Bowdun Offshore Wind Farm, Offshore EIA Report

Volume 3, Technical Appendix 7.2: Model Design and Validation

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Glossary

Defined Term	Definition
Applicant (the)	Bowdun Offshore Wind Farm Limited (BOWFL).
Array Area	The Array Area is the area in which the Offshore Generation Assets will be located.
Bowdun Offshore Wind Farm Limited (BOWFL)	A Special-Purpose Vehicle (SPV) (legal entity) for the purpose of developing the Project. BOWFL are the Applicant for the Offshore Application.
Cumulative Effects	The effects of the Proposed Development assessed together with effects from the Onshore Infrastructure forming the Project as well as one or more different projects on the same receptor/resource.
Effect	Term used to express the consequence of an impact (i.e. the result of change or changes on specific environmental resources or receptors). The significance of an effect is determined by correlating the magnitude of the impact with the importance, or sensitivity of the receptor or resource in accordance with defined significance criteria.
Environmental Impact Assessment (EIA)	Process for the assessment of likely significant environmental effects of a project on the physical, biological and human environment during construction, Operation and Maintenance (O&M) and decommissioning.
Export Cable Corridor	The area seaward of Mean High Water Springs (MHWS) which connects the Array Area with the Landfall Area within which the Offshore Export Cables will be installed.
Harmonic Constituents	Individual sinusoidal components of a complex tidal signal, each characterised by a specific amplitude, phase, and frequency.
Impact	A change caused by an action that occurs during a project's lifetime.
Inter-Array Cables (IAC)	Cables which link the Wind Turbines to each other and with the Offshore Substation Platforms (OSPs).
Intertidal Area	The area between MHWS and Mean Low Water Springs (MLWS).
Landfall	The area in which the Offshore Export Cables make Landfall and is also the transitional area between the Offshore Transmission Assets and the Onshore Transmission Assets. Located in the Intertidal Area at Benholm.
Maximum Design Scenario (MDS)	The scenario within the design envelope likely to result in the greatest impact on a particular topic receptor, and therefore the one that should be assessed for that topic receptor.
Offshore Infrastructure	All of the Offshore Infrastructure associated with the Proposed Development that is located seaward of MHWS, comprising the Offshore Generation Assets and the Offshore Transmission Assets.
Offshore Substation Platform(s) (OSPs)	OSPs comprise the support structure, topside and electrical components used for collecting and/or converting electricity generated by the Wind Turbines for transmission by the Offshore Export Cables.

Defined Term	Definition
Operation and Maintenance (O&M)	The phase of the Proposed Development following completion of construction. This phase of development includes routine inspections, repairs and replacement of infrastructure and equipment (including Interconnector Cables and IACs), Scour Protection replenishment or replacement, major component replacement, painting and/or other coating works, removal of marine growth, and replacement of access ladders.
Plan Option Area (POA)	A location identified in the Sectoral Marine Plan (SMP) as a preferred area for commercial scale offshore wind development.
Project (the)	An overarching term for the Bowdun Offshore Wind Farm (Bowdun OWF) comprising the offshore and onshore infrastructure required to generate and transmit electricity from the Array Area to the onshore Grid Connection Point (GCP). The Project includes the Offshore Generation Assets, the Offshore Transmission Assets and the Onshore Transmission Assets.
Proposed Development	Term used to define the Offshore Infrastructure associated with the Project seaward of MHWS for which consent is being sought. Further details of the parameters are included in Volume 1, Chapter 3: Project Description.
Scour Protection	Protective materials installed to avoid sediment being eroded away from the base of the foundations and/or buried subsea cable due to the flow of water.
Spring Tidal Excursion	The distance suspended sediment is transported prior to being carried back on the returning tide.
Study Area	For each environmental topic, the baseline environment will be characterised, and the potential environmental impacts will be described within a topic-specific study area. Specific study areas are defined for each topic and are based on the maximum spatial extent across which potential impacts of the Project may be experienced by the relevant receptors (i.e. Zone of Influence).
Thistle Wind Partners (TWP)	Company established for the development of the Project.
Tidal Ellipse	The illustration of the variance of tidal currents in horizontal space.
Wind Turbines	Structures comprising of a tubular tower, rotor blades, and a nacelle which houses the Wind Turbine generator.

Acronyms

Acronym	Definition
ABPmer	ABP Marine Environmental Research
CEFAS	Centre for Environment, Fisheries, and Aquaculture Science
DHI	Danish Hydraulic Institute
DTU	Technical University of Denmark
EIA	Environmental Impact Assessment
ESE	East south-east
FM	Flexible Mesh
HD	Hydrodynamic
HW	High Water
LAT	Lowest Astronomical Tide
MDS	Maximum Design Scenario
MFE	Mass Flow Excavator
MHWS	Mean High Water Spring
MSL	Mean Sea Level
O&M	Operation and Maintenance
OSP	Offshore Substation Platform
OWF	Offshore Wind Farm
POA	Plan Option Area
PT	Particle Tracking
RP	Return Period
SE	South-east
SMP	Sectoral Marine Plan
SSC	Suspended Sediment Concentration
SSE	South south-east
SW	Spectral Wave
UCL	University College London
UKHO	United Kingdom Hydrographic Office
UTM	Universal Transverse Mercator
VORF	Vertical Offshore Reference Frame

Table of Units

Units	Definition
kg	Kilogram
kg/s	Kilograms per second
km	Kilometre
km^2	Square kilometre
m	Metre
m^2	Square Metre
m/hr	Metres per hour
mMSL	Metres below Mean Sea Level
m/s	Metre per second
m^2/s	Square metre per second
s	Second
°	Degree
°N, from	Degrees from North, travelling from
%	Percent
μm	Micrometre

1 Introduction

1.1.1 This Physical Processes Technical Report presents information about the design and validation of the numerical models developed to inform Volume 2, Chapter 7: Physical Processes for the offshore elements of the Bowdun Offshore Wind Farm (OWF) Project (hereafter referred to as the Proposed Development). The Proposed Development covers the Option Lease Area (OLA) comprises of the Array Area, which is located in the E3 Plan Option Area (POA) detailed in the Scottish Sectoral Marine Plan (SMP) (Scottish Government, 2020), and the Export Cable Corridor. The Array Area is located 38 km from the Aberdeenshire coast at its closest point, covering an area of 187 km^2. The Proposed Development will comprise of Wind Turbines (fixed foundations), Inter-Array Cables (IACs), Offshore Substation Platforms (OSPs), Interconnector Cables, Offshore Export Cables and any necessary scour/cable protection. The Export Cable Corridor will include a maximum of three High Voltage Alternating Current (HVAC) Offshore Export Cables, each with a length of up to 70 km and will make Landfall at Benholm, Aberdeenshire.

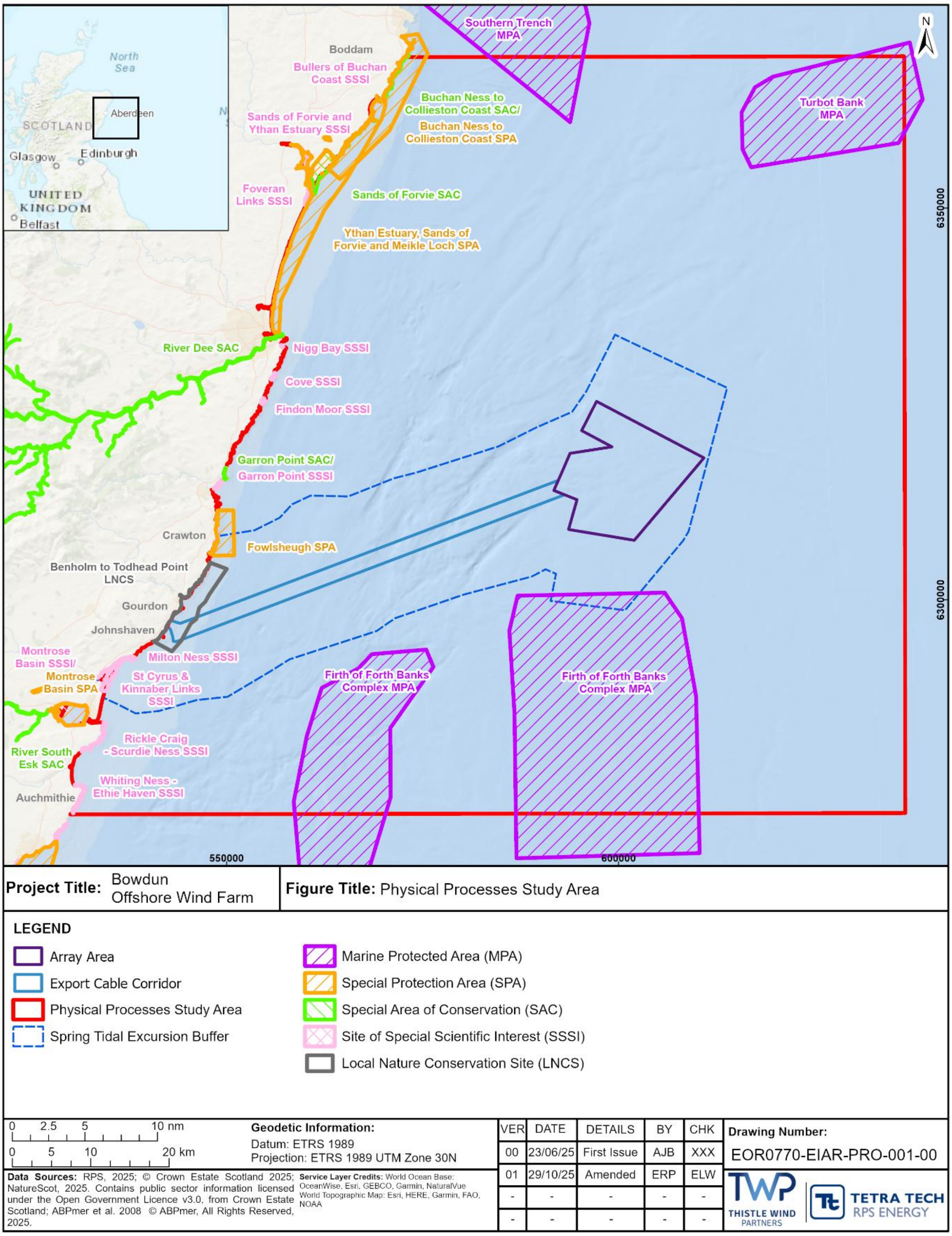
1.1.2 A range of numerical models have been developed to address the following aims:

- Hydrodynamics: Characterise the impact of wind farm foundations on the hydrodynamic regime (tidal currents and water levels) during the operation phase.
- Sediment plumes: Characterise the patterns of elevated Suspended Sediment Concentration (SSC) and sediment deposition resulting from sediment disturbance during the construction phase.
- Waves: Characterise the impact of wind farm foundations on the wave regime (wave height, period and direction) during the operation phase.

2 Physical Processes Study Area

2.1.1 The Physical Processes Study Area is located off the Aberdeenshire coast (Figure 2.1). It has been defined on the basis of:

- The distance away from the Proposed Development which suspended sediment plumes may be advected (and interact with potentially sensitive receptors). This has been defined by a spring tidal excursion ellipse buffer around the Array Area and Export Cable Corridor.
- The distance up/down drift from the Landfall, that littoral processes could theoretically be impacted by Offshore Infrastructure associated with the Proposed Development; has been defined through consideration of coastal sub-cell information set out in Ramsay and Brampton (2000).
- The distance from Array Area that wave blockage impacts could theoretically be detected has been informed by expert judgment, drawing upon (amongst other things), the evidence base from other projects (e.g. ABPmer, 2021) and consideration of the prevailing wave directions.



