Hornsea Project Four: Environmental Statement (ES)

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Volume A5, Annex 1.1: Marine Processes Technical Report

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Glossary

Term	Definition
Advect	To be carried along with the tidal flow.
Amphidrome	A nodal point with minimal tidal range.
Commitment	A term used interchangeably with mitigation and enhancement measures. The purpose of Commitments is to reduce and/or eliminate Likely Significant Effects (LSEs), in EIA terms. Primary (Design) or Tertiary (Inherent) are both embedded within the assessment at the relevant point in the EIA (e.g. at Scoping, Preliminary Environmental Information Report (PEIR) or Environmental Statement (ES)). Secondary commitments are incorporated to reduce LSE to environmentally acceptable levels following initial assessment i.e. so that residual effects are acceptable.
Cumulative effects	The combined effect of Hornsea Four in combination with the effects from a number of different projects, on the same single receptor/resource. Cumulative impacts are those that result from changes caused by other past, present, or reasonably foreseeable actions together with Hornsea Four.
Dispersion	To be mixed into the water body by turbulent effects.
Drill arisings	All materials (solids and liquids produced from the activity of drilling into the seabed.
Drill cuttings	Larger sized casts produced from drilling that are likely to settle to the seabed.
Far-field	An area remote from the near-field which is connected by a pathway.
Hornsea Project Four Offshore Wind Farm	The term covers all elements of the project (i.e. both the offshore and onshore). Hornsea Four infrastructure will include offshore generating stations (wind turbines), electrical export cables to landfall, and connection to the electricity transmission network. Hereafter referred to as Hornsea Four.
Inshore	Between the nearshore and offshore. Generally, an area with more shelter than the offshore and where some coastal influences can still be expected.
Isobath	A seabed depth contour commonly referenced to chart datum.
Long-term	Of several years or decades, accounting for year to year variations.
Longshore drift	Movement of (beach) sediments approximately parallel to the coastline, a process mainly driven by the oblique approach of waves.
Maximum Design Scenario	The maximum design parameters of each Hornsea Four asset (both on and offshore) considered to be a worst case for any given assessment.
Megaripples	Bedform features commonly formed of sands, defined here with crest to crest wavelengths between 0.5 to 25 m.
Mixed layer depth	Depth of surface mixed layer above density stratification formed by thermocline or halocline, if present.
Near-field	The area immediately associated with a source of change, such as around the base of a wind turbine foundation.
Nearshore	Generally, a shallow water area close to the coast.
Offshore	Generally, a more exposed and deeper water area away from any coastal influence.
Order Limits	The limits within which Hornsea Project Four (the 'authorised' project) may be carried out.

Term	Definition
Orsted Hornsea Project Four Ltd.	The Applicant for the proposed Hornsea Project Four Offshore Wind Farm Development Consent Order (DCO).
Sandwave	A bedform feature commonly formed of sands, defined here with a crest to crest wavelength greater than 25 m, often superimposed with megaripples.
Short-term	A sub-set of a repeating cycle, e.g. likely to be a few days, weeks, or months but much less than a year.

Acronyms

Acronym	Definition
2D-H	Two-dimensional in horizontal plane
ABS	Acoustic Back-Scatter
AfL	Agreement for Lease
AODN	Above Ordnance Datum Newlyn
AVHRR	Advanced Very-High-Resolution Radiometer
BGS	British Geological Survey
BODC	British Oceanographic Data Centre
CBRA	Cable Burial Risk Assessment
CCO	Channel Coastal Observatory
CCS	Carbon Capture and Storage
CD	Chart Datum, the vertical datum of a navigation chart
C_D	Drag coefficient
CFE	Controlled Flow Excavator
CO_2	Carbon Dioxide
D	Diameter (of pile)
DCO	Development Consent Order
DWR	Directional Wave Recorder
D_{50}	Sediment diameter representing 50% by mass is larger and 50% smaller
D_{90}	Sediment diameter where 90% of the sample by mass is smaller
E	East
ECC	Export Cable Corridor
EIA	Environmental Impact Assessment
EMODnet	European Marine Observation and Data Network
ERYC	East Riding of Yorkshire Council
ES	Environmental Statement
EUNIS	European Nature Information System
GBS	Gravity Base Structure (also sometimes referred to as Gravity Base Foundation or GBF)
h	Water depth
HAT	Highest Astronomical Tide
HDD	Horizontal Directional Drilling
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
H_s	Significant wave height (m)
IECS	Institute of Estuarine and Coastal Studies, University of Hull

Acronym	Definition
JFE	Johnston Field Extension
JNCC	Joint Nature Conservation Committee
L	Wavelength (of surface water waves)
LAT	Lowest Astronomical Tide
MBES	Multi-Beam Echo Sounder
MDS	Maximum Design Scenario
MHWN	Mean High Water Neaps
MHWS	Mean High Water Springs
MLD	Mixed Layer Depth
MLWN	Mean Low Water Neaps
MLWS	Mean Low Water Springs
MNR	Mean Neap Range
MSL	Mean Sea Level
MSR	Mean Spring Range
NCERM	National Coastal Erosion Risk Mapping
N	North
NE	North-east
NNE	North-north-east
NUI	Normally Unmanned Installation
OBS	Optical Back-Scatter
ODN	Ordnance Datum Newlyn
OSS	Offshore Substation
PEIR	Preliminary Environmental Information Report
PML	Plymouth Marine Laboratory
P_{str}	Power consumption per unit area
RP	Return Period
SAC	Special Area of Conservation
SBP	Sub-Bottom Profile
SEAL	Shearwater Elgin Area Line
SMP	Shoreline Management Plan
SPM	Suspended Particulate Matter
SSC	Suspended Sediment Concentration
SSS	Side-Scan Sonar
SWAN	Simulating WAves Nearshore; a third-generation spectral wave model
TSHD	Trailing Suction Hopper Dredger
T_z	Zero up-crossing wave period (s)
u_{bot}	bottom orbital velocity
UHRS	Ultra-High Resolution Survey
UKCP18	United Kingdom Climate Projections 2018
UKHO	United Kingdom Hydrographic Office
WTG	Wind Turbine Generator
WWII	World War Two
Yr	Year

Units

Unit	Definition
km	kilometre
kg	kilogram
l	litre
m	metre
mg	milligram
mm	millimetre
m/s	metres/second
phi	Logarithmic scale of sediment size
s	Second
W	Watts
°C	Degrees Centigrade
%	Percent / percentage

1 Introduction

1.1 Project background

1.1.1.1 Orsted Hornsea Project Four Ltd. (hereafter the 'Applicant') is proposing to develop the Hornsea Project Four Offshore Wind Farm (hereafter 'Hornsea Four'). Hornsea Four will be located approximately 69 km offshore (at the closest point) from the coastline of East Riding of Yorkshire in the Southern North Sea. This will be the fourth project to be developed in the former Hornsea Zone. Hornsea Four will comprise of both offshore and onshore infrastructure including offshore generating stations (wind turbines), electrical export cables to landfall, and connection to the electricity transmission network. The location of Hornsea Four is shown in **Figure 1**.

1.1.1.2 The Hornsea Four Agreement for Lease (AfL) area was 846 km^2 at the Scoping phase of project development. In the spirit of keeping with Hornsea Four's approach to Proportionate Environmental Impact Assessment (EIA), Hornsea Four has given due consideration to the size and location (within the existing AfL area) of the final project that is being taken forward to Development Consent Order (DCO) application. This consideration is captured internally as the "Developable Area Process", which includes Physical, Biological and Human constraints in refining the developable area, balancing consenting, and commercial considerations with technical feasibility for construction.

1.1.1.3 The combination of Hornsea Four's Proportionality in EIA and Developable Area Process has resulted in a marked reduction in the array area taken forward at the point of completing the Environmental Statement (ES). Hornsea Four adopted a major site reduction from the array area presented at Scoping (846 km^2) to the Preliminary Environmental Information Report (PEIR) boundary (600 km^2), with a further reduction adopted for the ES and DCO application (468 km^2) due to the results of the PEIR, technical considerations and stakeholder feedback. The evolution of the Hornsea Four Order Limits is detailed in **Volume A1, Chapter 3: Site Selection and Consideration of Alternatives** and **Volume A4, Annex 3.2: Selection and Refinement of the Offshore Infrastructure**.

1.1.1.4 Cooper Marine Advisors Ltd was commissioned by the Applicant to undertake a Marine Geology, Oceanography and Physical Processes assessment of the marine areas being developed for Hornsea Four and the surrounding areas. The assessment is developed largely using an evidence-based approach, drawing on previous studies of comparable projects in comparable offshore settings, but is also supported by project specific modelling of waves, tides, and sediment plumes (**Appendix C**).

1.2 Marine Processes

1.2.1.1 The topic of Marine Geology, Oceanography and Physical Processes is also commonly referred to as "Marine Processes", or when issues pertain to the nearshore and coastline then the term "Coastal Processes" is also frequently used. The use of either term is intended to be inclusive of marine geology, oceanography, and physical processes at either location. For simplicity, the term "Marine Processes" is used throughout this document.

1.2.1.2 A baseline assessment of marine processes provides an understanding of how the seabed and coastline respond to driving "metocean" conditions; notably waves and tides. The morphological response of the seabed and coastline to these conditions is linked to understanding their potential erodibility as well as any geological constraints which may act to moderate a more rapid change.

1.2.1.3 The impact assessment of Hornsea Four considers how the proposed development may modify the baseline conditions during construction, operation, and decommissioning periods.

1.3 Report Structure

1.3.1.1 This Technical Report is supplementary to **Volume A2 Chapter 1: Marine Geology, Oceanography and Physical Processes** of the ES, and serves to provide a more detailed description of the approach, evidence base, site-specific modelling and provides the findings of an assessment of the potential for change to marine processes because of the construction, operation and maintenance, and decommissioning of Hornsea Four, as well as supporting technical material. This approach allows for a more proportionate chapter, in line with Hornsea Four's proportionate approach to EIA.

1.3.1.2 The report is structured as follows:

- **Section 1** introduces Hornsea Four and the topic of marine processes;
- **Section 2** outlines the assessment approach and scope;
- **Section 3** provides a baseline review and identifies key receptors in the marine physical environment;
- **Section 4** considers the potential effects from Hornsea Four; and
- **Section 5** offers a list of all the technical references informing this assessment.

1.3.1.3 The following technical appendices are also included for supporting information:

- **Appendix A** provides a review of comparable baseline conditions across the former Hornsea Zone;
- **Appendix B** sets out the primary baseline evidence, including a summary of the geophysical surveys relevant to marine processes; and
- **Appendix C** gives details the marine process modelling of Hornsea Four which supports the EIA.

2 Assessment Approach

2.1 Overview

2.1.1.1 The assessment is based on the "source-pathway-receptor" approach. This approach also helps confirm a relevant study area to extend across all locations with development activities that create potential sources of effects in the marine environment and the process influences which may link such effects via pathways to environmental receptors. A baseline understanding is then established for this study area to act as the reference condition against which the scale of these potential effects can be determined. Both the baseline and the impact assessment are delivered using an evidenced-based approach, supported by site-specific surveys and modelling, as appropriate.

2.2 Source-pathway-receptor

2.2.1.1 A development activity which has the potential to create a physical change in the marine environment establishes a source of an effect in the near-field; the origin of a potential impact. There are many different types of development activities which are planned to occur at different locations and at different periods in the Hornsea Four lifecycle (i.e. construction, operation, and decommissioning periods). These sources are typically associated with site-specific activities related to either seabed preparation, cable laying or the installation (and presence thereafter) of a large number of individual foundation structures. Each type of source may lead to a different type of local change in the near-field marine processes. All sources of effect will occur within the boundary of the Order Limits.

2.2.1.2 Given the various design options under consideration, the Maximum Design Scenario (MDS) is taken to represent the conservative case which leads to the greatest scale of effect at source.

2.2.1.3 Once a change in near-field marine processes has occurred (e.g. elevated levels of suspended sediment during seabed preparation activities, etc.) then the potential exists for that change to be transmitted beyond the source and to extend over a larger area; the far-field. The means by which any extended effect reaches a receptor sensitive to that change defines the pathway connecting source to receptor. The far-field can be expected to extend beyond the boundary of the Order Limits in some cases. For example, the scale of tidal advection may have the potential to carry sediment plumes beyond the Order Limits.

2.2.1.4 Receptors which are connected to a source effect via a pathway may be part of the marine physical environment (e.g. Flamborough Front, the sandbank feature Smithic Bank and the Holderness Coast) or related to other receptors such as those associated with the marine ecological environment. The marine processes topic identifies the receptor features which are only related to the marine physical environment.

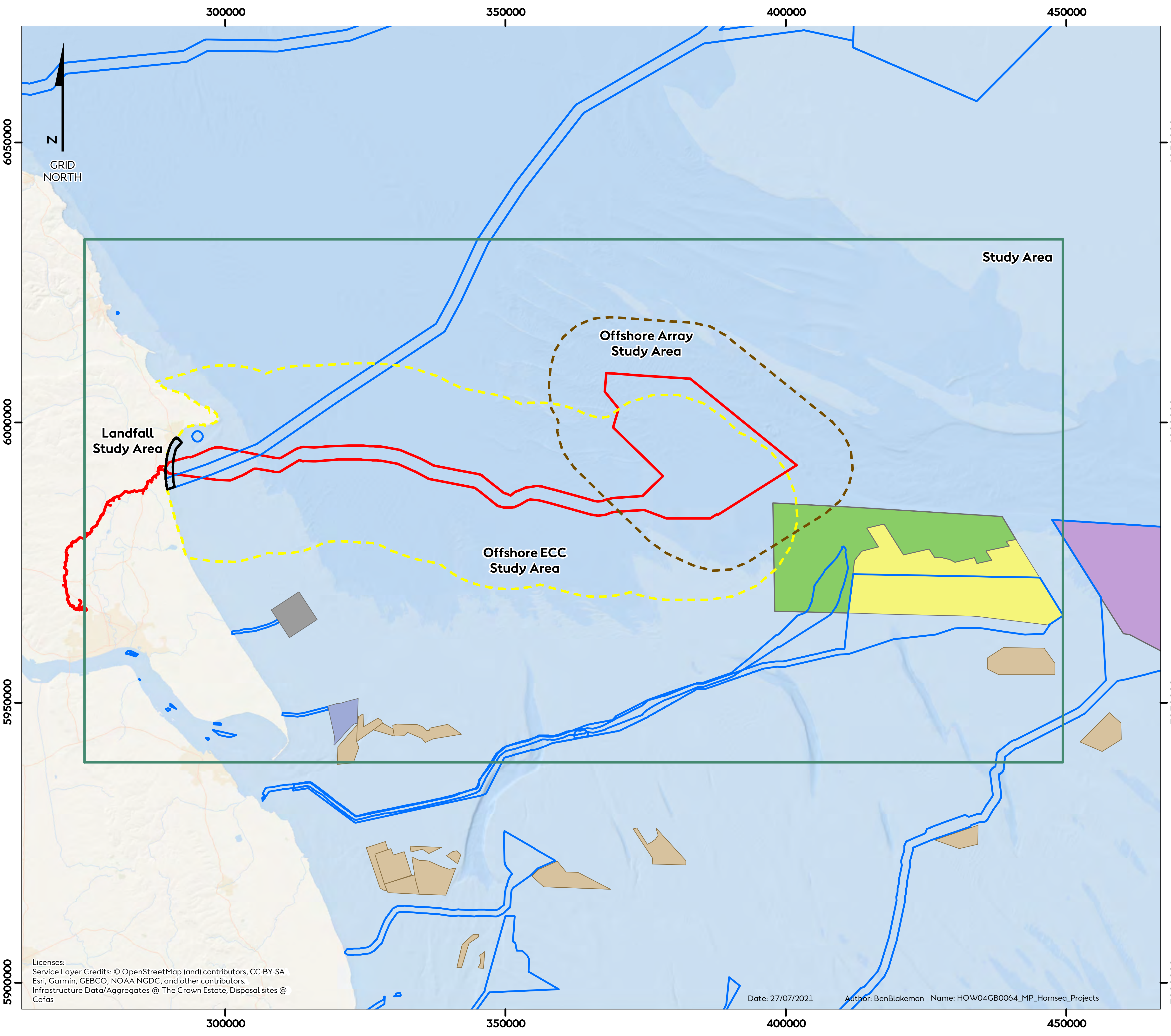
2.3 Establishing the study area

2.3.1.1 The marine processes study area encompasses the near-field sources created by any project activities that have a potential to disturb sediments or block waves and flows, and the pathways which have the capacity to extend effects from a source across a wider area (the far-field). In addition, where there are adjacent activities which may also create a similar type of effect over a similar period then this is also considered to be part of the study area in order that cumulative effects between such activities can be considered. In relation to Hornsea Four, these include Hornsea Project One and Hornsea Project Two Offshore Wind Farm (hereafter Hornsea Project One and Hornsea Project Two) which are around 3.4 km to the south west at the closest point.

2.3.1.2 Hornsea Project Three Offshore Wind Farm (hereafter Hornsea Three) is less relevant to cumulative interactions because of the further distance to the east from Hornsea Four (around 46.5 km at the closest point), such that flow and sediment pathways do not pass between these two projects and waves are mainly from the northerly sector which would not pass effects from one project to another. An additional moderation on potential cumulative interactions is that final layouts and foundation types now installed at both Hornsea Project One and Hornsea Project Two utilise a fewer number of smaller diameter structures than the more conservative cases considered in their respective EIAs. The expected consequence of this moderation is for much reduced potential overlapping wave or tidal wake type effects between arrays across the former Hornsea Zone. On this basis, Hornsea Three does not present a rationale for inclusion in the study area or for consideration of cumulative impacts with Hornsea Four.

2.3.1.3 The study area also recognises sub-areas for different types of project activity and contrasting marine process environments. For example, short-term installation activities at the cable landfall will occur in a shallow and sheltered nearshore environment which will be very distinct from construction activities required across the more exposed offshore array area where the placement of a large number of foundations may then create longer lasting blockage type effects over the operational period. Accordingly, activities across the landfall, offshore export cable corridor (ECC) and the offshore array form the basis of describing sub-areas. Importantly, sources which may occur in any sub-area may still have the potential to affect more remote receptors in other parts of the study area where there are connecting pathways.

2.3.1.4 **Figure 1** presents the marine processes study area for Hornsea Four, along with sub-areas established for the landfall, offshore ECC and offshore array area. The offshore ECC and offshore array areas include buffer zones to represent a potential "zone of influence" for any sediment plumes that might be created within the main areas of activity. It is important to note that a zone of influence is not an area of impact. The buffer zones are scaled to conservatively represent the equivalent distance of tidal excursion on a mean spring tide. For the offshore ECC, this is taken as around 15 km based on the nearshore flows and for the offshore array area this is taken as a distance of around 10 km representing slightly weaker offshore flows. The wider study area aims to represent where changes in wave energy transmission might occur for waves which pass from the offshore, across the array and reach the adjacent coastline, especially where there is a potential for wider interactions with other adjacent offshore wind farms.



Hornsea Four

Figure 1

Marine processes study area and sub-areas

- Order Limits
- Landfall Study Area
- Offshore Array Study Area
- Offshore ECC Study Area
- Study Area
- Hornsea Project One
- Hornsea Project Two
- Hornsea Three
- Humber Gateway
- Westermost Rough
- Existing Licence Areas for Export Cables and Disposal Sites
- Minerals Aggregates Site Agreements (TCE)

Coordinate system: ETRS 1989 UTM Zone 31N

Scale@A3: 1:650,000

0 10 20 Kilometres

0 5 10 Nautical Miles

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...	First Issue	07/06/2019
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Marine processes study area and sub-areas
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2.4 Establishing the baseline

2.4.1.1 The baseline description of marine processes is established for the study area and each sub-area; landfall, offshore ECC and offshore array area and by drawing on the evidence base of data and information for these locations. This baseline represents conditions that are expected to prevail without any development taking place and with consideration of an equivalent period as the lease (i.e. 35 years for the operational period). This description provides the reference conditions against which potential effects of the development are expected to occur. **Section 3** provides details of the baseline assessment.

2.5 Establishing the scope of the assessment

2.5.1 Issues scoped into assessment

2.5.1.1 The issues which have been assessed have been established from a full review of the Scoping Opinion received in November 2018 (Planning Inspectorate 2018) and are summarised in **Table 1** (see also **Volume 4, Annex 5.1 Impacts Register**). These issues are identified as impact pathways and receptors and can be grouped by project phase and type of effect as either:

- Short-term (days to months) sediment disturbance events during construction, maintenance and decommissioning periods which may lead to sediment plumes of elevated suspended sediment concentration and the associated areas of the seabed with increased levels of deposition once the material settles out of the water column; and
- Long-term (several years) blockage related effects during the operational period of the wind farm which are due to foundation or rock berm structures being placed on the seabed which have a sufficiently large profile to individually and/or collectively interfere with waves or flows to develop wake effects, as well as interrupt sediment pathways.

Table 1: Summary of impact sources and pathways.

Project Phase	Impact sources and pathways
Construction	Seabed preparation activities (e.g. levelling for foundation bases, sandwave clearance for cable installation, etc.) which may lead to a requirement for removal of seabed sediment and associated spoil disposal elsewhere, creating short-term periods of elevated turbidity (advected away as sediment plumes) and potential smothering of receptors by deposition (due to settling of excavated material).
Construction	Installation activities which may lead to short-term locally elevated turbidity at source (e.g. pile drilling and cable laying, etc.) which could subsequently spread by tidal advection (as a sediment plume) and potential smothering of receptors by deposition (due to settling of excavated material).
Operation and Maintenance	Installed foundations creating long-term local blockage of flows causing local (near-field) scouring of the seabed (assumes scour protection is not pre-installed).
Operation and Maintenance	Installed foundations creating long-term local blockage of flows leading to turbulent wakes which extend to potentially interfering with far-field receptors.
Operation and Maintenance	Installed foundations creating long-term local blockage and modification to wave energy transmission which propagate to a far-field receptor, including cumulative effect with adjacent offshore wind farms.

Project Phase	Impact sources and pathways
Operation and Maintenance	Rock armouring at nearshore cable crossing creating long-term local blockage to sediment pathways.
Operation and Maintenance	Reburial of cables with cable protection (rock armour) which leads to a modified seabed profile which may have an effect on local seabed processes (sediment pathways and morphology).
Decommissioning	Activities to remove installations (e.g. foundations) which may lead to short-term locally raised turbidity at source.
Decommissioning	Removal of foundations with cessation of blockage related effects on waves and tidal flows, reverting to a (future) baseline condition.

2.5.1.2 **Section 4** provides details of the assessment of potential pathways and impacts for each of the issues identified in **Table 1**.

2.5.2 Issues scoped out of assessment

Changes to offshore sediment pathways

2.5.2.1 Previous EIAs for Hornsea Project One (SMart Wind 2013), Hornsea Project Two (SMart Wind 2015a) and Hornsea Three (Orsted 2018a; 2018b) have each indicated that impacts on sediment pathways are likely to be of minor adverse significance, at least for the offshore array areas. A revision on this issue for Hornsea Project One and Hornsea Project Two is that the MDS options used in their respective EIAs assumed a larger number of more closely spaced foundations with wider diameters (Gravity Base Structure (GBS) options in each case) than the final designs now installed for Hornsea Project One and Hornsea Project Two which have both now installed a fewer number of smaller diameter monopiles spaced further apart. The moderation from MDS to the final design configuration markedly reduces any potential blockage effects from either project, and also in-combination, on offshore sediment pathways. The reduction in array-scale blockage for these projects is discussed in greater detail in **Section 4.8.3**.

2.5.2.2 Given the anticipated equivalent localised scale of changes in tidal currents and waves for the Hornsea Four offshore array to those assessed for the MDS cases of Hornsea Project One and Hornsea Project Two, there is expected to be an equivalent scale of impact on offshore sediment pathways of minor adverse significance for the MDS case of Hornsea Four. Based on a proportionate approach, the issue of changes to offshore sediment pathways is therefore scoped out of the EIA.

2.5.2.3 Changes to nearshore sediment pathways remain a consideration for Hornsea Four, noting the specific comment from the Planning Inspectorate in the Scoping Opinion that sediment pathways should be scoped in from Smithic Bank inshore to the mean high water spring tide (MHWS) level (Planning Inspectorate 2018).

2.6 Evidence-based approach

2.6.1.1 The assessment of Marine Processes adopts an evidence-based approach which is consistent with current best practice (COWRIE 2009). The evidence-based approach was presented to the Marine Ecology & Processes Evidence Plan Technical Panel at Meeting 1 on 12th

September 2018 (Orsted 2018c). An overview of the project consultation process is presented within **Volume A1, Chapter 6: Consultation** of the ES, with consultation specific to marine processes set out in **Volume A2, Chapter 1: Marine Geology, Oceanography and Physical Processes**. This consultation included a series of meetings with the Marine Ecology & Processes Evidence Plan Technical Panel, as detailed in **Volume B1, Annex 1.1: Evidence Plan**.

2.6.1.2 The application of an evidence-based approach to offshore wind farms is now well-established and has been successfully demonstrated in several recent DCO applications, including Hornsea Three.

2.6.1.3 The evidence-based approach is most suited to an area of development which is already well provided with baseline data and information, and where assessment of comparable developments in comparable settings can be drawn upon to offer relevant evidence of the likely effects on the marine physical environment. In such situations, the need for additional baseline surveys and detailed numerical modelling is much reduced and existing assessments can be drawn on instead.

2.6.1.4 **Appendix A** provides a summary of the comparable conditions between Hornsea Four and the adjacent projects in the former Hornsea Zone to further justify the applicability of using the evidence-based approach. Of particular note is Hornsea Project Two which is the closest project to Hornsea Four with the most similar environmental conditions.

2.6.1.5 The baseline description is developed from existing data and information, as well as studies of equivalent projects (the evidence base). **Appendix B** identifies the main data and information sources which have informed this assessment and **Section 5**. provides a reference list of relevant technical literature and reports. This evidence also includes the extensive geophysical, benthic and metocean surveys which supported the characterisation of the former Hornsea zone (SMart Wind 2012).

2.6.2 Baseline surveys

2.6.2.1 The evidence base also includes new geophysical surveys which extend across both the offshore ECC and offshore array area . These surveys provide detailed mapping of seabed sediments, bathymetry, bedforms and sub-bottom profiles which complement pre-existing data. A summary of the main survey achievements is provided in **Appendix B**, with the full reports provided in **Volume A5, Annex 2.1 :Appendix A Array Area Benthic Survey Report**; **Volume A5, Annex 2.1: Appendix B ECC Geophysical Survey Report** and **Volume A5, Annex 2.1: Appendix E Export Cable Corridor Geophysical Results Report**.

2.7 Policy and Guidance

2.7.1.1 The assessment approach has been developed with consideration of the following policy documents, guidance notes and industry technical reviews:

- Turbidity due to dredging and dumping of sediments (van Rijn 2019);
- Natural England Offshore wind cabling: ten years' experience and recommendations (Natural England 2018);
- Technical Guidance – Environmental Impact Assessment of Marine Dredging Proposals (EPA 2016);

- Environmental impact assessment for offshore renewable energy projects - Guide (BSI 2015);
- Overview of the offshore transmission cable installation process in the UK (OWPB 2015);
- Review of environmental data associated with post-consent monitoring of licence conditions of offshore wind farms (MMO 2014);
- Offshore Wind Guidance Document: Oceanography and Sediment Stability. Development of a Conceptual Site Model (SNL 2014);
- Guidelines for data acquisition to support marine environmental assessments for offshore renewable energy projects (Cefas 2011);
- Overarching National Policy Statement for Energy (EN-1) (DECC 2011a);
- National Policy Statement for Renewable Energy Infrastructure (EN-3) (DECC 2011b);
- East Inshore and East Offshore Marine Plans (Defra 2014);
- A Further Review of Sediment Monitoring Data (COWRIE 2010);
- Coastal Process Modelling for Offshore Wind Farm Environmental Impact Assessment: Best Practice Guide (COWRIE 2009);
- Assessment of the environmental impacts of cables (OSPAR 2009); and
- Review of Cabling Techniques and Environmental Effects applicable to the Offshore Wind Farm Industry (BERR 2008).

3 Baseline description of the study area

3.1 Overview

3.1.1.1 A baseline description is provided for each of the main components of the study area; landfall, offshore ECC and offshore array sub-areas. Features in these sub-areas which are potentially sensitive to changes due to Hornsea Four are identified. These features may be either marine process receptors or pathways for an effect on other receptor types, such as; benthic communities, fish, and shellfish.

3.2 Landfall study area

3.2.1 General description

3.2.1.1 The landfall study area incorporates the proposed site for landfall works on Fraisthorpe Sands (including a potential temporary access ramp onto the beach) and extends north to the end of the beach at Bridlington Harbour, and south to incorporate the Dogger Bank A and B export cable landfall. The total longshore extent of the landfall study area covers around 9 km.

3.2.1.2 Open cut trenching is no longer a design option for cable installation across the landfall which will now be achieved with horizontal directional drilling (HDD) or other trenchless techniques (see Commitment Co187, **Volume A4, Annex 5.2: Commitments Register**).

3.2.1.3 The inshore extent of the landfall study area is defined by the low-lying soft cliffs which tend to coincide with MHWS. The seaward extent is sufficient to encompass the option for sub-tidal cofferdams associated with up to eight HDD exit pits (**Volume A1, Chapter 4: Project Description**). These exits pits may be up to 1 km offshore (depths up to around 6 m below Lowest Astronomical Tide (LAT), an area which remains within the surf zone). The seaward extent of the landfall area is around 1.2 km from MHWS and approximates the 7 m below LAT depth contour to represent the main width of the littoral zone for longshore sediment transport.

3.2.1.4 The general description of the landfall study area is an open, intertidal sandy beach, backed by soft cliffs, gently shelving into a shallow sub-tidal environment. The sands can be thin in places exposing an underlying clay till. This environment mainly responds to wave driven processes which erode the cliffs and transport mobile sandy sediments along the beach.

3.2.1.5 World War Two (WWII) tank traps were originally placed in a continuous line from Bridlington to Barmston to protect the low-lying coastline from invasion. Sections of tank traps still remain along the beach in the landfall area and become visible around low tide. **Figure 2** overlays the Hornsea Four Order Limits and mean high and low water lines (from Ordnance Survey) on a Google Earth image taken on 27th September 2011 (a date shortly after the autumnal equinox when the largest annual tidal ranges occur and low waters approximate LAT, which recede lower than mean low water). When submerged by the tide these features are involved in local wave breaking.

Figure 2: Alignment of WWII tank traps at landfall (background image from Google Earth).

3.2.2 Marine process description

Cross-shore profile

3.2.2.1 Figure 3 presents a typical cross-shore profile for the landfall works area based on Channel Coastal Observatory (CCO) Lidar surveys (from 2017) and multi-beam surveys (from 2014). A low-lying cliff backs the beach area with a height of around 7 to 8 m above Ordnance Datum Newlyn (AODN). The cliff has a near-vertical drop onto the beach with the level of MHWS effectively at the base of the cliff. The beach then shelves in a relatively uniform manner to low water over a distance of around 225 m. This gradient continues to around -10.35 m AODN (around 7 m below LAT), a depth typically reached around 1.0 to 1.4 km from the base of the soft cliffs.

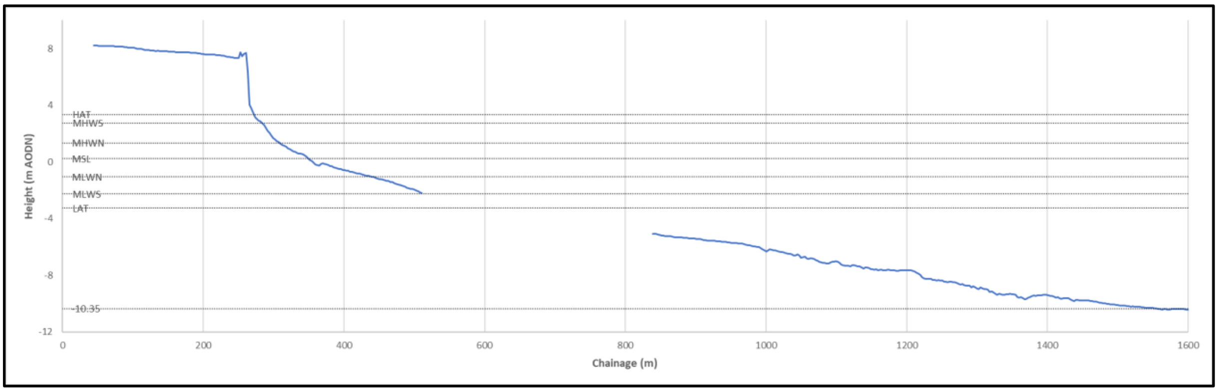


Figure 3: Typical cross-shore profile at landfall works area (based on CCO 2017 surveys).

Intertidal sediments

3.2.2.2 An inter-tidal walkover survey of the landfall works area was undertaken on 22nd March 2019 by the Institute of Estuarine and Coastal Studies (IECS). The survey qualitatively described beach material as coarse sands, thinning in places to reveal hard boulder clay (IECS 2019).

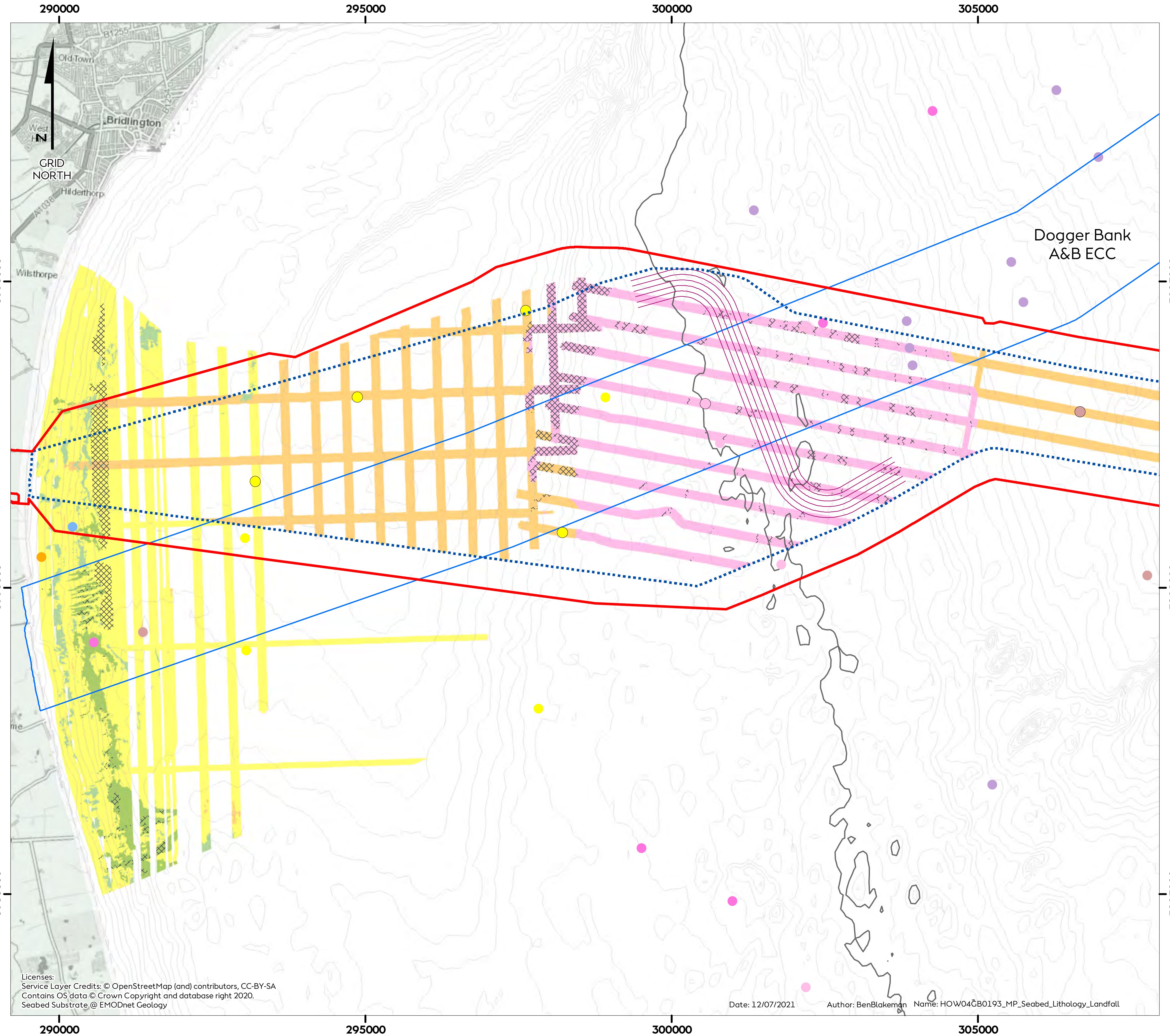
3.2.2.3 Figure 4 shows a typical view of the intertidal with relics of WWII tank traps in the foreground.

Figure 4: View of intertidal area at landfall (IECS 2019).

Subtidal sediments

3.2.2.4 **Figure 5** presents the interpretation of seabed lithology from the recent geophysical surveys. This data shows near 100% coverage at landfall. In addition, a collation of sediment particle size information is also shown at discrete locations, including geophysical survey grab samples (outlined by black circles). All grab samples are interpreted according to Folk (1954), for consistency.

3.2.2.5 Subtidal sediments in the landfall works area as mainly sands with patches of gravelly sand. In places, this sediment cover thins to expose underlying glacial till (stiff glacial till of Bolders Bank Formation) (Bibby HydroMap 2019a; 2019b). Megaripples are observed at the seaward limit of the landfall area in depths of around 6 to 8 m below LAT, however, these appear to be very low profile relict features.



Hornsea Four

Figure 5

Seabed lithology in the landfall area and nearshore

Coordinate system: ETRS 1989 UTM Zone 31N
Scale@A3: 1:60,000

REV	REMARK	DATE
...	First Issue	12/07/2021

Sediment lithology landfall area
Document no: HOW04GB0193
Created by: BPHB
Checked by: BC
Approved by: LK

Water levels

3.2.2.6 Tidal variation in water levels for the landfall area are expected to be equivalent to those at Bridlington, a secondary non-harmonic port for tidal predictions, located around 5 km north of the landfall works area.

3.2.2.7 **Table 2** provides standard tide levels for Bridlington based on Admiralty Tide Tables (UKHO 2019). For reference, the transformation between the sea datum of Chart Datum (CD) to the land datum of Ordnance Datum Newlyn (ODN) is -3.35 m. Therefore, the level of Highest Astronomical Tide (HAT) of 6.70 m above CD equates to 3.35 m above (AODN).

Table 2: Standard tidal levels for Bridlington.

Standard Tidal Level	Abbreviations	Relative to CD (m)	Relative to ODN (m)
Highest Astronomical Tide	HAT	6.70	3.35
Mean High Water Springs	MHWS	6.10	2.75
Mean High Water	MHW	5.40	2.05
Mean High Water Neaps	MHWN	4.70	1.35
Mean Sea Level	MSL	3.60	0.25
Ordnance Datum Newlyn	ODN	3.35	0.00
Mean Low Water Neaps	MLWN	2.30	-1.05
Mean Low Water	MLW	1.71	-1.64
Mean Low Water Springs	MLWS	1.10	-2.25
Lowest Astronomical Tide	LAT	0.10	-3.25
Mean Spring Range (m)	MSR	5.00	
Mean Neap Range (m)	MNR	2.40	

3.2.2.8 The tidal range on mean spring tides, and any higher tidal ranges, is sufficient to reach the base of the soft cliffs.

3.2.2.9 Water levels also vary under the influence of strong winds and atmospheric pressure variations leading to (non-tidal) surge effects. These effects can result in both positive and negative variations on the tidal level. Positive surge events have the capacity to augment tidal levels and increase the number of tides reaching the base of the cliffs.

