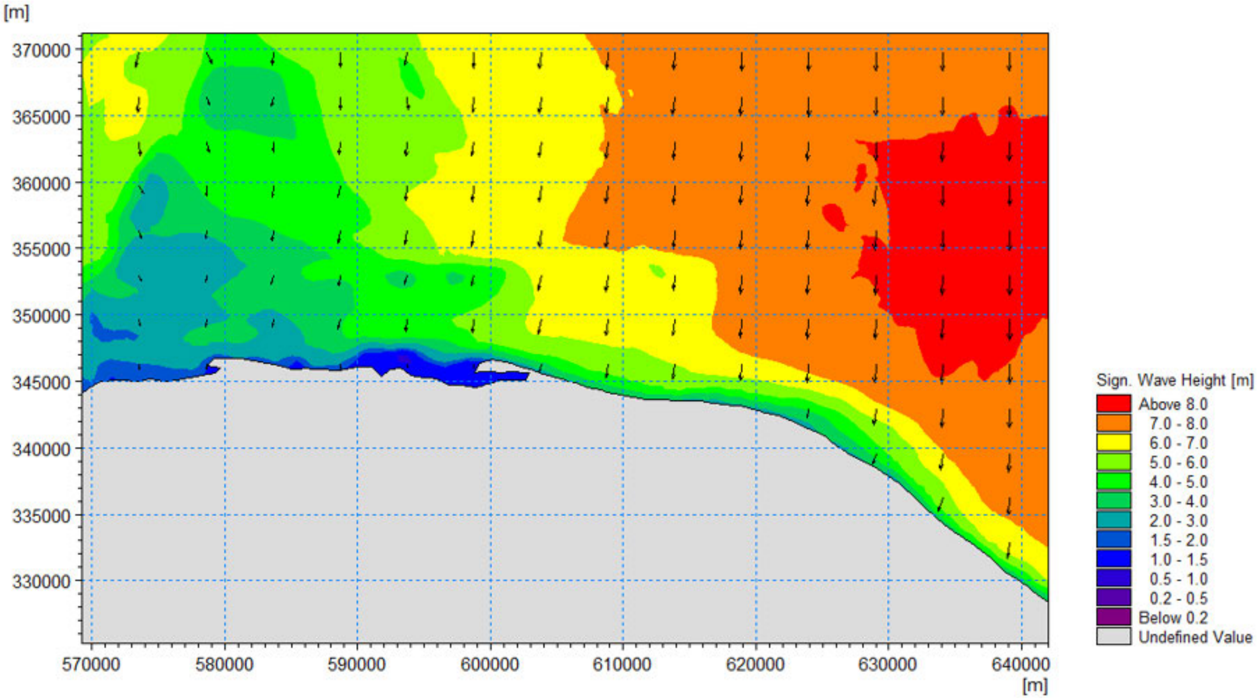

Figure B- 10: Significant wave height for the 1 in 50 year return period event 'Extensions' scenario – 0ºN offshore wave direction