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Service Layer Credits: World Ocean Base: OceanWise, Esri, GEBCO, Garmin, NaturalVue World Topographic Map: Esri, HERE, Garmin, FAO, NOAA

Figure 2.1: Physical Processes Study Area

3 Methodology

3.1.1 The numerical modelling for this study has been undertaken using the MIKE21FM (Flexible Mesh) software package from the Danish Hydraulic Institute (DHI), which has been developed specifically for application in oceanographic, coastal, and estuarine environments.

3.1.2 When used by an experienced modeller, and in conjunction with suitable data inputs, these models provide reliable and realistic representations of both baseline environmental conditions, and the potential effects of offshore wind farm infrastructure and other construction related activities.

3.1.3 The hydrodynamic modelling described in this report is undertaken using a 2D (depth averaged) hydrodynamic model, utilising a flexible mesh with high resolution in the Physical Processes Study Area. The model is run in a tide only mode (no effect of winds or air pressure) to simulate a continuous timeseries of tidally varying water levels and currents over a representative spring-neap period.

3.1.4 The sediment plume modelling described in this report is undertaken using a particle tracking approach, whereby particles representing discrete amounts of sediment are released and subject to advection and dispersion within the simulated flow fields from the hydrodynamic model.

3.1.5 The wave modelling described in this report is undertaken using a spectral wave model, utilising a flexible mesh with high resolution in the Physical Processes Study Area. The model is run in a quasi-stationary mode to simulate a range of discrete representative seastates. The wave model is not required to simulate historical timeseries of actual wave conditions.

4 Tidal Currents and Water Levels

4.1 Overview

4.1.1 This section describes the design and inputs to a hydrodynamic model simulating tidal currents and water levels across the Physical Processes Study Area for the Proposed Development. The model will be used to simulate baseline conditions, and the impact of wind farm foundations on baseline conditions. This hydrodynamic model also provides the flow field inputs for the sediment plume model described in Section 5.

4.1.2 Scenario specific information and model inputs are described in Volume 3, Technical Appendix 7.3: Physical Processes Technical Assessment, including:

- time period of simulation (typically one representative spring-neap cycle); and
- foundation type, dimensions, number and layout for:
  - Bowdun OWF Maximum Design Scenario (MDS);
  - Aberdeen OWF MDS;
  - Kincardine OWF MDS;
  - Seagreen 1 OWF MDS;
  - Seagreen 1A OWF MDS;
  - Morven North OWF MDS;
  - Morven South OWF MDS; and
  - Ossian OWF MDS.

4.1.3 Scenario specific results are also provided in Volume 3, Technical Appendix 7.3: Physical Processes Technical Assessment, including:

- baseline water levels, current speed and direction;
- baseline residual current speed and direction;
- baseline (current related) sediment transport rate and direction;
- baseline (current related) residual sediment transport rate and direction; and
- patterns of change to all of the above as a result of the presence of wind farm foundations.

4.2 Hydrodynamic Model Design

Hydrodynamic General Design

4.2.1 The Hydrodynamic (HD) model is built using the MIKE21FM HD module, which simulates the propagation of the tidal wave and associated movements of water volume in offshore and coastal settings.

4.2.2 The HD model creates a timeseries simulation of tidal water levels and depth averaged current speed and direction throughout the model domain.

4.2.3 The HD model is based on the ABPmer SEASTATES validated regional scale European Shelf Tide and Surge model, used in a tide only mode, with locally enhanced resolution in the Physical Processes Study Area. The design and performance of the regional model are described in a separate report (ABPmer, 2017).

Hydrodynamic Model Mesh

4.2.4 The HD model mesh is based on that used by the ABPmer SEASTATES European Shelf Tide and Surge model (ABPmer, 2017). The extent of the model mesh and the distribution of mesh resolution is shown in Figure 4.1. A flexible mesh design is used (interlocking triangular 'elements' of varying shape and orientation), providing tailored spatially variable resolution within a single model mesh.

4.2.5 The (variable) resolution of the mesh outside of the Physical Processes Study Area is sufficient and suitable to simulate the general progression of the tidal wave and associated movement of water volume around the European continental shelf, up to the edges of the local Physical Processes Study Area.

4.2.6 Resolution is increased throughout the Physical Processes Study Area, from Fraserburgh to St Andrews and extending approximately 150 km offshore. The highest mesh resolution is approximately 100 m covering the Proposed Development, existing neighbouring OWFs (Aberdeen, Seagreen 1 and Kincardine), and planned neighbouring OWFs (Morven North, Morven South, Seagreen 1A and Ossian), in order to assess cumulative impacts with the neighbouring existing/planned OWF, and extending approximately 150 km offshore. The higher resolution provides a more detailed description of the key bathymetric and coastal features affecting flow patterns in these areas.

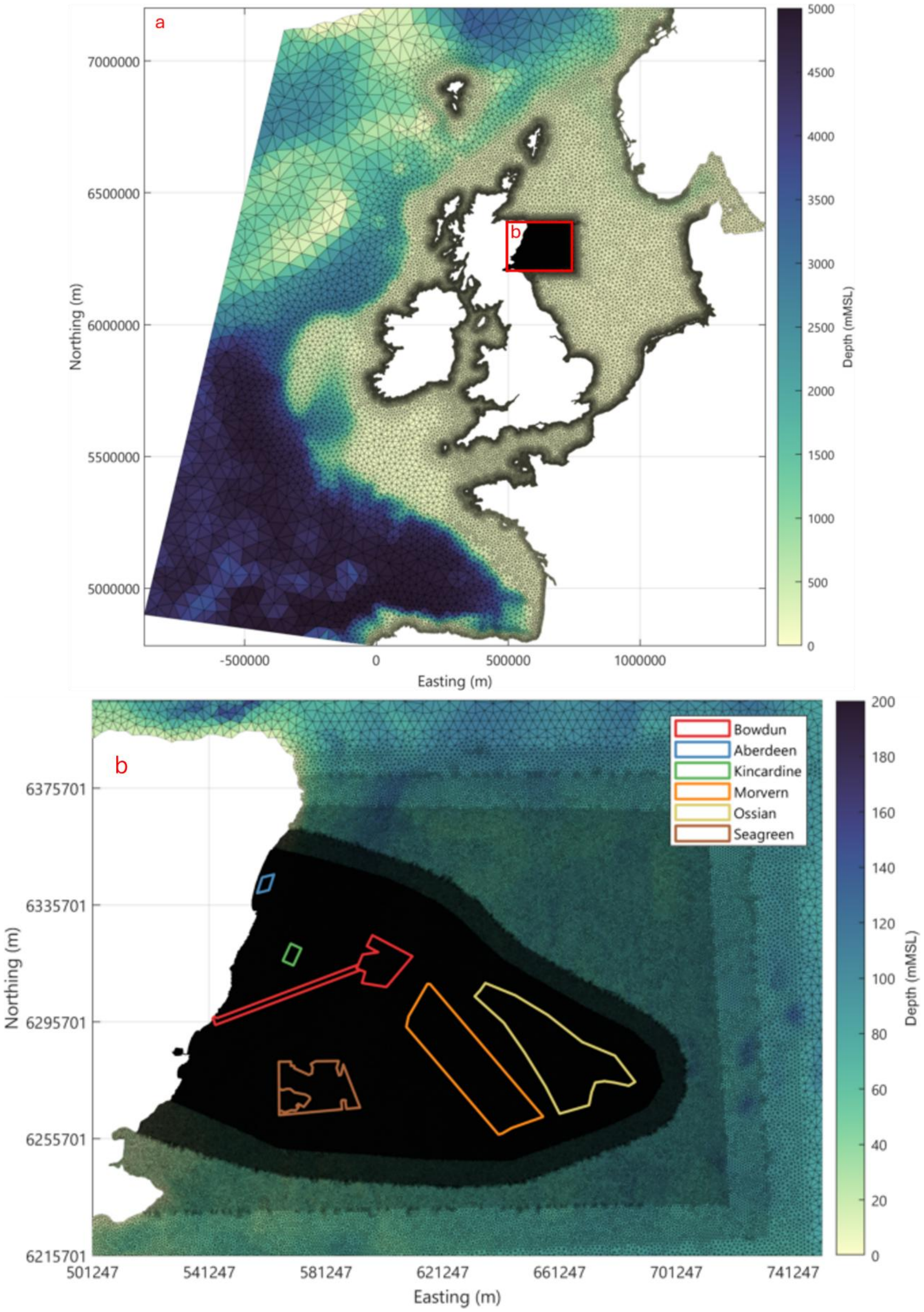

Figure 4.1: Hydrodynamic Model Mesh

Hydrodynamic Model Bathymetry

4.2.7 The HD model bathymetry is sourced from EMODnet (EMODnet, 2024), which is a freely available and generally reliable data source. Depth values from EMODnet across the Proposed Development were compared with those obtained from the 2024 geophysical survey. The comparison shows a very strong correlation between the two data sets. The good level of validation achieved by the regional model with respect to water levels and currents (ABPmer, 2017) also provides indirect validation of the bathymetry data source across the rest of the domain.

4.2.8 Spatially varying adjustments are made to convert the bathymetry data from the standard Lowest Astronomical Tide (LAT) datum at source, to Mean Sea Level (MSL), as is required for use in the model. Adjustments are made using a combination of Vertical Offshore Reference Frames (VORF) (University College London (UCL) and United Kingdom Hydrographic Office (UKHO), 2005) and tidal water level statistics from tide gauges for locations elsewhere in Europe outside of the VORF data extent.