3.2.2.10 The Environment Agency has produced a national dataset of design sea levels based on the analysis of Class A tide gauge data which incorporate the effect of surges (Environment Agency 2019). **Table 3** provides the estimated extreme water levels for return periods (RP) up to the 1,000-year level for the landfall site (based on data for chainage 3,798 km), along with the 2.5 % and 97.5% confidence levels. In the interval between these confidence levels there is a 95 % probability of observing the true extreme sea level. This interval is often referred to as the 95 % confidence interval and is commonly used to quantify the uncertainty associated with parameter estimates of a statistical model.

Table 3: Estimated extreme water levels for landfall study area.

RP (years)	Extreme level, AODN (m)	2.5 % confidence level (m)	97.5 % confidence level (m)
1	3.54	3.52	3.55
2	3.63	3.61	3.66
5	3.76	3.72	3.80
10	3.88	3.81	3.92
20	3.98	3.90	4.06
25	4.00	3.92	4.10
50	4.10	4.01	4.25
75	4.16	4.05	4.35
100	4.21	4.08	4.43
150	4.27	4.13	4.53
200	4.32	4.15	4.61
250	4.35	4.17	4.68
300	4.38	4.19	4.73
500	4.47	4.24	4.89
1,000	4.58	4.31	5.12

3.2.2.11 For context, the HAT level of 3.35 m AODN (an event which is approximated each year by the vernal and autumnal equinox spring tides) is relatively close to the 1 in 1-year RP extreme water level of 3.54 m AODN.

3.2.2.12 A notable major storm surge influencing the North Sea occurred on 5 December 2013. This event produced a peak water level of 4.56 m AODN at Bridlington, comprising a surge influence of 1.76 m above the predicted high tide level of 2.80 m AODN (ERYC 2014). Based on the information provided in **Table 3**, this event would have a return period close to 1 in 1,000 years, based on existing statistical distributions.

3.2.2.13 Over a 50-year period, MSL is expected to increase due to climate change. The United Kingdom Climate Projections 2018 (UKCP18) provides climate projections for sea level rise up to the year 2100 based on different emission scenarios (representative concentration pathways). Based on the 50th percentile for low and high emission scenarios, an illustrative change in MSL after 50 years would be between +0.22 to +0.35 m. This effect would also redefine both tidal levels and extreme water levels presented in **Table 2** and **Table 3**, respectively, translating the position of high water further landward (by up to around 7.8 m over 50 years) and increasing the pressure for coastal erosion along the frontage of soft cliffs.

Waves

3.2.2.14 Flamborough Head provides local sheltering to the landfall area for waves from northerly sectors (the prevailing wave directions). Due to the orientation of the coastline, only waves from north-east to south-east sectors have a direct approach onto the landfall area.

3.2.2.15 In the lee of Flamborough Head there is a shallow sandbank feature known as Smithic Bank (also commonly referred to as Smithic Sands). The relatively shallow profile of this bank has the capacity to cause attenuation and shoaling of larger waves approaching the shoreline, especially around the times of low water.

3.2.2.16 As waves arrive onto the shallowing foreshore, they typically break to form a surf zone. When waves arrive oblique to the beach this process creates longshore (wave-driven) currents which can transport sandy material along the shore (longshore drift). Since northerly waves cannot reach this section of coastline, then only waves from north-east through to south-east sectors have the capacity to drive longshore drift which has a fundamental influence on the direction of net transport.

Sediment transport – longshore drift

3.2.2.17 North of the landfall (Fraisthorpe Sands) there is weak net longshore drift along the coast to the north-east, driven by (infrequent) waves from southerly sectors with Flamborough Head sheltering this section of the coast from the influence of larger and prevailing northerly waves.

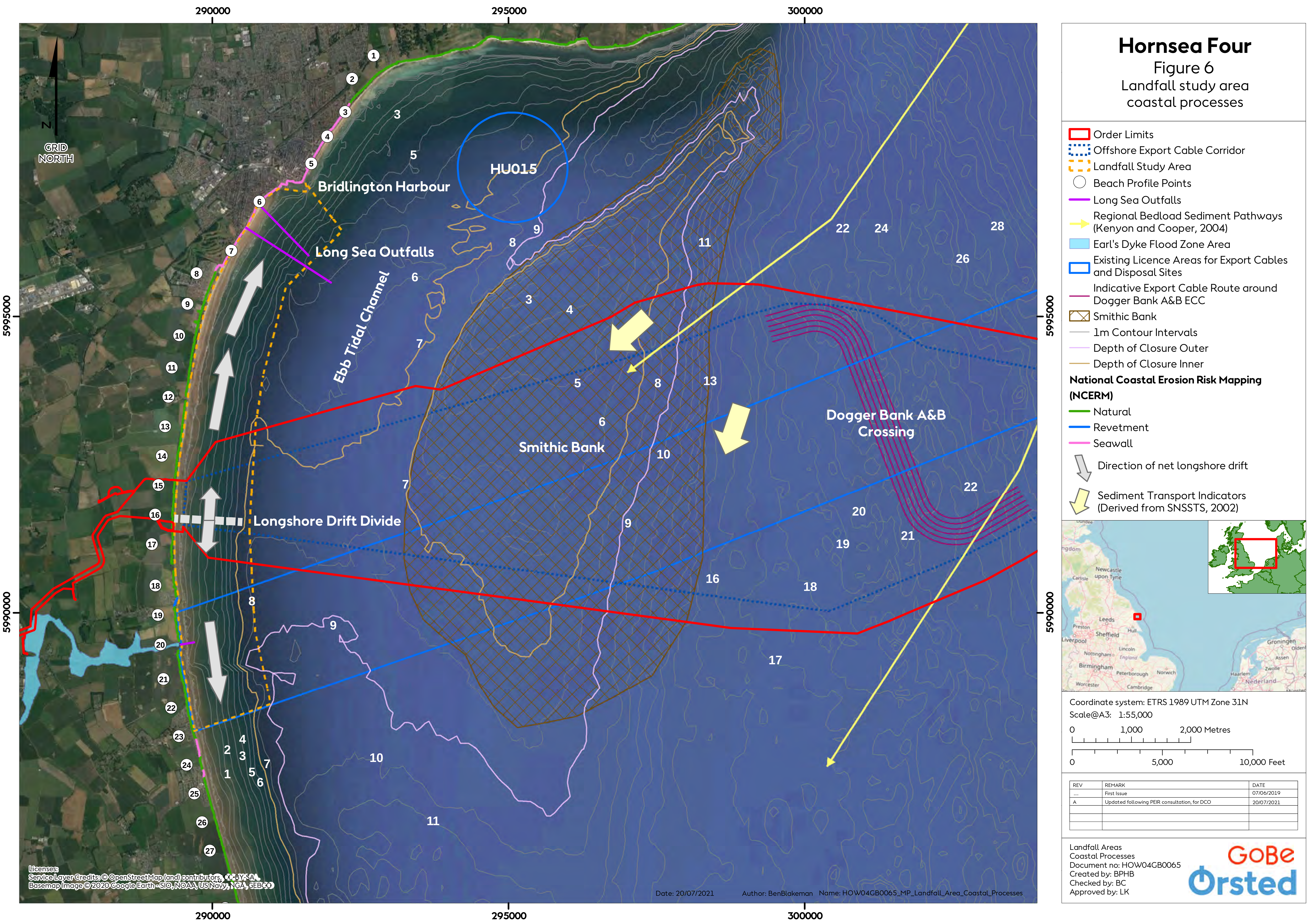
3.2.2.18 South of the landfall the coastline (Barmston Sands) receives less sheltering from Flamborough Head (and Smithic Bank) as well as showing a slight change in orientation to the east leading to increased exposure to northerly waves which results in a progressively stronger net longshore drift towards Spurn Head (Pye & Blott 2015).

3.2.2.19 The area around the landfall can be regarded as a drift divide for longshore drift with the sum of all drift rates and directions in a year being effectively nil (**Figure 6**).

3.2.2.20 The seaward limit of the wave-driven littoral zone for longshore drift can be estimated by the theoretical "Inner – Depth of Closure". In addition, the "Outer – Depth of Closure" represents the seaward limit of the effect of wave shoaling. Based on standard expressions developed by Hallermeier (1983), and by applying relevant environmental parameters for waves and sediments, the "Inner – Depth of Closure" is estimated to be 7 m (below LAT) and the "Outer – Depth of Closure" is estimated to be equivalent to 9 m (below LAT).

Pathways

3.2.2.21 The main process pathway in the landfall study area is wave-driven currents. Depending on the angle of approach, these wave-driven currents may drive sediment to the north or south along the beach, noting that the landfall area coincides with a drift divide meaning these drift rates are expected to be minimal.



Hornsea Four
Figure 6
Landfall study area coastal processes
Order Limits
Offshore Export Cable Corridor
Landfall Study Area
Beach Profile Points
Long Sea Outfalls
Regional Bedload Sediment Pathways (Kenyon and Cooper, 2004)
Earl's Dyke Flood Zone Area
Existing Licence Areas for Export Cables and Disposal Sites
Indicative Export Cable Route around Dogger Bank A&B ECC
Smithic Bank
1m Contour Intervals
Depth of Closure Outer
Depth of Closure Inner
National Coastal Erosion Risk Mapping (NCERM)
Natural
Revetment
Seawall
Direction of net longshore drift
Sediment Transport Indicators (Derived from SNSSTS, 2002)
Bridlington Harbour
HU015
Long Sea Outfalls
Ebb Tidal Channel
Smithic Bank
Longshore Drift Divide
Dogger Bank A&B Crossing
GRID NORTH
N
290000
295000
300000
5995000
5990000
Coordinate system: ETRS 1989 UTM Zone 31N
Scale@A3: 1:55,000
0 1,000 2,000 Metres
0 5,000 10,000 Feet
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A Updated following PEIR consultation, for DCO 20/07/2021
Landfall Areas
Coastal Processes
Document no: HOW04GB0065
Created by: BPHB
Checked by: BC
Approved by: LK
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Date: 20/07/2021
Author: BenBlakeman
Name: HOW04GB0065_MP_Landfall_Area_Coastal_Processes

3.2.3 Marine physical environment receptors – landfall study area

Holderness Coast

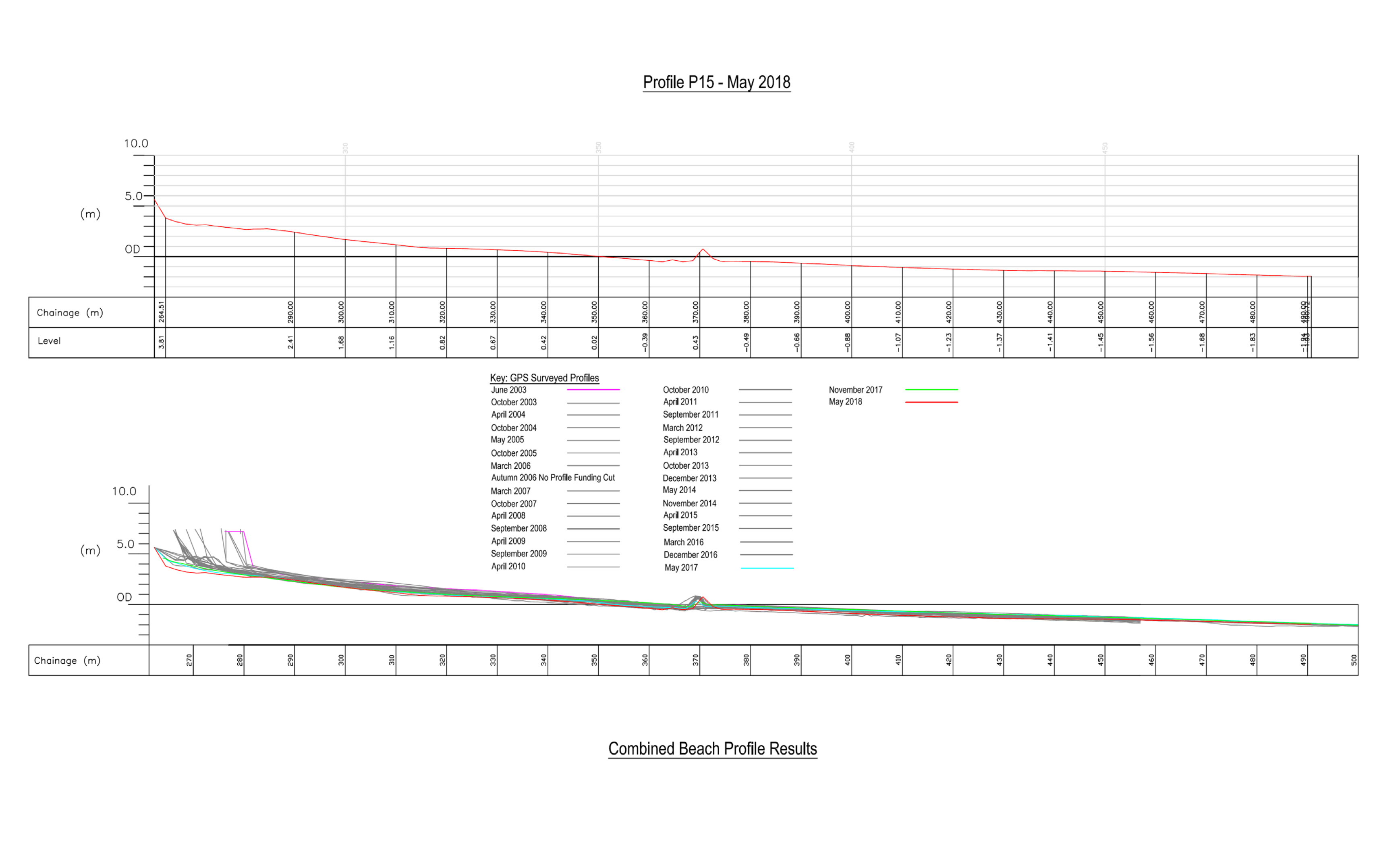
3.2.3.1 The main receptor extending north and south, and including the landfall study area, is the Holderness Coast. The coastline comprises of a sandy intertidal beach (Barmston Sands and Fraisthorpe Sands) backed by low-lying soft cliffs formed of a heterogeneous sediment mixture (from boulders to clay sized material) of Quaternary glacial till (Newsham, Balson, Tragheim, & Denniss 2002). The toe of the cliff is close to the high water line making it susceptible to erosion during stormy periods with large waves. The greatest amount of cliff erosion would be expected when this process coincides with the high water period during positive storm surges. The cliffs are considered to be one of the fastest eroding coastlines in Europe (Sistermans & Nieuwenhuis 2003; JNCC 2007; IECS 2016).

3.2.3.2 ERYC undertake routine monitoring of the Holderness Coast which includes beach profiles from the top of the sea cliffs down to low water. These profiles are surveyed in spring and autumn each year, notionally at 500 m spacing (shown on **Figure 6**). This survey record extends from 2003 to present and provides the basis of determining rates of cliff recession. **Table 4** provides a summary of cliff retreat rates for the beach profiles coincident with the immediate landfall works area (profiles 15 and 16). Cliff recession rates vary along the entire coast, as well as year-to-year, but with a general increased rate towards the more southerly section of the coast, in line with increased exposure to northerly waves (i.e. less sheltering effects from Flamborough Head and Smithic Bank).

Table 4: Cliff recession rates at Profiles 15 and 16.

Profile	Location	Height of cliff (m AODN)	Average cliff recession (m/year)	Maximum annual recession (m)	Year of maximum recession
15	South of Earls Dyke – Barmston	7.2	1.22	5.00	2005
16	Watermill Grounds – north of Barmston	8.3	1.57	6.54	2007

3.2.3.3 **Figure 7** shows the survey record for Profile 15 (see **Figure 6** for location of profiles). From June 2003 to May 2018 beach levels have varied but with a general reduction in vertical level by around 1 m over this 16-year period with the position of the base of the cliff retreating by around 20 m. The apparent anomaly at around chainage 370 m is associated with the line of WWII tank traps. The generally stable beach profile is likely to be indicative of a thin layer of mobile sands over a more resistant underlying glacial till (stiff glacial till of Bolders Bank Formation), as evidenced from the geophysical survey across this area (Bibby HydroMap 2019a; 2019b).



EAST RIDING OF YORKSHIRE COUNCIL Nigel Leighton Director of Environment and Neighbourhood Services	Title. Cross Section Analysis - Profile P15.	Profile Start. E 516629.224 N 461289.845	Profile End. E 517948.656 N 461233.809	Drawn. EKP.	Checked. N.M.	Scale @ A2. Horiz. 1:500 Vert. 1:250
Project. East Riding Beach Monitoring	Location. Opposite Fraisthorpe Village.			Job No. ERYC-P15		Date. 05.09.2018

Figure 7: Example of beach profile monitoring within landfall works area, from ERYC.

3.2.3.4 The regular tidal inundation of the beach between high and low water, along with associated wave conditions, sweep the finer material released from cliff erosion into the sea creating a visible nearshore plume. The coarser material produced by cliff erosion (sands and gravels) provide a primary source of new beach material (Newsham, Balson, Tragheim, & Denniss 2002). The sandy beach material is susceptible to longshore drift by wave-driven currents with the direction of drift at any time determined by the oblique angle of approaching waves.

3.2.3.5 The Shoreline Management Plan (SMP) policy for the stretch of undefended coast (Policy Unit C: Wilsthorpe to Atwick) which covers the landfall area is given as; "No Active Intervention" for the Short Term (present day to 2025), Medium Term (2025 to 2055) and Long Term (2055 to 2105) (Scott Wilson 2010).

3.2.3.6 The National Coastal Erosion Risk Mapping (NCERM) identifies the characteristics of the relevant section of shoreline as "natural" defence and "erodible". Assuming the SMP policy remains unchanged for the lease period of Hornsea Four then the projected retreat distance for the short term (0 to 20 years) and medium term (20 to 50 years) are given as 33 and 82 m, respectively, (for the 50^{th} percentile confidence level, +/- 30 % for 5^{th} and 95^{th} percentile confidence levels) (Environment Agency 2020). These projected retreat distances are based on an extrapolation from measured rates of cliff erosion.

3.2.3.7 Sea level rise in this period (see **paragraph 3.2.2.13**) would also expect to increase the rate of cliff erosion[1] since the position of a higher mean sea level would translate slightly landwards, with a corresponding move of the high water line. Cliff erosion rates would also respond to any changes in the frequency and severity of storm surges and waves.

Dogger Bank A and B export cable landfall

3.2.3.8 The landfall for Dogger Bank A and B export cables is around 1.2 km to the south of the Hornsea Four landfall (**Figure 6**). The anticipation is this landfall installation will be completed prior to any works commencing for Hornsea Four. Depending on the final installation method of the Dogger Bank A and B export cables at landfall, and the period between completion and commencement of Hornsea Four landfall works, this section of beach may still be in a state of partial recovery.

Marine outfalls

3.2.3.9 Yorkshire Water operate two long sea outfalls located approximately 4.2 km north of the landfall works area (**Figure 6**). The 1.25 km long Bridlington Stormwater Outfall was installed in June 2014 and involved a 5 m deep open-cut trench inside a temporary cofferdam running 350 m down the beach at a location approximately 600 m to the southwest of the entrance to Bridlington Harbour. During construction, there is a suggestion that raised levels of suspended sediment led to some siltation within shellfish holding tanks within the harbour. The cofferdam was subsequently removed with the trench backfilled (UK Water Projects 2015). Presently, there is no visible evidence of marine works at this location which demonstrates the recovery of the beach area to temporary construction works. There is a raised diffuser section at the end of each outfall that could be sensitive to large scale deposition events.

[1] https://www.eastriding.gov.uk/environment/sustainable-environment/looking-after-our-coastline/coastal-change-in-the-east-riding

Bridlington Harbour

3.2.3.10 Bridlington Harbour is around 5 km north of the landfall works area (**Figure 6**). The bed of the harbour is noted as being muddy (silts) and is generally considered to be a sink for fine sediments. Estimates suggest that approximately 75 % of the silts are from marine sources (principally the sediment plume of fine sediments created by cliff erosion) with the remaining 25 % from terrestrial sources with material discharged into the back of the harbour from the freshwater stream known as Gypsey Race (HR Wallingford 2005).

3.2.3.11 The estimated average build-up of silts in the harbour is nine inches (0.23 m) every year across the 10.5 acres (42,500 m^2) of the harbour bed. This creates a typical dredging requirement of between 12,000 to 14,000 tonnes per year (Maritime Journal 2017). These sediments are dredged to maintain suitable depths with the spoil taken offshore to disposal ground HU015, situated in the lee of Flamborough Head (**Figure 6**). Bridlington Harbour has a licence for a maximum permitted disposal of 20,000 tonnes per annum at HU015. This disposal ground is identified as a receptor within the offshore ECC study area.

3.2.4 Summary of marine physical environment receptors within the landfall study area

3.2.4.1 **Table 5** summarises the receptors associated with the landfall study area. The potential sensitivity of each receptor is expressed prior to consideration of the scale of any impact related to the development.

Table 5: Marine physical environment receptors in the landfall study area.

Receptor	Potential sensitivity to marine processes
Holderness Cliffs	Changes in (storm) wave energy dissipation at toe of cliff that modify rates of cliff recession and supply of material to the beach. Short-term effects due to beach access ramp.
Holderness Coast / Fraisthorpe Sands	Changes in sediment supply from cliff erosion. Changes in wave energy dissipation (wave height and direction) on the intertidal area that alter the rate and direction of longshore drift.
Dogger Bank A and B export cable landfall	Beach lowering exposing export cables.
Marine outfalls	High rates of deposition of sediment onto diffusers which may block effective discharge of wastewater.
Bridlington Harbour	Increased suspended sediment concentrations in the nearshore leading to higher rates of harbour siltation from marine sources.

3.3 Offshore ECC study area

3.3.1 General description

3.3.1.1 The offshore ECC study area extends for around 107 km between the landfall and into the offshore array area to provide a corridor for up to six export cables. In addition, there is an option for High Voltage Alternating Current (HVAC) booster station infrastructure within a search area from around 35 to 42 km from the coast. The offshore ECC is typically around 2.5 km wide, including the temporary works area, but widens in places to nearly 6 km to accommodate the Dogger Bank A and B export cable crossing, HVAC Booster Station Search Area, and fans out onto the offshore array. With the inclusion of a 15 km buffer zone to conservatively accommodate the excursion of a mean spring tide, this develops an overall width of around 32 to 33 km for the offshore ECC study area. This buffer can be considered to represent an indicative zone of influence for the dispersion of fine sediments disturbed at the seabed (from foundation levelling, sandwave clearance or cable trenching) or disposed of as spoil at sites within the offshore ECC.

3.3.1.2 The HVAC Booster Station Search Area includes the option for three foundations to mount surface booster stations. The largest proposed foundation option is a box-type gravity base with a dimension of 75 by 75 m. These structures have the potential to create blockage type effects on waves and currents, leading to formation of wakes that could extend into the far-field.

3.3.1.3 The marine process environment across the offshore ECC study area varies from the shallow nearshore area in the lee of Flamborough Head to more exposed offshore conditions in deeper water towards the offshore array.

3.3.2 Marine process description

Seabed Profile

3.3.2.1 **Figure 8** illustrates the variation in seabed depths along the offshore ECC, from the nearshore to the offshore and based on bathymetry data from European Marine Observation and Data Network (EMODnet). At the seaward extent of the landfall area depths are approximately 7 m below LAT with a flattish seabed profile. This flat area is the southern end of an ebb tidal channel that extends to Flamborough Head and defines the inshore flank of Smithic Bank. From this nearshore location, the seabed profile gently shallows onto the southern part of Smithic Bank where depths reduce to around 5 m below LAT. Approximately 9 km from the coastline, the offshore ECC reaches the eastern edge of the bank, which also aligns with the seaward limit of Flamborough Head to the north. Further to the east, this headland no longer provides direct sheltering from north and north-easterly waves and the seabed drops to around 20 m below LAT. The profile of the seabed continues to deepen in an easterly direction and reaches around 51 m below LAT at the HVAC Booster Station Search Area (located approximately 35 km offshore). This is also the deepest section of the offshore ECC. East from the HVAC Booster Station Search Area the seabed shallows slightly with the offshore ECC passing just to the south of The Hills, a series of sinuous inter-related sandbank features with near symmetrical sandwaves. When the offshore ECC reaches the offshore array area water depths are around 40 m below LAT.

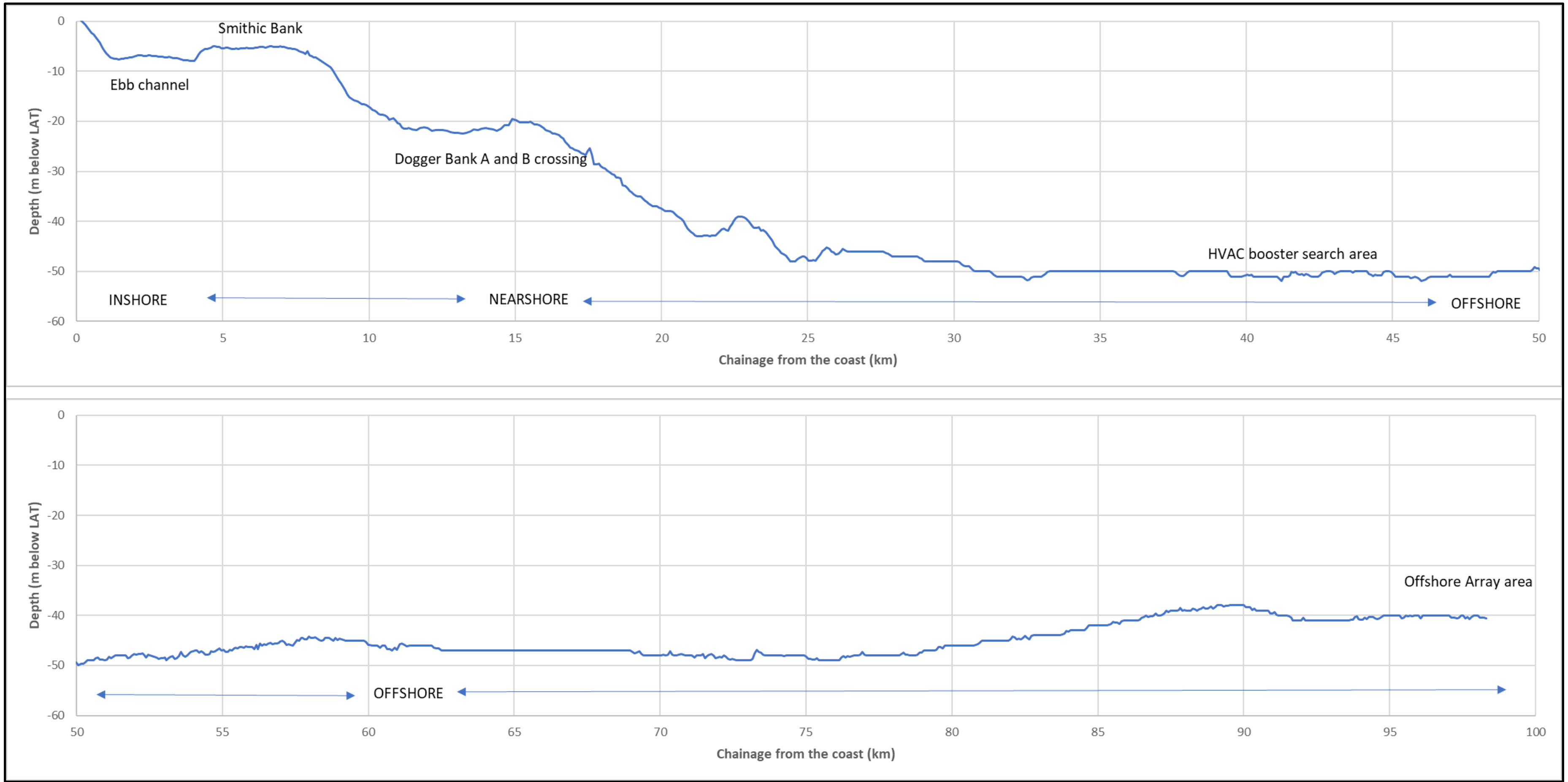
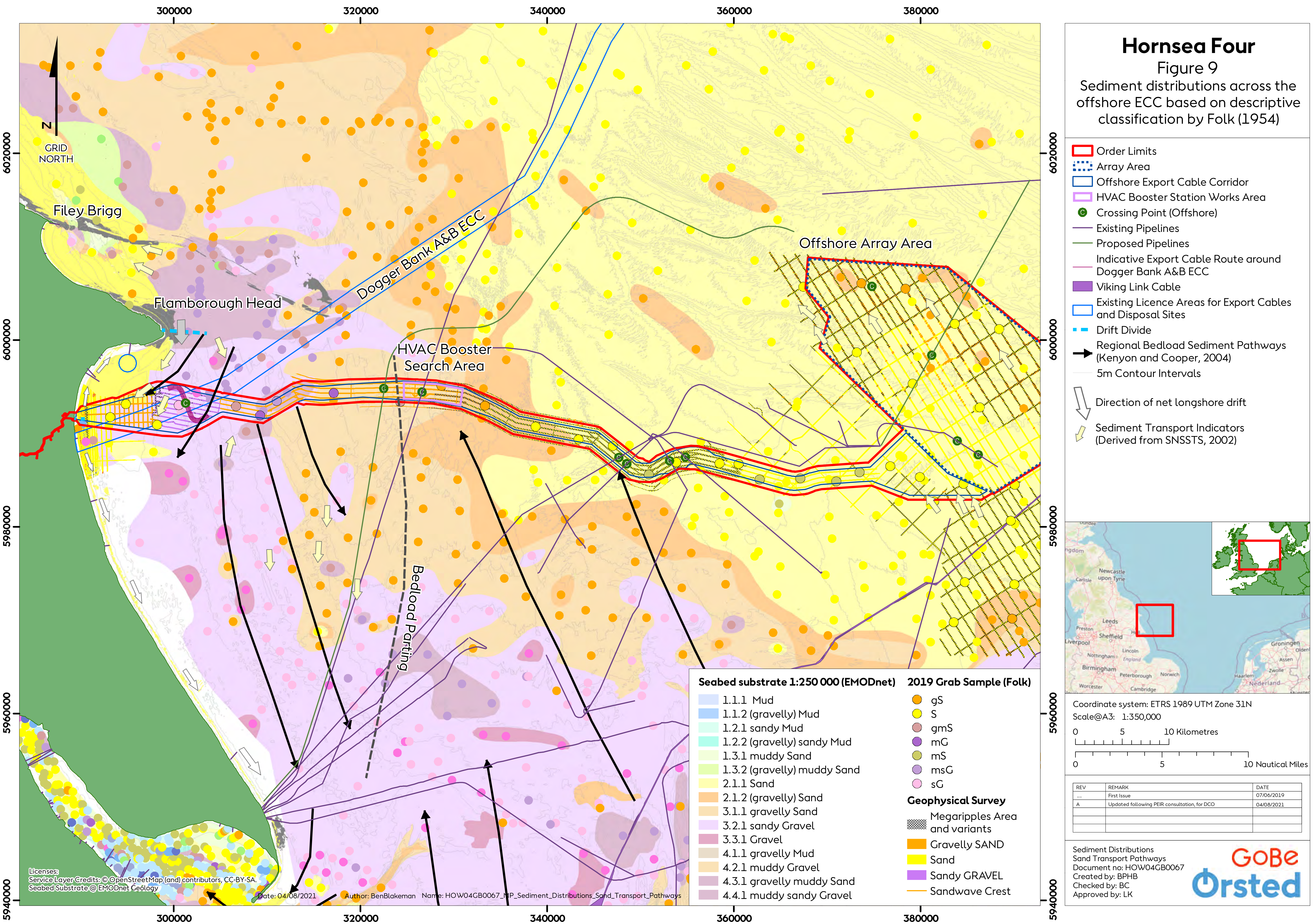


Figure 8: Seabed profile along offshore ECC, from landfall into the offshore array (derived from EMODnet bathymetry).

Subtidal sediments

3.3.2.2 A description of sediment cover along the offshore ECC is established from geophysical survey evidence, notably the interpretation of seabed lithology (Bibby HydroMap 2019a and 2019b) and particle size analysis of grab samples (26 sites) (Bibby HydroMap 2019c). This evidence is augmented with comparable regional scale (e.g. British Geological Survey (BGS) 1:250,000 surficial sediment maps) and local scale (e.g. CCO surveys for ERYC) mapping, where available, along with a collation of other grab samples (e.g. from GeoIndex) to provide a wider view of surficial sediments across the whole of the offshore ECC study area (**Figure 9**).

3.3.2.3 The nearshore section (landfall to Smithic Bank) comprises sands with patches of gravelly sands, becoming sands across the shallower Smithic Bank (< 10 m below LAT). As the bank shelves into slightly deeper water (>10 m below LAT) the seabed coarsens to sandy gravel, an area which extends across the location of the proposed crossing of the Dogger Bank A and B export cables and to around 30 m below LAT. Further to the east, and out to the HVAC Booster Station Search Area, the seabed becomes gravelly sand to slightly gravelly sand. As the sand content further increases there is evidence of megaripples from the HVAC Booster Station Search Area for around 32 km to the east. From this area, and up to the fan area connecting with the offshore array, the seabed is relatively featureless with grab samples typically indicating muddy sand (Bibby HydroMap 2019c). For the fan area adjoining the offshore array, the seabed returns to being sandy.



Hornsea Four
Figure 9
Sediment distributions across the offshore ECC based on descriptive classification by Folk (1954)
Order Limits
Array Area
Offshore Export Cable Corridor
HVAC Booster Station Works Area
Crossing Point (Offshore)
Existing Pipelines
Proposed Pipelines
Indicative Export Cable Route around Dogger Bank A&B ECC
Viking Link Cable
Existing Licence Areas for Export Cables and Disposal Sites
Drift Divide
Regional Bedload Sediment Pathways (Kenyon and Cooper, 2004)
5m Contour Intervals
Direction of net longshore drift
Sediment Transport Indicators (Derived from SNSSTS, 2002)
Seabed substrate 1:250 000 (EMODnet)
1.1.1 Mud
1.1.2 (gravelly) Mud
1.2.1 sandy Mud
1.2.2 (gravelly) sandy Mud
1.3.1 muddy Sand
1.3.2 (gravelly) muddy Sand
2.1.1 Sand
2.1.2 (gravelly) Sand
3.1.1 gravelly Sand
3.2.1 sandy Gravel
3.3.1 Gravel
4.1.1 gravelly Mud
4.2.1 muddy Gravel
4.3.1 gravelly muddy Sand
4.4.1 muddy sandy Gravel
2019 Grab Sample (Folk)
gS
S
gmS
mG
mS
msG
sG
Geophysical Survey
Megaripples Area and variants
Gravelly SAND
Sand
Sandy GRAVEL
Sandwave Crest
Filey Brigg
Flamborough Head
Dogger Bank A&B ECC
HVAC Booster Search Area
Offshore Array Area
Bedload Parting
GRID NORTH
N
300000
320000
340000
360000
380000
6020000
6000000
5980000
5960000
5940000
Coordinate system: ETRS 1989 UTM Zone 31N
Scale@A3: 1:350,000
0 5 10 Kilometres
0 5 10 Nautical Miles
REV | REMARK | DATE
... | First Issue | 07/06/2019
A | Updated following PEIR consultation, for DCO | 04/08/2021
Sediment Distributions
Sand Transport Pathways
Document no: HOW04GB0067
Created by: BPHB
Checked by: BC
Approved by: LK
GoBe
Ørsted
Licenses:
Service Layer Credits: © OpenStreetMap (and) contributors, CC-BY-SA
Seabed Substrate @ EMODnet Geology
Date: 04/08/2021
Author: BenBlakeman
Name: HOW04GB0067_MP_Sediment_Distributions_Sand_Transport_Pathways
Newcastle upon Tyne
Leeds
Sheffield
Liverpool
Nottingham
Birmingham
Peterborough
Norwich
Cambridge
Groningen
Nederland

Seabed features

3.3.2.4 Bedform features are resolved in the multi-beam bathymetry at several locations along the offshore ECC (Bibby HydroMap 2019a; 2019b). For the inshore section, a narrow band of megaripples is observed in water depths between 10 to 15 m below LAT, on the seaward flank of Smithic Bank, with crest heights < 0.5 m and wavelengths between 4 to 8 m. Sediments in this area are described as sandy gravel. This area of megaripples extends seaward across the sandy gravel, in small patches, to depths of 30 m below LAT, an area which encompasses the planned cable crossing with Dogger Bank A and B export cables, noting megaripples in this area are also described as being relic features.

3.3.2.5 A more expansive area of megaripples extends east of the HVAC Booster Station Search Area where there is a transition of seabed sediments from slightly gravelly sand to sand. This area continues for around 32 km in depths between 40 to 50 m below LAT. Individual crest heights are typically < 0.5 m and wavelengths in the range 5 to 20 m. Within this area of megaripples there are a few heightened features which have developed as the convergence and superposition of megaripples migrating from the north-west and south-east (**Figure 10**).

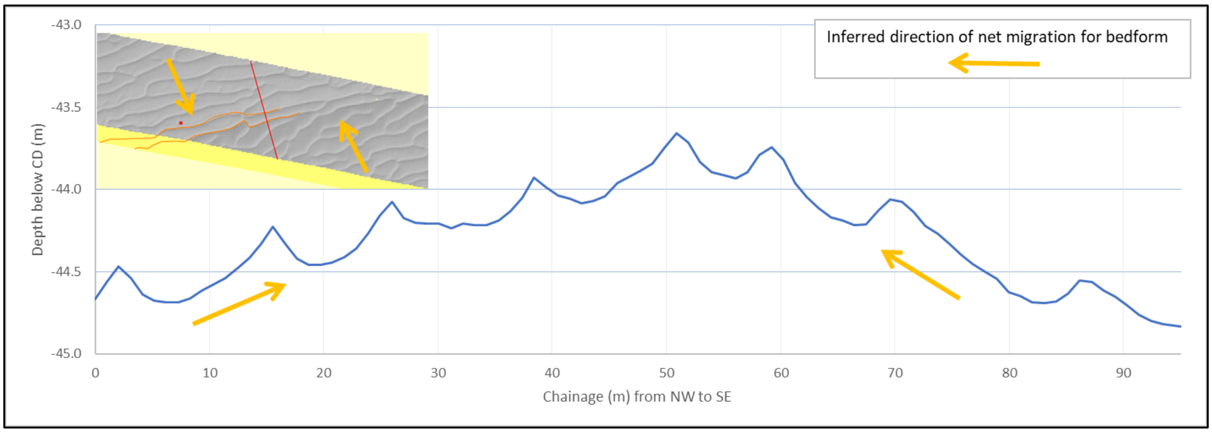


Figure 10: Example cross-section profile of bedform features within the offshore ECC (vertical exaggeration 1:15) (derived from geophysical survey).

3.3.2.6 Very few sandwaves are resolved from the geophysical survey data which fall within the offshore ECC. The main cluster of sandwaves is found in the most southerly part of the fan area adjoining with the offshore array. The asymmetry of the larger sandwaves infers a net transport direction to the north west. **Figure 11** provides an example of these sandwaves which also shows superposition of megaripples. The larger sandwave is around 4.6 m high with a crest to crest separation of around 500 m to the smaller adjacent feature to the north-west.

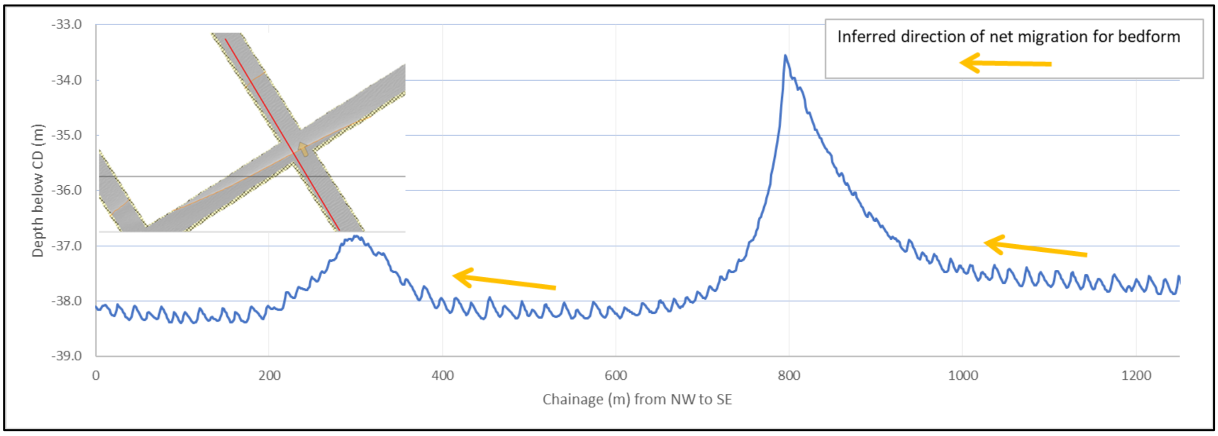


Figure 11: Example cross-section profile of sandwave features within the offshore ECC fan area (vertical exaggeration around 1:67) (derived from geophysical survey).