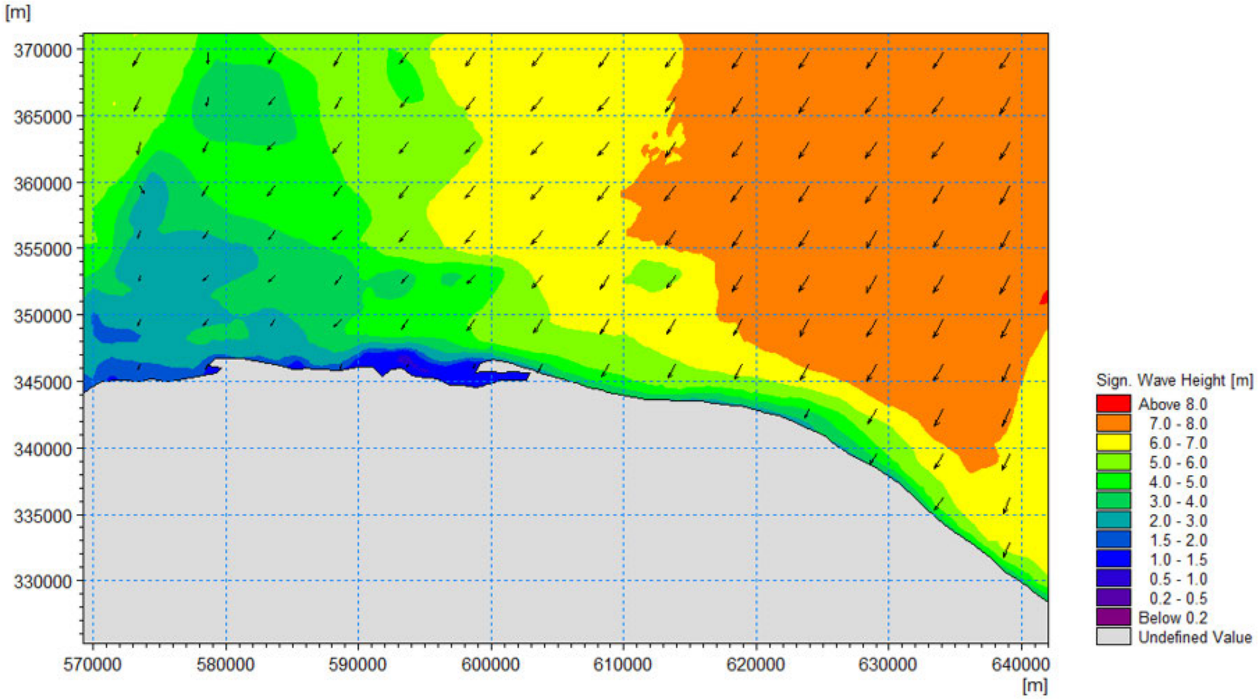

Figure B- 11: Significant wave height for the 1 in 50 year return period event 'Extensions' scenario – 30ºN offshore wave direction

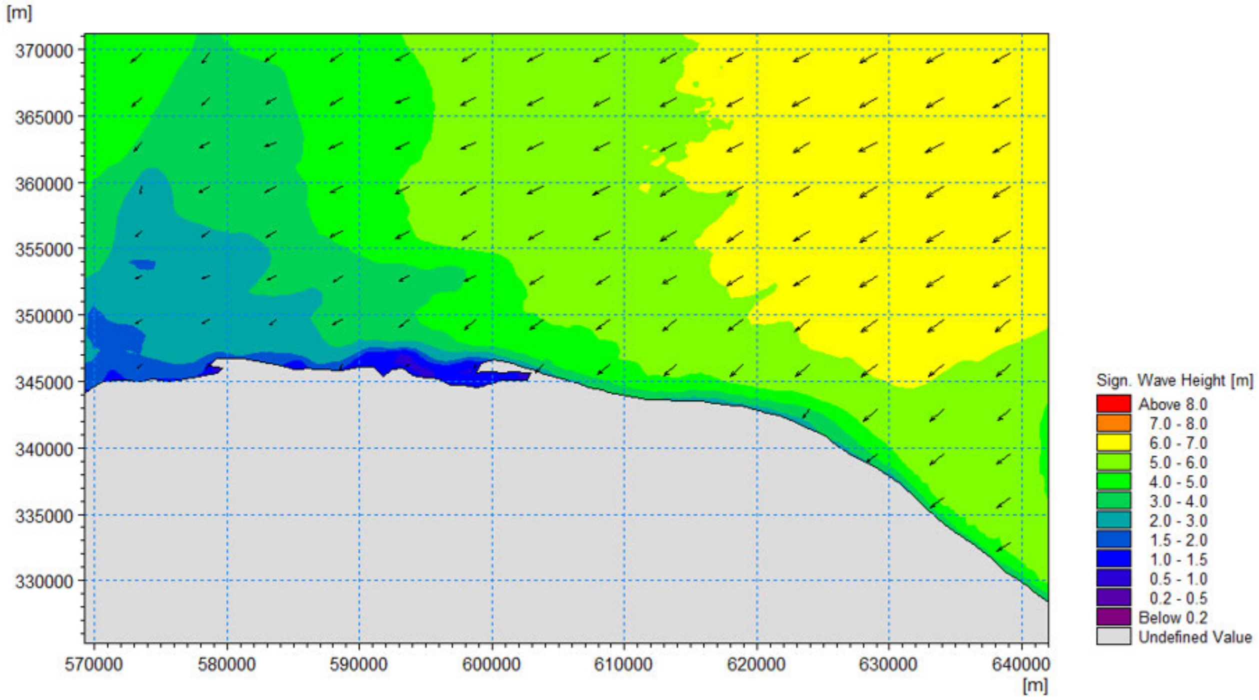

Figure B- 12: Significant wave height for the 1 in 50 year return period event 'Extensions' scenario – 60ºN offshore wave direction