Hydrodynamic Model Boundary Conditions

4.2.9 The HD model has four open water level boundaries, shown in Figure 4.2.

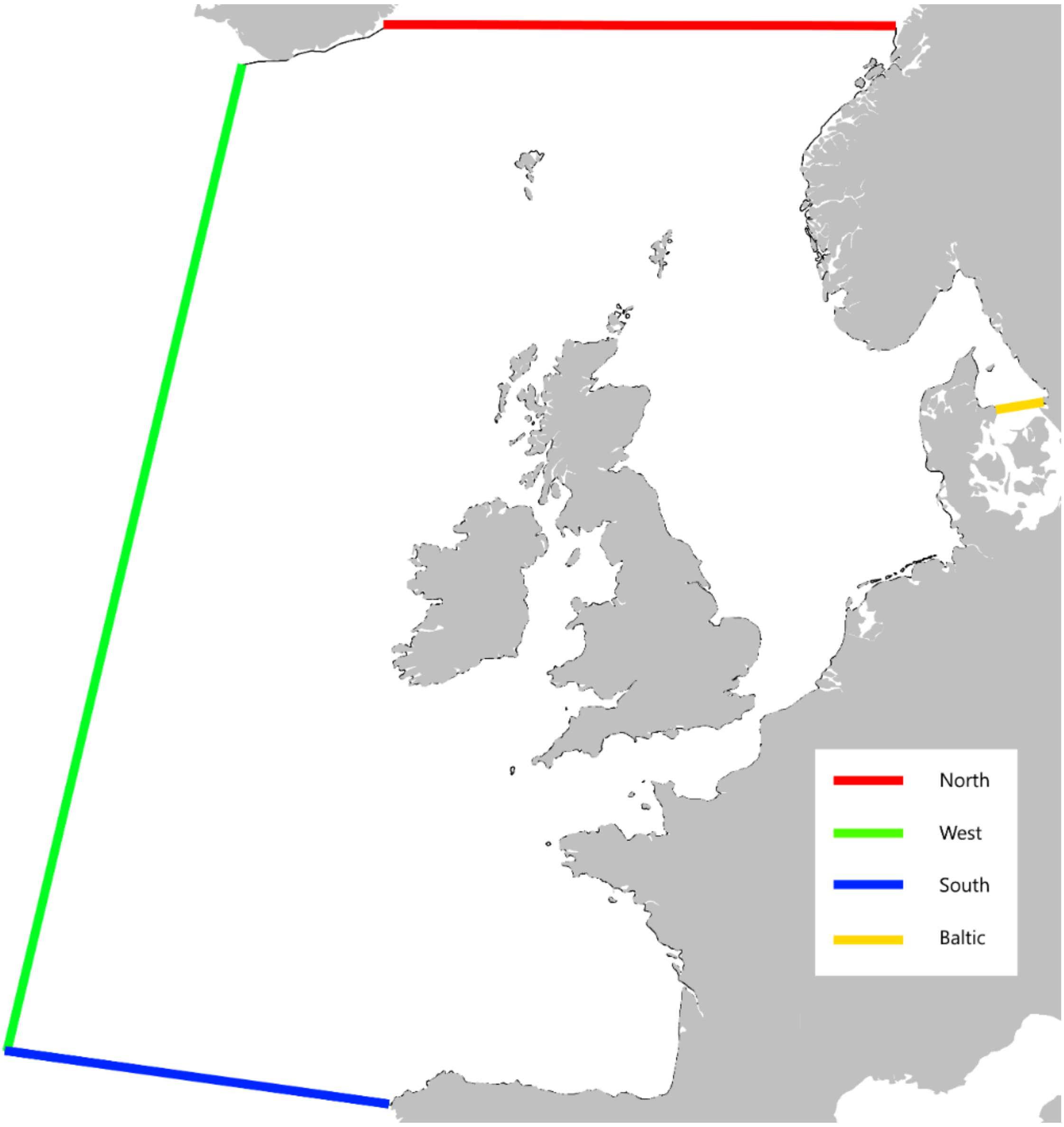

Figure 4.2: Hydrodynamic Model Boundaries

4.2.10 Temporally and spatially varying tidal water levels are applied at these boundaries, representing the passage of the deep ocean tidal wave from the North Atlantic onto the European shelf (and smaller exchanges with the Baltic Sea). Tidal boundary data are obtained using the Technical University of Denmark (DTU) 10 (DTU, 2010) database of Harmonic Constituents. The good level of validation achieved by the model with respect to water levels and currents (ABPmer, 2017) also provides indirect validation of the tidal boundary data source.

4.2.11 The effect of winds and air pressure (for non-tidal surge related influences) are not included in this (tide only) model.

Hydrodynamic Model Bed Roughness

4.2.12 Bed roughness in the model describes the friction from the seabed 'felt' by moving water. Changing the magnitude of bed roughness locally effects the rate at which water moves in that area and so can affect both tidal range and phasing, and (mainly the speed of) tidal currents. As such bed roughness is a key variable in the model that can be varied to optimise the model performance in comparison to coincident measured data.

4.2.13 The ABPmer SEASTATES European Shelf Tide and Surge model utilises a bespoke spatially varying map of bed roughness (Figure 4.3), created by combining information about the distribution of seabed and sediment type, and water depth. The good level of validation achieved by the model with respect to regional scale patterns of water levels and currents (ABPmer, 2017) also provides indirect validation of the bed roughness values.

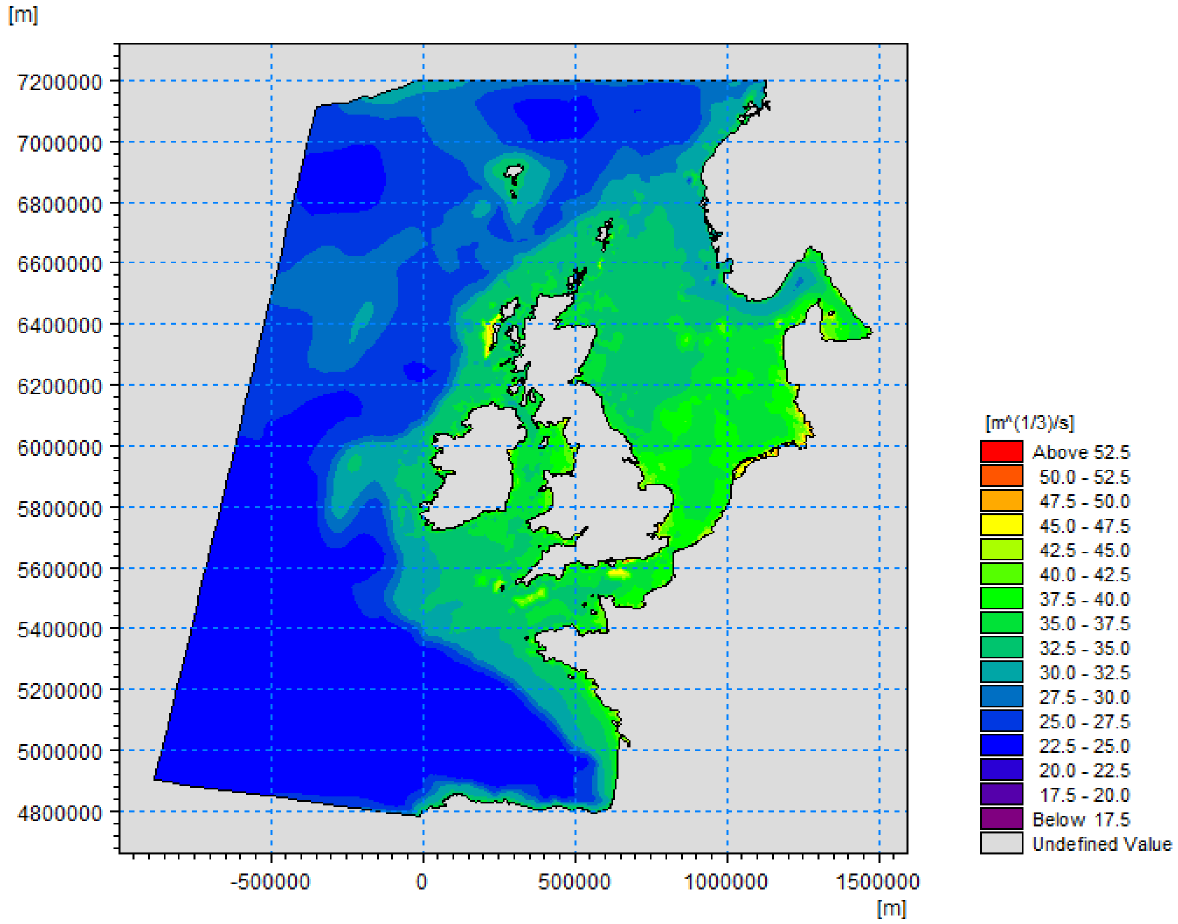

Figure 4.3: Hydrodynamic Model Bed Roughness Manning's Number

4.2.14 The same validated spatially variable bed roughness distribution is applied in the present study, with no adjustments made.

Hydrodynamic Model Structures

4.2.15 To simulate a realistic worst-case blockage scenario for tidal currents and water levels, the largest cross-sectional area within the water column for the Proposed Development foundation types described in Volume 1, Chapter 3: Project Description, has been calculated. This is used to derive a MDS depth averaged blockage width for a model structure. These sub-grid scale Wind Turbine and OSP foundations, are represented in the model as a single triangular element centred on their locations, each containing a MIKE 'pier' structure assigned with the appropriate MDS blockage width and a height exceeding the water column depth.

4.2.16 To assess cumulative impacts with neighbouring existing (Aberdeen, Kincardine and Seagreen 1) and planned OWFs (Seagreen 1A, Morven North and Morven South and Ossian), a version of the model is also run with structures representing Wind Turbines and OSPs within these Array Areas. For operational OWFs, turbine locations and MDS depth averaged blockage is determined from the infrastructure present. For proposed projects, turbine locations and MDS blockage are calculated from site-specific Environmental Impact Assessment (EIA) and or Scoping Reports. For Morven North and Morven South, information detailing the specific location of the Wind Turbines and OSPs could not be found at the time of modelling, therefore a uniform grid layout was assumed to estimate their positions within the Morven North and South Array Areas, this has been grouped under the label Morven in the figure below. Similarly Seagreen 1 and Seagreen 1A are grouped under the label Seagreen in the figure below.

4.2.17 Structure locations included in the model runs are shown in Figure 4.4.

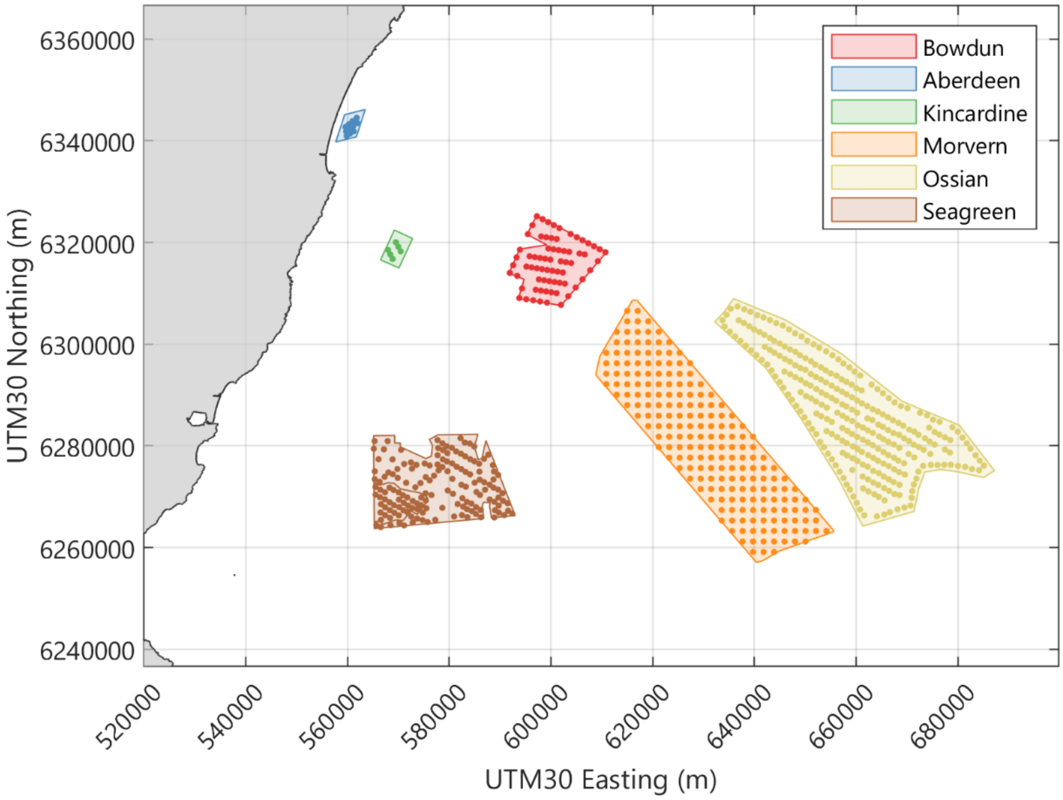

Figure 4.4: Model Structure Locations

4.3 Hydrodynamic Model Validation

4.3.1 The regional SEASTATES tide model largely controls the timing, magnitude and direction of water levels and currents entering and propagating through the Physical Processes Study Area. The regional model has been separately validated against the tide gauge and current meter data in numerous locations around the European continental shelf, including national tide gauges at Lerwick, Aberdeen and Leith (ABPmer, 2017).