Water levels

3.3.2.7 MSR varies from around 5.0 m at the landfall to around 3.5 m at the seaward limit of the offshore ECC (**Figure 12**). Equivalent MNR values are 2.4 and 1.6 m (DECC 2008a). The larger tidal range at the western end of the offshore ECC is due to the greater distance from (two) tidal amphidromes in the Southern North Sea.

3.3.2.8 The combination of water depth being typically deeper than 40 m along the majority of the offshore ECC, plus the associated tidal variation in water levels, means that waves are unlikely to influence bedload transport, apart from where larger waves begin to shoal onto the shallower nearshore area approaching Smithic Bank and then onto the shoreline (in the landfall area). **Figure 6** shows the estimated location for the Outer – Depth of Closure represented by the 9 m (below LAT) depth contour. The Outer – Depth of Closure provides an indication of the limits for wave related influences on sediment transport.

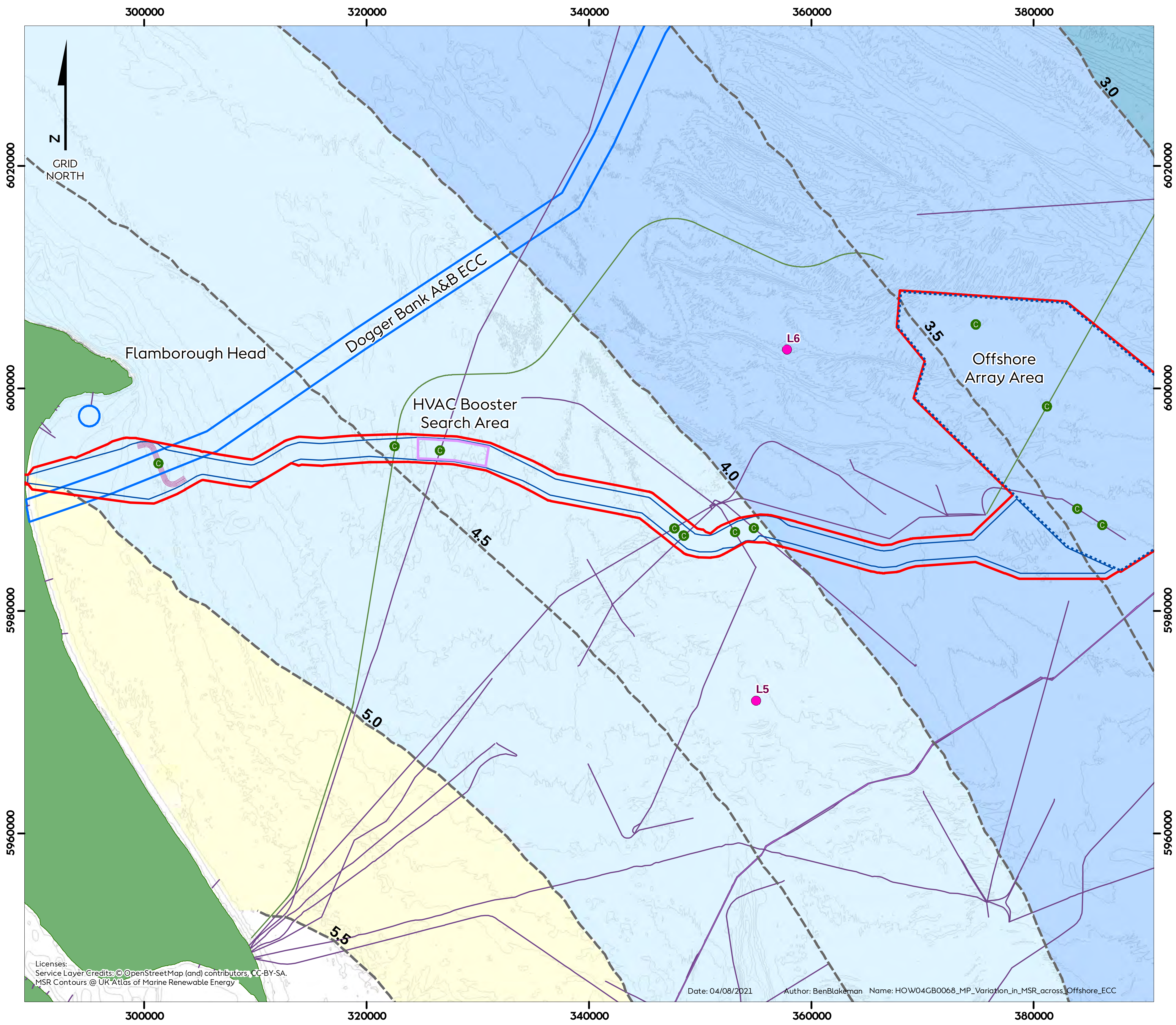
Tidal flows

3.3.2.9 In open water, tidal flows are generally to the south-east on the flood tide and north-west on the ebb. Closer inshore flows become more aligned with the orientation of the coastline, especially around Flamborough Head where they are also strongest (peak of 1.2 m/s on mean spring tide). Regional mapping of tides (DECC 2008a) indicates that flows tend to reduce from west to east along the offshore ECC, but the most sheltered conditions are nearshore in the lee of the Flamborough Head (**Figure 13**). Peak flows on a mean spring tide for the HVAC Booster Station Search Area are expected to be around 0.84 m/s.

Hornsea Four

Figure 12

Variation in MSR across offshore ECC



- Order Limits
- Array Area
- Offshore Export Cable Corridor
- HVAC Booster Station Works Area
- Crossing Point (Offshore)
- Existing Pipelines
- Proposed Pipelines
- Indicative Export Cable Route around Dogger Bank A&B ECC
- Viking Link Cable
- Existing Licence Areas for Export Cables and Disposal Sites
- Metocean Deployment Sites
- 5m Contour Intervals
- Mean Spring Tidal Range Contours

Mean Spring Tidal Range (m)

(UK Atlas of Marine Renewable Energy)

- 2 - 3
- 3 - 4
- 4 - 5
- 5 - 5.5

Coordinate system: ETRS 1989 UTM Zone 31N

Scale@A3: 1:325,000

0 5 10 Kilometres

0 4 8 Nautical Miles

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Variation in MSR
Across Offshore ECC
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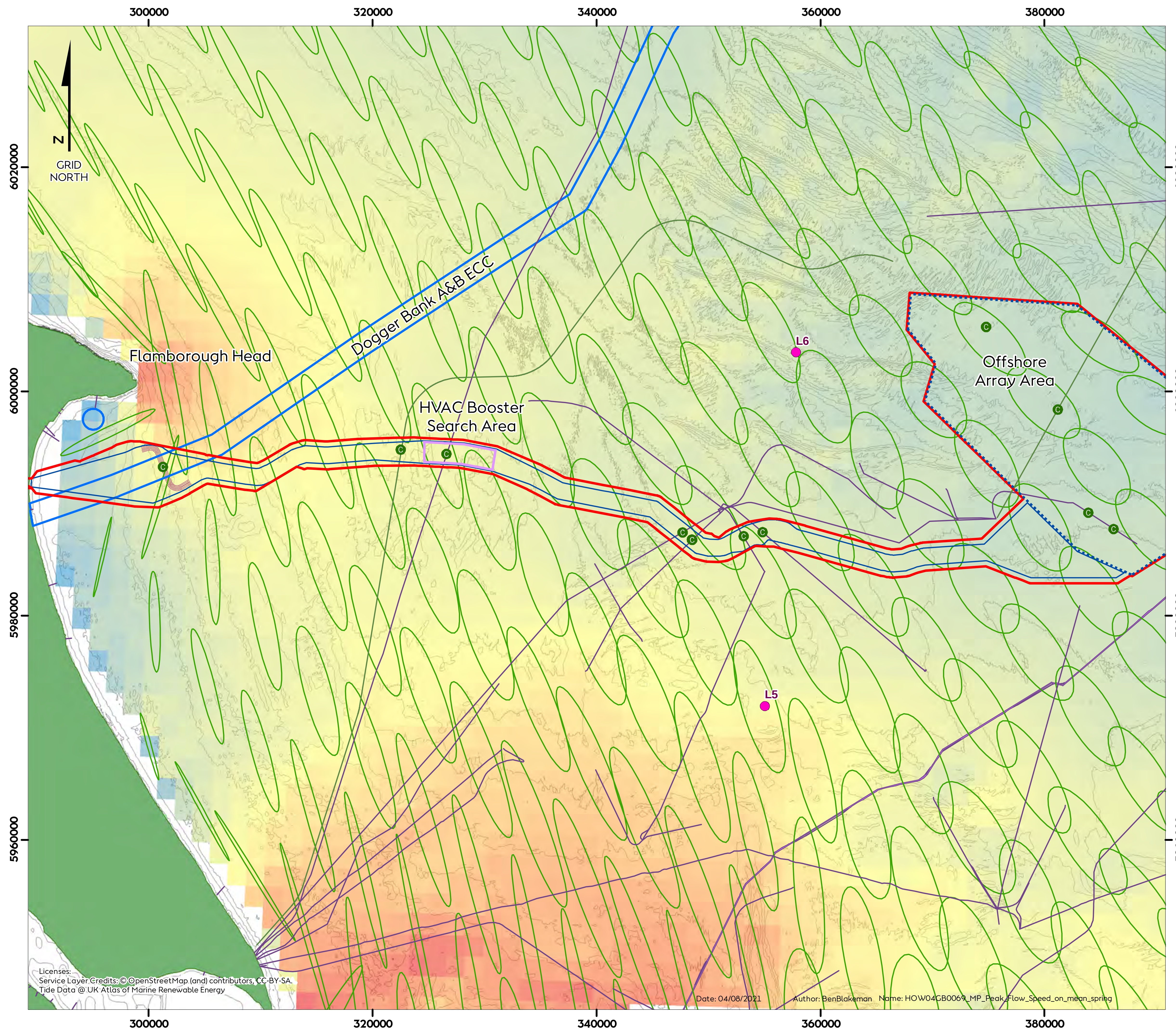

Hornsea Four

Figure 13

Mean spring tide, peak flow speed along with orientation of tidal ellipse scaled to represent the tidal excursion

- Order Limits
- Array Area
- Offshore Export Cable Corridor
- HVAC Booster Station Works Area
- Crossing Point (Offshore)
- Existing Pipelines
- Proposed Pipelines
- Indicative Export Cable Route around Dogger Bank A&B ECC
- Viking Link Cable
- Existing Licence Areas for Export Cables and Disposal Sites
- Metocean Deployment Sites
- 5m Contour Intervals
- Spring Tidal Ellipses

Peak Flows (m/s)
1.48
0.31

Coordinate system: ETRS 1989 UTM Zone 31N
Scale@A3: 1:325,000
0 5 10 Kilometres
0 4 8 Nautical Miles

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Peak Flow Speed on Mean Spring Across Offshore ECC
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Waves

3.3.2.10 **Figure 14** presents the spatial variation in winter wave heights across the offshore ECC area based on a regional wave model (DECC 2008a). The general pattern is for lower wave heights closer to shore due to sheltering by Flamborough Head and Smithic Bank, increasing in the offshore as sites become less sheltered (more exposed). Seasonal variation reduces wave heights during the summer period. **Table 6** provides summary wave height information for three locations along the offshore ECC, from nearshore to offshore (areas defined in **Figure 8**).

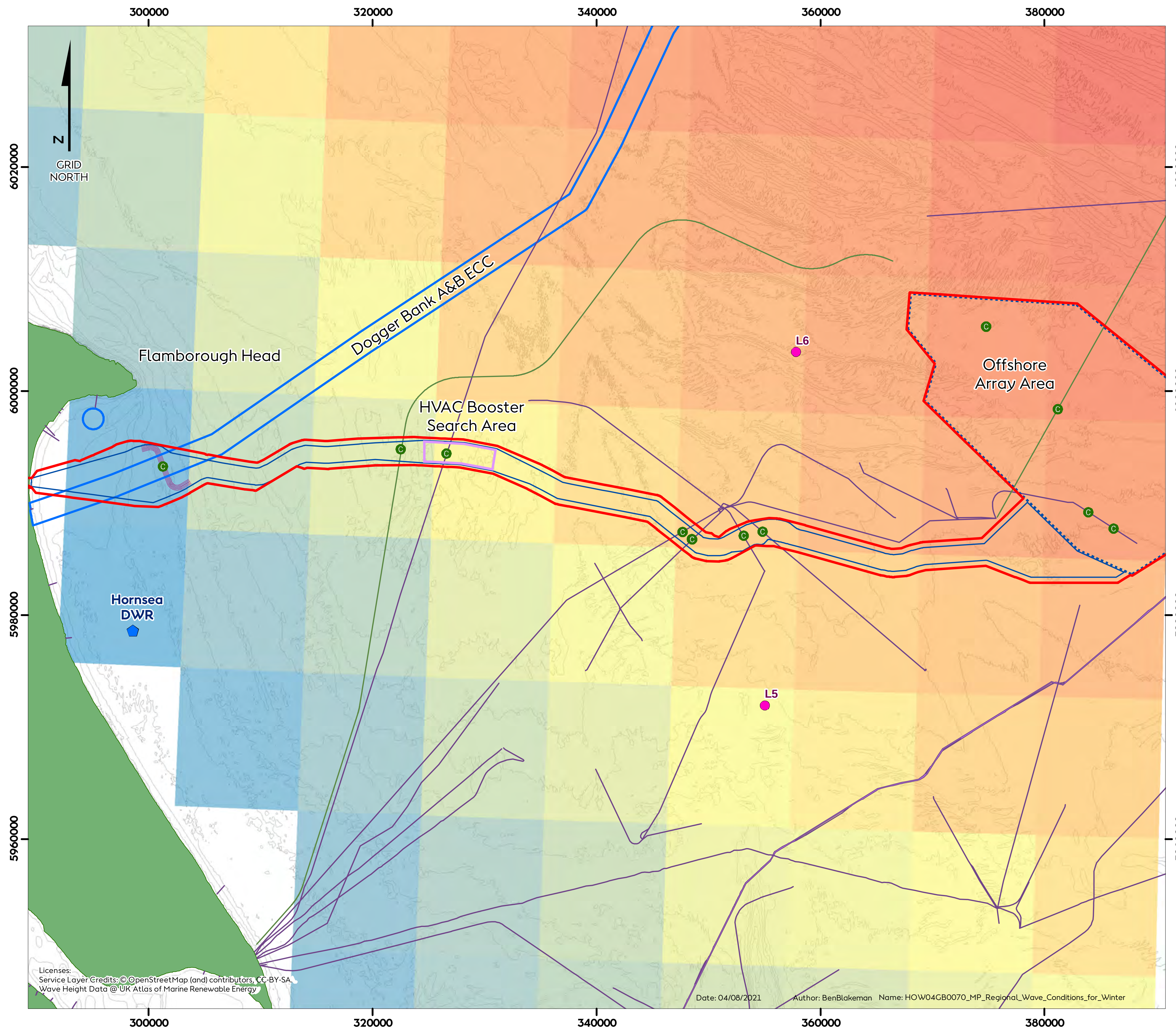
Table 6: Summary wave height variability at sites along the offshore ECC.

Location	Winter average wave height (m)	Summer average wave height (m)
Nearshore section	1.20	0.79
HVAC Booster Search Area	1.84	1.06
Offshore section	2.03	1.15

Hornsea Four

Figure 14

Regional wave conditions for winter



- Order Limits
- Array Area
- Offshore Export Cable Corridor
- HVAC Booster Station Works Area
- Crossing Point (Offshore)
- Existing Pipelines
- Proposed Pipelines
- Indicative Export Cable Route around Dogger Bank A&B ECC
- Viking Link Cable
- Existing Licence Areas for Export Cables and Disposal Sites
- Metocean Deployment Sites
- 5m Contour Intervals
- DWR Monitoring Site

Wave Height (m) (winter)

2.21

1.08

Coordinate system: ETRS 1989 UTM Zone 31N

Scale@A3: 1:325,000

0 5 10 Kilometres

0 4 8 Nautical Miles

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Regional Wave Conditions for Winter

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3.3.2.11 Wave observations are available at two locations around 12 km to the south of the offshore ECC (observation sites shown on **Figure 14**); Hornsea Directional Wave Recorder (DWR) (local depths around 12 m below LAT) and L5 – Off Grounds (local depths around 38.8 m below LAT). Wave roses have been developed for the common period between these two locations; September 2010 to end of July 2011 (**Figure 15**). Site L6 (15 km to the north of the offshore ECC and 8.5 km west of the offshore array area) also recorded waves but only for a 6-month period (from end of January 2011 to July 2011).

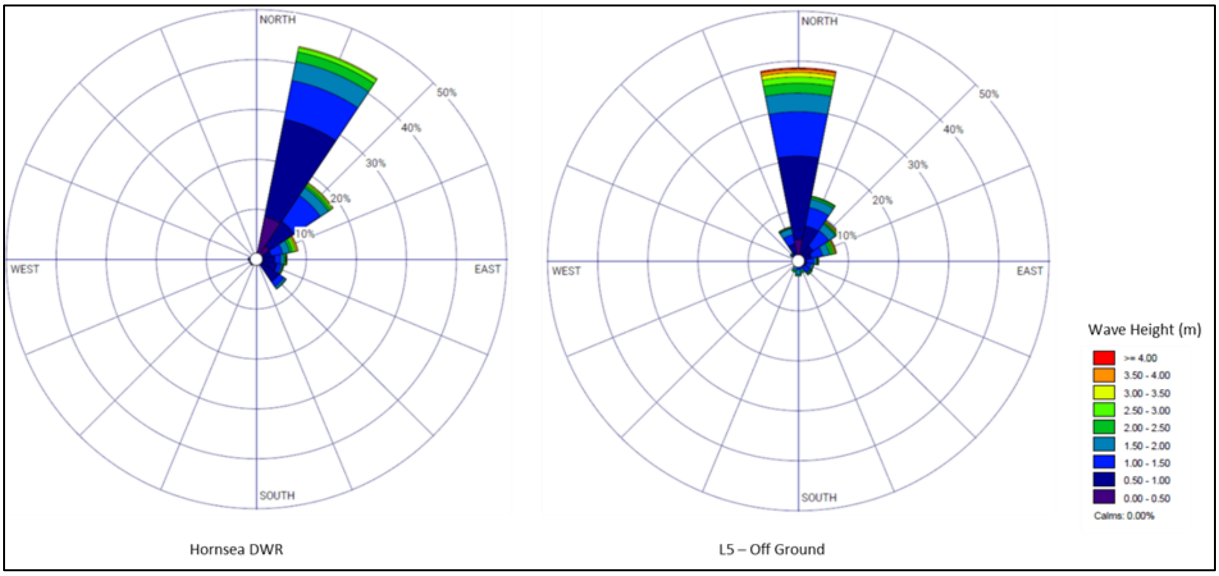


Figure 15: Wave roses for Hornsea DWR and Site L5.

3.3.2.12 Measurements from Hornsea DWR (site shown on **Figure 14**) are considered to represent nearshore wave conditions which exhibit local sheltering from northerly waves by Flamborough Head and the commencement of shallow water shoaling of larger waves. Both these effects are expected to be more strongly represented at the inshore part of the offshore ECC. Northerly waves approaching Site L5 are not influenced by such effects and are representative of deeper water, unsheltered, offshore conditions. Waves from southerly sectors are infrequent in comparison to northerly sectors.

3.3.2.13 Wave periods for both locations are typically in the region 3 to 6 s, and on a few occasions reached 7 to 8 s. These periods are typical of wind generated seas without a strong influence of swell.

Bedload sediment transport pathways

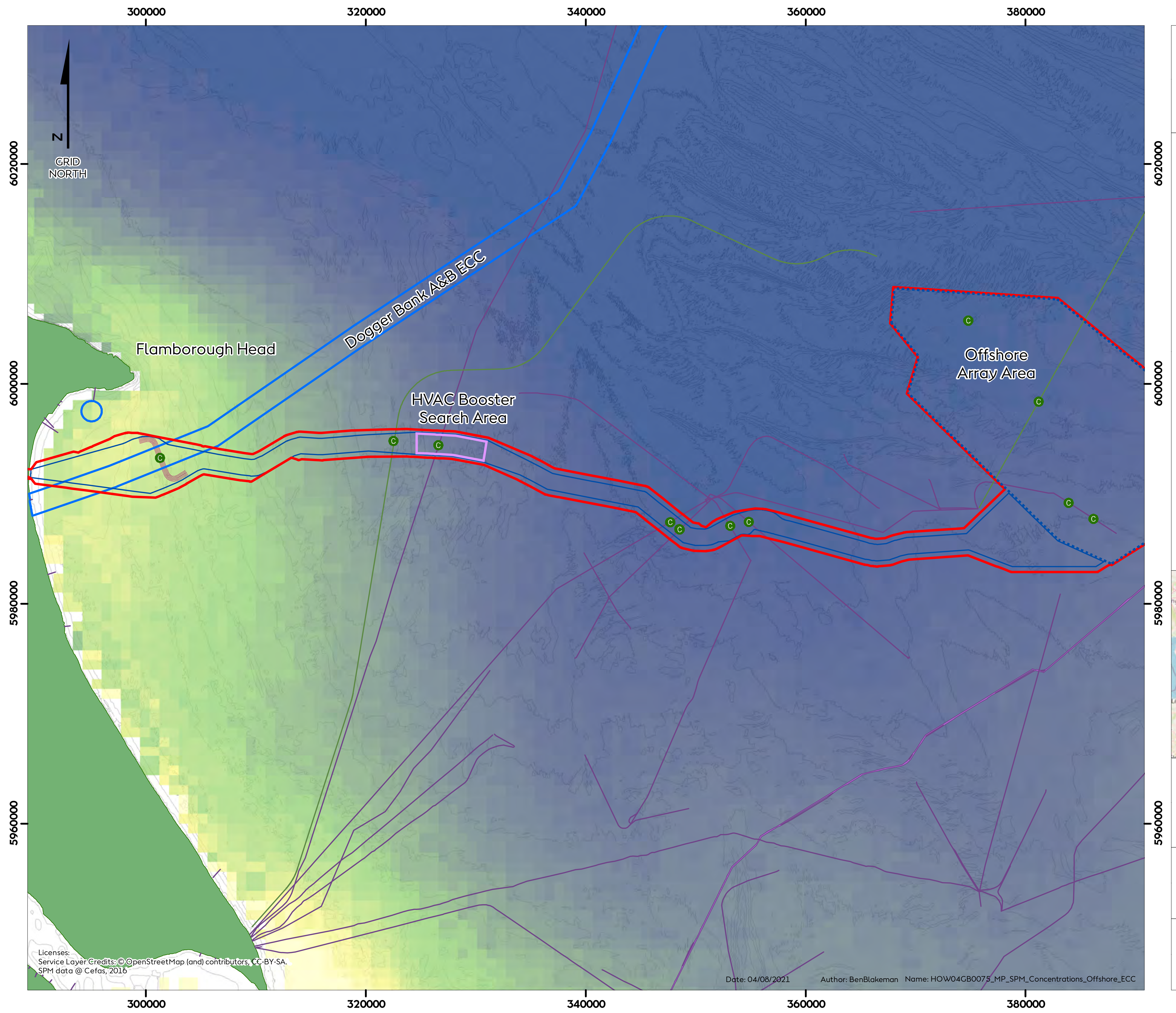
3.3.2.14 Interpretations of regional sand transport pathways (Kenyon & Cooper 2005) suggests that there is an overall net southerly transport for the area between the coast (from Flamborough Head) and the HVAC Booster Station Search Area and net north-easterly transport from the HVAC Booster Station Search Area across to the offshore array. A bedload parting zone separates these two areas (**Figure 9**).

3.3.2.15 Waves in deeper water (e.g. Site L5) have too short a wave period to exert any influence on the seabed, so these pathways are driven mainly by tides and surge currents. In shallower water (e.g. Hornsea DWR), waves begin to exert a stirring effect onto the seabed which can increase sediment mobility and rates of sediment transport. As an illustration, the largest measured wave for Hornsea DWR in period of the observations was a significant wave height, H_s of 3.79 m and a wave period, T_z of 6.7 s at 15:00 on 1 December 2010. At this time, the water level was +4.1 m above LAT (16.1 m total depth). Based on shallow water wave theory, the maximum wave induced bottom orbital velocity, u_{bot}, on the seabed would be 0.77 m/s, a magnitude similar to the peak flow on a mean spring tide for this location.

Suspended particulate matter

3.3.2.16 Suspended particulate matter (SPM) comprises of suspended sediments and other material held in suspension which can reduce light penetration through the water column and lead to higher levels of turbidity. High turbidity levels can be detected by *in situ* sensors (such as optical back-scatter (OBS) and acoustic back-scatter (ABS) devices), as well as airborne sensors and satellites. The baseline description of SPM is applicable to assessing relative increases during sediment disturbance activities due to project development. When disturbed sediments become present in the water column this property is commonly referred to as an increase in suspended sediment concentration (SSC) and the material becomes part of the overall SPM load. When the increased SSC advects from the source this is referred to as a sediment plume.

3.3.2.17 Spatial mapping of monthly mean non-algal SPM concentrations has been derived from satellite observations based on 18-years of data from 1998 to 2015 (Cefas 2016). These data represent near-surface concentrations, but for well-mixed water bodies the variation over depth is expected to be minimal. **Figure 16** presents SPM variations across the offshore ECC for the month of February which generally represents the maximum concentrations during the year. Concentrations are highest for around the first 10 km from the coastline and for the area around Flamborough Head. This is mainly in response to fine sediments from the beach being washed into the sea. July is typically the month with the lowest SPM concentrations.



Hornsea Four

Figure 16

Monthly averaged surface SPM concentrations, February

- Order Limits
- Array Area
- Offshore Export Cable Corridor
- HVAC Booster Station Works Area
- Crossing Point (Offshore)
- Existing Pipelines
- Proposed Pipelines
- Indicative Export Cable Route around Dogger Bank A&B ECC
- Viking Link Cable
- Existing Licence Areas for Export Cables and Disposal Sites
- 5m Contour Intervals

SPM Concentrations (mg/l)

83.92

0.88

Coordinate system: ETRS 1989 UTM Zone 31N

Scale@A3: 1:325,000

0 5 10 Kilometres

0 4 8 Nautical Miles

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Surface SPM Concentrations
Across Offshore ECC
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3.3.2.18 SPM concentrations vary seasonally and are generally in the range 2 to 14 mg/l closer inshore (Figure 17). Concentrations reduce further offshore to levels around 2 to 3 mg/l. The larger variations and higher concentrations in the inshore region are mainly due to fine sediments eroded from the cliffs during winter periods, shallower water and locally stronger wave and tidal stirring influences maintaining the fine material in suspension and inhibiting local deposition.

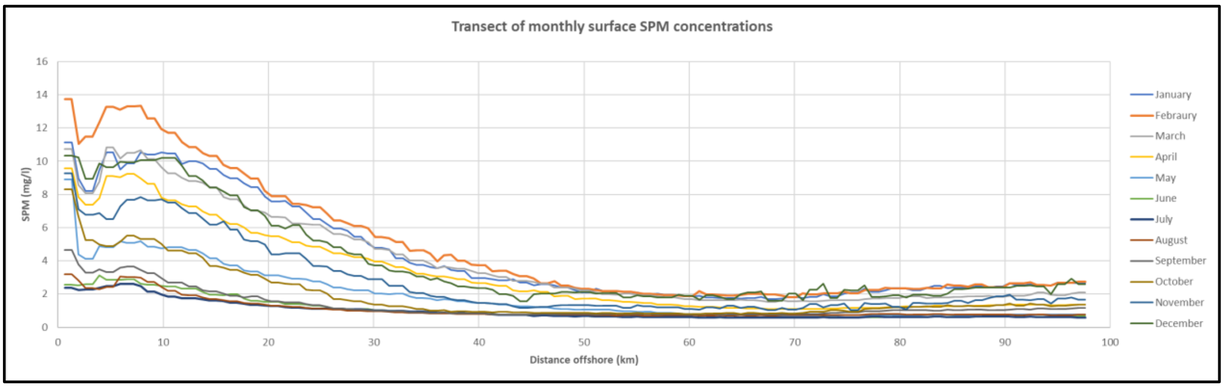
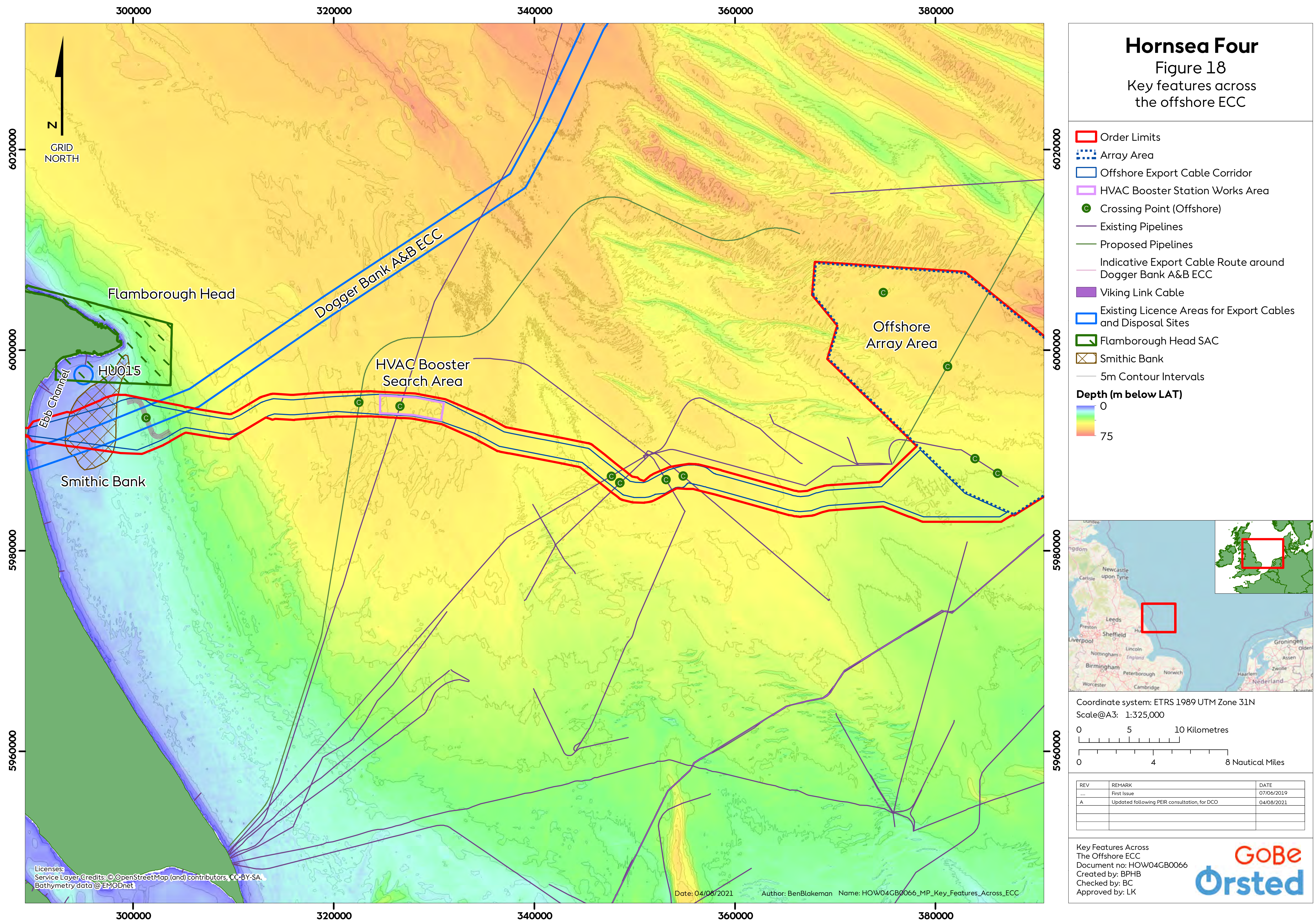


Figure 17: Transect along offshore ECC of monthly average surface SPM concentrations (derived from Cefas 2016).

3.3.3 Marine physical environment receptors – offshore ECC study area

3.3.3.1 Figure 18 shows the location of key receptor features in the marine physical environment related to the offshore ECC study area.



Hornsea Four
Figure 18
Key features across the offshore ECC
Order Limits
Array Area
Offshore Export Cable Corridor
HVAC Booster Station Works Area
Crossing Point (Offshore)
Existing Pipelines
Proposed Pipelines
Indicative Export Cable Route around Dogger Bank A&B ECC
Viking Link Cable
Existing Licence Areas for Export Cables and Disposal Sites
Flamborough Head SAC
Smithic Bank
5m Contour Intervals
Depth (m below LAT)
0
75
Coordinate system: ETRS 1989 UTM Zone 31N
Scale@A3: 1:325,000
0 5 10 Kilometres
0 4 8 Nautical Miles
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Key Features Across The Offshore ECC
Document no: HOW04GB0066
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Approved by: LK
GoBe
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GRID NORTH
N
Flamborough Head
Dogger Bank A&B ECC
HU015
Ebb Channel
Smithic Bank
HVAC Booster Search Area
Offshore Array Area
300000
320000
340000
360000
380000
6020000
6000000
5980000
5960000
Licenses:
Service Layer Credits: © OpenStreetMap (and) contributors, CC-BY-SA
Bathymetry data @ EMODnet
Date: 04/08/2021
Author: BenBlakeman
Name: HOW04GB0066_MP_Key_Features_Across_ECC
Newcastle upon Tyne
Leeds
Sheffield
Liverpool
Nottingham
Birmingham
Peterborough
Norwich
Groningen
Nederland

Spoil Ground HU015

3.3.3.2 The maintenance dredgings (of mainly silts) from Bridlington Harbour are disposed of at spoil site HU015 which is located at the northern end of the ebb tidal channel and in the lee of Flamborough Head. The circular spoil site is 1.85 km wide with charted depths between 4.5 to 8.5 m below LAT. Prior to 1985, a site HU010 3.5 km to the south-west was used for dredging disposals, however, activity was shifted to the new site HU015 to accommodate concerns of the fishing industry that HU010 was accumulating silty material (Cefas 2010). HU015 is approximately 2.3 km to the north of the offshore ECC, beyond the Hornsea Four Order Limits and is not a site being considered for any spoil disposal from activities related to Hornsea Four.

3.3.3.3 The present yearly maximum permitted disposal at HU015 from Bridlington Harbour is 20,000 (wet) tonnes of maintenance dredged material (typically silts), however, the actual amount disposed of each year is typically far less. Dredging returns in the period 1999 to 2009 varied between 2,550 to 21,380 tonnes (Cefas 2010), and averaging at 9,748 tonnes. These records also show spoil disposal may occur at any month of the year, but not necessarily every month.

3.3.3.4 In 2017, Bridlington Harbour took possession of a new dredger, *Gypsey Race*, who has a capacity of up to 100 tonnes (Martime Journal 2017). Based on past dredging records suggests this capacity dredger would be used on average 97 times a year, with January typically being the month with most disposals.

3.3.3.5 The location of HU015 mostly falls within the boundary of Flamborough Head Special Area of Conservation (SAC). Field investigations were undertaken in 2009 to address a concern by English Nature (now Natural England) that that spoil disposal activity could have the potential to impact the SAC. The field data indicated that there was currently little evidence that the disposal operation was affecting the integrity of the ecological features of the Flamborough Head SAC and no further monitoring was warranted in the immediate future unless significant changes to the disposal activities were anticipated. A repeat of the monitoring was advocated in five years' time (Cefas 2010) but this recommendation does not appear to have advanced at this time.

Flamborough Head SAC

3.3.3.6 Flamborough Head SAC encompasses the entire headland, and surrounding waters, and is around 1.6 km to the north of the offshore ECC at the closest point. The SAC is designated for various Annex I habitats, including reefs (geogenic; cobles and rock) (JNCC 2016). This habitat may be susceptible to changes in SPM and high rates of sediment deposition, noting there is no evidence that maintenance dredgings (presumably fine sediments accumulating within Bridlington Harbour) disposed of at HU015 within the SAC has led to any significant impact on these habitats at this time (Cefas 2010).

3.3.3.7 The seabed substrate around the headland is mainly rock (**Figure 9**), indicating an area scoured of mobile sediments by the locally faster flows.

Smithic Bank

3.3.3.8 Joint Nature Conservation Committee (JNCC) has previously identified Smithic Bank as a potential Annex I feature (sub-tidal sandbank) (JNCC 2017), noting this feature is not presently designated and may also not be designated in the future. The bank extends south from Flamborough Head by over 12 km, with the southern part of the bank planned to be crossed by the offshore ECC as well as the Dogger Bank A and B export cables (**Figure 18**).

3.3.3.9 The typology for Smithic Bank is a headland-associated banner type bank (HR Wallingford, Cefas/UEA, Posford Haskoning, and D'Olier B. 2002), formed in the lee of Flamborough Head by a clockwise tidal gyre (flood tide dominance to the south on the outer eastern flank and ebb tide dominance to the north on the inner western flank).

3.3.3.10 The bank is maintained by local sediment supply with cliff erosion from the south likely to be a primary source of sandy material. This supply is initially transported by northerly longshore drift and ebb tides (for beach areas north of the drift divide). This pathway is then deflected eastwards by the South Pier of Bridlington Harbour into an ebb tidal channel running between the bank and Flamborough Head (this channel exhibits higher flows during the ebb phase of the tide compared to the flood, as well as over a longer duration, making the channel ebb dominant). The bank acts as a local sediment store for sands within the tidal gyre (HR Wallingford, Cefas/UEA, Posford Haskoning, and D'Olier B. 2002, and IECS 2016).

3.3.3.11 The sediment cover through the ebb channel is described as a thin veneer over rock (CCO 2014), scouring down to rock at the narrowest point at the northern end of the bank where the channel is around 1.3 km from the tip of the headland and flows become strongest. Spoil site HU015 is located within this channel, suggesting fine sediments dumped here are likely to be rapidly dispersed without becoming deposited either in the channel or on the bank.

3.3.3.12 To the north of the bank, Flamborough Head is regarded as one-way drift divide between regional sediment cells (Cell 1 and 2) (HR Wallingford 1993), with a net sediment supply of sands to the south which feed Smithic Bank (providing a secondary source). This sediment supply is complicated and partially restricted by Filey Brigg, a further headland feature which defines the northern limit of Filey Bay and extends offshore as a rocky submarine ridge (Corallian Limestone) for over 30 km to the south-east. This extensive ridge has several gaps which encourage faster flows, prevent local sand deposition, and leave coarser sediments as a lag deposit. Seabed mapping conducted in 2016 for Scarborough Borough Council (CCO 2017) identified a line of prominent sandwaves south of the ridge with an asymmetric profile indicating a net transport direction into Filey Bay from the offshore, most likely due to deflected near-bed ebb flows running along the ridge. North of Filey Brigg other areas of nearshore sandwaves appear to be near symmetrical in profile, suggesting a balance between ebb and flood bedload transport directions for these locations.