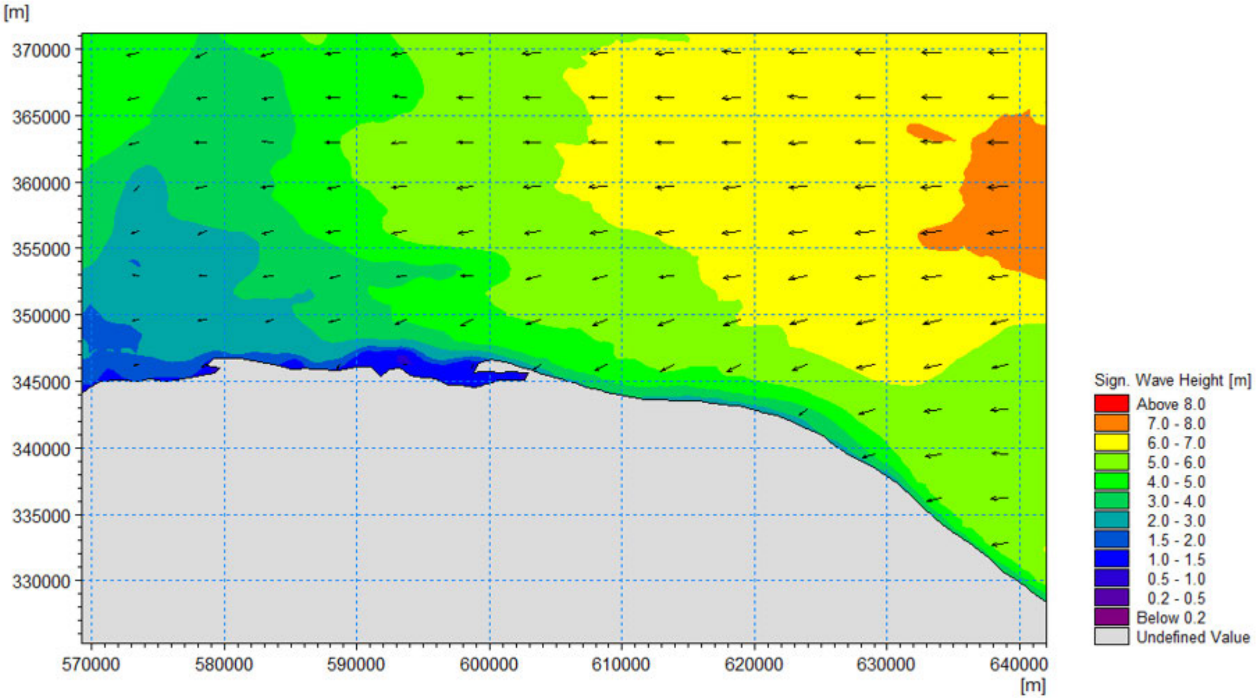

Figure B- 13: Significant wave height for the 1 in 50 year return period event 'Extensions' scenario – 90ºN offshore wave direction

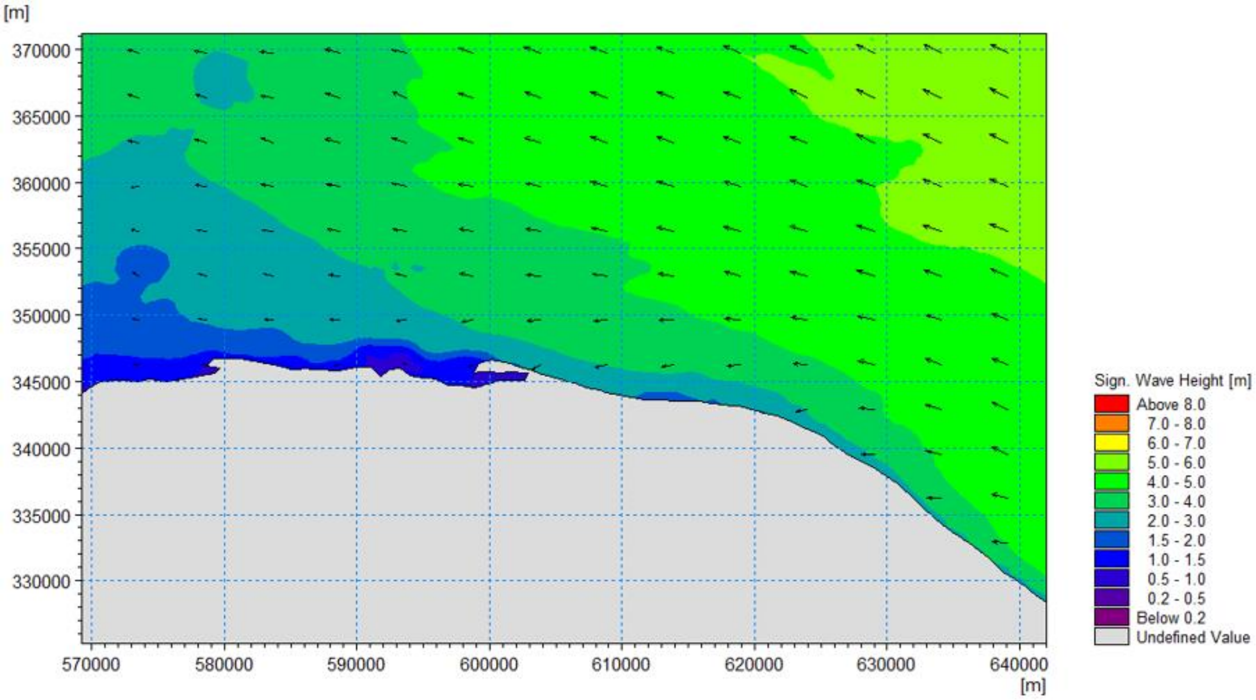

Figure B- 14: Significant wave height for the 1 in 50 year return period event 'Extensions' scenario – 90ºN offshore wave direction