4.3.2 The HD model has also been locally validated against water level data at the Aberdeen tide gauge, and against current data at two tidal diamonds (representative current speed and direction information found on Admiralty navigation charts) within the Physical Processes Study Area (Figure 4.4). No project specific HD data (waters levels or currents) were available at the time of validating the model.

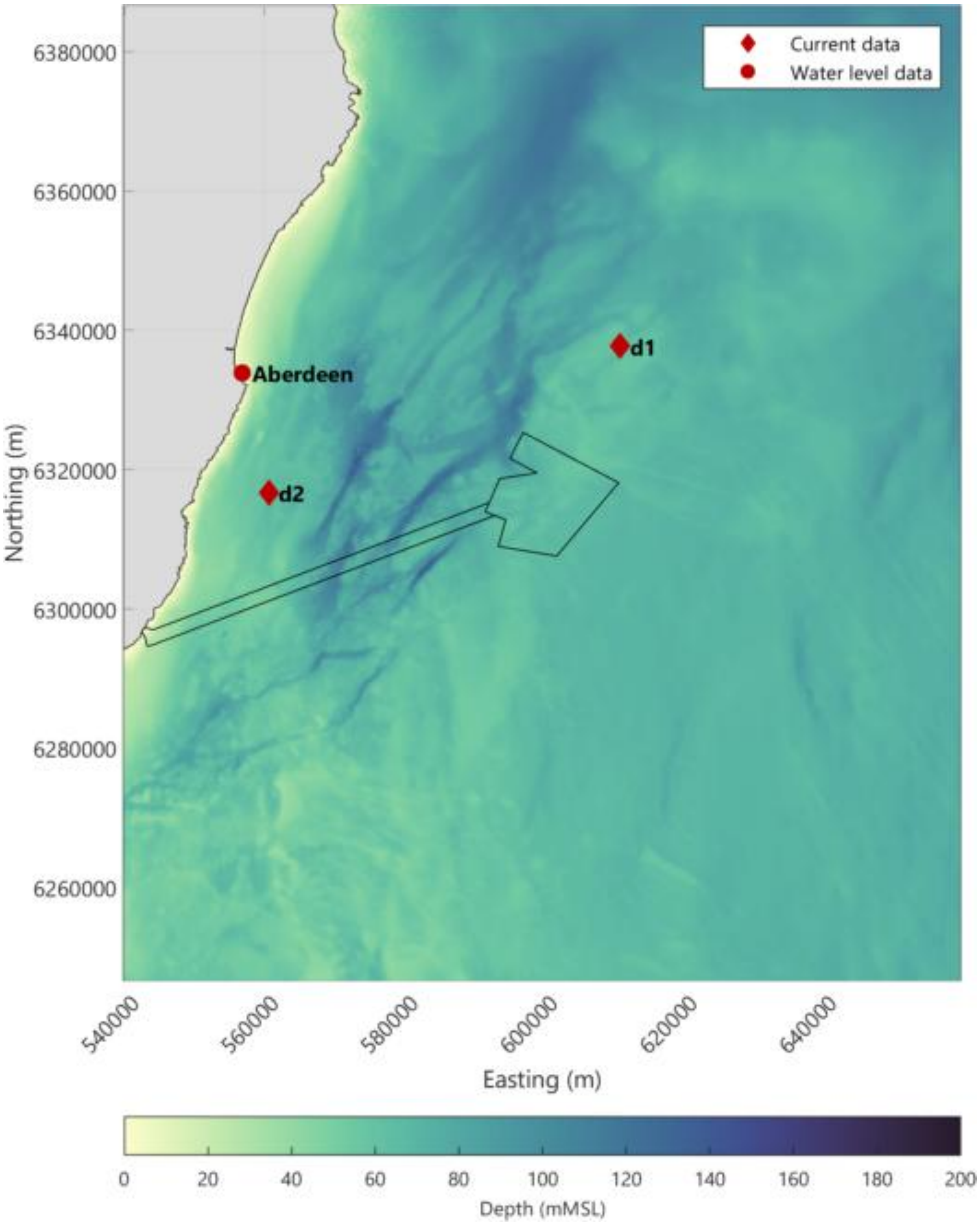

Figure 4.5: Data Locations for Hydrodynamic Model Validation

Water Levels

4.3.3 Water level model predictions against concurrent tide gauge observations over a representative 15-day period (29 April 2022 to 14 May 2022) have been analysed both visually and statistically. The HD model validation process has focused on this representative (approximately mean) spring-neap tidal cycle, identified and selected from a long time-series of modelled water level data at Aberdeen.

4.3.4 Water levels at the location of the Aberdeen tide gauge were extracted from the model and compared to the harmonically extracted tide only water level measured at the Aberdeen tide gauge for the same period.

4.3.5 Figure 4.6 and Figure 4.7 show timeseries and scatter comparison plots of the modelled water levels and measured water levels. The visual comparison shows the general levels, shape and phasing of the tide is reproduced well. A review of validation metrics indicates the model results reproduce the measured water levels well within the vicinity of the Aberdeen tidal gauge, and therefore are also likely to reproduce observed water levels equally as well, if not better, within the Proposed Development.

4.3.6 Some minor differences are observed, where the model simply cannot be calibrated further to simultaneously reproduce all details of all tides at all locations. Some differences may also be the result of local effects of complex bathymetry that are either not represented in the available bathymetry data, or not fully resolved by the 100 m resolution of the model. On individual tides, there may also be intermittent meteorological influence in the observed data, when compared to the tide only model prediction.

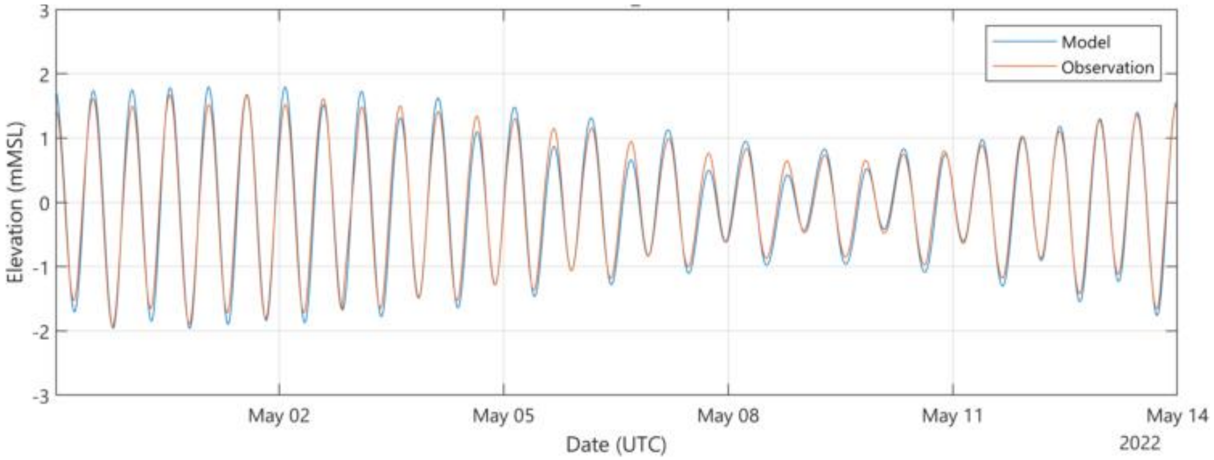

Figure 4.6: Comparison of Measured and Modelled Water Levels at Aberdeen Tide Gauge

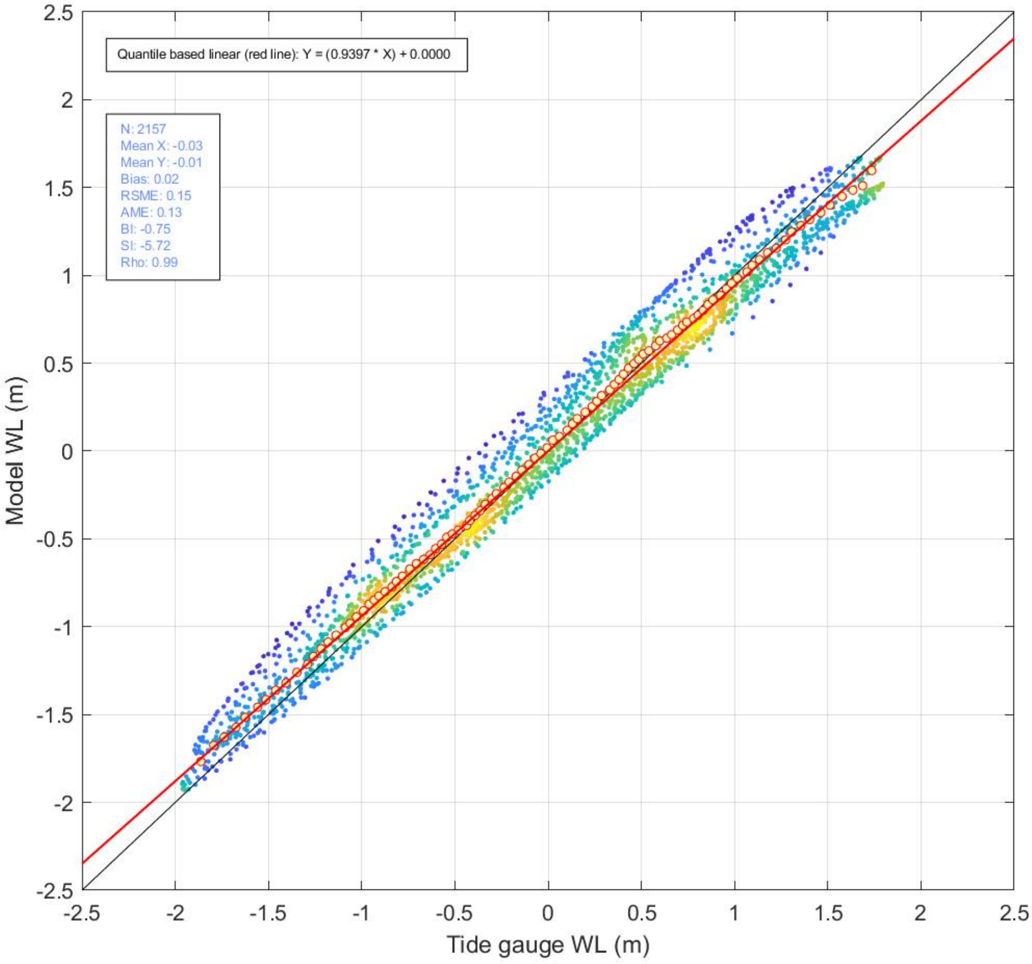

Figure 4.7: Quantile-Quantile Density Scatter Plot of Aberdeen Tide Gauge Water Levels vs. Modelled Water Levels

Current Speed and Direction

4.3.7 Figure 4.8 and Figure 4.9 compares the model tidal current speed and direction to tidal diamond data throughout a mean neap and mean spring tide. The model shows good agreement with these benchmark harmonic flow vectors, satisfactorily replicating both the general phasing, direction and magnitude of the flow around the Array Area.