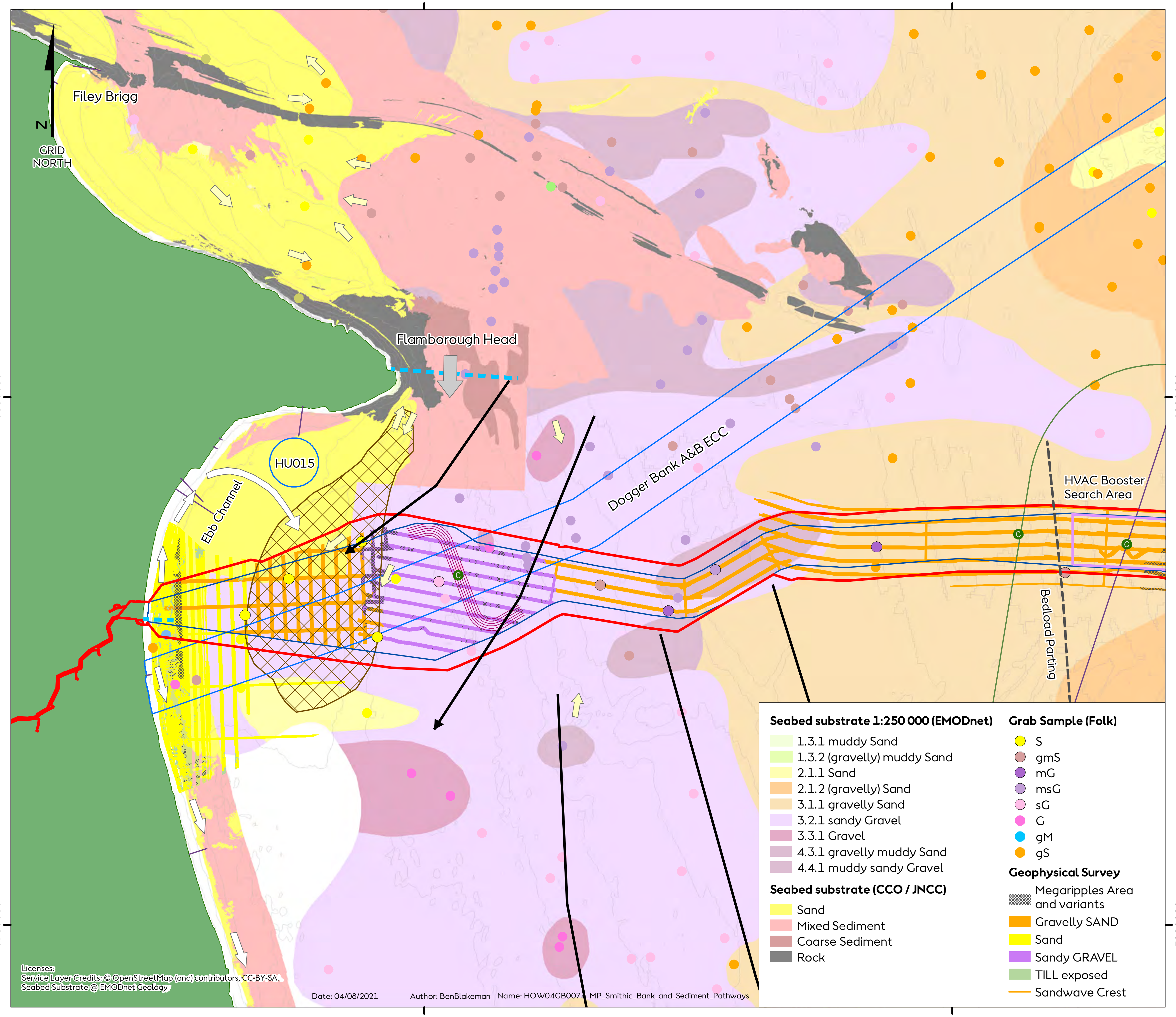
3.3.3.13 Bedload transport across the bank is prominent at the northern end (referred to on charts as North Smithic) in the form of large sandwaves (CCO 2014). The asymmetric cross-section of these sandwaves offers supporting evidence for the net clockwise direction of bedload transport around the bank. On the outer (easterly) flank, sandwave asymmetry is with the flood tide, moving sands to the south-west onto the bank, whereas for the inner (westerly) flank the dominant ebb tide develops a net sediment pathway to the north-east (**Figure 19**).

Hornsea Four

Figure 19

Smithic Bank and nearshore sediment pathways

- Order Limits
- Offshore Export Cable Corridor
- HVAC Booster Station Works Area
- Crossing Point (Offshore)
- Existing Pipelines
- Proposed Pipelines
- Indicative Export Cable Route around Dogger Bank A&B ECC
- Existing Licence Areas for Export Cables and Disposal Sites
- One-way Drift Divide
- 5m Contour Intervals
- Regional Bedload Sediment Pathways (Kenyon and Cooper, 2004)
- Smithic Bank
- Direction of net longshore drift
- Sediment Transport Indicators (Derived from SNSSTS, 2002)



Coordinate system: ETRS 1989 UTM Zone 31N

Scale@A3: 1:140,000

0 3 6 Kilometres

0 2 4 Nautical Miles

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Sediment Distributions
Sand Transport Pathways
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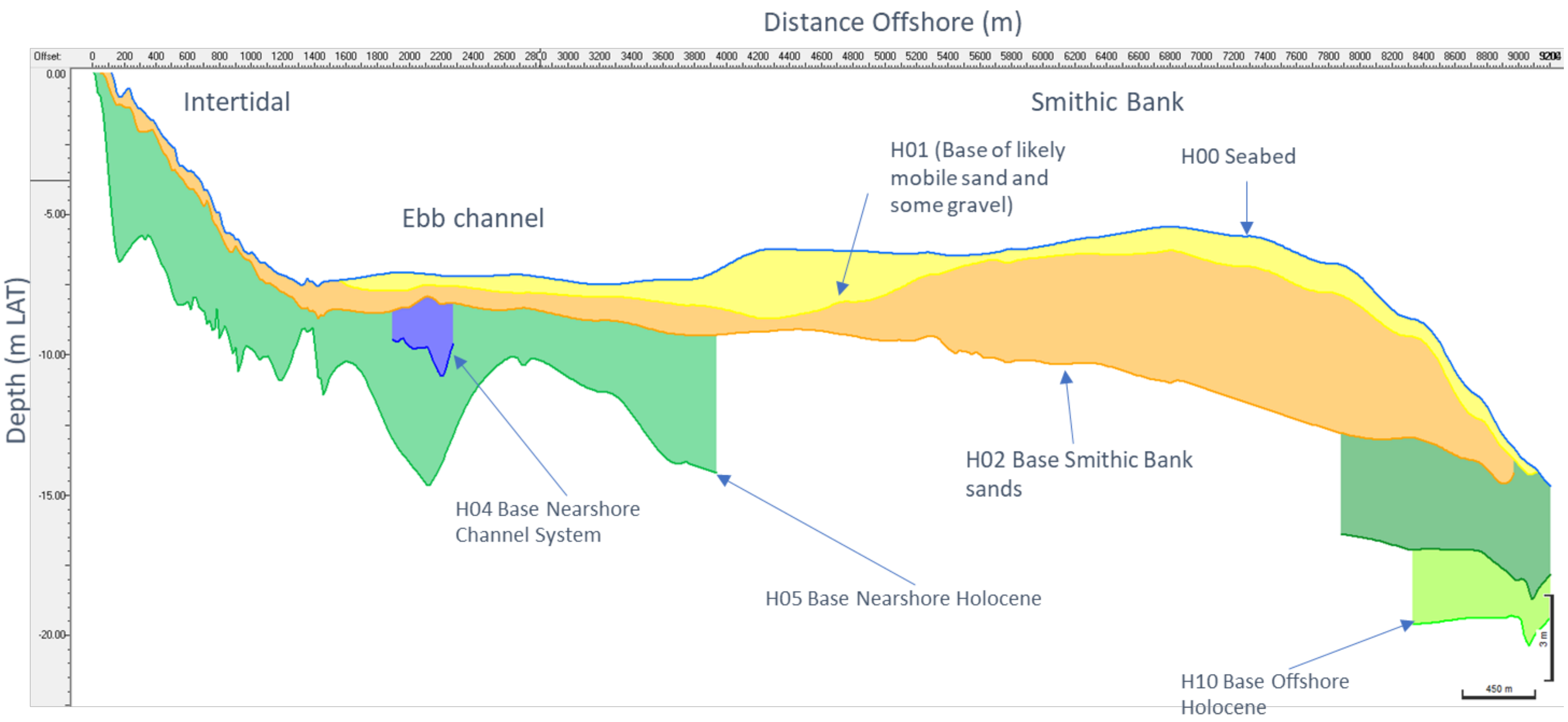
3.3.3.14 The bank is shallowest (depths less than 3 m below LAT) towards the northerly inshore flank (North Smithic) where a steep slope drops around 6 m into the ebb tidal channel. The bank morphology shows evidence of responding to both waves and tides (CCO 2014). Tidal flows are a key influence on driving sandwave migration whereas wave attenuation through refraction and shoaling is likely to be a main cause of smoothing and broadening the profile of the bank across the more wave exposed southern extents. The shallow profile of Smithic Bank is considered to provide some sheltering to the leeward coastline around Bridlington, especially during periods of stormy waves (Scott Wilson 2010).

3.3.3.15 The profile of Smithic Bank becomes less distinctive to the south and eventually flattens into the background bathymetry to the south of the drift-divide around Barmston. At this location, the bank is beyond the sheltering effects of Flamborough Head from prevailing northerly waves. The net transport pathway at this location becomes wave-driven moving sediments further down the Holderness Coast.

3.3.3.16 Over the longer-term, any increase in mean sea level due to climate change has the potential to place the profile of Smithic Bank lower in the tidal frame which could lead to a partial reduction in wave sheltering effects and potentially increased rates of cliff erosion for the leeward shoreline. If increased erosion led to increased sediment supply to the bank, then the profile of the bank may be maintained in a new dynamic equilibrium.

3.3.3.17 The offshore ECC crosses the southern part of Smithic Bank. At this location, the bank shoals on the seaward flank, from around 20 m below LAT, to a relatively flat and wide surface with a shallow profile between 5 to 7 m below LAT. The distance across Smithic Bank at this point is around 4 km (to the 7 m contour). The geophysical survey conducted for Hornsea Four offers a seabed interpretation of sand with patches of gravelly sand and reports depths of Holocene sands of < 6 m for this area (Bibby HydroMap 2019b), thinning to < 2.5 m into the ebb channel and < 1 m to the intertidal. A nearshore SBP transect from this survey (interpreted by the Applicant) is shown in **Figure 20**, identifying a depth of Holocene sands across Smithic Bank.



Unit	Formation
U01	
U02	
U04	Inshore Channel system
U05	Holocene (HOL)
U06	Sand Wave
U07	Local feature
U08	Buried Sand Waves
U09	Intra Holocene Clay
U10	Holocene (HOL)

H00
H01
H02
H04 – Base channel system
H05 – Base Holocene
H06 – Base local sandwave
H07
H08 – Top Buried sandwaves
H08 –Top Intra Holocene Clay
H09 – Base Intra Holocene Clay
H10 – Base Holocene

Figure 20: Nearshore SBP across Smithic Bank (interpreted by the Applicant).

3.3.3.18 The proposed Dogger Bank A and B export cables also plan to cross Smithic Bank just to the south of the Hornsea Four offshore ECC. Separate geophysical surveys conducted for this project also identified sands and gravels across the bank, along with some areas with ripples and megaripples. Over the southern end of Smithic Bank the depth of Holocene sands extends to around 6 m below seabed. Between the bank and the intertidal, the surface layer of Holocene sands thins to < 1 m thick and in some places underlying glacial till is exposed (ForeWind 2013), consistent details with the latest geophysical surveys obtained for Hornsea Four.

Cable and Pipeline Crossings

3.3.3.19 There are seven planned locations for cable crossings (for up to 54 crossings) along the offshore ECC (**Table 7** and **Figure 18**), this excludes a further two offshore ECC crossings within the offshore array area (see **Volume A4, Annex 4.1: Offshore Crossing Schedule**). The number of cable crossings at each location depends on the separation between adjacent obstacles. Where this separation is small then only a single set of cable crossings is likely to be required. For example, Cleeton to Minerva Umbilical, Minerva to Cleeton Gas Export and Minerva to Cleeton Piggy pipelines are all within 40 m of each other and will most likely be achieved as a single location combining multiple crossings.

Table 7: Summary details for cable crossing locations along the offshore ECC study area.

Easting (m) UTM 31N	Northing (m) UTM 31N	Type of Obstacle	Name	Number of cable crossings	Local depth (m LAT)	Lithology	Comment
301,284	5,993,244	Offshore Wind Export Cables	Dogger Bank A & B Export Cables	12	21 to 22	sandy gravel	Up to two High Voltage Direct Current (HVDC) cable pairs.
322,502	5,994,805	CO_2 pipeline to Easington	Endurance	6	50	Gravelly sand	In planning
326,617	5,994,417	44" Gas Pipeline	Langeled Pipeline	6	51	gravelly sand	HVAC Booster Station Search Area
347,696	5,987,435	36" Gas Pipeline	Cleeton CP to Dimlington	6	46 to 47	sand	
348,524	5,986,778	5.75" Chemical Pipeline	Cleeton to Minerva Umbilical	18	46 to 47	sand with megaripples	38 m apart
348,554	5,986,754	16" Condensate Pipeline	Minerva to Cleeton Gas Export		46 to 48		0.5 m apart
348,554	5,986,754	16" Condensate Pipeline/ 3" Chemical Pipeline	Minerva to Cleeton & Piggy		46 to 48		
353,135	5,987,079	16" Gas	Neptune to	6	47 to 48	sand with	

Easting (m) UTM 31N	Northing (m) UTM 31N	Type of Obstacle	Name	Number of cable crossings	Local depth (m LAT)	Lithology	Comment
		Pipeline	Cleeton Pipeline			megaripples	
354,833	**5,987,442**	**12" Gas Pipeline**	**Platypus Pipeline**	**6**	**40**	**sand with megaripples**	**Due for construction**

3.3.3.20 The Langeled gas pipeline crosses the HVAC Booster Station Search Area where depths are around 51 m below LAT. This is the largest pipeline to be crossed which has a 44 inch (1.12 m) diameter and was surface laid (no burial) in 2006. The recent geophysical survey (Bibby HydroMap 2019a; 2019b) shows the pipeline is discernible on a relatively featureless gravelly sand seabed from. In a few places the pipeline is partially covered by accumulated sediment but without any obvious areas of local scouring (**Figure 21 a**). This evidence demonstrates a largely stable seabed at this location.

3.3.3.21 Further to the east, in depths of around 47 m below LAT, and mid-way between the HVAC Booster Station Search Area and the offshore array, the offshore ECC crosses the Cleeton CP to Dimlington gas export pipeline. This is a 36 inch diameter (0.91 m) gas pipeline which was installed in 1988. The pipeline is mostly buried under a cover of sand with megaripples but is also visible in places on the seabed due to local scouring (**Figure 21 b**) demonstrating a mobile seabed.

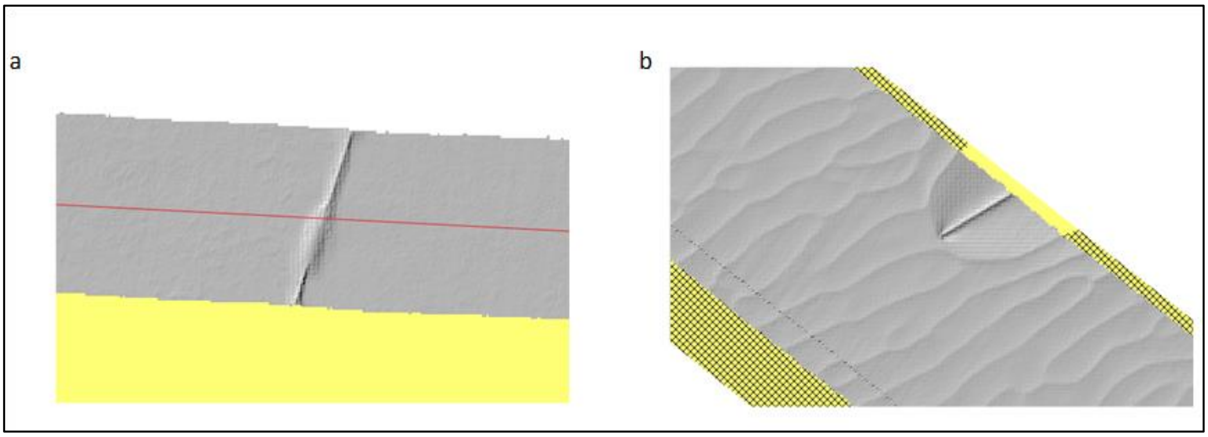


Figure 21: Visible pipelines crossing the offshore ECC. (a) Langeled pipeline, (b) Cleeton CP to Dimlington pipeline (image derived from geophysical survey).

3.3.3.22 All other existing pipelines are smaller diameter assets and are not detected as surface features in the geophysical survey data.

3.3.3.23 The Platypus Project is expected to involve development drilling, pipeline installation and the installation of a small Normally Unmanned Installation (NUI) around 9 km south of the offshore ECC. The projected field of life of Platypus is 20 years with first gas production anticipated for the fourth quarter of 2022. Platypus is expected to be constructed, and drilling would have commenced prior to the beginning of construction of Hornsea Four. The Platypus pipeline is considered as a potential impact from Hornsea Four in relation to the requirement for an additional cable crossing along the offshore ECC.

3.3.3.24 One of the two proposed pipelines to the proposed Endurance CO_2 storage facility is currently targeting a landfall at Easington. This will be a surface laid pipeline requiring a cable crossing to the west of the HVAC Booster Search Area. Water depths at this location are estimated to be around 50 m below LAT with a seabed composed of gravelly sand. If the Endurance scheme is approved then any requirement for cable crossings over the pipeline will be at one of the deepest sections of the ECC and on a relatively immobile sediment.

3.3.3.25 The offshore ECC also requires crossings with the proposed export cable from the Dogger Bank A and B offshore wind farms (**Figure 18**). This crossing is planned at right-angles in an area around 3 km seaward of Smithic Bank where local depths are around 21 to 22 m below LAT. Seabed sediments in the local area are described as sandy gravel (grab sample ECC_23) and gravelly sand (Bibby Hydromap 2019c). This crossing location is reflected in Commitment Co189; *The Dogger Bank cable crossing will be positioned east of Smithic Bank and seaward of 20 m depth contour* (see **Volume A4, Annex 5.2: Commitments Register**).

3.3.4 Summary of marine physical environment receptors within the offshore ECC study area

3.3.4.1 **Table 8** summarises the receptors associated with the offshore ECC study area. The potential sensitivity of the receptor is expressed prior to consideration of the scale of any impact related to the development.

Table 8: Marine physical environment receptors in the offshore ECC study area.

Receptor	Potential sensitivity to marine processes
Spoil Ground HU015	Modification to local flows altering local dispersion characteristics, as a consequence of any large-scale changes in Smithic Bank morphology. Use of the spoil site also has the potential to act cumulatively if disposal events of maintenance dredgings occur in the same period as export cable laying activities in the nearshore region.
Smithic Bank	Impact of storm waves. Insufficient / interruption of sediment supply. Long-term increase in MSL (due to climate change) reducing sheltering effect to the adjacent section of coastline if bank levels not sustained within the tidal frame by sufficient sediment supply.
Flamborough Head SAC	Deposition of sediments onto designated features (Annex I reefs).
Pipeline and cable crossings	Local "edge" scouring around periphery of rock berms where the local seabed demonstrates active seabed mobility. Potential greater level of interaction with waves and flows for the nearshore Dogger Bank A and B export cable crossing.

3.4 Offshore array study area

3.4.1 General description

3.4.1.1 The offshore array is located around 69 km seaward of Flamborough Head (at the closest point) and covers an area of approximately 468 km^2 of seabed. Within this area there are provisions for up to 180 wind turbine generator (WTG) foundations, nine offshore substation

(OSS) foundations and one offshore accommodation platform foundation. Up to 600 km of array cables will link up the wind turbines to the OSS.

3.4.1.2 The offshore array study area includes the offshore array and surrounding areas which may be reached by sediment plumes created during installation activities. In addition, the offshore array study area also includes the locations where structures installed on the seabed (e.g. foundations) may individually act to block passing waves, tidal flows, or sediment pathways across the array. Some of these effects also have the potential to extend beyond the offshore array area (e.g. reduction in wave energy transmission towards the coast).

3.4.1.3 Given the relatively close proximity between Hornsea Four and Hornsea Project Two (around 3.4 km to the south-east), which itself abuts with Hornsea Project One, the offshore array study area also includes a consideration of these adjacent wind farms which might lead to a potentially larger cumulative blockage effect on waves, tides and sediment pathways due to the collective set of all foundations.

3.4.1.4 A review of operational wave monitoring data obtained during the construction phase of Hornsea Project One has been agreed with the Marine Ecology and Processes Evidence Plan Technical Panel (Orsted 2020). This review demonstrates that wave energy transmission through the array has no detectable reduction due to the wind farm monopile foundations for the final scheme layout now installed. This outcome is also expected to remain true for Hornsea Project Two based on a similar final design. Together this greatly alleviates the case of potential cumulative impacts with Hornsea Four for wave reduction effects which would have existed if all three projects were still being considered based on their respective MDS cases for WTG-GBS foundations.

3.4.2 Marine process description

Seabed profile

3.4.2.1 The general seabed profile across the array area shelves from < 40 to 45 m below LAT along the southern boundary to around 50 to 55 m below LAT along the northern boundary. Outer Silver Pit, a large geological "tunnel valley" depression, establishes the north-westerly / south-easterly alignment of the eastern boundary (**Figure 22**).

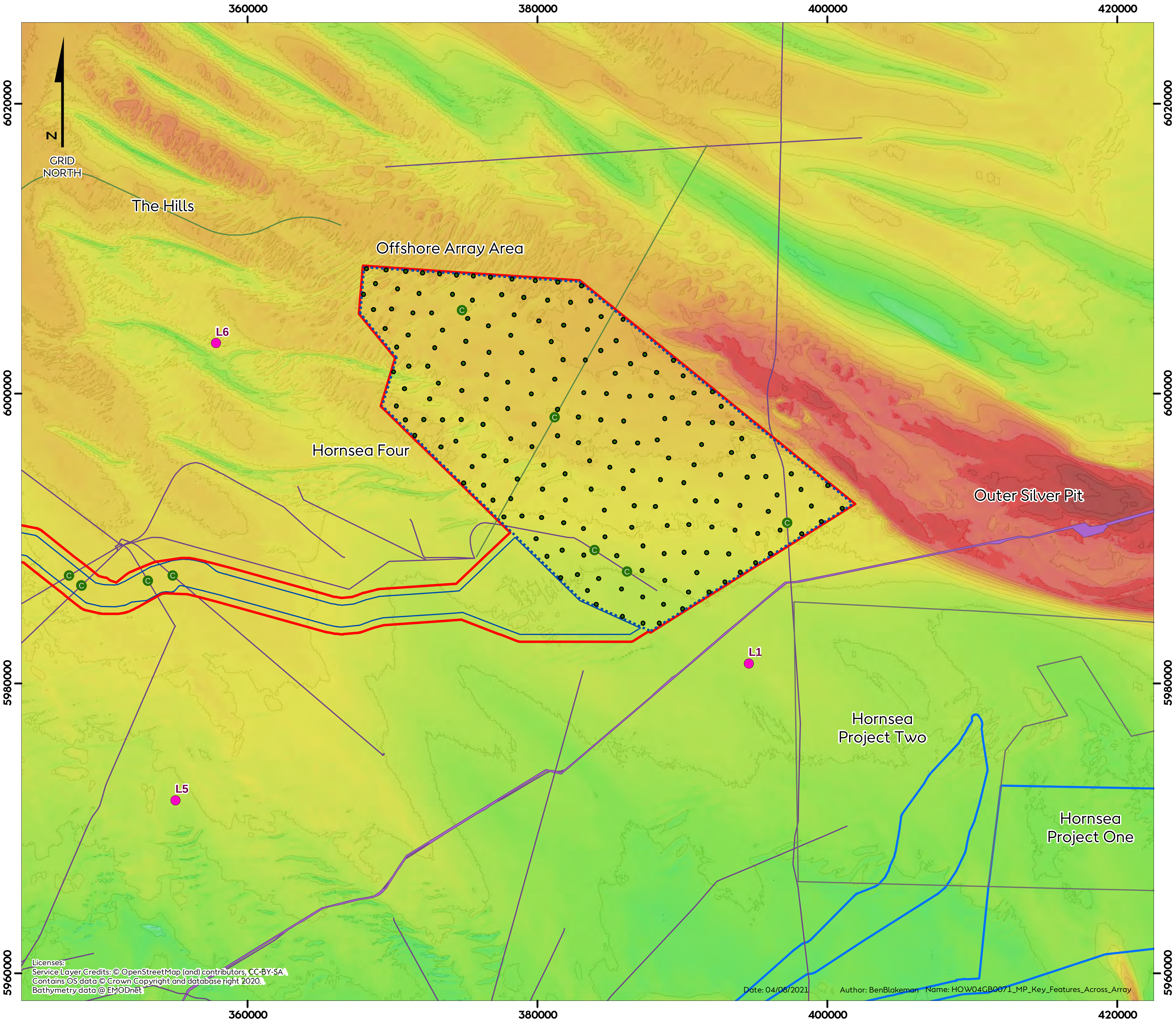
3.4.2.2 There is a small area midway along the eastern boundary of the offshore array area which coincides with the westerly slope of Outer Silver Pit. This is the deepest part of the array area with the geophysical survey indicating depths as low as 62.07 m below LAT.

3.4.2.3 To the north and west of the offshore array there is a series of large flow aligned sand ridges known as The Hills. These ridges are associated with a series of smaller flow transverse sandwaves.

Hornsea Four

Figure 22

Key features across the offshore array study area



- Order Limits
- Array Area
- Offshore Export Cable Corridor
- Indicative Turbine Layout
- Crossing Point (Offshore)
- Existing Pipelines
- Proposed Pipelines
- Viking Link Cable
- Existing Licence Areas for Export Cables and Disposal Sites
- Metocean Deployment Sites
- 5m Contour Intervals

Depth (m below LAT)
0
90

Coordinate system: ETRS 1989 UTM Zone 31N
Scale@A3: 1:250,000

0 5 10 Kilometres

0 2.5 5 Nautical Miles

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Key Features Across The Offshore Array Study Area
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3.4.2.4 The shallowest area within the offshore array area has a depth of around 34 m below LAT and is associated with one of the sand ridge features (part of The Hills) in the north-west part of the offshore array area (Figure 23). This is a (near) flow aligned bedform feature associated with large sandwaves and megaripples. Around the perimeter of the sand ridge the sandwave crests are between 45 to 90° to the alignment of the ridge. The asymmetry of these sandwaves at this location suggests convergence to the crest of the ridge feature.

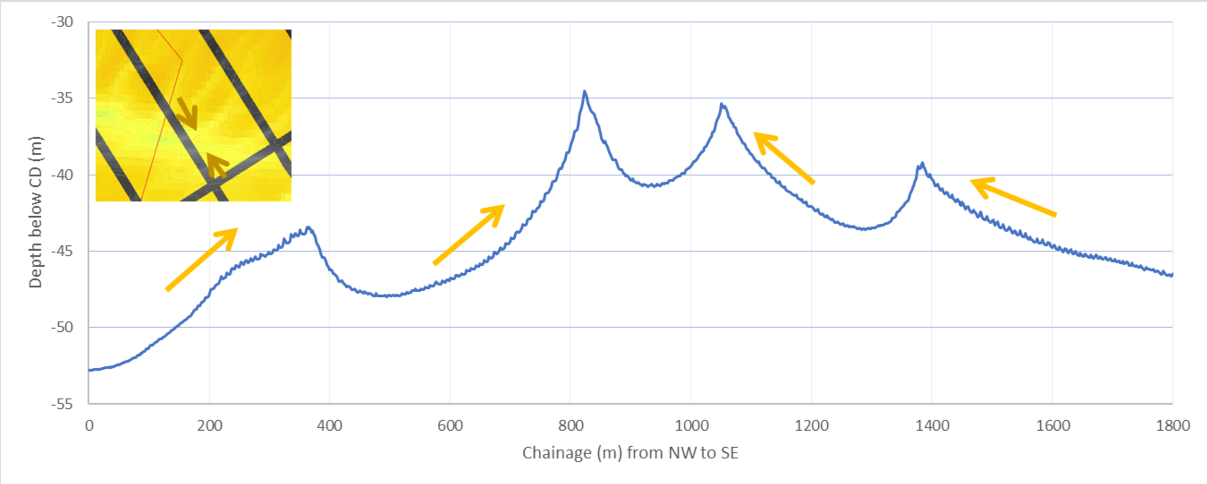
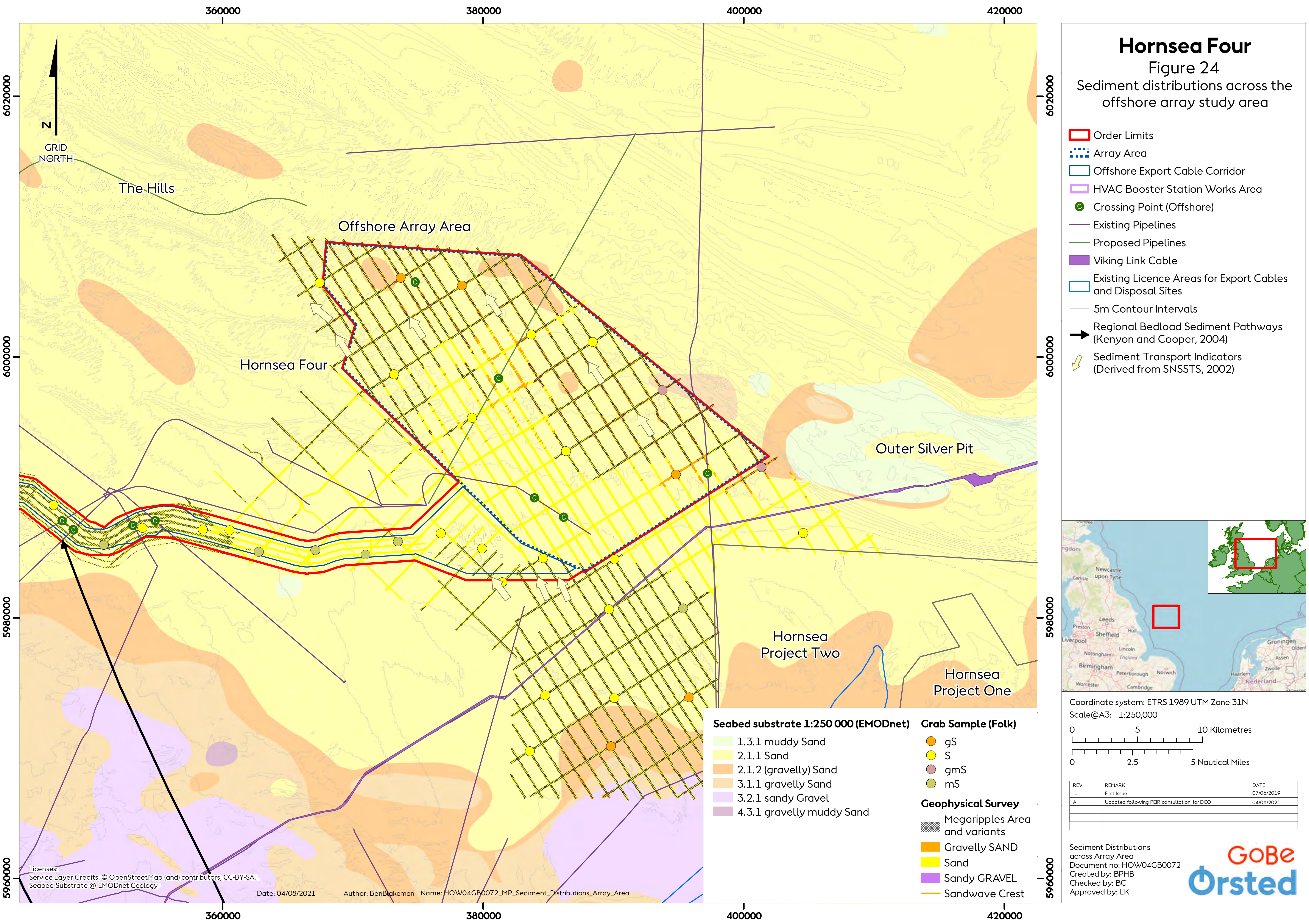


Figure 23: Area of shallow sand ridge and associated sandwaves in north-west of offshore array area (horizontal exaggeration around 1:20) (derived from geophysical survey).

<u>Subtidal sediments</u>

3.4.2.5 The geophysical survey interprets the seabed lithology across the offshore array area as mainly fine sands (Gardline 2019a) with some areas described as fine sand with some gravels in the south-easterly area and fine, medium to coarse sand in the north western segment. Particle size information (Gardline 2019b) classifies the main sediment fraction as medium sands with a generally low (< 5 %) contribution of fine sediments (muds and silts), with a few exceptions and with a similar low gravel content (typically less than 10 %) (Figure 24).

3.4.2.6 Sandwaves (associated with megaripples) are present across the majority of the offshore array area apart from the south-western corner joining with the offshore ECC, an area described as a plain seabed. The orientation of sandwave crests and slope asymmetry suggests bedload pathways are mainly to the north-west (sandwave crests are only resolved for areas covered by the survey lines, however, they are also expected to extend across the un-surveyed areas in a similar manner).



Hornsea Four
Figure 24
Sediment distributions across the offshore array study area
Order Limits
Array Area
Offshore Export Cable Corridor
HVAC Booster Station Works Area
Crossing Point (Offshore)
Existing Pipelines
Proposed Pipelines
Viking Link Cable
Existing Licence Areas for Export Cables and Disposal Sites
5m Contour Intervals
Regional Bedload Sediment Pathways (Kenyon and Cooper, 2004)
Sediment Transport Indicators (Derived from SNSSTS, 2002)
Seabed substrate 1:250 000 (EMODnet)
1.3.1 muddy Sand
2.1.1 Sand
2.1.2 (gravelly) Sand
3.1.1 gravelly Sand
3.2.1 sandy Gravel
4.3.1 gravelly muddy Sand
Grab Sample (Folk)
gS
S
gmS
mS
Geophysical Survey
Megaripples Area and variants
Gravelly SAND
Sand
Sandy GRAVEL
Sandwave Crest
The Hills
Offshore Array Area
Hornsea Four
Outer Silver Pit
Hornsea Project Two
Hornsea Project One
GRID NORTH
N
360000
380000
400000
420000
6020000
6000000
5980000
5960000
Coordinate system: ETRS 1989 UTM Zone 31N
Scale@A3: 1:250,000
0 5 10 Kilometres
0 2.5 5 Nautical Miles
REV REMARK DATE
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Sediment Distributions across Array Area
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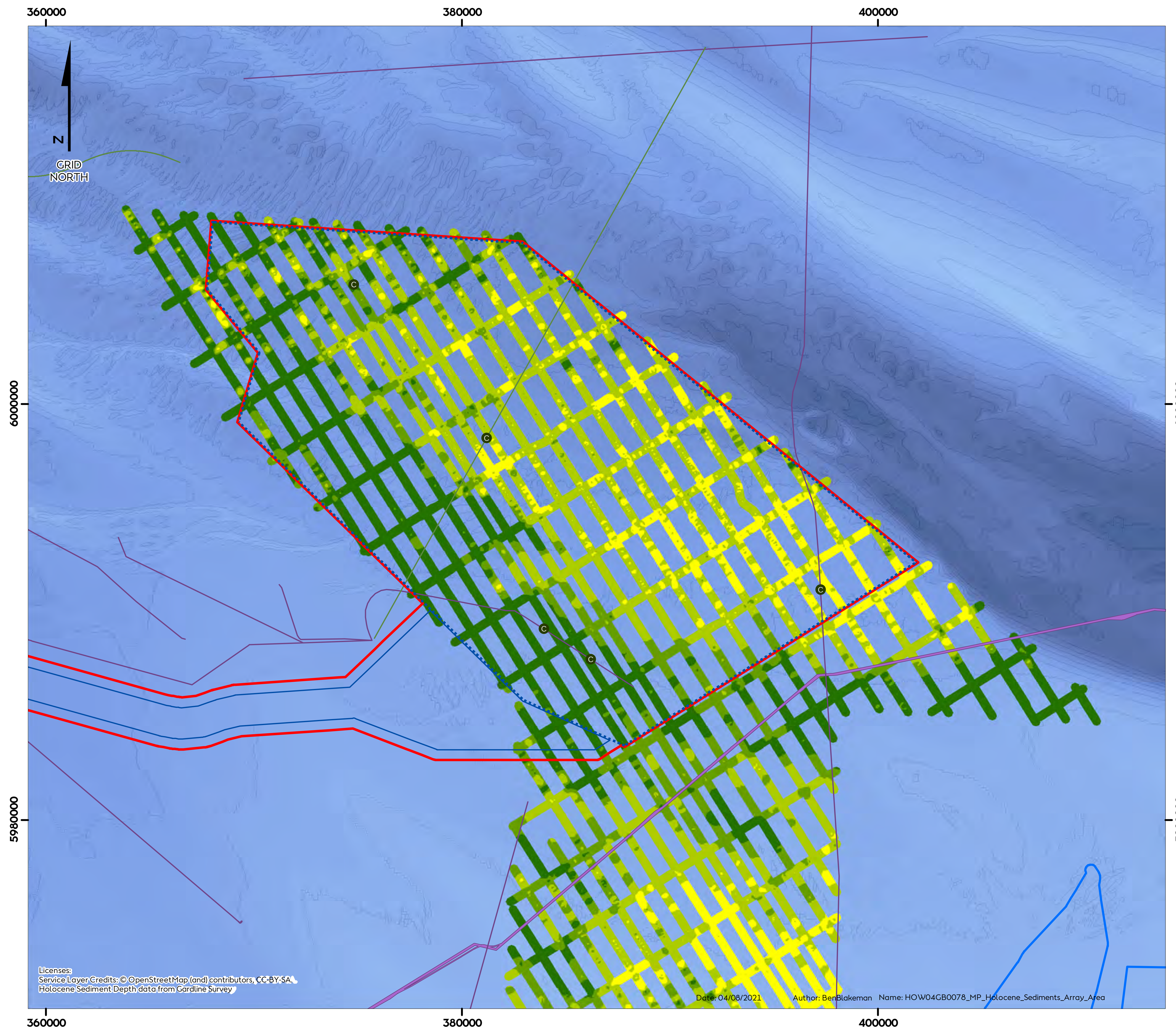
GoBe
Ørsted
Licenses:
Service Layer Credits: © OpenStreetMap (and) contributors, CC-BY-SA.
Seabed Substrate @ EMODnet Geology
Date: 04/08/2021
Author: BenBlakeman
Name: HOW04GB0072_MP_Sediment_Distributions_Array_Area

Sub-bottom profiles (SBP)

3.4.2.7 The geophysical survey data includes an interpretation of SBP across the offshore array area (GeoSurveys 2019) which suggests that the base of the surface Holocene sands is typically < 1 m thick across the majority of the area. There are local deviations where the thickness of the sand layer is > 1 m, for example across the large sand ridge along the western boundary with sediment thickness greater than 10 m (up to 19 m), as well as areas along the northern boundary (typically > 5 m thick) (**Figure 25**). Beneath the surface layer of Holocene sands is the firm to stiff clay till of the Bolders Bank Formation (Gardline 2019a).



Hornsea Four

Figure 25

Depth below seabed to base of Holocene sediments

- Order Limits
- Array Area
- Offshore Export Cable Corridor
- Crossing Point (Offshore)
- Existing Pipelines
- Proposed Pipelines
- Viking Link Cable
- Existing Licence Areas for Export Cables and Disposal Sites
- 5m Contour Intervals

Depth of Holocene Sediment

(metres below sea bed)

27

0

Depth (m below LAT)

15

80

Coordinate system: ETRS 1989 UTM Zone 31N

Scale@A3: 1:175,000

0 4 8 Kilometres

0 2 4 Nautical Miles

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Isopach Depths of Holocene Sediment Offshore Array
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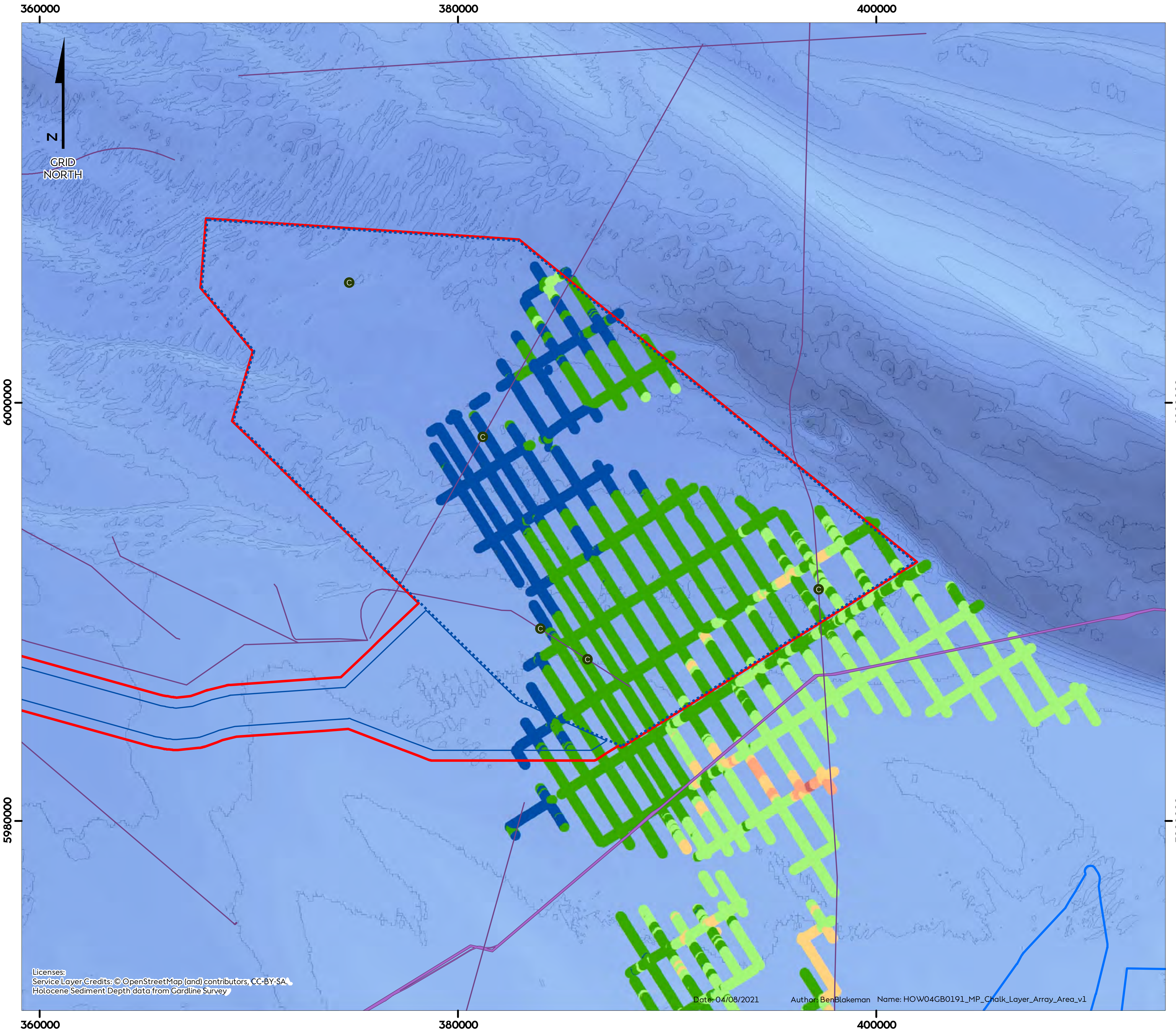
3.4.2.8 The Bolders Bank Formation is present across the majority of the site, however, there are instances where this layer becomes very thin and, at times absent, leaving the Holocene sediments directly overlying the Cretaceous Chalk and pre-chalk sediments. **Figure 26** presents an interpretation of the depth below seabed to the top of the chalk layer along with indicative locations for wind turbine generators (WTG). Chalk appears to be absent for the north and western parts of the offshore array area but present from the eastern to southern parts with increasing depths below seabed from around 3 to 100 m. An area along the eastern boundary also appears to have no sub-surface chalk. For reference, monopile embedment depths are up to 40 m and for piled jacket foundations the equivalent pin pile embedment depth would be 70 m.



Hornsea Four

Figure 26

Depth below seabed to top of chalk layer

- Order Limits
- Array Area
- Offshore Export Cable Corridor
- Crossing Point (Offshore)
- Existing Cables and Pipelines
- Viking Link Cable
- Existing Licence Areas for Export Cables and Disposal Sites
- 5m Contour Intervals

Top Chalk Depth (m)

- 0 - 20
- 20 - 40
- 40 - 70
- 70 - 100
- 100 - 120
- 120 - 140

Depth (m below LAT)

15

80

Coordinate system: ETRS 1989 UTM Zone 31N

Scale@A3: 1:175,000

0 4 8 Kilometres

0 2 4 Nautical Miles

REV	REMARK	DATE
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Depth below seabed to top of chalk layer

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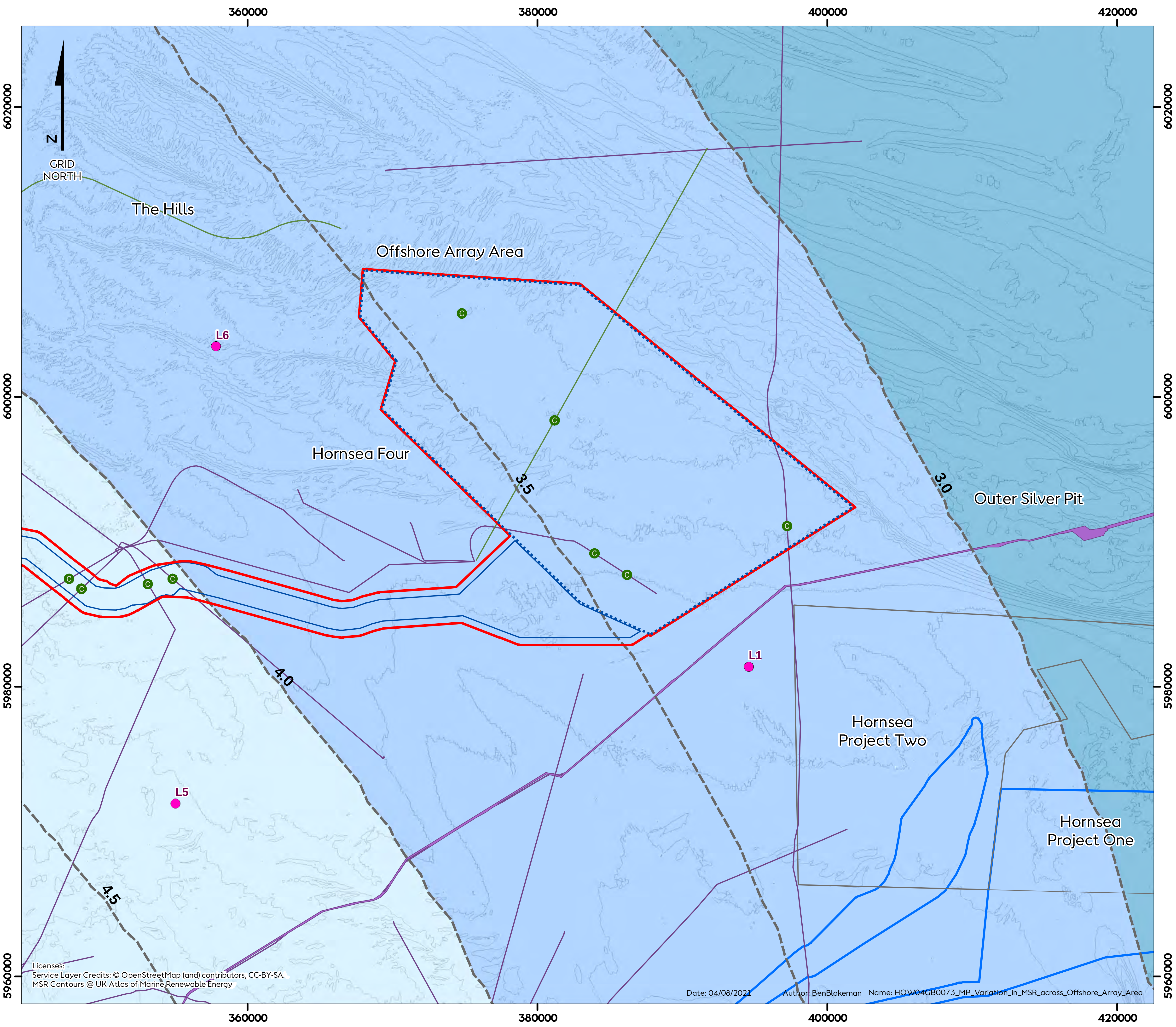
Water levels

3.4.2.9 The metocean survey for the former Hornsea zone included 12-months of observations from Site L1 – Well Bank Flat (29 June 2010 to 4 July 2011). This site is around 5.4 km to the south-east of the southern boundary of the offshore array area with a reported water depth of 37.5 m below LAT (**Figure 27**). This dataset provides timeseries variations in current velocity profiles, surface waves, water levels and near-bed temperature and turbidity measurements.

3.4.2.10 The spatial variance across the offshore array is considered with reference to relevant details from the Atlas of UK Marine Renewable Energy Resources which are based on a regional scale model. Tidal range increase from east to west across the offshore array due to increasing distance from tidal amphidromes in the Southern North Sea. MSR is around 3.1 m at the easternmost extent increasing to around 3.6 m at the westernmost extent (DECC 2008a) (**Figure 27**). At Site L1 MSR is assessed to be 3.28 m (EMU 2013). Equivalent tidal range values for MNR are 1.50 to 1.77 m from east to west, and 1.61 m at Site L1 (around 5.4 km to the south-east of Hornsea Four).

Tidal flows

3.4.2.11 The most common sediment fraction present across the offshore array is medium sands (particle size in the range 0.25 to 0.50 mm) (Gardline 2019b). This sediment size requires flows in excess of 0.5 to 0.6 m/s to become mobilised, based on standard theoretical expressions (Soulsby 1997). Tidal mapping from the Atlas of UK Marine Renewable Energy Resources (DECC 2008a) suggests this magnitude is generally limited to peak flows during spring tides (**Figure 28**), and larger tidal ranges, and is not attained during neap tides. The orientation of the tidal ellipses is mainly to the south-east on the flood tide and north-west on the ebb tide.



Hornsea Four

Figure 27

Variation in MSR across offshore array study area

- Order Limits
- Array Area
- Offshore Export Cable Corridor
- Crossing Point (Offshore)
- Existing Pipelines
- Proposed Pipelines
- Viking Link Cable
- Existing Licence Areas for Export Cables and Disposal Sites
- Mean Spring Tidal Range Contours
- Metocean Deployment Sites
- 5m Contour Intervals

Mean Spring Tidal Range (m)

(UK Atlas of Marine Renewable Energy)

- 2 - 3
- 3 - 4
- 4 - 5

Coordinate system: ETRS 1989 UTM Zone 31N
Scale@A3: 1:250,000

0 5 10 Kilometres

0 2.5 5 Nautical Miles

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Variation in MSR
Across Offshore Array Area
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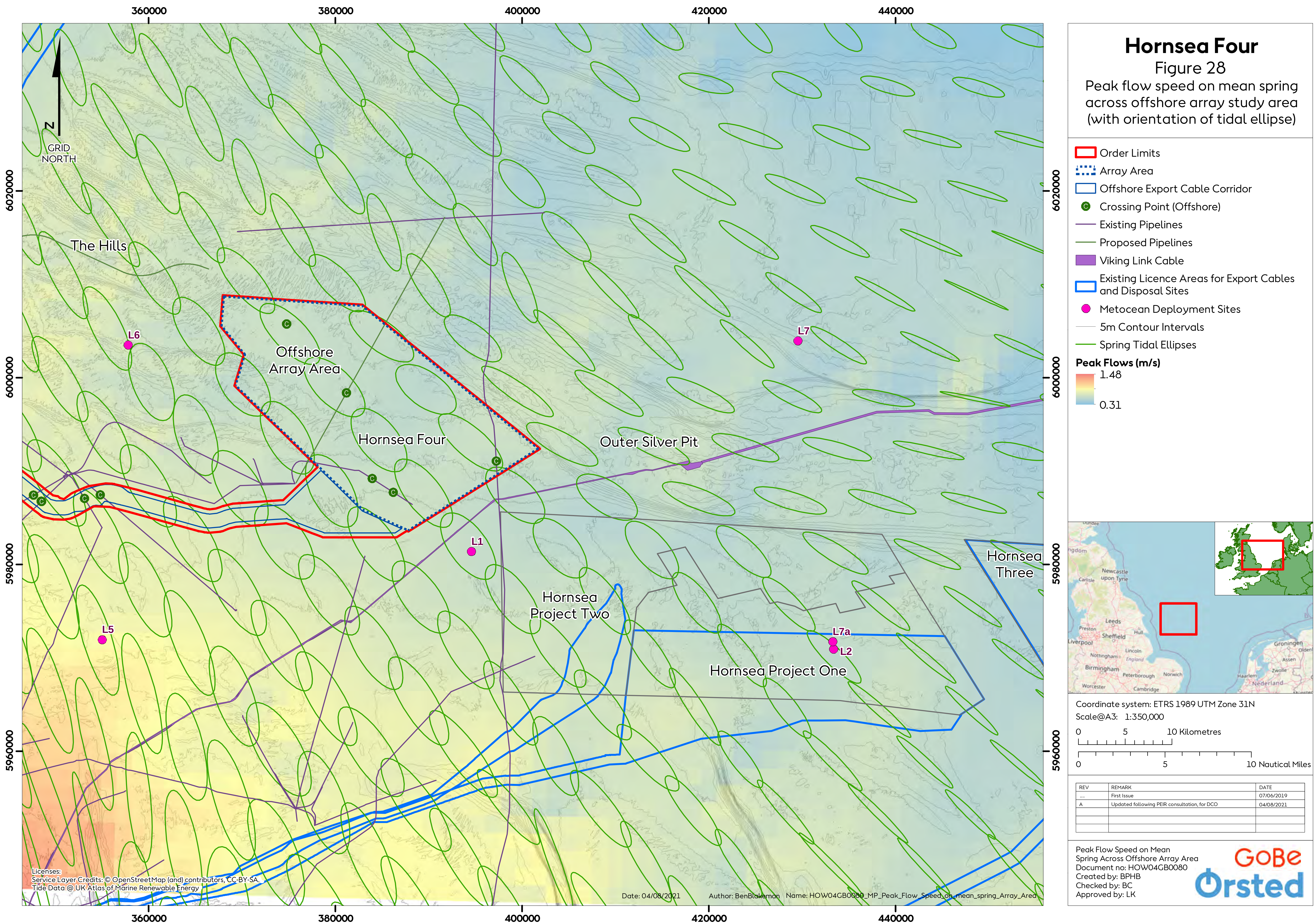

Date: 04/08/2021 Author: BenBlakeman Name: HOW04GB0080_MP_Peak_Flow_Speed_on_mean_spring_Array_Area

Hornsea Four

Figure 28

Peak flow speed on mean spring across offshore array study area (with orientation of tidal ellipse)

- Order Limits
- Array Area
- Offshore Export Cable Corridor
- Crossing Point (Offshore)
- Existing Pipelines
- Proposed Pipelines
- Viking Link Cable
- Existing Licence Areas for Export Cables and Disposal Sites
- Metocean Deployment Sites
- 5m Contour Intervals
- Spring Tidal Ellipses

Peak Flows (m/s)
1.48
0.31

Coordinate system: ETRS 1989 UTM Zone 31N
Scale@A3: 1:350,000

0 5 10 Kilometres

0 5 10 Nautical Miles

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Peak Flow Speed on Mean Spring Across Offshore Array Area
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3.4.2.12 A current rose of depth-average flows at Site L1 (**Figure 29**) confirms the main tidal axis is south-east for the flood phase of the tide and north-west for the ebb (validating the information from the Atlas). There is also a slight asymmetry between peak flood and ebb flows (i.e. peak flows > 0.6 m/s required for sediment transport of local sandy sediments) which supports a south-easterly (flood) net transport direction for sands at this southerly location within the offshore array. Site L6 – Ravenspurn Field is just west of the offshore array area, in a depth of 46.7 m below LAT, but still offers a useful indication of likely flow conditions for the more northerly areas. The asymmetry between peak flood and ebb flows at Site L6 indicates a slight north-westerly (ebb) net transport direction, supportive of the sandwave asymmetry in this general area. The data also indicates that times of peak flows occur at approximately high and low water.

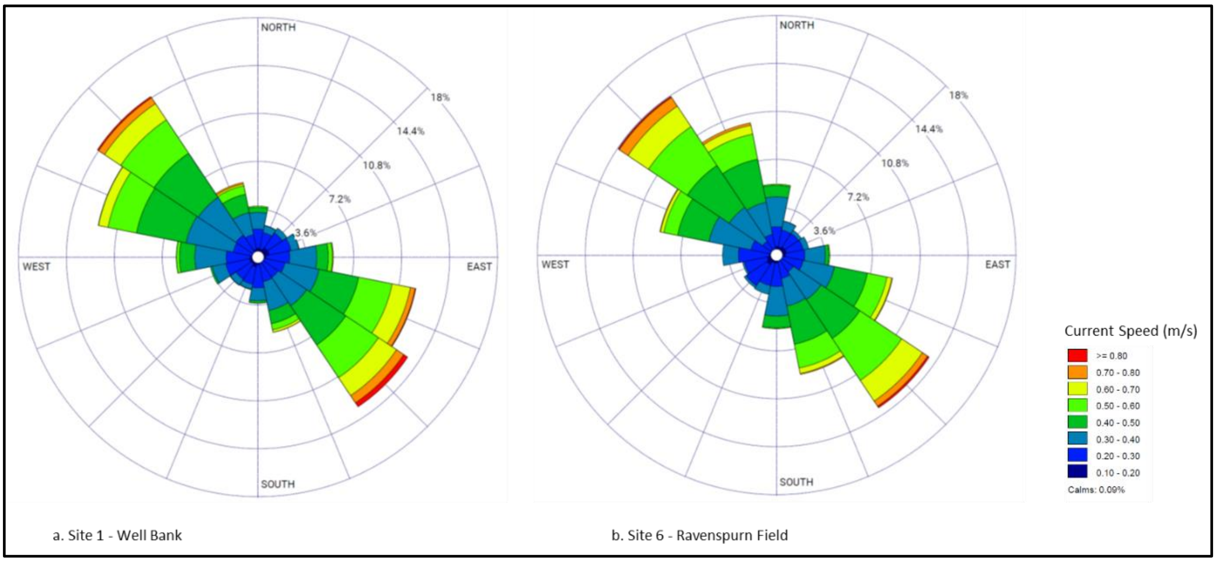


Figure 29: Current roses for Sites L1 and L6.

<u>Waves</u>

3.4.2.13 Waves measured at Site L1 (to the south of the offshore array area) from 29 June 2010 to 4 July 2011 indicate wave periods (T_z, zero up-crossing period) in the range 3 to 6 s, and typically around 4 s. Significant wave heights, H_s, were typically less than 1.0 m in this period but reached 4.5 m during a storm event in November 2011 (EMU 2013). The wave period, T_z at this time was 6 s and from a south-westerly direction, with a water elevation of 1.8 m above LAT at this time. The equivalent maximum wave induced orbital seabed velocity would have been 0.05 m/s. If the same wave was in a deeper section of the offshore array area (e.g. around 55 m below LAT) then the equivalent orbital velocity would be < 0.01 m/s. For the shallowest part of the offshore array, on the crest of the sand ridge, the equivalent wave orbital velocity would be 0.10 m/s. On this basis, even the largest measured wave event was incapable of stirring local sediments alone. This means peak tidal currents during spring tides (and higher tidal ranges) are the main mechanism for developing sediment transport across the offshore array area.

3.4.2.14 The distribution of wave heights measured at Site L1 is presented in **Figure 30** as a wave rose to demonstrate the prevalence of the north-north-westerly direction, which is also the direction which contains most of the largest wave events (43% of all waves > 3.5 m are from the north-north-westerly sector).

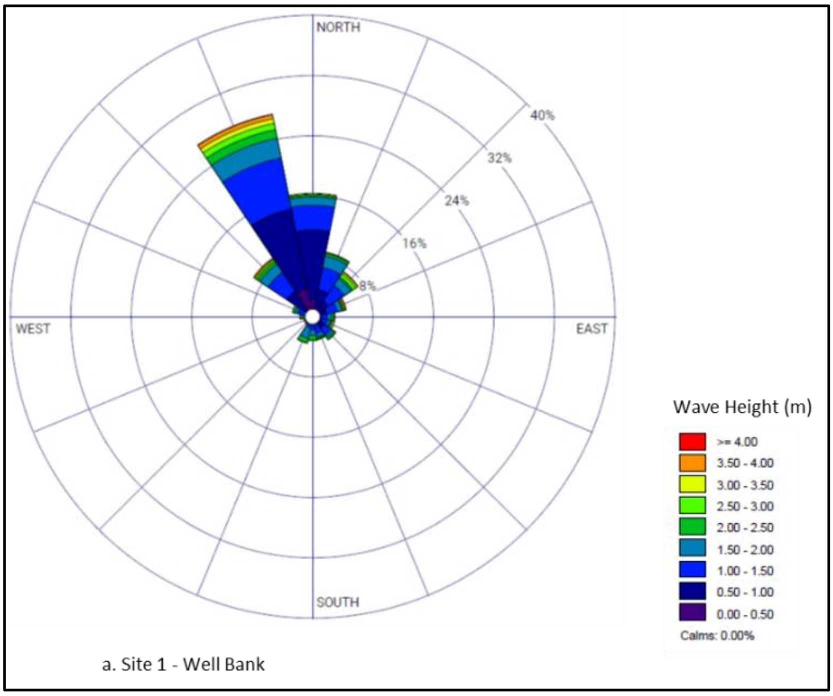


Figure 30: Wave rose for Site L1.

<u>Bedload sediment transport pathways</u>

3.4.2.15 Sandwaves and associated megaripples are evident across the majority of the offshore array area apart from the central and southerly regions (**Figure 24**). These bedforms are essentially a continuum of scales moving at different rates. Megaripples are able to migrate fastest over the surface of the seabed and where they converge, they may form a larger feature which eventually reaches the scale of a sandwave (regarded as a macro bedform feature). Smaller sandwaves may then converge to form a larger sandwave which is likely to have slow rates of migration. Sand ridges (the largest scale of bedform identified in the offshore array area) are likely to be relatively stationary features. The cross-section of a sandwave may also indicate an asymmetry in slopes with a longer shallower gradient stoss slope and a steeper shorter lee. This asymmetry helps infer a net direction of bedload transport towards the steeper lee. In the present case, the lee slope is on the northern side of most sandwaves indicating net migration with the ebb tide. Sandwave crests resolved from the geophysical survey are generally aligned perpendicular to the axis of tidal flows.

3.4.2.16 **Figure 31** provides an example of sandwaves along a transect from the northern part of the offshore array area. Zero chainage is at the north-west with increasing chainage to the south-east. This figure shows a sequence of larger sandwaves (3 to 3.5 m high with wave lengths of 400 to 500 m) with distinct asymmetry indicating a net transport direction to the north-west. Between the larger sandwaves there are also smaller sandwaves (lower height and smaller wavelength) with megaripples superimposed across the trough and up the lee slopes. The steeper lee slopes are typically smooth, being relatively sheltered from the boundary layer turbulence and due to steep slopes being unable to support bedform features.

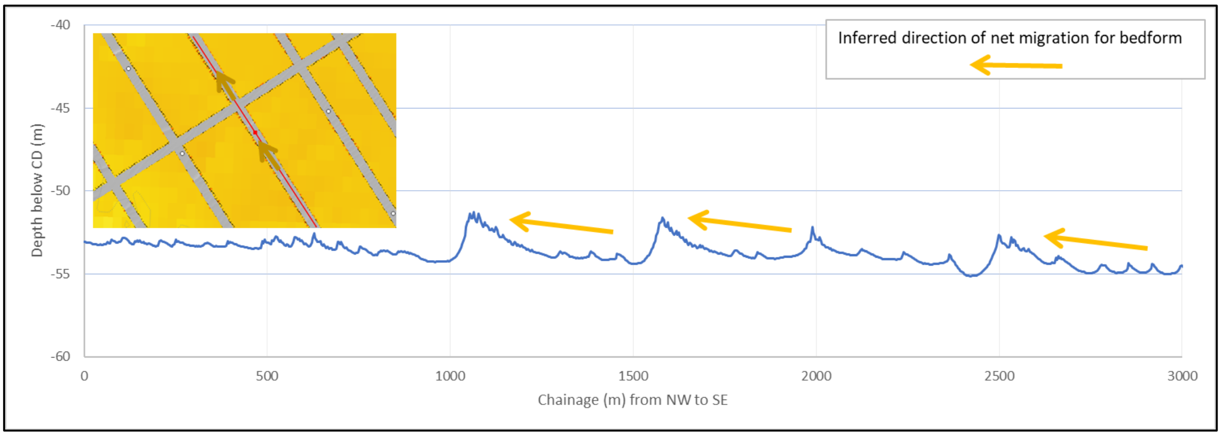


Figure 31: Example of sandwaves and megaripples within northern part of array area (horizontal exaggeration of around 1:45) (derived from geophysical survey).

3.4.2.17 Figure 32 provides an example of sandwaves along a transect from the central part of the offshore array, towards the southern extent of sandwaves. Zero chainage is at the north-west with increasing chainage to the south-east. In comparison to areas further to the north, these sandwaves appear to have lower crest heights of 1 to 1.5 m and shorter wavelengths of 50 to 100 m, megaripples are again superimposed on the sandwaves. Whilst the sandwave asymmetry appears to be less distinctive (more symmetrical) in comparison to the northern area, there remains a general indication of a net transport direction to the north-west.

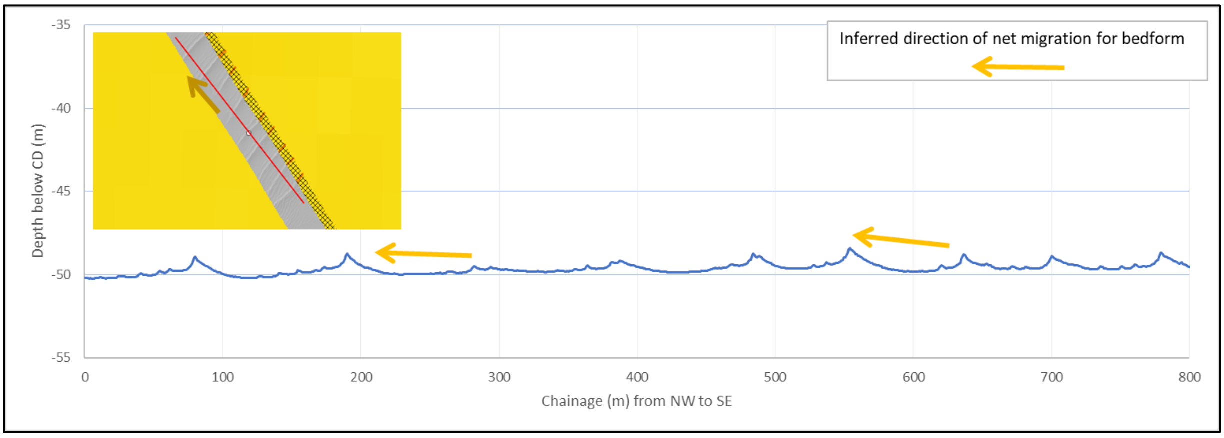
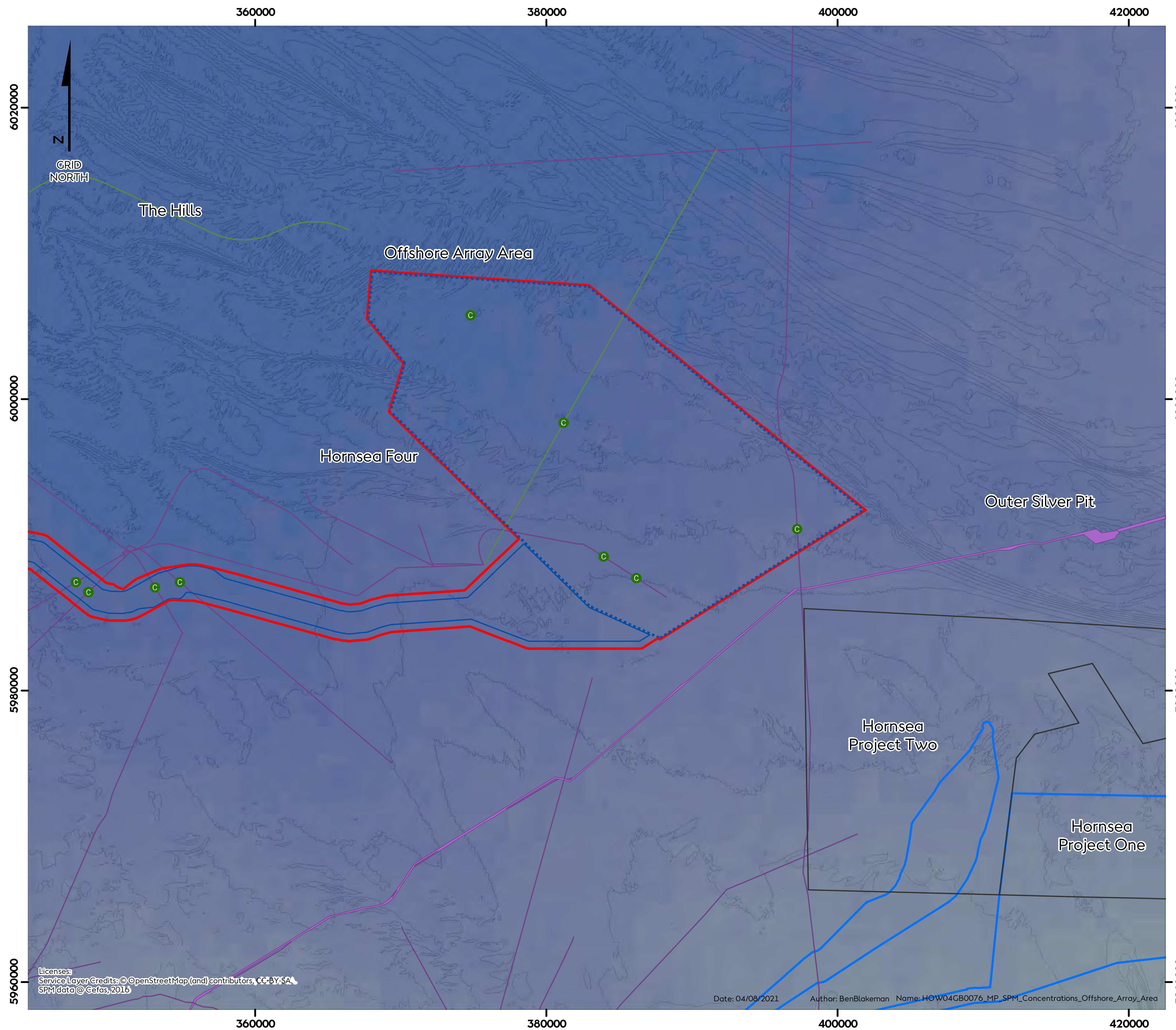


Figure 32: Example of sandwaves and megaripples within central part of array area (horizontal exaggeration around 1:10) (derived from geophysical survey).

3.4.2.18 Based on an interpretation of macro bedform features, the primary bedload transport direction appears to be to the north-west, driven by the peak flows during the ebb tide which are generally more persistent above the threshold for sand transport than the flood tide. The mobility and transport of sands in this direction is evidenced by megaripples, small and larger sandwaves which eventually converge into larger features in the northern part of the offshore array area. Waves are not considered to be involved in bedload transport in this area given the relatively large water depths (i.e. deep water wave conditions).

Suspended particulate matter

3.4.2.19 Turbidity levels across the offshore array area are described from spatial mapping of monthly mean non-algal SPM concentrations of the surface layer derived from 18-years of satellite observations from 1998 to 2015 (Cefas 2016). SPM is relatively low across the offshore array area with monthly averaged concentrations typically less than 5 mg/l across the whole year (Cefas 2016), with minimal seasonal variation. The relatively low concentrations are due to both a low content of fine material in the seabed sediments and the area being distant from any terrestrial sources of fine sediments, such as the Humber Estuary and the Holderness Cliffs. **Figure 33** shows the spatial variation of monthly averaged SPM concentrations for the month of February (generally the month with the highest SPM concentrations).



Hornsea Four

Figure 33

Monthly averaged surface SPM concentrations across offshore array study area, February

- Order Limits
- Array Area
- Offshore Export Cable Corridor
- Crossing Point (Offshore)
- Existing Pipelines
- Proposed Pipelines
- Viking Link Cable
- Existing Licence Areas for Export Cables and Disposal Sites
- 5m Contour Intervals

SPM Concentrations (mg/l)

83.92

0.88

Coordinate system: ETRS 1989 UTM Zone 31N

Scale@A3: 1:250,000

0 5 10 Kilometres

0 2.5 5 Nautical Miles

REV	REMARK	DATE
...	First Issue	07/06/2019
A	Updated following PEIR consultation, for DCO	04/08/2021

Surface SPM Concentrations
Across Offshore Array Area
Document no: HOW04GB0076
Created by: BPHB
Checked by: BC
Approved by: LK

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3.4.3 Marine physical environment receptors – offshore array study area

Pipelines and Cables

3.4.3.1 Due to sections of the Johnston Field Extension (JFE) and Shearwater to Bacton (Shearwater Elgin Area Line - SEAL) gas pipelines being present within the offshore array area there is provision for up to 32 cable crossings (**Volume A4, Annex 4.1: Offshore Crossing Schedule**). The majority of these crossings would be in the southern half of the array area in relatively deep water (> 40 m) and on a sandy seabed (**Figure 24**).

3.4.3.2 The Shearwater to Bacton gas pipeline is 34 inch (0.86 m) in diameter and is visible in the geophysical data as a surface feature (Gardline 2019a). **Figure 34** shows a section of the pipeline in the southern part of the offshore array area which has a relatively featureless sandy seabed. At this location there is evidence of some local scouring on either side of the pipeline.

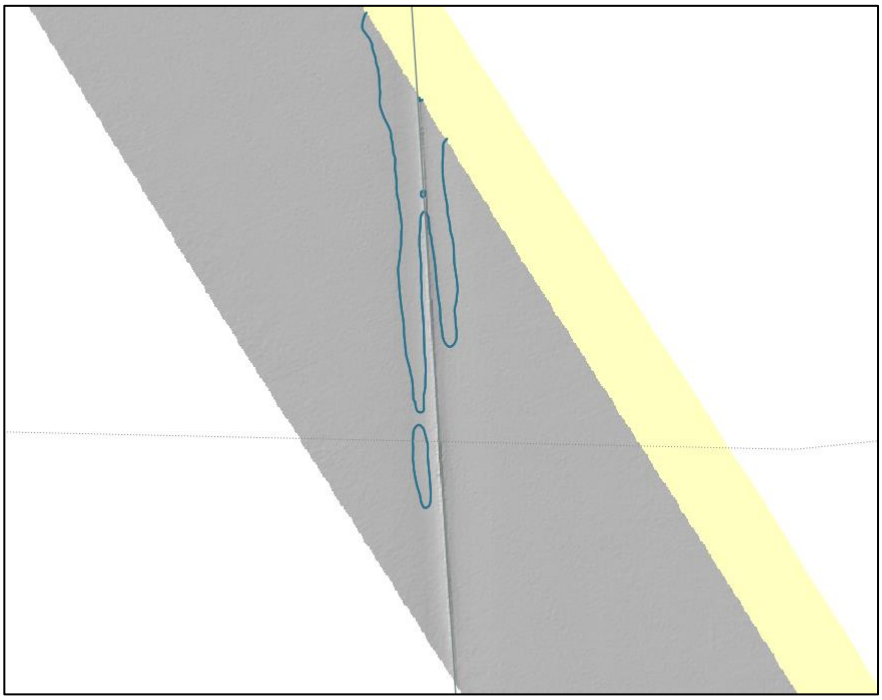


Figure 34: Section of Shearwater – Bacton SEAL pipeline in southern part of offshore array area(blue lines represent seabed contours encompassing area of local scouring).

Flamborough Front

3.4.3.3 The Southern North Sea is generally described as a well-mixed water body. These well-mixed conditions are mainly due to relatively shallow depths and the ability of winds and tides to continually stir water sufficiently to prevent the onset of any stratification (DECC 2016). In contrast, the Northern North Sea is relatively deeper with slightly weaker currents, this helps temperature stratification (thermocline) develop from the spring into the summer months. During this period, a transition between these two water bodies develops from about 10 km offshore of Flamborough Head in the form of a temperature front, this feature is known as the Flamborough Front. The surface waters of the front tend to move around this alignment with the scale of tidal advection. The front becomes nutrient rich and is considered to be ecologically important. During autumn / winter the front dissipates due to increased wind and wave related stirring effects which re-establish well-mixed conditions for this part of the northern part of the North Sea. The front gives rise to nutrient-rich water, increased primary production and fisheries providing a feeding ground for birds (English Nature 2004).

3.4.3.4 A baseline description of the Flamborough Front has been established from to complementary data sources:

- A 3-D baroclinic model of the European Continent–l Shelf - (Tonani, et al. 2019); and
- Long-term seasonal averages of sea-surface temperature from 10-years of satellite data (Miller & Christodoulou 2014).

3.4.3.5 Data from the 3-D baroclinic model provides the basis of examining the temporal development of the Flamborough Front over a full representative year. This model has a spatial resolution of 0.016° Latitude x 0.016° Longitude, equivalent to around 1.5 km north to south and 2.0 km east to west for the study area. The database of forecast outputs is held by the Copernicus Marine Environment Monitoring Service. The latest full year of daily mean values from 2018 has been assessed for variation in near-bed and near-surface temperature, as well as mixed layer depth (MLD).

3.4.3.6 Three locations in the North Sea have been examined for annual variation in water temperature (surface and near bed) and for development in MLD:

(a) North Site – around 40 km to the north of the offshore array area in a water depth of around 66 m below LAT, representing the Northern North Sea water body (**Figure 35 a**). This area is expected to demonstrate temperature stratification over the spring and summer period;

(b) Offshore Array - a site within the area to verify local conditions relative to the Flamborough Front (**Figure 35 b**). Depths at this location are around 42 m below LAT; and

(c) South Site – around 40 km to the south of the offshore array in a water depth of around 37 m below LAT, representing the Southern North Sea water body (**Figure 35 c**). This area is expected to demonstrate no temperature stratification and maintain well-mixed conditions over whole year.

Figure 35: Annual variation in water temperature and MLD at; (a) North Site, (b) Offshore array and (c) South Site (derived from Tonani et al. 2019).