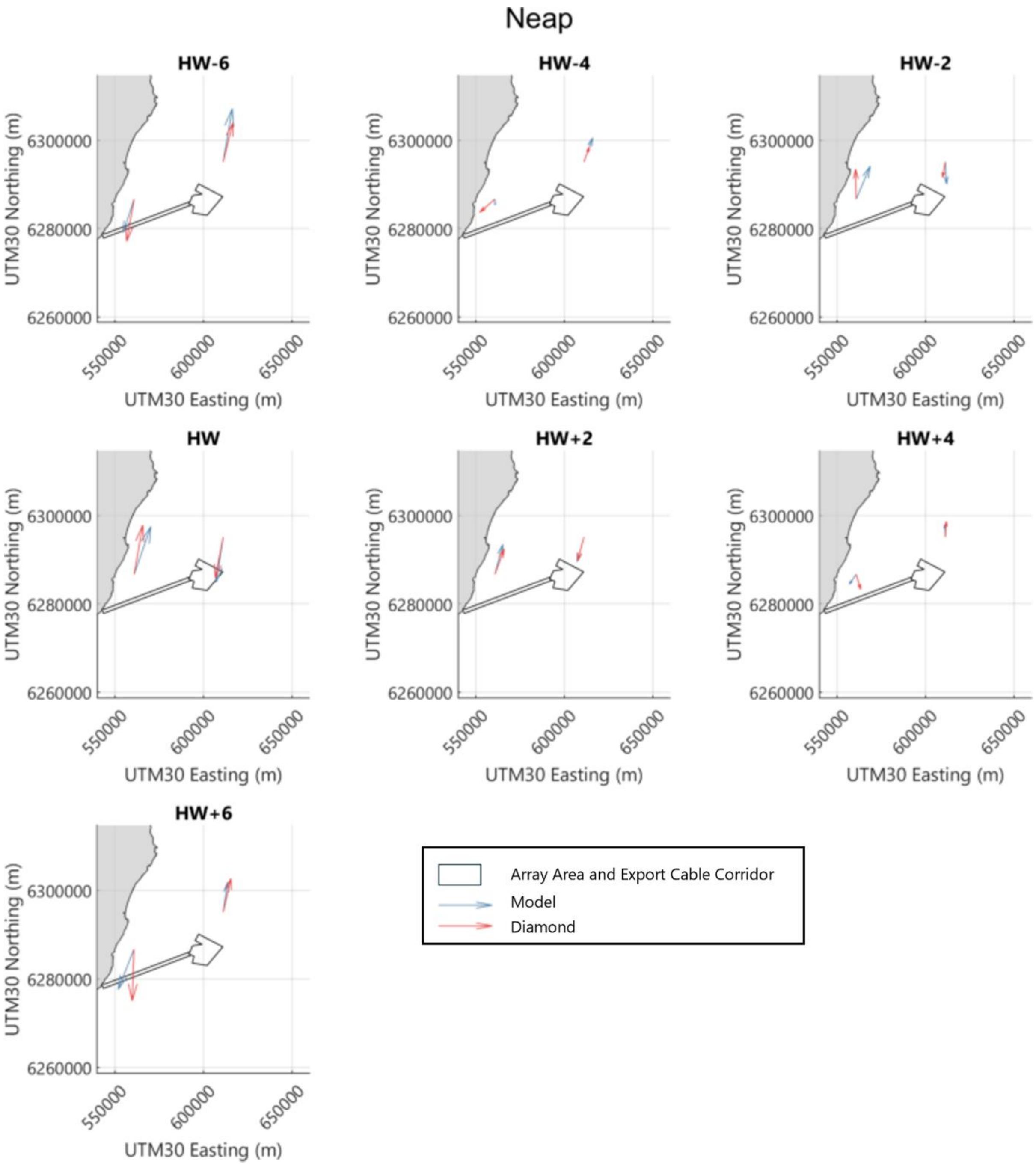

Figure 4.8: Comparison Between Tidal Diamond and Model Current Speed and Direction Over a Mean Neap Tidal Cycle, Referenced to Time of High Water (HW) in the Array Area

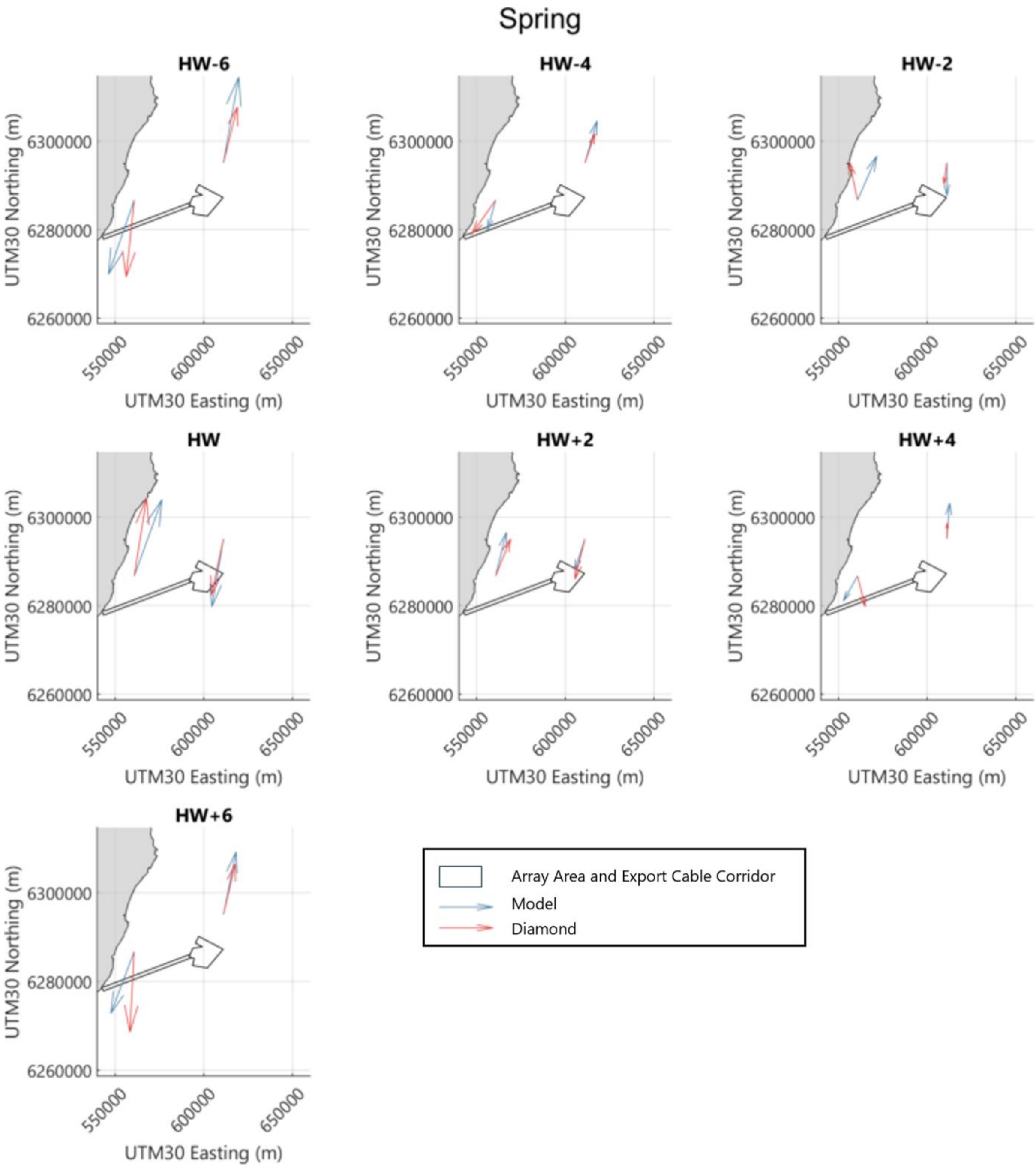

Figure 4.9: Comparison Between Tidal Diamond and Model Current Speed and Direction Over a Mean Spring Tidal Cycle, Referenced to Time of High Water (HW) in the Array Area

5 Sediment Disturbance

5.1 Overview

5.1.1 This section describes the design and inputs to a sediment plume model simulating patterns of SSC and resulting sediment deposition thickness in the Physical Processes Study Area. The model will be used to simulate the impact of various activities that may disturb sediment from the Proposed Development and the neighbouring proposed Morven North OWF, whose construction period may overlap with that of the Proposed Development. Activities such as foundation drilling, sandwave clearance using Mass Flow Excavation (MFE), and dredging could occur concurrently, potentially resulting in cumulative changes in SSC and bed levels.

5.1.2 Morven North has been included in the cumulative SSC modelling due to its proximity to the Proposed Development - approximately 10 km - which is only slightly beyond the extent of the spring tidal excursion ellipse. While cumulative impacts are not anticipated at this distance, the potential zone of interaction lies close to a designated area. As a precaution, sediment release from Morven North was modelled to confirm whether any cumulative effects could arise. The only other offshore wind farm with a potentially overlapping construction period is Ossian, located around 25 km from the Proposed Development. This distance is far greater than the spring tidal excursion ellipse, and therefore, no cumulative SSC impacts are expected from Ossian.

5.1.3 Scenario specific information and model inputs are described in Volume 3, Technical Appendix 7.3: Physical Processes Technical Assessment, including:

- disturbance activity type;
- release location;
- rate of movement of the source or static release;
- height of sediment release in the water column;
- rate of sediment release; and
- proportion of sediment in each grainsize category.

5.1.4 Scenario specific results are also provided in Volume 3, Technical Appendix 7.3: Physical Processes Technical Assessment, including:

- distribution of SSC at the end of active disturbance and one and three days thereafter;
- distribution of maximum instantaneous SSC at any time during and up to three days after the end of active disturbance;
- timeseries of SSC at the site of active disturbance and at nearby observation points during and after the end of active disturbance; and
- distribution of resulting sediment deposition thickness.

5.2 Sediment Plume Model Design

Sediment Plume Model General Design

5.2.1 The sediment plume model provides a timeseries simulation of SSC and settled sediment thickness in response to sediment release, advection and dispersion within the model domain. The sediment plume model is built using the MIKE21FM Particle Tracking (PT) module which simulates the horizontal and vertical advection and dispersion of sediment, represented as numerous discrete particles, within a temporally and spatially varying flow field.

Sediment Plume Model Extent, Resolution, Bathymetry and Hydrodynamic Model Inputs

5.2.2 The sediment plume model utilises the same forcing, roughness, bathymetry and model grid extent as the validated HD model described in Section 4, however with slightly reduced mesh resolution across the Physical Processes Study Area (~150 m compared to ~100 m compared to the HD model) in order to keep output file size manageable. The model is therefore able to consider a range of representative (e.g. spring and neap) tidal conditions.

Sediment Plume Model Sediment Types, Settling, Dispersion and Erosion Rates

5.2.3 Five different sediment grain size fractions are considered in the plume dispersion modelling, although only certain grades may be relevant to specific scenarios. The sediment grain size fractions considered and their associated settling rates (from Soulsby, 1997) are summarised in Table 5.1.

Table 5.1: Sediment Grain Size Fractions

Sediment Fraction Name	Representative Grain Size (μm)	Representative Settling Velocity (m/s)
Gravel	~8,000	0.5
Coarse sand	~1,000	0.1
Medium sand	~250	0.03
Fine sand	~150	0.01
Silt	~10	0.0001

5.2.4 A higher than default horizontal dispersion rate of 1.0 m^2/s is applied to all sediment grain size fractions. Smaller values (0.1 m^2/s and 0.01 m^2/s) were also considered but resulted in very narrow plumes with a very limited footprint of effect that did not appear to measurably disperse over the model simulation period. The value used is within the (relatively wide) range of generally reported values based on observations of this parameter. As a result, the rate of increase in plume width with time is (slightly) increased, which provides a more conservative indication of area of effect. The corresponding SSC values are (slightly) reduced but are still realistically elevated in comparison to typical baseline values. A vertical dispersion rate of 0.01 m^2/s is applied to all sediment grain size fractions.

5.2.5 Once deposited to the seabed, sediment in the model cannot be eroded and will remain in place. In practice, sediment in a plume that has been deposited to a similar area of seabed will immediately re-join the natural sedimentary environment and will be naturally eroded at the same time and rate as all other naturally present sediment in that location. By restricting re-erosion, the area and thickness of initial deposition from the sediment plume can be observed in more detail.

Sediment Plume Model Scenarios

5.2.6 Table 5.2 provides a summary of the sediment plume scenarios modelled, the location of each release, the mass of sediment and the type of sediment at each site.

Table 5.2: Sediment Disturbance Scenarios

Scenario No.	Mean Tidal Condition	Activity	Release Location (UTM 30)	Rate and Duration of Release	Grain Size Fractions (% of Total)
Array Area					
1	Neap	Pre-lay Trenching (MFE)	L-shaped route in Array Area	795 kg/s for 24 hours 50 min, 400 m/hr, at 3 m above bed. Rate assumes 100% release of material from the trench	10% gravel, 30% coarse sand, 30% medium sand, 20% fine sand, 10% silt
2	Spring				
3	Neap	Sand wave clearance (MFE)	Southern boundary of the Array Area (597857, 6308405)	1000 kg/s for 12 hours 20 min, static, at 3 m above bed	10% gravel, 30% coarse sand, 30% medium sand, 20% fine sand, 10% silt
4	Spring				
5	Neap	Drilling of foundations	Two neighbouring foundation locations at the southern boundary of the Array Area (597857, 6308405 and 598150, 6309490)	260.1 kg/s for 22.5 hours, static, at water surface	10% gravel, 30% coarse sand, 30% medium sand, 20% fine sand, 10% silt
6	Spring				
7	Neap	Dredge spoil disposal	Southern boundary of the Array Area (597857, 6308405)	1,749,000 kg, sudden release, static, at water surface	10% gravel, 30% coarse sand, 30% medium sand, 20% fine sand, 10% silt
8	Spring				

Scenario No.	Mean Tidal Condition	Activity	Release Location (UTM 30)	Rate and Duration of Release	Grain Size Fractions (% of Total)
Export Cable Corridor					
9	Neap	Pre-lay Trenching (MFE)	Export Cable Corridor (along whole length)	795 kg/s for ~5.5 days, 400 m/hr, at 3 m above bed. Rate assumes 50% release of material from the trench	10% gravel, 30% coarse sand, 30% medium sand, 20% fine sand, 10% silt
10	Spring				
11	Neap	Sand wave clearance (MFE)	Centre of Export Cable Corridor (571415, 6306188)	1,000 kg/s for 12 hours 20 min, static, at 3 m above bed	10% gravel, 30% coarse sand, 30% medium sand, 20% fine sand, 10% silt
12	Spring				
13	Neap	Dredge spoil disposal	Centre of Export Cable Corridor (571415, 6306188)	1,749,000 kg, sudden release, static, at water surface	10% gravel, 30% coarse sand, 30% medium sand, 20% fine sand, 10% silt
14	Spring				
Nearshore Region					
15	Neap	Sand wave clearance (MFE)	~2.5 km from Landfall (544948, 6296254)	1,000 kg/s for 12 hours 20 min, static, at 3 m above bed	10% gravel, 20% coarse sand, 50% medium sand, 10% fine sand, 10% silt
16	Spring				
17	Neap	Dredge spoil disposal	~2.5 km from Landfall (544948, 6296254)	1,749,000 kg, sudden release, static, at water surface	10% gravel, 20% coarse sand, 50% medium sand, 10% fine sand, 10% silt
18	Spring				
19	Neap	Landfall punch-out	Exit pit (542880, 6296983)	79.8 kg/s for 1 hour, static, at 5 m above bed	100% silt

Scenario No.	Mean Tidal Condition	Activity	Release Location (UTM 30)	Rate and Duration of Release	Grain Size Fractions (% of Total)
20	Spring				
Morven North OWF					
21	Neap	Sand wave clearance (MFE)	Closest point within Morven North OWF to the Bowdun Array Area aligned along the tidal axis (611227, 6300090)	1,000 kg/s for 12 hours 20 min, static, at 3 m above bed	10% gravel, 20% coarse sand, 30% medium sand, 20% fine sand, 20% silt
22	Spring				
23	Neap	Drilling of foundations	Two neighbouring foundation locations in the Morven North array area (611227, 6300090 and 61127, 6298854)	2,60.1 kg/s for 22.5 hours, static, at water surface	10% gravel, 20% coarse sand, 30% medium sand, 20% fine sand, 20% silt
24	Spring				
25	Neap	Dredge spoil disposal	Closest point within Morven North OWF to the Bowdun Array Area aligned along the tidal axis (611227, 6300090)	1,749,000 kg, sudden release, static, at water surface	10% gravel, 20% coarse sand, 30% medium sand, 20% fine sand, 20% silt
26	Spring				

5.2.7 Further details on the release scenario settings and assumptions applied are provided in Volume 3, Technical Appendix 7.3: Physical Processes Technical Assessment.

5.3 Sediment Plume Model Validation

5.3.1 Predictive location specific plume models are not normally validated, as location specific observations of the activities being simulated are rarely available. However, this type of modelling approach, in conjunction with validated HD inputs, is generally accepted to provide a realistic description of sediment plumes in the marine environment, as found in numerous similar recent offshore wind farm modelling studies undertaken by ABPmer (e.g. Awel y Môr Offshore Wind Farm Limited (ABPmer, 2021); Five Estuaries Offshore Wind Farm Limited (ABPmer, 2024)).

5.3.2 The following additional points also support confidence in the modelling process and results:

- Section 4.3 validates the accuracy and representativeness of the water level, current speed and direction data that control the rate and direction of sediment plume advection in the particle tracking model.
- The representative rate of dispersion is controlled by the model settings but can be variable in practice depending on other environmental conditions (e.g. wave conditions).
- The inputs and settings used in the model and the definitions of the sediment disturbance activities are considered to be conservatively realistic.
- The modelling process and analysis of the results are undertaken by an experienced coastal processes modeller.

6 Waves

6.1 Overview

6.1.1 This section describes the design and inputs to a wave model simulating patterns of wave height, period and direction in the Physical Processes Study Area. The model will be used to simulate baseline conditions, and the impact of the Wind Turbine foundations on baseline conditions.

6.1.2 Scenario specific information and model inputs are described in a separate report (Volume 3, Technical Appendix 7.3: Physical Processes Technical Assessment), including:

- foundation type, dimensions, number and layout for:
    - Bowdun OWF MDS;
    - Aberdeen OWF MDS;
    - Kincardine OWF MDS;
    - Seagreen 1 OWF MDS;
    - Seagreen 1A OWF MDS;
    - Morven North OWF MDS;
    - Morven South OWF; and
    - Ossian OWF MDS.

6.1.3 Scenario specific results are also provided in Volume 3, Technical Appendix 7.3: Physical Processes Technical Assessment, including:

- baseline wave height and wave direction; and
- patterns of change to wave height, wave period and wave direction as a result of the presence of wind farm foundations.

6.2 Wave Model Design

Wave Model General Design

6.2.1 The wave model is built using the MIKE21FM Spectral Wave (SW) module, which simulates the growth, decay and transformation of wind-generated waves and swell in offshore and coastal areas.

6.2.2 The wave model creates discrete simulations of wave height, period and direction throughout the domain, for a representative range of selected ‘everyday’ and extreme wave conditions (return periods and directions).

Wave Model Mesh

6.2.3 The extent and resolution of the wave model mesh is shown in Figure 6.1. A flexible mesh design (interlocking triangular ‘elements’ of varying shape and orientation) is used, providing tailored spatially variable resolution within a single model mesh.

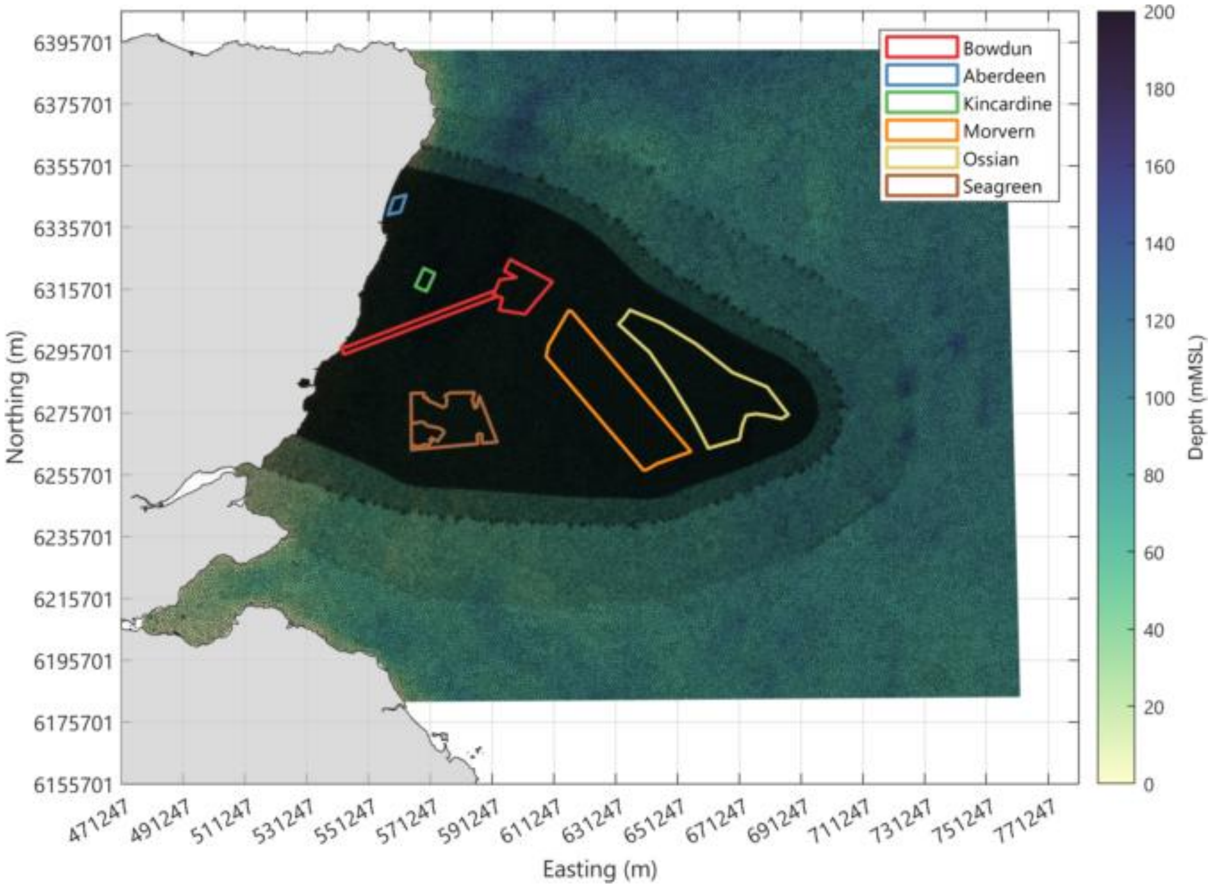

Figure 6.1: Spectral Wave Model Mesh

6.2.4 The overall extent of the model is smaller than that of the HD and PT model. The resolution of the flexible mesh is spatially variable, approximately 180 m in the central area, covering the coastline, Proposed Development and neighbouring existing and planned OWFs, gradually reducing to approximately 1 km at the open boundaries.