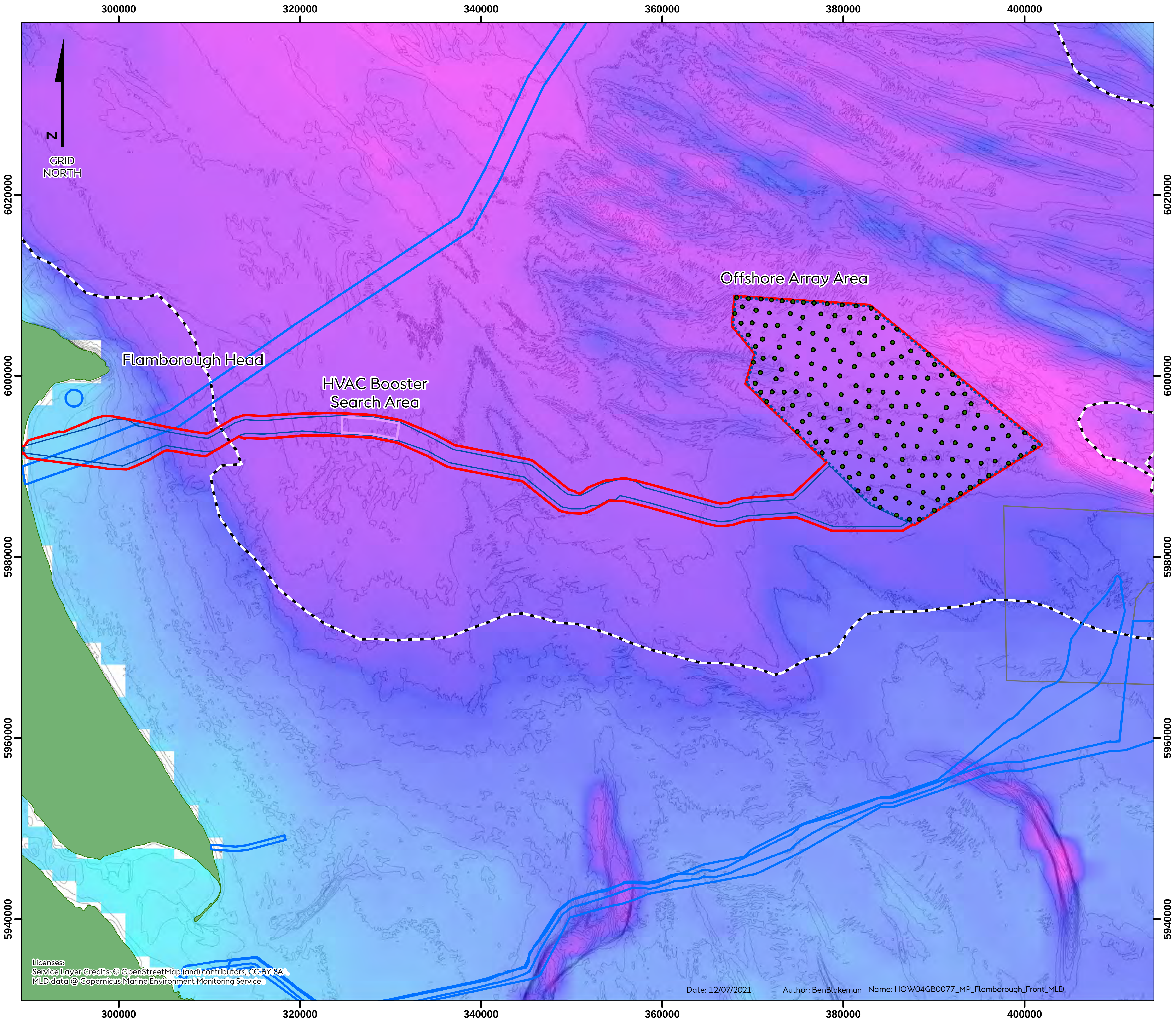
3.4.3.7 Figure 35 shows a clear representation of seasonal temperature rise and fall at all three sites, with a peak summer temperature evident around the end of July. For the South Site (c), the near-surface and near-bed water temperatures appear equivalent throughout the year and the MLD is sustained over the full water column, demonstrating this location remains effectively well-mixed. In contrast, at the North Site (a) there appears to be mainly warming of surface waters from around April which develops stratification in the water column, reducing the MLD. The largest difference between near-surface and near-bed temperatures is around the end of July at around 10°C. From August to September the MLD is re-established due to reduced solar warming and increased wind and wave related stirring influences to re-establish well-mixed conditions with near-surface and near-bed water temperatures becoming equivalent again. Between these two locations there is an area where the Flamborough Front develops as a seasonal feature lasting approximately five months.

3.4.3.8 For the array area, a pattern similar to the North Site occurs, but with slightly less distinctive stratification between near-surface and near-bed water temperature. This is partly due to the array area being 24 m shallower than the North Site. This evidence locates the array area to the north of the Flamborough Front.

3.4.3.9 The location of the front can be defined as the spatial transition between mixed and thermally stratified water. **Figure 36** shows the MLD for the period of maximum stratification identified towards the end of July. Where the MLD is minimal the water is stratified, for well-mixed areas the MLD tends to represent the total water depth. On this date, the front is around 10 km offshore of Flamborough Head then appears to closely follow the 40 m isobath where an east-west alignment develops which continues to run south of the array area by approximately 8.8 km at the closest point.

3.4.3.10 A separate assessment of the development of fronts across the UK continental shelf by Plymouth Marine Laboratory (PML) is based on evaluating cloud-free satellite images over the 10-year period (December 1998 to November 2008). This data is from an Advanced Very-High-Resolution Radiometer (AVHRR) with a spatial cell resolution of 1.1 km. Long-term seasonal averages have been produced which deduce the percentage of time a strong front was observed for each cell.

3.4.3.11 **Figure 37** presents the seasonal average percentage frequency of occurrence of an observed front for the study area, along with the position between well-mixed and stratified water bodies deduced independently from the 3-D baroclinic model for the month of July 2018. Despite these being separate datasets covering different time periods, which are also interpreting different parameters to deduce the position of the front, there remains very close agreement in the general alignment of the front. Notably, Hornsea Four also occupies a location where there is an apparent reduced frequency of occurrence for the front.



Hornsea Four

Figure 36

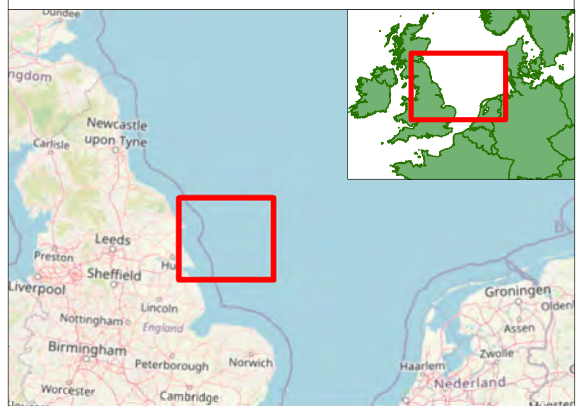
Location of Flamborough Front, based on variation in MLD for July 2018

- Order Limits
- Array Area
- Offshore Export Cable Corridor
- HVAC Booster Station Works Area
- Indicative Turbine Layout
- Existing Licence Areas for Export Cables and Disposal Sites
- 5m Contour Intervals
- Location of Front - July 2018

Mixed Layer Depth (m below sea surface)

70

3



Coordinate system: ETRS 1989 UTM Zone 31N

Scale@A3: 1:400,000

0 10 20 Kilometres

0 5 10 Nautical Miles

REV	REMARK	DATE
...	First Issue	07/06/2019
A	Updated following PEIR consultation, for DCO	12/07/2021

Flamborough Front variation in MLD
Document no: HOW04GB0077
Created by: BPHB
Checked by: BC
Approved by: LK

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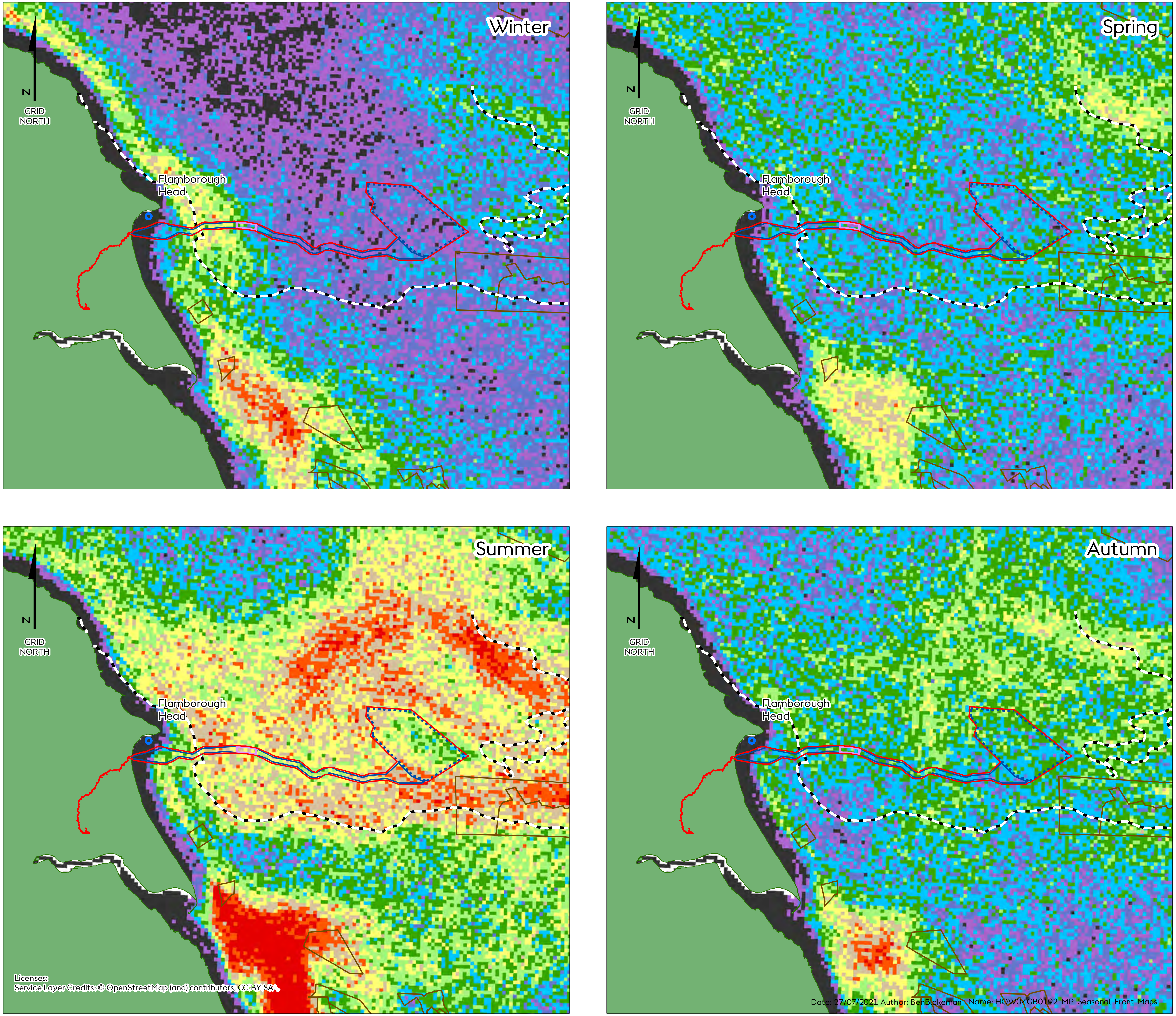
Figure 37

Seasonal front maps for the frequency of occurrence across the study area, along with the alignment of the front deduced from the 3-D baroclinic model for the period of July 2018

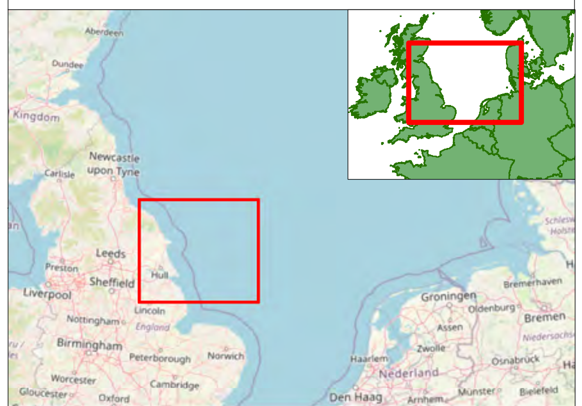


- Order Limits
- Array Area
- Offshore Export Cable Corridor
- HVAC Booster Station Works Area
- Offshore Wind Farm
- Disposal Sites
- Location of Front - July 2018

Frequency (%) Occurance of Front

(after Miller and Chritodoulou, 2014)

- 0 - 10%
- 10 - 20%
- 20 - 30%
- 30 - 40%
- 40 - 50%
- 50 - 60%
- 60 - 70%
- 70 - 80%
- 80 - 90%
- 90 - 100%



Coordinate system: ETRS 1989 UTM Zone 31N
Scale@A3: 1:1,250,000

0 25 50 Kilometres

0 10 20 Nautical Miles

REV	REMARK	DATE
....	First Issue for PEIR	27/07/2021

Seasonal Front Maps
Study Area
Document no: HOW04GB0192
Created by: BPHB
Checked by: BC
Approved by: LK

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3.4.4 Summary of marine physical environment receptors within the offshore array study area

3.4.4.1 **Table 9** summarises the receptors associated with the offshore array study area. The potential sensitivity of the receptor is expressed prior to consideration of the scale of any impact related to the development.

Table 9: Marine physical environment receptors in the offshore array study area.

Receptor	Potential sensitivity to marine processes
Pipeline and cable crossings	Local "edge" scouring around periphery of rock berms
Flamborough Front	Changes in tidal mixing process which may inhibit formation of the front

4 Assessment of potential impacts on marine processes

4.1 Overview

4.1.1.1 The Hornsea Four Scoping Report (Orsted 2018d), together with the Scoping Opinion (Planning Inspectorate 2018), identify the issues for assessment of potential effects due to the proposed Hornsea Four development. The issues related to marine processes have been further clarified through the Evidence Plan discussions and are summarised in **Table 1** (see also **Volume 4, Annex 5.1 Impacts Register**). These issues have the potential to create impact pathways on receptors in the marine environment. The key receptors associated with the marine physical environment are summarised in **Table 5**, **Table 8** and **Table 9**.

4.1.1.2 This assessment is based on a combination of an evidence-based approach, expert opinion, and project-specific modelling to evaluate source and pathway related issue on the identified marine receptors. The project-specific modelling scenarios include an assessment of:

- Hydrodynamic effects resulting from a nearshore cable crossing with Dogger Bank A and B export cables seaward of Smithic Bank;
- Blockage related effects from foundations across the offshore array along with large box-type foundations in the HVAC Booster Station Search Area; and
- Sediment plumes due to installation activities along the offshore ECC and within the offshore array area.

4.1.1.3 **Appendix C** offers further details for the modelling specifically commissioned for Hornsea Four.

4.2 Maximum Design Scenario for marine processes

4.2.1.1 Where multiple options remain for project development activities the definition of sources for marine processes is based on the MDS. This option represents the conservative case of any of the design options with an alternative option to the MDS considered to have a lesser environmental effect. The MDS for marine processes has been determined from a review of the Project Description for Hornsea Four (**Volume A1, Chapter 4: Project Description**).

4.2.1.2 The MDS is considered for activities that are planned for construction, operation, and decommissioning phases.

4.2.2 MDS for Construction Phase

4.2.2.1 The MDS for installation activities during the construction phase relates to issues which are likely to disturb the greatest volumes of sediment in the shortest period of time (i.e. those which result in highest rates of disturbance) which then lead to highest levels of suspended sediment and/or greatest risk of smothering of a seabed receptor. The installation activities include:

- Seabed levelling for foundations;
- Sandwave clearance for cable installation;
- Cable installation, including jointing pits;
- Temporary beach access ramp;
- Inshore HDD exit pits, with the potential use of cofferdams or bentonite spills;
- Drilling for foundation piles; and
- Spoil disposal.

4.2.3 MDS for Operation Phase

4.2.3.1 During operation of the wind farm (the longest phase of the development, expected to be around 35 years) the main consideration for marine processes is persistent blockage effects on waves, flows and sediment pathways from structures placed in the water column (including; foundations, subsea structures, and rock armour at cable crossings), as well as consequential local scouring (if no scour protection is provided prior to installation of foundation).

4.2.3.2 Blockage effects formed by individual structures can manifest as local-scale flow and wave related wakes (retardation of flows with increased turbulence in a wake, flow separation around large obstacles, diffraction and scattering of wave energy, etc.) and the potential to modify sediment transport pathways in the far-field, including longshore transport.

4.2.3.3 The MDS for any array-scale blockage effect is a product of the greatest number of closest spaced and widest foundations (with high solidity ratio[2]) that could potentially interfere with the normal passage of flows, waves, and sediment pathways.

4.2.3.4 During the operation phase there may also be various maintenance activities, such as cable repairs and re-burial requirements, which have the potential to create short-term periods of disturbed sediments; however, these are considered to be minor in comparison to those occurring during either the construction or decommissioning phases. Remedial cable burial may also consider the use of cable protection measures, such as rock armour.

4.2.4 MDS for Decommissioning Phase

4.2.4.1 The MDS for decommissioning issues relates to excavation activities which may lead to the greatest volumes of potential disturbed sediment in the shortest period (highest rates of disturbance), along with a consideration of subsequent seabed recovery to conditions which might have occurred at this time in a baseline environment without the development.

[2] **Solidity ratio** is defined as the ratio of the effective vertical area of a frame (the sum of all individual elements of the face of a structure) normal to the incident wave, tidal flow or sediment transport direction divided by the area enclosed by the boundary of the frame. A solid structure will have a solidity ratio of 1 whereas an open frame lattice structure (e.g. jacket type) will generally have a much lower solidity ratio towards 0.2 (typical values between 0.1 and 0.3).

4.3 Seabed preparation activities

4.3.1 Overview

4.3.1.1 Seabed preparation is defined here as activities which excavate material from source with a requirement for spoil disposal elsewhere. The excavation and disposal activities may each create elevated levels of suspended sediment, and spoil disposal may also lead to rapid smothering by large volumes of sediment falling to the seabed.

4.3.1.2 Seabed preparation activities planned for the construction phase include provisions for:

- Construction of a temporary beach access ramp;
- Seabed excavation at landfall for up to eight HDD exit pits;
- Sandwave clearance prior to cable laying along the offshore ECC and within the offshore array. This process will target mobile bedforms that are unfavourable to cable installation due to their gradient;
- Excavation of jointing pits for cables; and
- Seabed preparation (levelling) for foundations in both the HVAC Booster Station Search Area and offshore array. This activity aims to level the seabed to aid the installation of foundation bases that need an even surface. The levelling may require removing larger bedforms, boulders or excavating the consolidated surface sediments that have an uneven profile.

4.3.1.3 The likelihood is that excavations in shallow water (intertidal or below mean low water) for the HDD exit pits will be achieved using a long reach excavator (e.g. backhoe dredger or similar) located on a jack-up or lay barge.

4.3.1.4 The MDS assumption for pre-sweeping for sandwave clearance and levelling is that a trailing suction hopper dredger (TSHD) would be used. Alternative methods are possible, such as jetting or pre-trenching plough, however, these methods only locally disturb material from the seabed, and this would limit the time for any material to fall through the water column and become advected. In contrast, the dredging discharges overspill into surface waters which may create a larger sediment plume. In addition, the spoil dumping introduces a high volume of sediment in a more focused but separate location, rather than along the path of area being cleared. Given that some clearance operations are planned for completion a year before cable and foundations are installed, the advantage of a TSHD is that cleared seabed features have potentially a lesser opportunity of being locally re-established, depending on where the spoil is disposed.

4.3.1.5 The TSHD process hydraulically sucks sediments from the seabed without creating any significant near-bed sediment spill layer (Bray 2008). The sediment-water mix is pumped from the seabed into the hopper and the excess water is allowed to overspill (overflow) leaving the (relatively coarser) sediment to fill the hopper. The overspill process is required to maximise the hopper load; the majority of overspill is likely to be seawater but some of the finer sediments will also be present. The overspill creates a sediment plume that would initially fall towards the seabed as a density flow due to the content of sediment, this is often described as the active phase of the plume. Once the overspill has been entrained by the receiving water then a passive phase of plume dispersion into the far-field will take place which is governed by advection and diffusion due to tidal flows. Eventually the sediment in the plume falls out of suspension and settles onto the seabed. **Figure 38** provides a schematic representation of the sediment plume during the dredging activity.

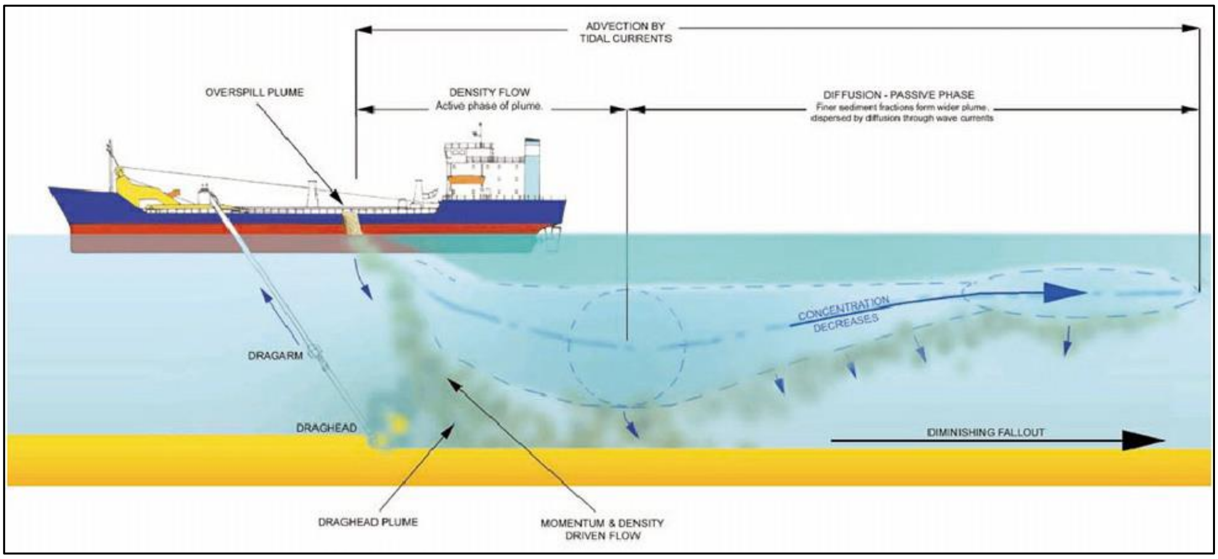


Figure 38: Schematic of sediment plume development during dredging activity (The Crown Estate and BMPA 2009).

4.3.1.6 Once the hopper is full then the spoil is expected to be disposed of close by. All spoil sites will remain within the Hornsea Four Order Limits. The spoil disposal will be achieved as a surface release by opening the hopper doors. Initially, sediments will fall to the seabed under a density flow (active phase of plume) with remaining fine sediments subject to advection and dispersion as a passive phase. Coarse sediments are expected to fall quickly to the seabed.

4.3.1.7 The time taken to fully discharge the hopper load, the transit direction of the dredger during this time, the sediment volume, sediment grain sizes, associated settling velocities, local water depth and ambient flow conditions will all influence the formation of any sediment plume as well as the shape of any spoil deposit on the seabed in terms of area involved and height of any mound, as well as the longevity of the feature thereafter.

4.3.1.8 For present purposes, the assumed hopper volume is 11,000 m^3, which is consistent with the assumptions used for Hornsea Project One, Hornsea Project Two, and Hornsea Three. The further assumption for sand dredging with a conventional TSHD is that a discharge via the bottom doors takes approximately five to ten minutes[3]. The MDS assumption is that up to two TSHD will be operating on site at the same time, however, logistical constraints would most likely prevent them for work the same location at the same time.

4.3.2 Representation of sediment plumes in modelling

4.3.2.1 Marine process modelling is applied to help examine the far-field reach of effects, such as sediment plumes.

[3] https://www.startdredging.com/dredging-cycle-trailing-suction-hopper-dredger/

4.3.2.2 In the near-field there are sediment releases from either near-surface or near-bed sources and at these locations the sediment concentrations will be highest since they are present within a relatively small volume of water. In addition, these concentrations only last as long as the source of such effect continues. The modelling report (**paragraph 5.5.26** of **Appendix C**) states that within 5 m of the source SSC might be millions of mg/l or more, i.e. more sediment than water.

4.3.2.3 From the near-field to the far-field (i.e. distances > 100 m) released sediments will start to advect with the tide and be carried away from the source as a sediment plume to mix (through dispersion) with a larger volume of water and as well as settling out to the seabed, processes which then reduce SSC. The modelling report (**paragraph 5.5.28** of **Appendix C**) states that the width of the plume of finer material (silt) is initially in the order of 10 to 50 m (within 10 to 20 minutes of release, up to 500 to 1,000 m downstream). The SSC in this section of plume is relatively high (up to 1,000 mg/l for all sediment types and up to 100 mg/l for silts alone).

4.3.3 Excavation of Landfall HDD exit pits

<u>Activities</u>

4.3.3.1 Eight HDD exit pits are required for up to four HVDC circuits where one circuit comprises of two cable conductors. For the HVAC circuits, only six exit pits would be required. The exit pits would be located between 400 to 1,500 m from the transition joint bays which would themselves be located around 300 m landward. This places the exit pits up to 1,200 m offshore (or less) where water depths are around 10 m below ODN. Each exit pit may cover up to 900 m^2 of seabed in a configuration which is likely to be up to 50 m long (cross-shore) and 18 m wide (longshore). The minimum separation between exit pits would be around 50 m. Only up to three exit pits will be open at any time, and up to three months, with the option to use cofferdams, if required

4.3.3.2 Whilst cofferdams are not the preferred solution at exit pits, they would provide a means for managing drilling fluids (e.g. bentonite) to avoid any marine release at punch-out, noting other fluid management systems may be considered. When used as a drilling mud, bentonite can be considered as a non-toxic solute of clay sized particles. Any accidental release into the marine environment would be relatively short-lived and of low volume, and quickly disperse into the background nearshore suspended sediments.

4.3.3.3 During HHD works, there will also be a temporary beach access ramp at the southern end of the landfall works area (**Figure 2**) to allow access for small 4x4 type vehicles related to emergency response associated with any bentonite break-out, including small vacuum tankers for any required clean-up of the beach, and a small vehicle associated with monitoring of the drill head under the beach using hand-held equipment. The location of the ramp is at a relatively low lying part of the cliff to ensure minimal construction, with use of a small bridge to protect the clifftop and beach. The toe of the ramp is expected to be above mean high water. The ramp is expected to be in place for the duration of the HDD exit pit activity within a 32 month construction window. There is expected to be no permanent impact on the cliff or beach due to the temporary access ramp.

Sediment types

4.3.3.4 Depending on their distance offshore, the likelihood is that the shallow water excavations to form the HDD exit pits can be achieved using a long reach excavator (e.g. backhoe dredger) either mounted on a jack-up or a lay barge. The geophysical evidence for this location suggests a thin surface layer of sands and gravels overlying glacial till of stiff clays (Bibby HydroMap 2019a; 2019b). The target depth of exit pits at 5 m means that most of the excavated soil type is likely to be the glacial till.

Maximum sediment volumes

4.3.3.5 The MDS volume for each HDD exit pit excavation is up to 2,500 m^3, and up to 20,000 m^3 for eight pits. A typical backhoe dredger can excavate up to 100 to 500 m^3/hr, but this depends greatly on the bucket size, soil types and configuration of the required excavation. Nevertheless, each exit pit is expected to be formed within a few hours.

4.3.3.6 The excavation operation for each exit pit is likely to be sequential, with up to three pits open at any one time and for up to three months, limiting the chance for any spill events acting in combination. The MDS option is that the excavated material will be side-cast and left on the seabed.

Local hydrodynamic conditions

4.3.3.7 The nearshore shallow water conditions are likely to be dominated by shoaling waves which eventually break along the beach to drive longshore transport for sands. The same process washes the fine sediments off the beach to create a nearshore plume.

4.3.3.8 Tidal range is also an important consideration in the nearshore as this modulates the local water depth and the volume of water into which any material might be spilt during excavation, as well as the relative influence of waves, with strongest wave influences around low water.

Fate of excavated sediments

4.3.3.9 Depending on the final method of excavation and the type of material being removed (consolidated till or unconsolidated sands), the chances remain for some of the excavated sediment to be spilt into the sea. Any fine sediments would be rapidly dispersed away to become part of the nearshore sediment plume. Coarser sediments would quickly drop back to the seabed.

4.3.3.10 The material that is cast aside of the excavated pit to form a temporary spoil mound would be subject to wave and tidal action with any eroded unconsolidated fine sediments and sands from the surface of the mound becoming assimilated into the local sediment transport process. The amount of sediment loss from a side-cast mound would depend on the sediment composition and local water depths, wave, and tidal processes as well as the period until back-filling. Any gravels or consolidated clays would most likely experience the lowest amount of loss.

4.3.3.11 Once duct installation is complete, the exit pits will be back-filled with sediments recovered from the surrounding seabed.

4.3.4 Sandwave clearance

Overview

4.3.4.1 Provisions exist for sandwave (and boulder) clearance along the offshore ECC and within the offshore array area. These provisions aim to remove seabed obstacles (e.g. steep sloped bedforms) which might prove difficult for some cable installation tools. In addition, to achieve adequate protection, cables need to be buried below the depth where seabed mobility may otherwise result in exposure. Since sandwaves are generally mobile bedforms, their removal before installation helps de-risk cable exposure and mitigate some of the potential requirements for use of rock armour for reburial.

4.3.4.2 The geophysical survey along the offshore ECC (Bibby HydroMap 2019a; 2019b) does not identify any large sandwaves between the landfall and the HVAC Booster Station Search Area, with only a few patches of poorly defined (relict) megaripples towards the coast (Bibby Hydromap 2019a; 2019b). In contrast, the area from the eastern boundary of the HVAC Booster Station Search Area towards the offshore array has a large area of well-defined megaripples. A few sandwaves are also identified in the fan area approaching the offshore array (**Figure 11**). In contrast, sandwaves and megaripples are very prominent across the northern half of the offshore array, some of these sandwaves are relatively large, especially towards the north-western side of the offshore array area where there is a sand ridge forming part of The Hills (**Figure 23**). The geophysical survey describes the southern part of the offshore array area as a plain seabed without any bedforms.

4.3.4.3 Importantly, since the geophysical survey which supports the EIA does not provide 100 % coverage there still remains the chance for other bedform features to exist which fall outside of the present survey coverage. The acquisition of further geophysical and geotechnical data is anticipated post-consent to inform final planning and design.

Sediment types

4.3.4.4 By definition, (active) sandwaves are bedform features formed as an accumulation of sand moving across the seabed as bedload. The grade of sand will be in dynamic equilibrium with the local environmental conditions (water depth, waves, and flows) that are able to move and maintain the bedform features.

4.3.4.5 As a mobile feature (rather than a stable consolidated deposit), the regular turn-over of sands in motion on a sandwave also tends to create a well-sorted sandy sediment with relatively little fines. **Figure 39** provides the sediment gradings distribution (resolved in intervals of 0.5 phi) for grab sample ENV23, a site is coincident with an identified sandwave crest in the north-west part of the offshore array area. In this example, the sediment has a unimodal, moderately well-sorted grading of coarse sand.

SAMPLE STATISTICS

SAMPLE IDENTITY: **ENV23** ANALYST & DATE: ,

SAMPLE TYPE: Unimodal, Moderately Well Sorted TEXTURAL GROUP: Sand

SEDIMENT NAME: Moderately Well Sorted Coarse Sand

	μm	ϕ
MODE 1:	603.6	0.750
MODE 2:		
MODE 3:		
D_{10}:	275.7	0.230
MEDIAN or D_{50}:	520.1	0.943
D_{90}:	852.6	1.859
(D_{90} / D_{10}):	3.093	8.082
(D_{90} - D_{10}):	576.9	1.629
(D_{75} / D_{25}):	1.800	2.539
(D_{75} - D_{25}):	303.4	0.848

GRAIN SIZE DISTRIBUTION			
GRAVEL:	0.0%	COARSE SAND:	53.6%
SAND:	98.6%	MEDIUM SAND:	40.2%
MUD:	1.4%	FINE SAND:	4.0%
		V FINE SAND:	0.8%
V COARSE GRAVEL:	0.0%	V COARSE SILT:	1.4%
COARSE GRAVEL:	0.0%	COARSE SILT:	0.0%
MEDIUM GRAVEL:	0.0%	MEDIUM SILT:	0.0%
FINE GRAVEL:	0.0%	FINE SILT:	0.0%
V FINE GRAVEL:	0.0%	V FINE SILT:	0.0%
V COARSE SAND:	0.0%	CLAY:	0.0%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic μm	Geometric μm	Logarithmic ϕ	Geometric μm	Logarithmic ϕ	Description
MEAN ($\bar{x}$):	542.4	485.3	1.043	506.3	0.982	Coarse Sand
SORTING (σ):	207.7	1.635	0.709	1.545	0.628	Moderately Well Sorted
SKEWNESS (Sk):	0.045	-1.717	1.717	-0.143	0.143	Fine Skewed
KURTOSIS (K):	2.263	8.140	8.140	0.992	0.992	Mesokurtic

GRAIN SIZE DISTRIBUTION

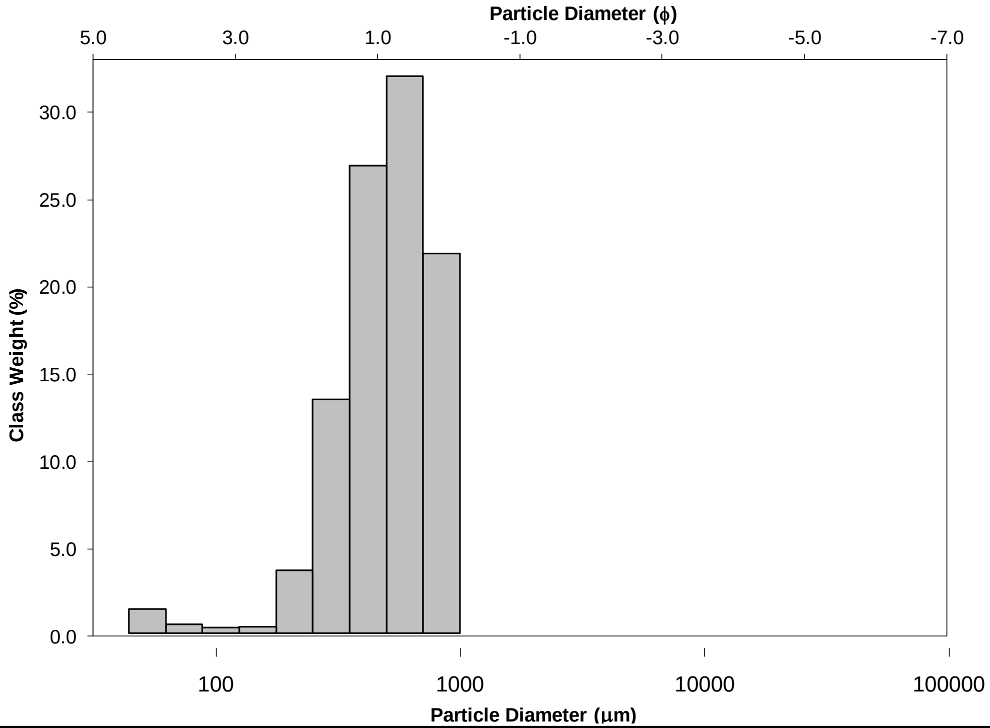


Figure 39: Gradings distribution for sample ENV23, coincident with sandwave feature (derived from Gardline 2019b).

Maximum sediment volumes

4.3.4.6 The MDS volume for sandwave clearance is a provision of up to 757,000 m^3 across six offshore export cables and by sweeping a width of 40 m per cable. In addition, sandwave clearance within the offshore array area requires the provision of up to 961,000 m^3, this includes an additional 10 km section of the offshore export cable that lies within the offshore array area. The requirement to make use of these provisions depends on the presence of sandwaves which require clearance in each area. This requirement appears to be less likely for the offshore ECC than the offshore array area based on the present mapping of sandwave features (Bibby HydroMap 2019a; 2019b).

4.3.4.7 For uniform sand which is loose (i.e. not a consolidated deposit) a dry bulk density value would be around 1.43 tonnes/m^3 (Terzaghi, Peck, & Mesri 1996), which suggests a mass equivalent of up to approximately 1,082,510 tonnes of sediment would need to be removed along the offshore ECC and up to approximately 1,374,230 tonnes within the offshore array.

4.3.4.8 The MDS method for removal of sandwaves is by TSHD since this creates two potential sources of release; (i) overspill from hopper of predominantly fine sediment plumes discharging across areas to be cleared, and (ii) instantaneous releases of higher volumes of mainly coarser sediment as spoil from the hopper at sites remote from dredging which create spoil mounds, sediment plumes of fines and subsequent sediment deposition.

4.3.4.9 The efficiency of the dredger discharging overspill means that less than 100 % of the excavated material remains in the hopper and the rest is discharged with the overspill (overflow losses). Overspill losses depend on many issues, not least pumping rates and sediment types. For sandwave clearance, the overspill losses are likely to be relatively low and mainly related to finer grained particles present in the sediment. A conservative value of 5 % of excavated material is assumed for average overspill losses over the loading cycle, noting that at commencement of filling the hopper this value may be lower and when the hopper is reaching capacity this value may be higher.

4.3.4.10 Once sediment is excavated from the seabed and pumped into the hopper there is an immediate bulking factor which accounts for the volume difference between a consolidated deposit and a hopper load of loose material. In addition, a hopper capacity of 11,000 m^3 will be carrying a mixture of sediment and seawater. A bulking factor of 1.20 has been assumed for present purposes which is mid-range of 1.15 to 1.25 for sand, medium soft to hard (Bray, Bates, & Land 1996).

4.3.4.11 Based on these stated assumptions, there are expected to approximately 78 hopper loads required for sandwave clearance along the offshore ECC. This is equivalent to approximately one hopper load every 8.3 km for each of the six export cables. The chance for sandwaves to be present along the entire offshore ECC appears to be quite low and not all of the dredging allowance is likely to be required.

4.3.4.12 For the offshore array, there are expected to be up to approximately 100 hopper loads required, although the chances for needing sandwave clearance in the southern half of the array appear to be much lower than in the northern half.

Local hydrodynamic conditions

4.3.4.13 Water depths and flow conditions along the offshore ECC show variability which will influence both the fate of overspill and spoil disposal. Five representative sites have been selected to demonstrate this variability; inshore in ebb channel, nearshore towards Smithic Bank, mid-section around the HVAC Booster Station Search Area, an offshore section of the offshore ECC towards the offshore array and a site central to the offshore array. **Table 10** summarises representative hydrodynamic conditions at each of these locations (n.b. The tidal excursions at the inshore location is further split between flood and ebb phases for both spring and neap tidal ranges to distinguish the strong asymmetry and ebb dominance).

Table 10: Representative hydrodynamic conditions for sandwave clearance activity.

Location	Water depth (m below LAT)	Spring / neap peak flows (m/s)	Spring / neap tidal excursion (km)	Annual range of SPM (mg/l)
Inshore ECC / ebb channel	7.5	0.47 / 0.25	Flood 6 / 4 Ebb 10 / 6	2 to 11
Nearshore ECC / Smithic Bank	22	0.89 / 0.45	14 / 7	2 to 14
Mid-section ECC / HVAC Booster Station Search Area	51	0.83 / 0.41	12.6 / 6	1 to 2
Offshore end ECC	40	0.62 / 0.31	8.6 / 4.3	1 to 3
Central to offshore array	50	0.56 / 0.28	8.3 / 4.1	1 to 3

Overspill considerations

4.3.4.14 The overspill from TSHD will occur local to the sandwave clearance operation along a section of the ECC or within the offshore array. In the average dredging cycle, this is typically a 7.5 km section of the offshore ECC where sandwaves are present, although where such features are sparse this distance may increase, or if there are very large sandwaves this distance may shorten.

4.3.4.15 Sediment sizes of fine sand and smaller are more likely to be discharged in the overspill than larger particle sizes of medium and coarse sand which will tend to be retained in the hopper, noting this hydraulic sorting cannot be considered as 100 % efficient.

4.3.4.16 The overspill of finer particle sediments will form a plume which will be advected away from the dredger by tidal flows. The duration of the overspill event per dredging cycle is likely to be comparable to the time required to fill the hopper. An indicative period of 4 hours is assumed to fill a 11,000 m^3 hopper.

4.3.4.17 The main axis of the plume trajectory will be governed by tidal advection (flood to the south-east and ebb to the north-west) with diminishing plume concentrations away from the axis due to dispersion and diffusion mixing processes spreading the plume. Plume concentrations will reduce over distance due to increased mixing as well as material gradually falling out of suspension. During a neap tide the plume will be advected over a shorter distance than a spring tide, and since the rate of mixing will be less at these times due to weaker flows, then plume concentrations can be expected to be proportionally higher. On spring tides, the plume will spread further and have a proportionally lower concentration. Winds would expect to have some influence, either by increasing mixing and/or modifying the plume trajectory.