Wave Model Bathymetry

6.2.5 The bathymetry data used for the SW model is the same as that used within the same extent of the HD and sediment plume models. See Section 4.2 for more details.

6.2.6 The wave model is run with a constant 'MSL' condition (fixed at mean sea level with no tidal water level variation). This provides a central description of the range of total water depths that might be experienced within the Physical Processes Study Area. The timing of larger extreme wave events is independent of the timing of tidal processes (high water/low water/spring/neap). A relatively higher water level might allow larger waves to extend further onto or beyond otherwise shallower areas of the domain, or vice versa. However, the main effect of the foundations on waves is within the relatively deep offshore Array Area (approximately -65 mMSL), where there is only a small relative difference in total water depth between a mean tidal water level and a mean spring high or low water (±1.6 m). Sensitivity testing of the model indicates minimal difference as a result.

Wave Model Spectral and Time Formulations

6.2.7 A fully spectral formulation is used. The fully spectral formulation is based on a wave action conservation relationship where the directional-frequency wave action spectrum is the dependent variable (DHI, 2025). Of the available choices, this formulation is considered to be the most appropriate and accurate for the nature of the processes being simulated with respect to both general wave propagation and the effect of the Wind Turbine foundations.

6.2.8 A quasi-stationary time formulation is used. Time is removed as an independent variable and a steady state solution is calculated for each seastate being simulated. This choice is appropriate for the limited size of the model domain, within which waves are likely to achieve an equilibrium state dependant on the input wave and wind boundary conditions.

6.2.9 A logarithmic distribution of 36 spectral frequencies are resolved, equivalent to wave periods in the approximate range from 1 s to 30 s, with smaller intervals at smaller wave periods. This exceeds the default number and range (25 spectral frequencies, from 1.8 s to 18 s) in order to better resolve a wider range of wave periods.

6.2.10 Directional calculations are made using 32 directional sectors (each sector covering a range of 11.25°). This exceeds the default number (16 directional sectors, 22.5°) in order to reduce the occurrence of small magnitude ‘radial artefacts’ in the scheme effect results when obstacles representing the Offshore Infrastructure are included in the model. The baseline wave maps are largely unaffected by the difference.

Wave Model Boundary Conditions

6.2.11 The wave model is forced by wave conditions (height, period, direction and directional spreading) at the three offshore wave boundaries (along the northern, eastern and southern extents of the model domain), and by a constant wind speed and direction applied over the whole domain. The wave model is run with a constant MSL (no tidal water level variation) and no currents.

6.2.12 The wave condition scenarios considered by the model for the assessment are:

- wave coming directions (south south-east (SSE), south-east (SE), east south-east (ESE), east (E) and north (N)); and
- return periods (50% non-exceedance, 0.1 yr; 1 yr; 10 yr; 50 yr; 100 yr).

6.2.13 An understanding of the potential impacts of Offshore Infrastructure within this range of conditions will inform the assessments regarding potential impacts on sedimentary/coastal processes and flood risk. These conditions were initially determined using Extreme Value Analysis (EVA) for a location at the central point of the Array Area, using hindcast timeseries data from the separately validated ABPmer SEASTATES NW European Shelf Wave Hindcast Model (ABPmer, 2013).

6.2.14 The wave boundary condition is applied uniformly along the three offshore wave boundaries. The condition is defined by the significant wave height (Hs), peak wave period (Tp), mean wave direction (DirM) and directional standard deviation (DirStd). The directional return period wave boundary conditions tested are listed in Table 6.1. The shortest return period is the wave condition not exceeded 50% of the time, representing a relatively frequent, everyday wave condition; more severe but infrequent conditions are described by the associated 'Return Period' (RP) or likelihood of occurrence expressed in years.

6.2.15 The wind forcing is applied uniformly across the whole model domain area, representing the wind speed at 10 m above sea level normally associated with the target seastate. The associated wind direction is the same as the wave direction at the boundary. The wind boundary condition is required for natural patterns of wave propagation and development through the model domain from the offshore boundaries. Wind is also a realistic mechanism contributing to wave recovery in the lee of the Proposed Development. The associated directional return period values of wind speed and direction used are also shown in Table 6.1.

Table 6.1: Wave and Wind Boundary Conditions for Seastate Conditions Tested

Directional Sector	Case (RP)	Hs (m)	Tp (s)	DirM (°N, from)	Wind Speed @ 10 m (m/s)	Wind Direction (°N, from)
SSE	50% not exc.	1.6	6.5	157.5	8.9	157.5
	0.1 yr RP	5.1	8.6	157.5	17.7	157.5
	1 yr RP	8.2	10.9	157.5	22.7	157.5
	10 yr RP	10.6	12.4	157.5	26.2	157.5
	50 yr RP	11.9	13.2	157.5	27.5	157.5
	100 yr RP	12.4	13.4	157.5	28.2	157.5
SE	50% not exc.	1.4	6.6	135	7.6	135
	0.1 yr RP	4.3	8.3	135	15.4	135
	1 yr RP	6.9	10.6	135	20.0	135
	10 yr RP	9.0	12.0	135	25.0	135
	50 yr RP	10.1	12.8	135	26.8	135
	100 yr RP	10.5	13.0	135	27.0	135
ESE	50% not exc.	1.5	7.3	112.5	7.6	112.5
	0.1 yr RP	5.2	9.4	112.5	15.9	112.5
	1 yr RP	8.4	12.0	112.5	21.2	112.5
	10 yr RP	10.8	13.6	112.5	25.0	112.5
	50 yr RP	12.2	14.4	112.5	27.2	112.5
	100 yr RP	12.7	14.7	112.5	27.8	112.5

Directional Sector	Case (RP)	Hs (m)	Tp (s)	DirM (°N, from)	Wind Speed @ 10 m (m/s)	Wind Direction (°N, from)
E	50% not exc.	1.6	8.0	90	6.7	90
	0.1 yr RP	4.9	9.7	90	16.0	90
	1 yr RP	8.0	12.3	90	21.1	90
	10 yr RP	10.3	14.0	90	24.8	90
	50 yr RP	11.6	14.8	90	26.7	90
	100 yr RP	12.1	15.1	90	27.2	90
N	50% not exc.	1.7	8.8	0	8.3	0
	0.1 yr RP	4.8	9.2	0	16.2	0
	1 yr RP	7.8	11.8	0	21.3	0
	10 yr RP	10.1	13.4	0	24.5	0
	50 yr RP	11.4	14.2	0	26.2	0
	100 yr RP	11.9	14.5	0	27.0	0

Wave Model Parameters

6.2.16 The settings and values below are either default settings or within the range of normally recommended values and are consistent with numerous similar recent offshore wind farm modelling studies undertaken by ABPmer (e.g. Awel y Môr Offshore Wind Farm Limited (ABPmer, 2021); Five Estuaries Offshore Wind Farm Limited (ABPmer, 2024)).

6.2.17 Depth-induced wave breaking is the process by which waves dissipate energy when the waves are too high to be supported by the water depth, (i.e. reach a limiting wave height/depth-ratio). Wave breaking is described in MIKE21SW by standard equations that are scaled by a coefficient ‘Gamma’. A constant Gamma value of 0.8 was used.

6.2.18 Bottom friction is relevant where, as waves propagate into shallow water, the orbital wave velocities penetrate throughout the full water depth and the source function due to wave-bottom interaction becomes important. A large part of the model domain (towards the adjacent coastlines) is shallow enough, relative to the waves being simulated, to be affected by choices relating to the implementation of bottom friction. The dissipation source function used in the spectral wave module is based on the quadratic friction law and linear wave kinematic theory. The dissipation coefficient depends on the HD and sediment conditions. Sediment roughness is characterised in the MIKE21SW wave model by a Nikuradse Roughness length value of 0.04 m.

6.2.19 The MIKE21SW wave model also takes account of the following wave transformation processes (using default settings):

- White capping (Dissipation coefficients, constant C_{dis} = 4.5, constant $DELTA_{dis}$ = 0.5); and
- Quadruplet-wave interaction.

Wave Model Structures

6.2.20 To simulate a realistic worst-case blockage scenario for waves, the largest cross-sectional area within the water column for the Proposed Development foundation types described in Volume 1, Chapter 3: Project Description, has been calculated. This is used to derive a MDS blockage width for a model structure. These sub-grid scale Wind Turbine and OSP foundations, are represented in the model as a single triangular element centred on their locations, each containing a MIKE21 SW point structure assigned with the appropriate MDS blockage width and a height exceeding the water column depth.

6.2.21 To assess cumulative impacts with neighbouring existing (Aberdeen, Kincardine and Seagreen 1) and planned OWFs (Seagreen 1A, Morven North and Morven South and Ossian), a version of the model is also run with structures representing Wind Turbines and OSPs within these Array Areas. For operational OWFs, turbine locations and MDS blockage is determined from the infrastructure present. For proposed projects, turbine locations and MDS blockage are calculated from site-specific EIA and or Scoping reports. For Morven North and Morven South, information detailing the specific location of the Wind Turbines and OSPs could not be found at the time of modelling, therefore a uniform grid layout was assumed to estimate their positions within the Morven North and South Array Areas, , this has been grouped under the label Morven in Figure 4.4. Similarly, Seagreen 1 and Seagreen 1A are grouped under the label Seagreen in Figure 4.4.

6.2.22 Structure locations included in the model runs are shown in Figure 4.4.

6.3 Wave Model Validation

6.3.1 The wave model is not required to provide historical (hindcast) predictions of wave conditions in a timeseries mode, therefore, no direct validation of the new wave model against measured timeseries data is required.