4.3.4.18 **Table 11** provides a summary of representative sediment types expected to be present in the overspill, their individual settling velocities from the sediment plume phase and the time required to reach the seabed.

Table 11: Representative sediment types in sandwave overspill.

Sediment type	Size range (mm)	Representative size (mm)	Representative settling velocity (m/s)	Time to fall out of suspension 20 / 40 / 50 m (minutes)
Fine sand	0.125 to 0.250	0.188	0.018	18 / 36 / 46
Very fine sand	0.063 to 0.125	0.094	0.005	66 / 133 / 166
Silt	0.004 to 0.063	0.033	0.001	Remains in suspension

4.3.4.19 The fine sand fraction will settle out of suspension relatively quickly and have limited time to advect and disperse. Even if this spill event occurred at peak spring flows the distance covered by fine sands in 18 minutes in the nearshore (20 m depth) would be less than 1 km, and in 46 minutes for the HVAC Booster Station Search Area (51 m depth) this would be a distance of around 2.3 km. The trajectory of the plumes would follow the axis of the tidal ellipse at their respective locations (**Figure 13** and **Figure 28**).

4.3.4.20 The silty sediments are likely to remain in suspension for relatively long periods and are expected to reach the full extent of tidal excursion, following the general path of the local tidal ellipse. To note, this sediment size is generally the least abundant in the material to be dredged so concentrations will be limited.

4.3.4.21 As a general consideration, suspended sediment concentrations within sediment plumes can be in the order of 100s of mg/l in the vicinity of the dredger, reducing to 10s of mg/l with distance (CIRIA 2000), but also with concentrations which quickly dissipate in time after release. Given the likely loading and dumping cycle each overspill event is expected to disperse away as a separate plume.

Evidence from Hornsea Project One and Hornsea Project Two

4.3.4.22 Hornsea Project One and Hornsea Project Two represent the closest comparable projects to Hornsea Four. Sandwave clearance based on comparable sized TSHD was modelled as part of their EIA (SMart Wind 2013; 2015a). These scenarios assumed a 1.5 % content of fine sediment (silty material finer than 0.063 mm) in the sandwaves. For a mid-section of the export cable, in water depths of 20 to 25 m, the model predicted a plume of fine sediments aligned with the tidal ellipse. A depth-averaged suspended sediment concentration of up to 40 mg/l was predicted at around 200 m from the cable route (source). Due to the settling and re-suspension of fine sediments, the predicted maximum extent of the sediment plume (defined at > 2 mg/l above background SSC levels) was 16 km north-west and 17 km south-east from the point of release (i.e. a full tidal excursion for this location).

4.3.4.23 The deposition of fine sediment under low flow conditions was predicted to be less than 2 mm. Based on a minimum thickness of 0.5 mm, the area of deposition extended 60 m to the north-west and 250 m to the south-east of the cable route, however, under higher flow conditions this material was dispersed away.

Spoil disposal

4.3.4.24 Once the dredger moves to discharge a full hopper load close by, the majority of the finer sediments are expected to have already been lost as overspill. The remaining sediments in the hopper should be predominantly the coarser sediment fractions, meaning that the disposal of the spoil is likely to have a lesser concern in the formation of any sediment plume. In contrast, the majority of the spoil will fall more quickly to the seabed with limited opportunity to disperse (but correspondingly leading to a greater depth of accumulation and therefore a higher risk of smothering to any benthic receptors at this location).

4.3.4.25 **Table 12** provides a summary of representative sediment types expected to be present in the spoil, their individual settling velocities and the time required to reach the seabed.

Table 12: Representative sediment types in sandwave spoil.

Sediment type	Size range (mm)	Representative size (mm)	Settling velocity (m/s)	Time to fall out of suspension 22 / 40 / 50 m (minutes)
Coarse sand	0.500 to 1.000	0.750	0.093	4 / 7 / 9
Medium sand	0.250 to 0.500	0.375	0.050	7 / 14 / 17

4.3.4.26 The depth of deposition and area covered by spoil will be determined by the course of the vessel over the period of opening hopper doors, the tidal flows at the time and the relative composition of the sediment being disposed of. The vessel speed could also act as means to ensure the deposition of spoil is more widely dispersed than opening the hopper doors when the vessel is stationary.

4.3.4.27 Once deposited close by, the sand is likely to re-join the same bedload transport environment responsible for creating and moving the original sandwaves. This process may progressively winnow down any spoil mound; however, sediment mobility in the offshore array is typically limited to peak flows during spring tides which may lead to a slower winnowing process. For the shallower nearshore environment, where flows are typically stronger and water depths shallower, sediment mobility can be expected to be more frequent and will also become influenced by waves.

Modelling of sandwave clearance

4.3.4.28 Modelling has represented an indicative sediment plume and spoil deposition event from sediment disturbance due to the dredging (sandwave clearance or seabed preparation) for a nearshore location seaward of Smithic Bank and coincident with the planned cable crossing with Dogger Bank A and B export cables. The definition of sediment composition is taken from closest grab sample ECC_23 (sandy gravel; 1.07 % muds, 39.86 % sands and 59.07 % gravels). The modelling describes the passive phase of the sediment plume only which represents 10 % of the volume of the spoil discharge with the remaining 90 % of the spoil considered to drop to the seabed as a density flow to create a spoil mound. The dimensions of spoil mounds are deduced separate to the modelling since they generally form in the near-field with minimal opportunity for any advection and dispersion.

4.3.4.29 Results from the modelling of sediment disturbance for a nearshore location are presented in **Appendix C**. Figure C21 provides neap tide results for the passive phase of the sediment plume for all sediments. The plume forms along the axis of the tide with an excursion of around 10 km which just reaches a location north of Flamborough Head. Plume concentrations of SSC remain less than 10 mg/l for all locations 2 km beyond the point of release which also reduce over the period of the simulation and are not detectable after about 20 hours. Figure C22 presents the same scenario but limited to just the silt sized material which demonstrates that the silt material is responsible for the formation of the plume. Comparable results are attained for the spring tide Figure C23 and Figure C24 but also demonstrating a proportionally longer sediment plume but also with lower concentrations due to high rates of mixing.

4.3.4.30 Sediment deposition from plume settlement after 3-days (72 hours) is presented in Figure C29 (all sediments) and Figure C30 (silt component only). The depth of deposition (for all sediments) is typically very small (around 0.1 mm) but reaches 59 mm for the spring tide in a confined area and 100 mm for a neap release. These depths of deposition cover a very small area and are due to coarser grained sediments (gravels). The contribution from silts in the depth of deposition represents a maximum of 0.2 mm meaning the remainder is made up of coarser sediments.

4.3.4.31 The fate of sediments from the active phase of spoil disposal is deduced from Table 8 of **Appendix C**. Taking medium sands as representative of the material likely to spread the widest during the active phase then for a water depth around 22 m and a peak spring flow of around 0.89 m/s the longest spreading distance is likely to be up to 390 m for the nearshore location. Coarse sand and weaker periods of flows would reduce this distance to possibly as low as 100 m, noting the immediate discharge will be through a series of hopper doors (e.g. multiple conical bottom valves) along the keel of the TSHD. Over a reduced spreading distance the spoil mound would have a greater height, largely in an elongated conical form. Taking representative scales of the deposit length of between 100 to 390 m provides spoil mound areas in the range 10,000 to 152,100 m^2. The associated maximum height of the spoil mound is likely to be in the range 0.99 to 0.07 m.

Evidence from Hornsea Project One and Hornsea Project Two

4.3.4.32 For spoil disposal, the coarser sands and gravels displaced by the dredging activity were considered not to disperse by tidal currents and were predicted to settle rapidly near the point of disposal. A single placement from a hopper with a capacity of 11,650 m^3 was considered to lead to an area of deposition approximately 200 m in diameter and up to 1 m in height at the centre of the mound. The available areas for spoil disposal were considered sufficient so that multiple placements of spoil could be separated out to avoid overlap (SMart Wind 2013; 2015a).

4.3.5 Seabed preparations in HVAC Booster Station Search Area

Overview

4.3.5.1 Seabed preparations in the HVAC Booster Station Search Area includes for boulder clearance, seabed levelling and dredging of mobile sediments to provide a flat and stable seabed for all non-piled foundation options. For three substation foundations (suction bucket jacket (small) option), a MDS area of up to 36,963 m^2 is required from a total search area of 12,986,891 m^2, equivalent to less than 0.3 % of the total area being considered.

Sediment types

4.3.5.2 For the HVAC Booster Station Search Area, the geophysical survey identifies a relatively flat and featureless seabed (i.e. no large mobile bedforms) with a lithology mainly formed of gravelly sands. The exceptions are several discrete seafloor contacts (e.g. boulders) with heights generally < 0.5 m and the very eastern boundary which overlaps with a sandy area of low profile megaripples (heights < 0.5 m, and typically less than 0.1 m).

4.3.5.3 Grab samples ECC_15, ECC_16 and ECC_17 span the HVAC Booster Station Search Area from east to west and provide a quantification of sediment types determined from particle size analysis. The sediment types are described as slightly gravelly sand at ECC_15 and ECC_16 and gravelly muddy sand at ECC_17 (Bibby HydroMap 2019c). The interpreted lithology is described as gravelly sand. Accordingly, sands are the dominant sediment type (representing between 51 to 94 %), muds (fines) account for between 4 to 35 % and gravels 2 to 13 % for the three sampling sites.

4.3.5.4 SBP interpretations suggest the surficial sediments are generally a thin layer (0 to 2 m) over the Bolders Bank formation.

Maximum sediment volumes

4.3.5.5 The MDS volume for seabed levelling within the HVAC Booster Station Search Area is a maximum value of 171,735 m^3 for the three six-legged Suction Caisson Jacket (Small OSS) foundation option. The mass equivalent for this amount of sediment is dependent on the soil characteristics to be removed, such as; voids ratio, porosity, and water content. Even for similar sediment types these values can vary dependent on the compaction and consolidation of the sediment. For dense, mixed-grained sand a dry bulk density value of 1.86 tonnes/m^3 is appropriate, for mixed-grained glacial till a dry bulk density value would be around 2.12 tonnes/m^3 (Terzaghi, Peck, & Mesri 1996). A bulk density value of 2.00 tonnes/m^3 has therefore been applied for illustrative purposes which suggests a mass equivalent of up to approximately 114,900 tonnes of sediment is removed per foundation (343,470 tonnes in total for all three foundations).

4.3.5.6 The MDS method for seabed levelling is by TSHD since this creates two potential sources of release; (i) overspill from hopper of predominantly fine sediment plumes discharging along the cable route sections requiring clearance, and (ii) instantaneous releases of higher volumes of mainly coarser sediment as spoil from hopper at sites remote from dredging which create spoil mounds, sediment plumes of fines and subsequent sediment deposition.

4.3.5.7 The efficiency of the dredger discharging overspill means that less than 100 % of the excavated material remains in the hopper and the rest is discharged with the overspill (overflow losses). Overspill losses depend on many issues, not least pumping rates, and sediment types. For slightly gravelly sand the overspill losses are likely to be relatively low and limited to any finer grained sands and silts present in the sediment. A conservative value of 5 % of excavated volume of material is assumed for average overspill losses over the loading cycle, noting that at commencement this value may be lower and when the hopper is reaching capacity this value may be higher. This equates to up to approximately 5,725 tonnes of the excavated material lost per foundation, with up to approximately 108,766 tonnes taken into hopper loads for spoil disposal.

4.3.5.8 Once sediment is excavated by a dredger and transferred into the hopper there is an immediate bulking factor which accounts for the volume difference between a consolidated deposit and a hopper load of loose material. In addition, a hopper capacity of 11,000 m^3 will be carrying a mixture of sediment and seawater. A bulking factor of 1.25 has been assumed for present purposes which is mid-range of 1.15 to 1.35 for sand/gravel/clay mixtures (Bray, Bates, & Land 1996).

4.3.5.9 Based on these stated assumptions, there are expected to be up to approximately 19 hopper loads required for seabed levelling.

Local hydrodynamic conditions

4.3.5.10 The HVAC Booster Station Search Area is relatively flat with water depths between 50.5 and 51.5 m below LAT. Predicted tidal flows reach a peak of around 0.83 m/s on mean spring tides and 0.41 m/s on mean neaps. The equivalent tidal excursions are around 12 and 6 km, respectively.

4.3.5.11 Flow measurements from 1989 at site bo592164 (1.9 km to the west of the HVAC Booster Station Search Area) recorded speeds more than 1 m/s on the flood tide when the tidal range is greater than MSR. Equivalent ebb speeds tend to be slightly less suggesting a net transport to the south-west, in line with generalised sand transport pathways for this area. The equivalent maximum flood tide excursion is determined as 12.6 km.

Overspill considerations

4.3.5.12 The surface overspill from the dredger is considered to occur locally to each seabed preparation area, notionally over a rectangular area of 111 x 111 m for each foundation with a depth of excavation of around 4.6 m.

4.3.5.13 The finer sediment sizes of silts, very fine sands and fine sands are likely to favour being discharged in the overspill rather than the larger particle sizes of medium sand through to gravels. These larger sediment particles are likely to favour being retained in the hopper, noting this hydraulic sorting cannot be considered as 100 % efficient.

4.3.5.14 Overspill will form a plume largely made up of the finer sediment which will be advected away by tidal flows. The duration of the overspill event per dredging cycle is likely to be comparable to the time required to fill the hopper. An indicative period of 4 hours is assumed to fill a 11,000 m^3 hopper.

4.3.5.15 The main axis of the plume trajectory will be governed by tidal advection with diminishing SSC concentrations away from the axis due to dispersion and diffusion mixing processes spreading the plume. Plume concentrations will reduce over distance due to mixing over an increasing volume of water and material falling out of suspension. During a neap tide the plume will be advected over a shorter distance than a spring tide, and since the rate of mixing will be less at these times due to weaker flows, then SSC concentrations can be expected to be proportionally higher. On spring tides, the plume will spread further and have a proportionally lower concentration. Winds would expect to have some influence, either by increasing mixing and/or modifying the plume trajectory.

4.3.5.16 **Table 13** provides a summary of representative sediment types expected to be present in overspill, their individual settling velocities from the sediment plume phase and the time required to reach the seabed, assuming a representative depth of 51 m below LAT.

Table 13: Representative sediment types in HVAC Booster Station Search Area foundation overspill.

Sediment type	Size range (mm)	Representative size (mm)	Settling velocity (m/s)	Time to fall out of suspension (minutes)
Fine sand	0.125 to 0.250	0.188	0.018	46
Very fine sand	0.063 to 0.125	0.094	0.005	166
Silts	< 0.063	< 0.033	< 0.001	Remains in suspension

4.3.5.17 The fine sand fraction will settle out of suspension relatively quickly and most likely within 2 km of the discharge position. The relatively short-lived and localised fate of this material will not create any lasting concerns for reduced turbidity. The very fine sand in overspill will remain in suspension for nearly three hours and during this period is likely to reach half the distance of a tidal excursion (full excursion is attained after six hours) which is expected to be around 6.3 km on spring tides and 3 km on neaps.

4.3.5.18 Only the silt fraction is unlikely to settle out of suspension quickly due to weak settling velocities which are likely to be exceeded by the upward turbulent component of local flows for most of the time. This material will rapidly disperse across a full tidal excursion leading to reduced concentrations over time and distance from source.

4.3.5.19 As a general consideration, suspended sediment concentrations within sediment plumes can be in the order of hundreds of mg/l in the vicinity of the dredger, reducing to tens of mg/l with distance (CIRIA 2000), but also quickly dissipating in time after release. Given the likely loading and dumping cycle each overspill event is expected to disperse away as a separate plume.

Spoil disposal

4.3.5.20 Once the dredger moves to discharge a full hopper load close by, the majority of the finer sediments are expected to have already been lost as overspill. The remaining sediments in the hopper should be predominantly composed of the coarser sediment fraction, meaning that the disposal of the spoil is likely to have a lesser concern in the formation of any sediment plume. In contrast, the majority of the spoil will fall more quickly to the seabed with limited opportunity to disperse (leading to a greater depth of accumulation at the seabed and therefore a higher risk of smothering of any local benthic receptors).

4.3.5.21 **Table 14** provides a summary of representative sediment types expected to be present in the spoil (dominantly coarse sediments), their individual settling velocities and the time required to reach the seabed, assuming a depth of 51 m below LAT.

Table 14: Representative sediment types in HVAC Booster Station Search Area spoil.

Sediment type	Size range (mm)	Representative size (mm)	Settling velocity (m/s)	Time to fall out of suspension (minutes)
Very fine gravel	2.000 to 4.000	3.000	0.216	4
Very coarse sand	1.000 to 2.000	1.500	0.147	6
Coarse sand	0.500 to 1.000	0.750	0.093	9
Medium sand	0.250 to 0.500	0.375	0.050	17

4.3.5.22 The depth of deposition and area covered will be determined by the vessel track in the period of opening hopper doors, the tidal flows at the time and the relative composition of the sediment being disposed of between sands and gravels (which will determine the angle of repose, nominally 25 to 30° for sandy gravel). The vessel speed could also act as means to ensure the deposition of spoil is more widely dispersed than opening the hopper doors when the vessel is stationary.

4.3.5.23 Once deposited, the coarser sediments are unlikely to be remobilised by the local tidal flows. Only the coarse and medium sands are likely to be remobilised (for material that is not covered and armoured by the immobile coarser sediments) when flows exceed around 0.8 and 0.6 m/s, respectively, noting these flow rates are only reached towards the peak flows during mean spring tides (and periods with higher tidal range).

Modelling of seabed levelling

4.3.5.24 Modelling has represented an indicative sediment plume and subsequent deposition from seabed levelling activities within the HVAC Booster Station Search Area. The definition of sediment composition is taken from grab sample ECC_17 (muddy gravelly sand) as this provides the highest content of fines which may lead to the formation of a plume which may remain in suspension for the longest period. A release site on the western boundary of the HVAC Booster Station Search Area is chosen as this offers the shortest distance to nearshore receptors. The modelling describes the passive phase of the sediment plume only which represents 10 % of the volume of the spoil discharge with the remaining 90 % of the spoil considered to drop to the seabed as a density flow to create a spoil mound. The dimensions of spoil mounds are deduced separate to the modelling since they generally form in the near-field with minimal advection and dispersion (see Table 7 of **Appendix C**).

4.3.5.25 Results from the modelling of seabed levelling within the HVAC Booster Station Search Area are presented in **Appendix C**. Figure C13 provides neap tide results for the passive phase of the sediment plume for all sediment types. The plume forms along the axis of the tide with an excursion of around 6 km either side of the release point. Plume concentrations remain less than 10 mg/l for all locations 2 km beyond the point of release which also reduce over the period of the simulation and are not detectable after about 60 hours. Figure C14 presents the same scenario but limited to just the silt sized material. This demonstrates that silts are responsible for the formation of the plume. Comparable results are attained for the spring tide Figure C15 and Figure C16 but also demonstrating a proportionally longer sediment plume.

4.3.5.26 Sediment deposition from plume settlement after three-days (72 hours) is presented in Figure C27 (all sediments) and Figure C28 (silt component only). The depth of deposition is typically very small (around 0.1 mm) but reaches 4 mm for the spring tide in a confined area. The contribution from silts in the depth of deposition represents only 0.1 mm meaning the remainder is made up of coarser sediments.

4.3.5.27 The fate of sediments from the active phase of spoil disposal is deduced from Table 8 of **Appendix C**. Taking medium sands as representative of the material likely to spread the widest during the active phase, then for a water depth around 51 m and a peak spring flow of around 0.83 m/s the longest spreading distance is likely to be up to 847 m from the HVAC Booster Station Search Area. Very fine gravels and weaker periods of flows would reduce this distance to possibly as low as 100 m, noting the immediate discharge will be through a series of hopper doors (e.g. multiple conical bottom valves) along the keel of the TSHD. Over a reduced spreading distance the spoil mound would have a greater height, largely in an elongated conical form. Taking representative scales of the deposit length of between 100 to 847 m provides spoil mound areas in the range 10,000 to 717,409 m^2. The associated maximum height of the spoil mound is likely to be in the range 0.99 to 0.01 m (i.e. a large spatial extent leads to a smaller deposition height).

4.3.6 Seabed levelling in offshore array area

Overview

4.3.6.1 Seabed levelling is required for all foundation types (with the exception of monopiles), and includes a single accommodation platform (12,321 m^2 for a suction caisson jacket), nine OSS (156,594 m^2 for suction bucket jacket and large GBS box-type) and 180 WTG (610,191 m^2). This represents a total area for seabed preparation of 779,106 m^2 from a lease area of 468,000,000 m^2, equivalent to around 0.17 % of the available area.

4.3.6.2 The MDS seabed preparation provisions for up to 180 WTG foundations is made up of a combination of up to 110 GBS WTG-type and 70 three-legged suction bucket jacket WTG-type for sites where GBS foundations cannot be used. The equivalent seabed preparation area for each GBS foundation is 3,739 m^2, or an equivalent diameter of 78 m. For reference, the maximum base diameter for a single GBS WTG-type foundation is 53 m. For reference, the equivalent seabed preparation area for the suction bucket jacket is 2,841 m^2.

Sediment types

4.3.6.3 Grab samples across the offshore array area indicate a mainly sand sediment type (Holocene sands), along with three samples which record slightly gravelly sand (ENV25, north), gravelly sand (ENV24, north), and gravelly muddy sand (ENV19 on the eastern boundary).

4.3.6.4 The content of fines (material < 0.063 mm) across the offshore array area is generally low (0 to 10 %, and typically < 5 %) apart from a location on the eastern boundary where the number of fines increases to 13.7 % with surficial sediments described as gravelly muddy sand. This site represents an area without any cover of Holocene sands and a soil type interpreted as exposed firm to stiff glacial till of the Bolders Bank formation (Gardline 2019a). The content of gravels across the offshore array (material > 2 mm) is generally low (0 to 9.1 %, and typically < 5 %) apart from the same location on the eastern boundary where the amount of gravel increases to 15.4 %. The sand content (> 0.063 mm and < 2 mm) is generally high (83.5 to 100 %, and typically > 95 %), apart from the area on the eastern boundary which has 70.9 % sand content. Medium sand fractions are the most abundant size across the offshore array area.

4.3.6.5 No allowance is made for the potential variability of sediment types over the excavation depth, although sample site ENV19 provides an indication of material type likely to be present below the relatively thin layer of Holocene sands.

Maximum sediment volumes

4.3.6.6 The MDS sediment volume for seabed preparation (levelling) within the offshore array is up to 1,045,221 m^3 for 180 WTG foundations. In addition, levelling is also required for offshore substations and an accommodation platform, up to 794,375 m^3 for six Suction Bucket Jacket (Small OSS), three GBS (Large OSS) and one Suction Bucket Jacket (Small OSS) for the accommodation platform. This is a total of up to 1,839,596 m^3 of sediment removal for a total of 190 foundations.

4.3.6.7 The MDS seabed preparation provisions for up to 180 WTG foundations is made up of a combination of 110 GBS WTG-type and 70 three-legged suction bucket jacket WTG-type for sites where GBS foundations cannot be used. The equivalent seabed preparation spoil volume for each GBS foundation is up to 6,234 m^3 and 5,135 m^3 for the three-legged suction bucket jacket foundation.

4.3.6.8 The equivalent mass for this amount of sediment is dependent on the soil characteristics to be removed, such as; voids ratio, porosity, and water content. Even for similar sediment types these values can vary depending on the compaction and consolidation of the sediment. For areas with dense, mixed grained sand a dry bulk density value of 1.86 tonnes/m^3 is appropriate, for loose mixed grained sand a dry bulk density value would be around 1.59 tonnes/m^3 (Terzaghi, Peck, & Mesri 1996). For areas without sand, or where the sand layer is thin, a dry bulk density relevant to excavating glacial till, very mixed grained would be 2.12 tonnes/m^3. A bulk density value of 1.75 tonnes/m^3 has been applied for illustrative purposes which suggests a mass equivalent of up to approximately 3,219,293 tonnes of sediment would be dredged from across the array area for seabed levelling.

4.3.6.9 The efficiency of the dredger discharging overspill means that less than 100 % of the excavated material remains in the hopper and the rest is discharged with the overspill (overflow losses). Overspill losses depend on many issues, not least pumping rates, and sediment types. For gravely sand and slightly gravelly sand the overspill losses are likely to be relatively low and limited to any finer grained sands and silts present in the sediment. A conservative value of 5 % has been assumed for average overspill losses over the loading cycle, noting that at commencement this value may be lower and when the hopper is reaching capacity this value may be higher. This equates up to approximately 160,965 tonnes of the excavated material lost as overspill and up to approximately 3,058,328 tonnes is taken away by hopper loads for spoil disposal.

4.3.6.10 Once sediment is excavated by a dredger and transferred into the hopper there is an immediate bulking factor which accounts for the volume difference between a consolidated deposit and a hopper load of loose material. In addition, a hopper capacity of 11,000 m^3 will be carrying a mixture of sediment and seawater. A bulking factor of 1.20 has been assumed for present purposes which is mid-range of 1.15 to 1.25 for sand, medium soft to hard (Bray, Bates, & Land 1996).

4.3.6.11 Based on these stated assumptions, there are expected to be up to approximately 191 hopper loads required for the offshore array area.

Hydrodynamic conditions

4.3.6.12 Water depths across the offshore array area are generally between 40 to 55 m below LAT with predicted tidal flows reaching a peak of around 0.52 to 0.63 m/s on mean spring tides and 0.27 to 0.31 m/s on mean neaps. The equivalent tidal excursions are around 8 to 8.5 and 4 to 4.3 km, respectively.

4.3.6.13 Flow measurements at Site L1 (just to the south of the offshore array) indicate speeds can exceed 0.8 m/s when the tidal range is greater than MSR. The equivalent maximum excursion at this time is determined as 8.8 km.

Overspill considerations

4.3.6.14 The overspill is considered to occur local to the seabed preparation area for each of the 190 foundations and along the cable routes planned for inter-array, interconnector and export cables (sections within the array area).

4.3.6.15 The finer sediment sizes of muds, very fine sands and fine sands are likely to favour being discharged in the overspill rather than the larger / heavier particle sizes of medium sand through to gravels which favour being retained in the hopper, noting this hydraulic sorting cannot be considered as 100 % efficient.

4.3.6.16 Overspill will form a plume largely made up of the finer sediment which will be advected away by tidal flows. The duration of the overspill event per dredging cycle is likely to be comparable to the time required to fill the hopper. An indicative period of four hours is assumed to fill a 11,000 m^3 hopper.

4.3.6.17 The main axis of the plume trajectory will be governed by tidal advection with reduced concentrations around this axis due to dispersion and diffusion mixing processes spreading the plume. Plume concentrations will reduce over distance due to increased mixing and material falling out of suspension. During a neap tide the plume will be advected over a shorter distance than a spring tide, and since the rate of mixing will be less at these times due to weaker flows, then suspended sediment concentrations can be expected to be proportionally higher. On spring tides, the plume will spread further and have a proportionally lower concentration. Winds would expect to have some influence on surface material, either by increasing mixing and/or modifying the plume trajectory.

4.3.6.18 **Table 15** provides a summary of representative sediment types expected to be present in overspill, their individual settling velocities from the sediment plume phase and the time required to reach the seabed, assuming representative depths of 40, 50 and 55 m below LAT.

Table 15: Representative sediment types in overspill across the offshore array area.

Sediment type	Size range (mm)	Representative size (mm)	Settling velocity (m/s)	Time to fall out of suspension 40 / 50 / 55 m (minutes)
Fine sand	0.125 to 0.250	0.188	0.018	36 / 46 / 50
Very fine sand	0.063 to 0.125	0.094	0.005	133 / 166 / 183
Silts	< 0.063	< 0.033	< 0.001	Remains in suspension

4.3.6.19 The fine sand fraction will settle out of suspension relatively quickly and have limited time to advect and disperse. Even if this spill event occurred at peak spring flows the distance covered by fine sands in 50 minutes for depths up to 55 m would be less than 2 km. For the shallower site this reduces to around 1 km. The trajectory of the plumes would follow the axis of the tidal ellipse at their respective locations (**Figure 28**).

4.3.6.20 The silty sediments would expect to remain in suspension for relatively long periods and reach the full extent of tidal excursion, following the path of a tidal ellipse. Measurable effects related to sediment plumes are expected to remain within the offshore array study area.

4.3.6.21 As a general consideration, suspended sediment concentrations within sediment plumes can be in the order of 100s of mg/l in the vicinity of the dredger, reducing to 10s of mg/l with distance (CIRIA 2000), but also quickly dissipating in time after release. Given the likely loading and dumping cycle each overspill event is expected to disperse away as a separate plume.

Evidence from Hornsea Project Two

4.3.6.22 Hornsea Project Two is the closest project to Hornsea Four with comparable seabed and tidal conditions for sediment dispersion. Seabed preparation was assessed for levelling requirements of gravity base foundations with up to 23,892 m^3 (78 m diameter and 5 m depth) of material to be removed per foundation using a TSHD (SMart Wind 2015a).

4.3.6.23 Sediment plume simulations focused on the overspill with an assumed composition of silts, and fine sands. Coarse sediment (sands and gravels) were not simulated and were assumed to deposit in close proximity to the point of release as spoil. Eight hopper loads were simulated to cover four foundations and four disposal locations, each with a three hour cycle time. Based on these assumptions, predicted depth-average increases of SSC of > 2 mg/l were predicted around the dredging site with excursions of up to 16 km north-west and 14 km to south-east. At the disposal site the sediment plume showed SSC > 10 mg/l above background over an excursion distance of up to 12 km to the north-west and up to 13.5 km to the south-east of each foundation. Peak concentrations of 500 to 800 mg/l were predicted at a site very close to the release of spoil. All peak concentrations were localised and short-lived. When concurrent preparation was simulated for two sites adjacent to each other comparable results were obtained.

4.3.6.24 The deposition of fine sediment (< 0.25 mm) was considered to be localised to the point of overspill, reaching a depth of a few millimetres.

Spoil disposal

4.3.6.25 Once the dredger moves to discharge a full hopper load close by, the majority of the finer sediments are expected to have already been lost as overspill. The remaining sediments in the hopper should be predominantly composed of the coarser sediment fraction, meaning that the disposal of the spoil is likely to have a lesser concern in the formation of any sediment plume. In contrast, the majority of the spoil will fall more quickly to the seabed with limited opportunity to disperse leading to a higher risk of smothering of any benthic receptors. **Table 16** provides a summary of representative sediment types expected to be present in the spoil, their individual fall velocities and the time required to reach the seabed.

Table 16: Representative sediment types in spoil disposal across offshore array.

Sediment type	Size range (mm)	Representative size (mm)	Settling velocity (m/s)	Time to fall out of suspension 40 / 50 / 55 m (minutes)
Very fine gravel	2.000 to 4.000	3.000	0.216	3 / 4 / 4
Very coarse sand	1.000 to 2.000	1.500	0.147	5 / 6 / 6
Coarse sand	0.500 to 1.000	0.750	0.093	7 / 9 / 10
Medium sand	0.250 to 0.500	0.375	0.050	14 / 17 / 19

4.3.6.26 The depth of deposition and area covered will be determined by the course of the vessel in the period of opening hopper doors, the tidal flows at the time and the relative composition of the sediment being disposed of between sands and gravels (which will determine the angle of repose, nominally 25 to 30° for sandy gravel). The vessel speed could also act as means to ensure the deposition of spoil is more widely dispersed than opening the hopper doors when the vessel is stationary.

4.3.6.27 Once deposited, the coarser sediments (coarse sand to very fine gravel) are unlikely to be remobilised by the local tidal flows. Only the medium sands are likely to be remobilised (for material that is not covered and armoured by the immobile coarser sediments) when flows exceed around 0.5 and 0.6 m/s, respectively; flow rates only reached towards the peak flows during spring tides.

Evidence from Hornsea Project Two

4.3.6.28 For spoil disposal, the placement of a single hopper load was considered to develop a spoil mound 120 m diameter and 1.5 m high (of coarser granular sediments), assuming a stationary release. For all placements required for a single GBS the area required was assessed as being up to 250 m in diameter (SMart Wind 2015a), but this scale of deposition was not considered to affect marine processes.

Modelling of seabed levelling

4.3.6.29 Modelling has represented an indicative sediment plume and spoil deposition event from seabed levelling activities (equivalent to sandwave clearance) within the offshore array area. The definition of sediment composition is taken from grab sample ENV15 (sand) which includes 4.7 % of fines. A representative release site located central to the offshore array area with a local depth of 47.5 m below LAT. The modelling describes the passive phase of the sediment plume only which represents 10 % of the volume of the spoil discharge with the remaining 90 % of the spoil considered to drop to the seabed as a density flow to create a spoil mound. The dimensions of spoil mounds are deduced separate to the modelling since they generally form in the near-field with minimal advection and dispersion.

4.3.6.30 Results from the modelling of seabed levelling within the offshore array area are presented in **Appendix C**. Figure C5 provides neap tide results for the passive phase of the sediment plume for all sediments. The plume forms along the axis of the tide with an excursion of around 6 km. Plume concentrations remain less than 2 mg/l for all locations 2 km beyond the point of release which also reduce over the period of the simulation and are not detectable after about 40 hours. Figure C6 presents the same scenario but limited to just the silt sized material which demonstrates that the silt material is responsible for the formation of the plume. Comparable results are attained for the spring tide Figure C7 and Figure C8 but also demonstrating a proportionally lower concentration and more dispersed sediment plume.

4.3.6.31 Sediment deposition from plume settlement after 3-days (72 hours) is presented in Figure C25 (all sediments) and Figure C26 (silt component only). The typical depth of deposition is very small (around 0.1 mm) but can reach 29 mm for the spring tide in a confined area and 38 mm for the neap tide scenario. The contribution from silts in the depth of deposition represents only 0.1 mm, meaning the remainder of the deposit depth is made up of coarser sediments.

4.3.6.32 The fate of sediments from the active phase of spoil disposal is deduced from Table 8 of **Appendix C**. Taking medium sands as representative of the material likely to spread the widest during the active phase then for a water depth around 55 m and an associated peak spring flow of around 0.63 m/s the longest spreading distance is likely to be up to 690 m for the offshore array area. Very fine gravel and weaker periods of flows would reduce this distance to possibly as low as 100 m, noting the immediate discharge will be through a series of hopper doors (e.g. conical bottom valves) along the draught of the TSHD. Over a reduced spreading distance the spoil mound would have a greater height, largely in a conical form. Taking representative scales of the deposit length of between 100 to 690 m provides spoil mound areas in the range 10,000 to 476,100 m^2. The associated maximum height of the spoil mound is likely to be in the range 0.99 to 0.02 m.

4.4 Seabed installation activities

4.4.1.1 Seabed installation activities planned for the construction phase include provisions for:

- Cable trenching along offshore ECC (for export cables) and through offshore array (for array cables); and
- Drilling for foundation options requiring piles to be inserted into the seabed in the HVAC Booster Station Search Area (three foundations) and offshore array (190 foundations).

4.4.2 Offshore ECC trenching

Sediment types

4.4.2.1 Sediment types along the offshore ECC are expected to vary in line with the sediment lithology and gradings resolved by the geophysical survey (**Figure 9**).

4.4.2.2 In areas where the depth of surficial sediments is less than the trench depth then the composition of material being trenched may vary, however, sediment variability over the depth of trenching remains largely unknown at this time. Based on this assumption, the main variability in sediment types is summarised in **Table 17**. Where collated grab sample evidence (i.e. geophysical surveys and other data sources) coincides with the offshore ECC then the percentage content of muds is given as a guide to the amount of fine sediment likely to be present and able to be dispersed away from the trenching process.

Table 17: Expected variation in surficial sediments along offshore ECC.

Location	Approximate distance offshore	Sediment type	% Muds from grab samples
Inshore	Ebb channel	Sand with patches of gravelly sand /exposed till	0.0 to 22.2
Nearshore	Smithic Bank	Sand	0.0
Offshore	7 to 14 km	Sandy gravel	0.4 to 4.8
Offshore	14 to 22 km	Gravelly sand	4.2 to 6.4
Offshore	22 to 34 km	Gravelly sand	0.9 to 47
Offshore	34 to 41 km	Slightly gravelly sand	0.2 to 0.6
Offshore	41 to 72 km	Sand	4.4 to 8.3
Offshore	72 to 85 km	Muddy sand	10.4 to 21.4
Offshore	85 to 93 km	Sand	5.8 to 8.8

4.4.2.3 For the inshore location. in the ebb channel (up to the HDD punch out), the highest reported mud content of 22.2 % in grab samples is suggested to represent the presence of the underlying glacial till, given than the surface layer of sands and gravels in this area is reported to be relatively patchy and thin. This glacial till is likely to be encountered up to the flank of Smithic Bank where the depth of Holocene sediments becomes locally deeper to form the sandbank.

Maximum sediment volumes

4.4.2.4 The maximum sediment volume expected to be displaced by CFE along the export cable route is approximately 3,903,000 m^3. This amount of sediment is apportioned between the six cables (each 109 km in length) which equates to an average sediment volume of 6 m^3 per metre length of excavation. In addition, provisions include for up to four cable joints per cable (up to 24 pits), each requiring a jointing pit which is up to 5 m deep and excavating a sediment volume of 17,500 m^3, a total of 420,000 m^3 for all pits.

4.4.2.5 The rate of trenching will determine the release rate of sediments into the water column, with higher trenching rates releasing the most amount of sediment per unit time and developing the highest source concentrations. A conservative trenching rate of 300 m/hour is assumed representative of jetting in soft sediment. In a one-hour period the release would be 1,800 m^3. If this trenching were through a soil type of "mixed grained sand, dense" then the dry bulk density would be 1,860 kg/m^3 (Bray, Bates & Land 1996) and the release rate would be 930 kg/s in this case.

4.4.2.6 In general, the majority of the excavated material is expected to be coarse sediments (sands and gravels) which will drop back to the seabed relatively quickly and remain close to the point of disturbance. The content of fines (fine sands, silts, and muds) is generally expected to be low and in line with the variations identified in **Table 17**.

4.4.2.7 The main exception to these assumptions is the inshore ebb channel where the mud and silt content from surficial grab samples is reported to be up to 22.2 %. Stiffer (cohesive) soils expected here (glacial till underlying a thin veneer of sandy gravel) will potentially reduce trenching rates to around 125 m/hr, or less, and this equates to a release rate of up to 407 kg/s for fines (assuming 93 % content) in this section of the trench (n.b. cohesive soils are less likely to disperse as fine granular material). The trenching towards the landfall is expected to terminate within this substrate to join with the HDD exit pits.

Hydrodynamic conditions

4.4.2.8 Four representative trenching sections of the offshore ECC are considered for potential plume formation; inshore ebb channel, location of cable crossing with Dogger Bank A and B export cables and the HVAC Booster Station Search Area. These sites have been selected on the basis of adjacent receptors; Bridlington Harbour, spoil site HU015 and Flamborough Head SAC. Sites further offshore are unlikely to lead to any greater impact than that already described for sandwave clearance and seabed levelling.

4.4.2.9 **Table 18** provides a summary of anticipated hydrodynamic conditions at the four selected locations. The peak tidal flow and excursion distance for the ebb channel is developed from the additional modelling undertaken for Hornsea Four. Further to this, the operating depth for CFE is likely to mean the site is only accessible during high waters.

Table 18: Representative hydrodynamic conditions for three locations along offshore ECC.

Location	Water depth (m below LAT)	Spring / neap peak flows (m/s)	Spring / neap tidal excursion (km)	Annual range of SPM (mg/l)
Inshore – ebb channel	1 to 8	0.47 / 0.25	Flood 6 /4 Ebb 10 / 6	2 to 14
Smithic Bank	5 to 10	0.54 / 0.28	12 / 6	2 to 13
Dogger Bank A and B cable crossing	21 to 22	0.85 / 0.43	11 / 6	2 to 11
HVAC Booster Station Search Area	50 to 51	0.84 / 0.42	12 / 6	1 to 4

Sediment plumes

4.4.2.10 Sediment plumes are likely to form by the advection and dispersion of finer sediments from the point of release in the water column. Coarse sediments will fall to the bed relatively quickly and are not likely to be present in a sediment plume.