6.3.2 Hindcast data from the ABPmer SEASTATES NW European Shelf Wave Hindcast Model are used to inform the boundary conditions. The SEASTATES wave hindcast model is described fully and has already been regionally validated against numerous wave buoys in ABPmer (2013). The SEASTATES wave hindcast model is also further locally validated against measured data from the Centre for Environment, Fisheries and Aquaculture Science (Cefas) Moray Firth Wave Buoy deployment, the closest measured wave dataset to the Physical Processes Study Area (Figure 6.2) – approximately 101 km from the Array Area. Wave data from January to December 2023 was found to capture a wide range of wave heights (<1 m to >3.5 m) and wave directions. Comparison against this period ensures the model performs well over a wide range of conditions.

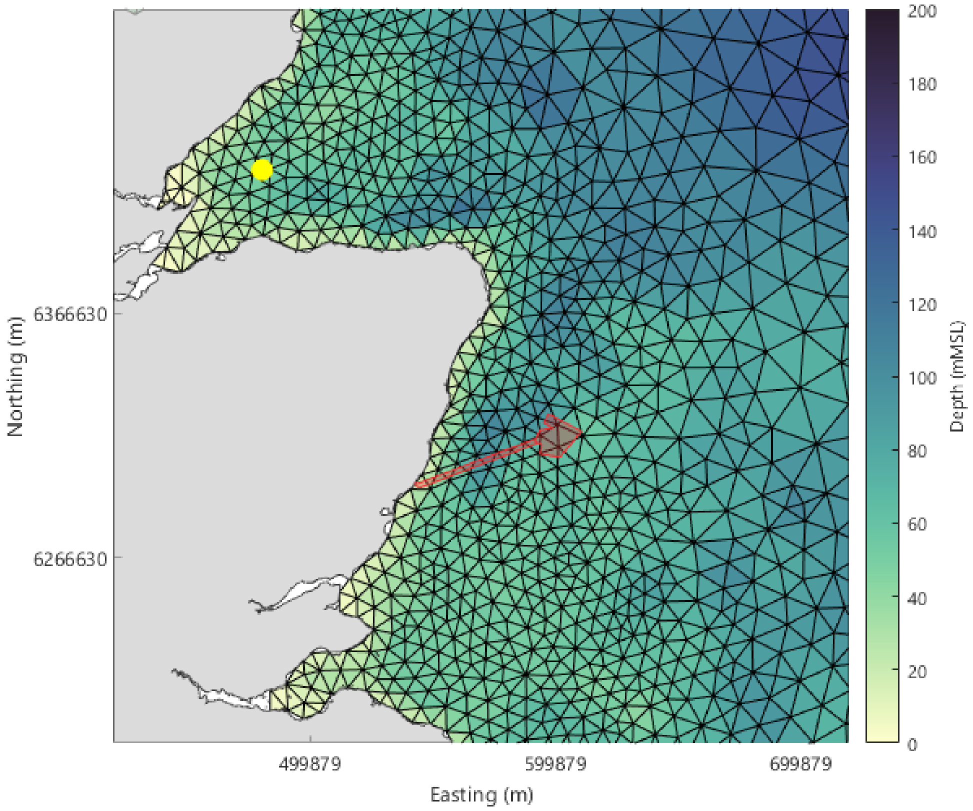

Figure 6.2: Wave Buoy and Bowdun Site Outline on the SEASTATES North Atlantic Spectral Wave Model Mesh

6.3.3 The accuracy of the SW model in predicting Hs, Tp and peak direction was assessed by comparing measured wave buoy data with coincident timeseries output at the location of the wave buoy extracted from the SEASTATES SW model.

6.3.4 Figure 6.3 show timeseries comparison plots of modelled Hs, Tp and peak direction against measured values. The visual comparison shows the general magnitude and timing of wave events are reproduced well. The above information validates the SEASTATES hindcast model data to provide a realistic representation of wave conditions and climate within the Physical Processes Study Area.

6.3.5 The local wave model performance is not validated explicitly. However, the important components of the model design and inputs (extent, resolution, bathymetry, coastlines and boundary conditions) have been individually validated to be realistic, accurate and detailed. The resulting model is therefore expected to perform to a similar level.

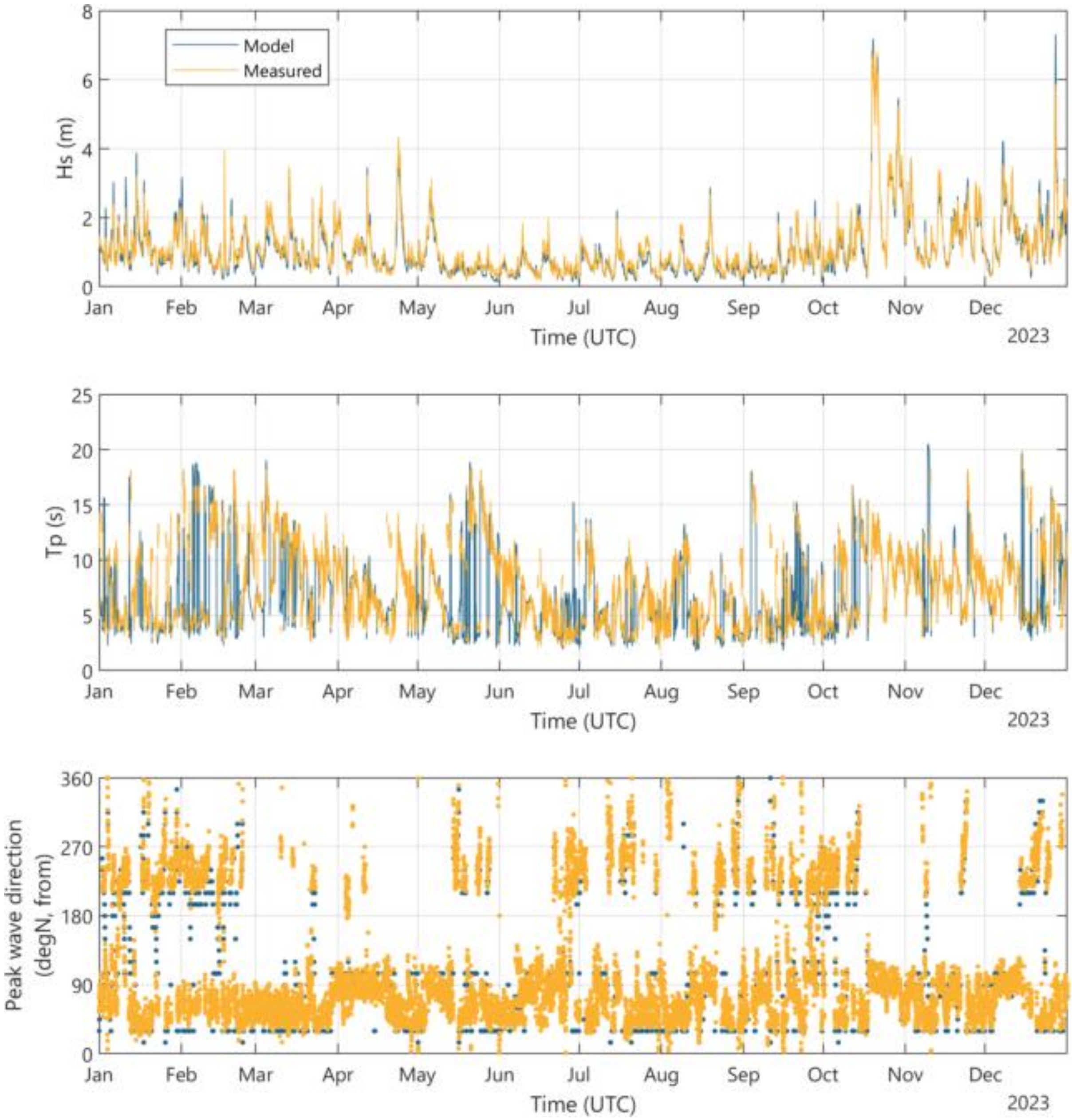

Figure 6.3: Comparison of Measured and Modelled Wave Parameters at Cefas Moray Firth Wave Buoy

7 Summary

7.1.1 This Physical Processes Technical Report outlines the design and validation of numerical models developed for Volume 2, Chapter 7: Physical Processes.

7.1.2 HD modelling has been undertaken to assess the impact of the Proposed Development, alongside cumulative impacts with neighbouring operational/proposed OWFs (Aberdeen, Kincardine, Seagreen 1, Seagreen 1A, Morven North, Morven South and Ossian), on tidal currents and water levels during the operational phase. The HD model was built using DHI's MIKE21FM HD module. The model utilises a flexible mesh with increased resolution in regions of interest (e.g. around the Proposed Development). Modelled water levels were validated against Aberdeen tide gauge measurements for a period covering a mean spring-neap tidal cycle. Modelled tidal currents were validated against Admiralty tidal diamond velocities near the Array Area. The HD model performs well, satisfactorily recreating the general phasing and magnitude of tide-only water levels and currents in the Physical Processes Study Area. To simulate a realistic worst-case blockage scenario for tidal currents and water levels, a MDS depth averaged blockage width was applied to sub-grid scale model structures representative of Wind Turbines and OSPs in the Bowdun, Aberdeen, Kincardine, Seagreen 1, Seagreen 1A, Morven North and Morven South and Ossian Array Areas (both separately and cumulatively).

7.1.3 Sediment plume modelling has been undertaken to characterise the patterns of elevated SSC and sediment deposition resulting from sediment disturbance during the construction phase of the Proposed Development. The sediment plume models were built using DHI's MIKE21FM PT module. Models simulating sediment release from MFE pre-lay trenching, MFE sandwave clearance, drilling, Landfall punch-out via trenchless techniques (such as Horizontal Directional Drilling) and dredge spoil disposal have been run.

7.1.4 Wave modelling has been undertaken to characterise the impact of the Proposed Development on the wave regime (wave height, period and direction). Cumulative impacts with neighbouring existing (Aberdeen, Kincardine and Seagreen 1) and planned OWFs (Seagreen 1A, Morven North and Morven South and Ossian) have also been separately assessed. The wave model was built using DHI's MIKE21FM SW module, simulating specific wind/wave events for a representative range of selected 'everyday' and extreme wave conditions (return periods and directions). To simulate a realistic worst-case blockage scenario for waves, a MDS blockage width was applied to sub-grid scale model structures representative of Wind Turbines and OSPs in the Bowdun, Aberdeen, Kincardine, Seagreen 1, Seagreen 1A, Morven North and Morven South and Ossian Array Areas (both separately and cumulatively).

7.1.5 The HD, particle tracking, and spectral wave numerical models described in this report are robust tools but are subject to a number of assumptions. These include the input parameters (using a representative sediment grain size for sediment transport for example), scenario assumptions (e.g. the volume and location of drilling spoil released under different release scenarios) as well as uncertainty in the underpinning datasets (e.g. wave data and bathymetry data).

Such uncertainty is managed in the design of the modelling study, validation (where appropriate and possible) of models and the interpretation of the model results in the context of the baseline and using expert judgement.

7.1.6 The model settings and assumptions applied are within the range of normally recommended values and are consistent with numerous similar recent offshore wind farm modelling studies undertaken by ABPmer (e.g. East Anglia Offshore Wind (East Anglia ONE, 2012); Moray Offshore Renewables Limited (Moray West Offshore Windfarm, 2018); Navitus Bay Development Limited (Navitus Bay, 2013); Awel y Môr Offshore Wind Farm Limited (ABPmer, 2021); Five Estuaries Offshore Wind Farm Limited (ABPmer, 2024)).

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