4.4.2.11 The CFE process uses high volumes of seawater at relatively low pressure to displace sediments away from under the device to form the cable trench. This hydraulic force is likely to mobilise the finer sediment fractions relatively high into the water column to form a suspension. In this case, the assumption is made for the finer sediment is raised 3 m above the seabed.

4.4.2.12 Table 19 offers theoretical settling velocities for finer sediments (fine sand, very fine sand, and silts) along with the estimated time for material to fall out of suspension for calm conditions (no waves). When wave influences are included then added stirring effects may prevent all finer sediments from settling out in the shallower nearshore sites and a wider, longer, and more dispersed plume is formed. All sediment fractions coarser than fine sand are expected to fall out of suspension (from 3 m above the seabed) relatively quickly without being present in any plume.

Table 19: Representative fine sediment types in plumes formed by CFE trenching at selected sites along offshore ECC.

Sediment type	Size range (mm)	Representative size (mm)	Settling velocity (m/s)	Time to fall out of suspension (minutes)
Fine sand	0.125 to 0.250	0.188	0.018	3
Very fine sand	0.063 to 0.125	0.094	0.005	10
Silts / muds	< 0.063	< 0.033	0.001	Remains in suspension

4.4.2.13 The main axis of any plume trajectory will be governed by the tidal advection at the point of release. Concentrations will reduce around this axis due to dispersion and diffusion mixing processes spreading the plume and from material falling out of suspension. During a neap tide the plume will be advected over a shorter distance than a spring tide, and since the rate of mixing will be less at these times, due to weaker flows, then suspended sediment concentrations can be expected to be proportionally higher. On spring tides, the plume will spread farther and have proportionally lower concentrations. Winds would expect to have some influence on surface material, either by increasing mixing or modifying the plume trajectory. In addition, the inshore location will be most prone to additional mixing due to wave stirring effects.

4.4.2.14 During the ebb phase of both a spring and neap tide, there is a theoretical pathway for the sediment plume formed during inshore trenching activity to be advected along the ebb channel towards Bridlington Harbour. On springs tides this plume could also reach disposal site HU015 and Flamborough Head SAC. The conditions at HU015 and the SAC are highly dispersive for muds and silts, so there is no expectation for material to settle in these locations, however, the water conditions within Bridlington Harbour are expected to be calm and conducive to settling for any material reaching this location. The harbour already has an existing exposure to siltation from marine sources, noting higher suspended sediment levels were reported in shellfish holding tanks during the installation of the Bridlington Stormwater Outfall in 2014.

4.4.2.15 Since the inshore ebb channel is around 1 km wide, trenching across this channel at a rate of 125 m/hr would take approximately 8 hours. In this period, the amount of muds brought into suspension by CFE could be around 6,000 tonnes. This activity is expected to occur up to six times (once for each HVAC export cable) but most likely on separate occasions which would mitigate the chance for a larger amount of sediment release and risk of material being deposited within the harbour. The further consideration of sediment plumes for this site is established from modelling.

4.4.2.16 Sediment fractions on Smithic Bank are characterised by grab samples ENV_24, ENV_26 and ENV_27 from the geophysical survey (Bibby HydroMap 2019c). These sediments are described as well-sorted fine sand with no silts. Trenching across Smithic Bank is expected to be at a rate up to 300 m/hr. There would be limited opportunity for any sediment plumes to form at this location with the majority of material expected to settle out of suspension in around three minutes. This site is not considered for sediment plume modelling on this basis.

4.4.2.17 At the Dogger Bank A and B export cable crossing location (offshore of Smithic Bank), grab sample ECC_23 describes a very poorly sorted sandy gravel with a silt content of around 1 % and around 2 % content of very fine sand. For the HVAC Booster Station Search Area, grab sample ECC_17 has a silt content of around 35 % and 8 % of fine sand. Trenching across these areas is expected to be at a rate up to 300 m/hr. The further consideration of sediment plumes for these sites is established from modelling.

Modelling of offshore ECC trenching

4.4.2.18 Modelling has represented indicative sediment plume and subsequent deposition events from the cable trenching across the inshore ebb channel, Dogger Bank A and B export cable crossing and the HVAC Booster Station Search Area. For each location, the trenching activity is simulated as a moving source for a representative section of trench. At the end of the release period there is a 72 hour recovery period to determine dissipation and settlement of the plume. These scenarios are undertaken for both neap and spring tides to help consider the variation in plume dispersion effects.

Inshore ebb channel release

4.4.2.19 Results from the modelling of trenching across the inshore ebb channel are presented in Appendix C. Figure C25 provides sediment plume results for a mean neap tide based on all sediments. The spread of the plume tends to be most pronounced to the north-east (due to ebb tidal asymmetry) and contained within an excursion distance of around 6 km. During the trenching period plume concentrations can reach around 10,000 mg/l at the source of activity but quickly diminishing to concentrations less than 60 mg/l at around 2 km north and south of the release location. At the end of the release period plume concentrations rapidly reduce to background levels (< 10 mg/l). Figure C26 presents the same scenario but limited to just the silt sized material confirming this sediment type is mainly responsible for the sediment plume with coarser sediments falling out of suspension relatively quickly and close to the source of activity. Results for a mean spring tide in Figure C27 (all sediments) and Figure C28 (silts only) show a comparatively larger tidal excursion and wider dispersion. Some material spreads beyond Flamborough Head with a small amount of material that advects further north before returning to the south on the flood tide but much further to the east of Smithic Bank. All sediment plumes appear to bypass Bridlington Harbour with relatively low concentrations.

4.4.2.20 Sediment deposition from the inshore trenching activity after 3-days (72 hours) is presented in Figure C35 - (all sediment) and Figure C36 - (silt component only). The maximum depth of deposition (all sediments) is around 134 mm on neaps and 142 mm on springs at sites close to the source. Spring tides show a wider spread of deposition than neaps at the lowest depth of deposition (circa 0.1 mm). The contribution from silts in the depth of deposition represents 10.9 mm on neaps and 8.5 mm on springs, showing the extent of deposition is due to the wider dispersion of silts compared to coarser sediments.

4.4.2.21 Given that the model does not resolve near-field (i.e. sub-grid) deposition at scales less than around 50 to 100 m a complementary assessment of maximum average settlement with range from the trench is offered in Table 6 of **Appendix C**. For a trench with a 6 m^2 cross-section, the maximum settlement depth will effectively be within the trench itself (estimate of 1.2 m after 5 m), especially during periods of slack water. The maximum settlement depth reduces exponentially in range from the trench reaching 0.12 m at 50 m and 0.06 m at 100 m.

<u>Dogger Bank A and B cable crossing release</u>

4.4.2.22 Results from the modelling of trenching in the vicinity of the Dogger Bank A and B export cable crossing are presented in **Appendix C**. Figure C17 provides neap tide results for the sediment plume for all sediments. The plume forms along the axis of the tide with an excursion of around 6 km, extending just to the north of Flamborough Head. During the trenching period plume concentrations can reach 10,000 mg/l as the source moves to the westerly monitoring site immediately across the path of the trenching activity. Generally, concentrations rapidly reduce with material advected north and south of the trench to levels around 1 mg/l. Figure C18 presents the same scenario but limited to just the silt sized material. The silt content in the plume at 2 km from source is approximately 100 mg/l during the trenching period and again fully dissipate. Comparable results are attained for the spring tide Figure C19 and Figure C20 with a larger excursion and wider dispersion.

4.4.2.23 Sediment deposition across the Dogger Bank A and B export cable crossing area from plume settlement after 3-days (72 hours) is presented in Figure C33 - upper (all sediment) and Figure C34 - upper (silt component only). The maximum depth of deposition (all sediments) is 119 mm on neaps reducing to 106 mm on springs for sites along the route of the trench. Spring tides show a wider spread of deposition than neaps at the lowest depth of deposition (circa 0.1 mm). The contribution from silts in the depth of deposition represents 0.4 mm on neaps and 0.3 mm on springs and shows the extent of deposition is due to the wider dispersion of silts.

4.4.2.24 Given that the model does not resolve near-field (i.e. sub-grid) deposition at scales less than around 50 to 100 m a complementary assessment of maximum average settlement with range from the trench is offered in Table 6 of **Appendix C**. For a trench with a 6 m^2 cross-section, the maximum settlement depth will effectively be within the trench itself (estimate of 1.2 m after 5 m), especially during periods of slack water. The maximum settlement depth reduces exponentially in range from the trench reaching 0.12 m at 50 m and 0.06 m at 100 m.

HVAC Booster Station Search Areas release

4.4.2.25 Results from the modelling of trenching across the HVAC Booster Station Search Area are presented in **Appendix C**. Figure C9 provides neap tide results for the sediment plume for all sediments. The plume forms along the axis of the tide with an excursion of around 6 km. During the trenching period plume concentrations can reach 300 mg/l for locations 2 km from source. At the end of the trenching period there is a relatively quick rate of dissipation with no detectable plume after around 45 hours. Figure C10 presents the same scenario but limited to just the silt sized material. The silt content in the plume at 2 km from source is approximately 100 mg/l during the trenching period and again fully dissipates after around 65 hours. Comparable results are attained for the spring tide Figure C11 and Figure C12 but with a wider excursion of around 12 km and showing full dissipation of the plume is slightly faster at 60 hours.

4.4.2.26 Sediment deposition across the HVAC Booster Station Search Area from plume settlement after 3-days (72 hours) is presented in Figure C31 - upper (all sediment) and Figure C32 - upper (silt component only). The maximum depth of deposition (all sediments) is 71 mm on neaps reducing to 53 mm on springs for sites along the route of the trench. Spring tides show a wider spread of deposition than neaps at the lowest depth of deposition (circa 0.1 mm). The contribution from silts in the depth of deposition represents 10.8 mm on neaps and 8.5 mm on springs and shows the extent of deposition is due to the wider dispersion of silts.

4.4.3 Offshore Array trenching

Overview

4.4.3.1 Trenching for array cables will occur after sandwave clearance and seabed levelling is completed. The composition of the seabed at this time may be slightly different to the present baseline, especially where the depth of surface sands has been cleared away to the underling till.

Sediment types

4.4.3.2 Surficial sediment types across the offshore array are presented in **Figure 24**. Sands (medium sized) are dominant with some areas including a small gravel content to create a gravelly sand substrate. Grab sample ENV15 classed as sand is used as a representative definition of sediment fractions for the majority of the offshore array and comprises 95.3 % sand (mainly medium sands) and 4.7 % muds (silts) (Gardline 2019b).

4.4.3.3 The geophysical survey (Gardline 2019a) resolves a relatively thin surface layer of Holocene sand for the majority of the offshore array of < 1 m deep. Sediments are deeper (> 2 m, equivalent to depth of trench) mainly along the western, northern, and southern boundaries (**Figure 25**). Below the Holocene sands there is expected to be stiff clays of the Bolders Bank formation. Grab sample ENV19, toward the eastern boundary of the offshore array area, coincides with limited sand cover (recorded as 0 m Holocene sediment depth) and where the percentage of fines (muds) is slightly higher at 13.7 %. This soil type is likely to be indicative of the wider area where trenching reaches the underlying soils.

Maximum sediment volumes

4.4.3.4 The maximum sediment volume expected to be displaced by CFE across the offshore array is approximately 4,140,000 m^3. The amount accounts for both array and interconnector cables, covering a total distance of up to 690 km.

4.4.3.5 The rate of trenching will determine the release rate of sediments into the water column, with higher trenching rates releasing the most amount of sediment per unit time and developing the highest source concentrations. A trenching rate of 125 m/hour is assumed to account for likely stiffer soils to be trenched. In a one-hour period the release would be 750 m^3 over a distance of 125 m. If this were through a soil type of "glacial till, very mixed grained" then the equivalent dry bulk density would be 2,160 kg/m^3 (Bray, Bates, & Land 1996) and the total sediment release rate would be 450 kg/s.

4.4.3.6 The composition of sub-soils is estimated by consideration of grab sample ENV19 which is described as gravelly muddy sand where the content of finer sized sediments (fine sand, very fine sand, and silts) is generally around 26 %. Based on this proportion the release rate of fines which could form a sediment plume would be 117 kg/s.

4.4.3.7 Some moderation on the release of fines is expected where the depth of Holocene sands remains greater > 2 m (burial depth). This is most likely to occur along the northern extent and western boundary where trenching rates could increase up to 300 m/hr.

4.4.3.8 For the offshore array area, the estimated sequential time required for a single vessel to complete all trenches is 230 days, assuming the trenching rate is not quicker when excavating areas with a thicker layer of sands. Up to three cable laying vessels will be operating across the offshore array area and ECC so the time required may also be shorter than 230 days depending where each vessel is operating.

Hydrodynamic conditions

4.4.3.9 Water depths across the offshore array area are generally between 40 to 55 m below LAT with predicted tidal flows reaching a peak of around 0.55 to 0.62 m/s on mean spring tides and 0.27 to 0.31 m/s on mean neaps. The equivalent tidal excursions are around 8 to 8.6 and 4 to 4.3 km, respectively.

4.4.3.10 Flow measurements at Site L1 (just to the south of the offshore array) indicate speeds can exceed 0.8 m/s when the tidal range is greater than MSR. The equivalent maximum excursion at this time is estimated as 8.8 km.

Sediment plumes

4.4.3.11 Sediment plumes are likely to form by the advection and dispersion of finer sediment from the point of release. Coarse sediments will fall to the bed relatively quickly.

4.4.3.12 The CFE process uses high volumes of seawater at relatively low pressure to displace sediments away from under the device. This hydraulic force is likely to mobilise the finer sediment fractions relatively high into the water column to form a suspension. In this case, the assumption is made for 3 m above the seabed.

4.4.3.13 As the plume is made up of sediments which are denser than seawater then the plume will initially behave with negative buoyancy. The longevity of the plume is determined by the particle settling velocity and the potential for maintaining suspension or resuspension of the component sediment types. **Table 15** offers theoretical settling velocities for fine sand, very fine sand and silts and muds along with time for material to fall out of suspension for representative depths of 40 to 50 m.

4.4.3.14 Fine sands and very fine sands can disperse over a short period only before they fall out of suspension and during this time, they are likely to still remain relatively close to the trench. If the release occurred during peak spring flows, then the very fine sand could reach a maximum distance of around 1.5 km from the trench and at all other times they would fall closer to the trench.

4.4.3.15 Silts are likely to remain in suspension and form a plume which may still be relatively close to the seabed. As the offshore array is not a deposition environment for silts then this plume is likely to only partially fall out of suspension during slack water / low flow periods and resuspend during peak flows. Over time, this material would expect to disperse more widely through this pattern of re-suspension, transport, temporary deposition, and re-suspension.

4.4.3.16 The main axis of plume trajectory will be governed by tidal advection at the point of release with reduced concentrations around this axis due to dispersion and diffusion mixing processes spreading the plume more widely. Plume concentrations will reduce over distance and in time due to the effects of increased mixing and material settling out of suspension. During a neap tide the plume will be advected over a shorter distance than a spring tide, and since the rate of mixing will be less at these times due to weaker flows, then suspended sediment concentrations can be expected to be proportionally higher. On spring tides, the plume will spread further and have proportionally lower concentrations.

Evidence from Hornsea Project Two

4.4.3.17 Sediment plume modelling was performed for Hornsea Project Two assuming jetting into till (at a site along the export cable route in water depths between 25 to 30 m and typically slightly higher flows than Hornsea Four offshore array). Sediment with a 20 % content of fines was assumed with a dry density of 1,700 kg/m^3. The predictions suggest a typical plume width of 100 m for concentrations above 20 mg/l and 40 m for concentrations above 30 mg/l. These values represent depth-average concentrations in and area between 25 to 30 m depth, rather than near-bed equivalents which would expect to be much higher. Initial deposition occurred during periods of low flow and was around 2 mm thick for locations at around 60 m from the release and based on a sediment with a settling velocity of 1 mm/s. Permanent deposition of fine sediments was considered to be negligible (SMart Wind 2015b).

Modelling of offshore array trenching

4.4.3.18 Results from the modelling of trenching for a representative section of the offshore array area within the middle of the array are presented in **Appendix C**. Figure C1 provides neap tide results for the plume comprising all sediments. The plume forms along the path of the trenching activity (from south to north) and is advected away by the tide along an axis to the north-west on the ebb and south-east on the flood. The excursion of the tide is around 4 km from the trenching path. Peak concentrations reach 1,000 mg/l around the trenching path but rapidly reduce away from the release to levels around 1 mg/l. The plume quickly dissipates at the end of the trenching period due to settling and wider dispersion. Figure C2 presents the same scenario but limited to just the silt sized material. The silt content in the plume at 2 km from source is approximately 100 mg/l during the trenching period and again fully dissipates once trenching ceases. Comparable results are attained for the spring tide Figure C3 and Figure C4 with a larger excursion, wider dispersion, and slightly reduced concentrations.

4.4.3.19 Sediment deposition across the offshore array area from plume settlement after 3-days (72 hours) is presented in Figure C29 - upper (all sediments) and Figure C30 - upper (silt component only). The maximum depth of deposition (all sediments) is predicted to be around 116 mm on neaps and 132 mm on springs for sites along the route of the trench. Spring tides show a wider spread of deposition than neaps at the lowest depth of deposition (circa 0.1 mm). The contribution from silts in the depth of deposition represents 2.3 mm on neaps and 1.6 mm on springs and shows the extent of deposition is due to the wider dispersion of silts.

4.4.3.20 Given that the model does not resolve near-field (i.e. sub-grid) deposition at scales less than around 50 to 100 m, a complementary assessment of maximum average settlement with range from the trench is offered in Table 6 of **Appendix C**. For a trench with a 6 m^2 cross-section the maximum settlement depth will effectively be within the trench itself (estimate of 1.2 m after 5 m), especially during periods of slack water. The maximum settlement reduces exponentially in range from the trench reaching 0.12 m in depth at 50 m and 0.06 m depth at 100 m.

Summary

4.4.3.21 Sediment disturbance issues for sandwave clearance, seabed levelling and trenching occur as sequential activities. The range of sediments being disturbed includes coarse and fine sized particles, with only the finer sediments (i.e. fine, sand, very fine sand, silts and muds) able to form sediment plumes which can advect away from the source and subsequently deposit elsewhere. Coarser sediments (i.e. medium, coarse sands and gravels) are the most abundant sediments but when disturbed they will rapidly fall back to the seabed close to source. The finest sediment fraction (silts) with the slowest settling rates may remain in suspension for very long periods due to ambient turbulent mixing in the flows maintaining material in suspension. This material will become widely dispersed over time to develop low residual concentrations and become part of the background ambient concentration.

4.4.3.22 Multiple phases of spoil disposal from dredging have the potential to lead to the main smothering risks and from the active phase of spoil disposal. Coarser sediments discharged from the hopper will fall quickly to the seabed as a density flow and may be relatively immobile which limits the spoil mounds from quickly dispersing and reducing in profile. The selection of disposal locations provides a means to minimise cumulative levels of deposition.

4.4.4 Foundation installation: drilling

Overview

4.4.4.1 Drilling may be required for foundation options which install piles into the seabed and where these piles cannot be installed solely using percussive piling through harder sub-soils or rock. The anticipation is that drilling will only be required for 10 % of pile installations (this may be either 10 % of sites or 10 % of the depth of installation).

4.4.4.2 Drilling produces drill arisings (drill cuttings are considered to be the larger sized fragments that fall to the seabed to form a cuttings pile) that will be brought back to the drilling vessel prior to surface discharge into the sea. Up to two drilling rigs may be operating at the same time, if required. If this occurred at adjacent sites along a tidal excursion, then there is the potential for sediment plumes to disperse together and lead to higher overall increases in SSC.

4.4.4.3 The particle size of drill arisings is unknown at present and depends on many variables, not least; local rock type(s), size of drill, drill speed, drill pressure, etc. The typical conservative assumption is to treat 100 % of material as fines, although existing evidence of drill cutting piles suggests this is unlikely and, in some cases, semi-permanent cuttings piles have formed of relatively large clasts, for example at North Hoyle (DECC 2008b).

4.4.5 Drilling at HVAC Booster Station Search Area

4.4.5.1 One of the foundation options in the HVAC Booster Station Search Area is the six-legged Piled Jacket (Small OSS) with 3.5 m pin piles (16 piles per foundation) with an embedment depth of up to 100 m. Provisions for drilling these piles assume a potential for up to 4,618 m^3 of drill arisings (10 % of the total volume of all piles and all foundations). This potential volume of sediment release is comparable to seabed levelling and the potential release of fines from the same location in overspill (see **Section 4.3.5**) which has a higher estimated total volume (5 % of 171,735 m^3).

4.4.6 Drilling within offshore array area

4.4.6.1 The MDS considerations for drilling within the offshore array area are summarised in **Table 20** with values based on a provision for up to 10 % of total pile volumes.

Table 20: Summary of drill arisings for foundations across the offshore array.

Unit	Foundation type	Number	Drill arising volume (m^3)	Equivalent volume per foundation (m^3)
WTG	Monopile	180	127,234	707 * 180 7070 * 18
OSS	Piled jacket (Small OSS)	9	13,854	1,540
Offshore Accommodation	Piled jacket (Small OSS)	1	1,540	1,540
	Total	**190**	**142,629**	

4.4.6.2 For illustrative purposes, 10 % of monopile sites equates to 18 locations each with a volume of approximately 7,070 m^3, and 10 % of all 180 sites a volume per foundation of approximately 707 m^3. The allocation of the maximum volume of drill arisings for monopiles in the offshore array could also be somewhere in this range.

4.4.6.3 In comparative terms, these quantities of drill arisings are lower than the overall volume requirements for seabed levelling at the same locations (see **Section 4.3.6**). For reference, the assessment of seabed levelling assumed 5 % of the total volume is represented as fines in the overspill.

4.4.6.4 The geophysical survey has resolved sub-bottom profiles (SBP) of stratigraphy across the offshore array area to around 150 m below seabed (GeoSurveys 2019). Nine seismic units have been described, including the surface layer of Holocene Sands to the base unit represented by Pre-Chalk Mesozoic sediments (medium to coarse-grained sands). Where the base unit is absent (i.e. below the seismic record) the next seismic unit (U80) is described as fine-grained limestones, with coccolith bioclasts in a matrix of coarser calcite components which correspond to the Chalk Formation (Upper Cretaceous). **Figure 26** presents an interpretation of the depth below seabed to the top of the chalk layer. For reference, pile depths for monopiles are up to 40 m below seabed whereas the pile depth for jacket foundations are up to 100 m (70 m for WTG jacket foundations).

4.4.6.5 The requirement to drill into chalk depends on pile depth reaching this horizon and the hardness of the substrate which is a present uncertainty. Notably, the Sheringham Shoal Offshore Wind Farm 90 km to the south of Hornsea Four, also encountered Cretaceous Chalk but was still able to drive all piles into the seabed without the need of drilling (Carotenuto et al. 2018).

4.4.6.6 At Lynn & Inner Dowsing offshore wind farms (two sites further to the south and offshore of The Wash), drilling was required through patches of hard chalk sub-surface geology at six of the 54 monopile installations. A licence was required to dispose of the drill cuttings which included conditions to monitor sediment plumes and drill cuttings mounds. Intensive monitoring found no significant increase in SSC above background levels but larger than expected drill cuttings mounds (initial diver surveys estimating a total coverage of around 689 m^2 with a spread of between 15 to 20 m north to south form the centre of the mound) that persisted (albeit slightly diminishing to a stable level with a maximum height of around 1 m above seabed) over the four year monitoring period. These findings were contrary to model predictions which had assumed smaller particle sizes (3.2 to 15 mm for the drill cuttings mound) which would have potentially been more easily dispersed. Drill cuttings samples observed on the spoil mound were in the range 50 to 100 mm (BOEM 2017).

4.4.6.7 If drilling is required, the drilling rate is expected to be between 0.5 to 1.0 m/hr, this equates to a production rate of drill arisings of between 88 to 177 m^3/hr for WTG foundations. For comparison, Hornsea Three assumed a production rate of 88 m^3/hr and Hornsea Project One and Hornsea Project Two a rate of 235 m^3/hr for 10 and 15 m diameter monopiles.

4.4.6.8 Based on presently available details, and assumed drilling rates, would suggest comparable sediment plumes and deposition effects to those previously discussed in **Section 4.3.6**.

<u>Evidence from Hornsea Project One</u>

4.4.6.9 Provisions for drilling in the offshore array were part of the Hornsea Project One (and Hornsea Project Two) application; however, when the installation of foundations at Hornsea Project One was completed in 2018 and 2019, no drilling was required.

4.4.6.10 Hornsea Project Two modelled the drill arising for monopile foundations with a volume of drill arisings of 3,927 m^3 and a jacket with a volume of 8,482 m^3. The contribution of fines was based on borehole information with a fine content of between 28 to 43 %.

4.4.6.11 Sediment plumes only formed from the release of fines with sand sized sediments falling rapidly out of suspension and local to the point of release. Fine sediment did not form any appreciable deposition but dispersed at the scale of the local tidal exclusion with depth-average concentrations of > 10 mg/l extending 2.5 to 8 km from the point of release. Any peaks in raised levels of sediment concentration were short-lived (SMart Wind 2015b).

4.5 Scouring around foundations

Overview

4.5.1.1 Scouring is a near-field process when flows (and / or waves) are locally blocked and need to accelerate past an obstacle (e.g. a foundation fixed to the seabed). The intensified flow speeds passing around the object create vortices (turbulence) that increase bed shear stress acting on the seabed which can then lead to local scouring when the sediment is susceptible to these higher erosion forces. The scouring continues to an equilibrium condition which eventually accommodates and dissipates the faster flows and vortices. This situation is generally described as the equilibrium scour depth. Scouring can be mitigated by placing suitable scour protection measures around the obstacle to armour the seabed against the heightened erosion forces. Use of scour protection is included in all foundation options, however, the timing of placement may leave a short period where some local scouring might occur.

4.5.1.2 The rate of scouring can be fast when the seabed is already highly mobile, this is generally referred to as a “live-bed” regime. Where wave forces act on the seabed then the rate of scouring can increase.

4.5.1.3 The rate of scouring to the equilibrium depth can be slow when there is limited active sediment transport because flows are too weak to erode the seabed material or there is no erosion because the soils are resistant to increased bed shear stress. When an object with a surface profile is introduced and blocks incident flows, the accelerated flows (relative to the ambient flows) may have the potential to create “clear water scour”.

4.5.1.4 The extent and depth of local scouring is mainly related to the scale and shape of the structure and the soil properties (e.g. angle of repose). For slender cylindrical monopiles (i.e. when the ratio of pile diameter, D, to water depth, h is < 0.5), the scour depth is a function of the pile diameter, D, and a near-circular form of scour is created, although this can also be asymmetric in shape depending on the way ebb and flood flows affect the structure. This is referred to as “local scour”.

4.5.1.5 When piles are closely spaced (e.g. multi-legged jacket structures) then the extents of local scouring around each pile can overlap and create a wider area of “group scour”.

4.5.1.6 Large (and non-cylindrical) foundations generally exceed the criteria of slender piles and flow separation occurs around the structure. Consequently, the shape of scouring may be spread differently around the base of the structure, rather than uniformly. In addition, the alignment and shape of the structure with incident flows will also determine where scouring occurs. For example, a larger rectangular structure facing incident flows may have greatest scour at the corners of the base.

4.5.1.7 General changes in seabed levels, separate to any influence of structures, can also occur which also present a risk to foundations. When the general seabed levels drop this is commonly referred to as “global scour”.

4.5.1.8 The present design option may place scour protection (or a pre-lay filter layer) on the seabed prior to foundation installation. In this case scouring is likely to be mitigated. The alternative option is to install the foundations first and then add scour protection soon after. In this case, the period between foundation installation and placement of scour protection leaves the structure prone to scouring. The amount of scour that may take place in this period depends on many factors, including; the local sediment types (surface and sub-surface), flow environment and structure shape.

4.5.1.9 The consequence of scouring is normally limited to the near-field of individual structures and is likely to be limited in extent to scales of tens of metres and scour holes of a few thousand cubic metres per foundation. The time to achieve the equilibrium scour depth is also relatively quick and likely to be within a few tidal cycles for a live bed condition. Any eroded material from the scouring process will also quickly become assimilated as part of the wider sediment transport regime. In some live-bed situations, scour "tails" have been observed over several hundred metres downstream of monopile foundations in shallow water which are considered to be a product of turbulent forces in the wake continuing to affect the seabed (DECC 2008c).

4.5.1.10 The environmental impact of scouring is minimal when the local scale of change is largely limited to each foundation. The separation distance between foundations is also typically sufficient to mitigate group scour which may lead to the risk of destabilising a large morphological feature, such as a sandbank.

4.5.1.11 The main environmental change is likely to be related to the introduction of rock armour as scour protection around the periphery of the foundation, e.g. situations where rock armour changes the ambient sediment substrate type. Apart from any ecological relevance, this change would also locally modify the roughness of the seabed.

4.5.2 Scour around temporary cofferdams: Landfall area

Structures

4.5.2.1 Temporary cofferdams are an option to enable drilling fluids (e.g. bentonite) to be manged within HDD exit pits and prevent any accidental spills into the marine environment during punch out. There is a provision for up to eight HDD exit pits (HVDC option) with up to three pits open at any time for up to three months. A cofferdam would expect to surround each HDD pit in a configuration which is likely to be up to 50 m long (cross-shore direction) and 18 m wide (longshore direction) covering an area of up to 900 m^2 per pit. The minimum separation between cofferdams would be around 50 m.

4.5.2.2 The precise location and arrangement of the temporary cofferdams is unknown at this time, but the likelihood is they will be dug into the glacial till (occasionally covered with a thin veneer of mobile sand).

4.5.2.3 Shore parallel flows have the potential to develop local scour in mobile sediments around the base of each cofferdam, most likely around the corners of the 50 m incident face. These scour holes may also overlap as group scour if the cofferdams were close together. Below the thin layer of mobile sediments the underlying glacial till is considered to be more resistant to scouring (i.e. likely slower rate of scouring).

4.5.2.4 The relative short duration (up to 3 months) for any group of cofferdams to be in place is likely to limit the development of full equilibrium scour depths.

Evidence base

4.5.2.5 The evidence for slow scour rates in glacial till is demonstrated from the local beach and from an existing offshore wind farm installation.

4.5.2.6 A series of tank traps remain on Fraisthorpe Sands which show evidence of shallow scour pools in the sandy beach (**Figure 40**). The depth of scour is likely to be limited by the underlying glacial till. These structures have been in place since WWII, around 80 years.

Figure 40: Example of scour around WWII tank traps (IECS 2019).

4.5.2.7 Scour observations from the Barrow Offshore Wind Farm reported near zero scour depths on glacial till bed material and with some marginal scouring which developed slower than foundations in sand (DECC 2008c).

4.5.3 Foundation scour: HVAC Booster Station Search Area

Structures

4.5.3.1 The MDS foundation option for the HVAC Booster Station Search Area is the three large 75 m wide GBS (Box-type) foundations in an area of 13 km^2 located around 35 to 41 km offshore and within the offshore ECC. The location of each foundation is yet to be determined and their orientation with respect to incident flows also remains unknown. If flows are at 45° to the structure, the effective width increases to 106 m. In the period prior to placement of scour protection, or if no scour protection is offered, then the scale of these structures in a water depth of around 51 m below LAT is likely to lead to edge scour (where the seabed is susceptible to erosion) rather than scour around the full perimeter of the foundation.

4.5.3.2 The base of each foundation will occupy an area of approximately 5,625 m^2 with provisions for scour protection adding an additional 25,000 m^2 (extending 50 m around the periphery of the 75 m width GBS (box-type) foundation). The minimum separation between each foundation is 100 m.

Sediment types

4.5.3.3 The seabed substrate described by the geophysical survey is gravelly sand with grab sample ECC_16 indicating slightly gravelly sand with mainly fine and medium sand. Sub-bottom profiling indicates this is a relatively thin surface layer of Holocene sediment (1 to 2 m depth of sediment) overlaying the firm to stiff clay till of the Bolders Bank Formation.

4.5.3.4 An area of megaripples overlaps the western boundary of the HVAC Booster Station Search Area indicating some active sand transport at this location.

Local hydrodynamic conditions

4.5.3.5 The profile of the seabed across the HVAC Booster Search Area is relatively flat with water depths varying between 50.5 to 51.5 m below LAT. Predicted tidal flows reach a peak of around 0.83 m/s on mean spring tides and 0.41 m/s on mean neaps. Only peak flows on spring tides are sufficient to mobilise the fine and medium sands.

4.5.3.6 Water depths are sufficient to mitigate any wave stirring affects acting on the seabed.

Scour assessment

4.5.3.7 Given the ratio between water depth and size of structure, the scour case exceeds slender pile assumptions. If the seabed is susceptible to increased flow speeds at these locations, then scouring will most likely be greatest at the edges of the structure and related to the orientation of the structure to incident flows.

4.5.3.8 If the foundations are close together, at the minimum separation of 100 m, then flow interactions between structures are likely and more complex scouring might occur between structures.

4.5.3.9 The amount of material that may be scoured from around the base is likely to be lower than the quantities considered for seabed levelling at the same location.

4.5.3.10 Material that is susceptible to being scoured is likely to be limited to the sand fraction with the gravel fraction more likely to remain *in situ* and helping to armour the seabed. The sand fraction only becomes mobile during peak flows on spring tides.

4.5.3.11 Deeper scour (> 2 m) could be limited by the underlying sediment layers comprising the firm to stiff clay till of the Bolders Bank Formation.

Evidence from F3 Offshore

4.5.3.12 There are less scour observations around large gravity bases compared to more common monopile foundations and more accessible bridge piers.

4.5.3.13 The F3 Offshore GBS Platform is part of oil and gas infrastructure installed in the Dutch part of the southern North Sea in 1992. The dimensions of the GBS are 70 by 80 m width and 16 m high, with three caissons on the top. Around the base of the foundation is a 1 m gravel filter layer with gabion mattresses placed on top which extend the width by 6 m on all sides. The gabions are fixed to the GBS to prevent scouring undermining the structure.

4.5.3.14 The platform is in a water depth of 42.3 m on a seabed of mainly fine sands. The spring tide peak flow at this location is reported as 0.41 m/s which would suggest no sediment transport unless storm events and surge currents exceeded this magnitude. The one-year return period storm wave is estimated to have a wave height of 4.9 m and a wave period of 9.4 s. This wave condition could also theoretically initiate sediment transport.

4.5.3.15 Based on seabed inspections of the structure, a scour hole is noted in the south-west corner with a maximum depth of 3 m (**Figure 41**). Without gabions protecting this corner, the scour would have expected to undermine the GBS in this location. A further and smaller scour hole was also reported in the south-east corner. The locations of the scour holes are considered to be due to the tidal currents which flow between east to west directions (Bos, Chan, Verheij, Onderwater, & Visser 2002).

4.5.3.16 The observations around F3 GBS provide a suitable insight for the expected scour around an individual GBS box-type foundations at the HVAC Booster Station Search Area for the situation without scour protection. Scouring around foundations is planned to be mitigated with seabed preparations to level the local seabed, the placement of a gravel bed filter layer, followed by placement of the foundation and finally scour protection extending 50 m around the base.

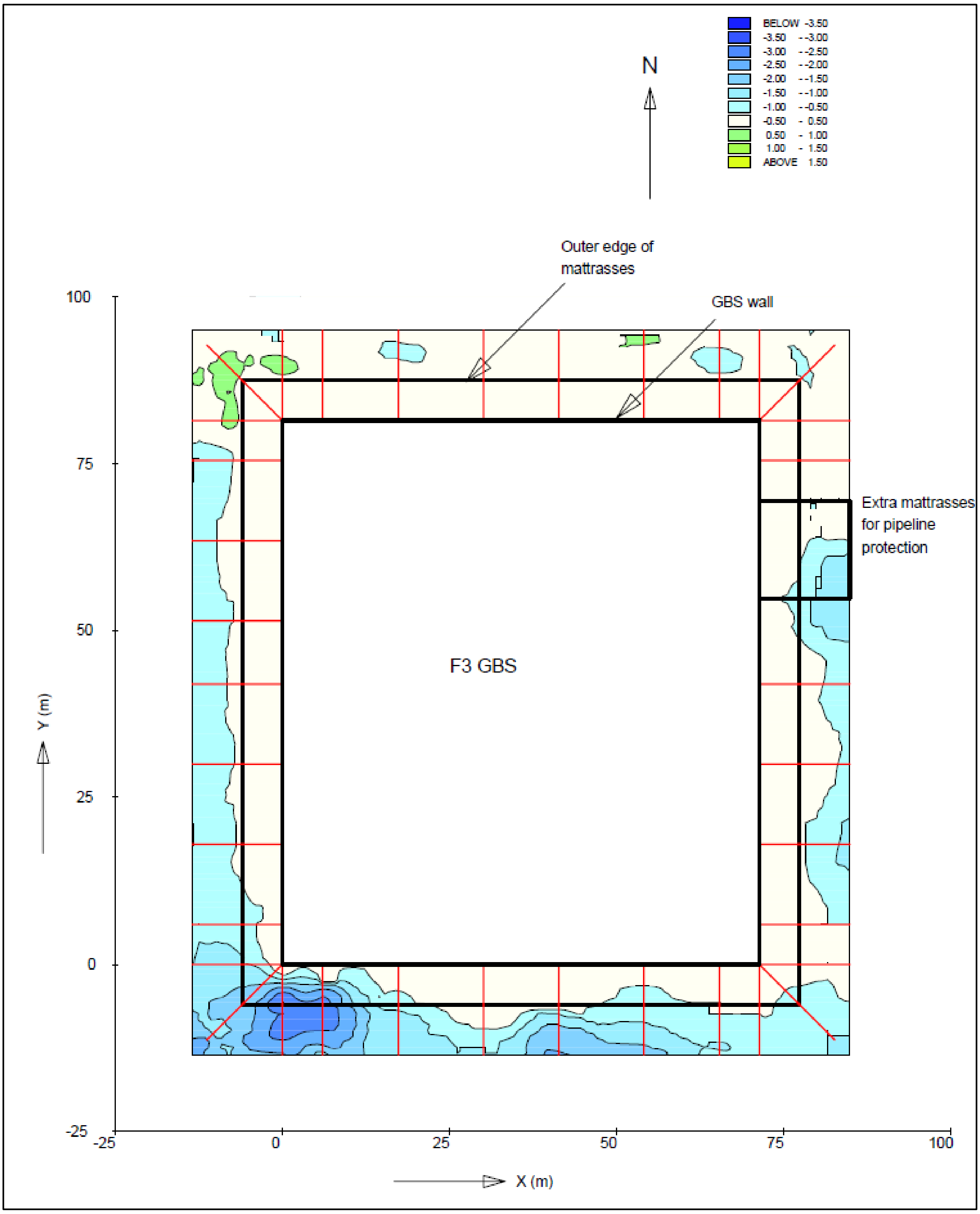


Figure 41: Observed scour around F3 Offshore GBS, after six years (Bos, Chan, Verheij, Onderwater, & Visser 2002).

4.5.4 Foundation scour: Offshore Array

Structures

4.5.4.1 The MDS foundation options for the offshore array are based on the structures which are considered to exert the greatest amount of blockage to incident flows and therefore create the largest amounts of turbulence which has the potential to induce the most amount of scouring of the local seabed around each individual foundation (assuming the case without scour protection). Relative scales of blockage for each foundation type have been assessed using indicative solidity ratios applicable across the cross-sectional area presented to incident flows. For example, a solid structure will have a solidity ratio of 1 whereas an open lattice jacket will typically have a solidity ratio of up to 0.3.

4.5.4.2 The MDS array-scale option is based on the combination of relevant foundation types which have the largest requirement for scour protection. This is made up of a 110 GBS WTG-type and 70 monopile WTG-type for sites where GBS foundations cannot be used, plus box-type GBS for the OSS foundations and offshore accommodation platform. **Table 21** summaries the MDS foundation options for scour protection for the offshore array.

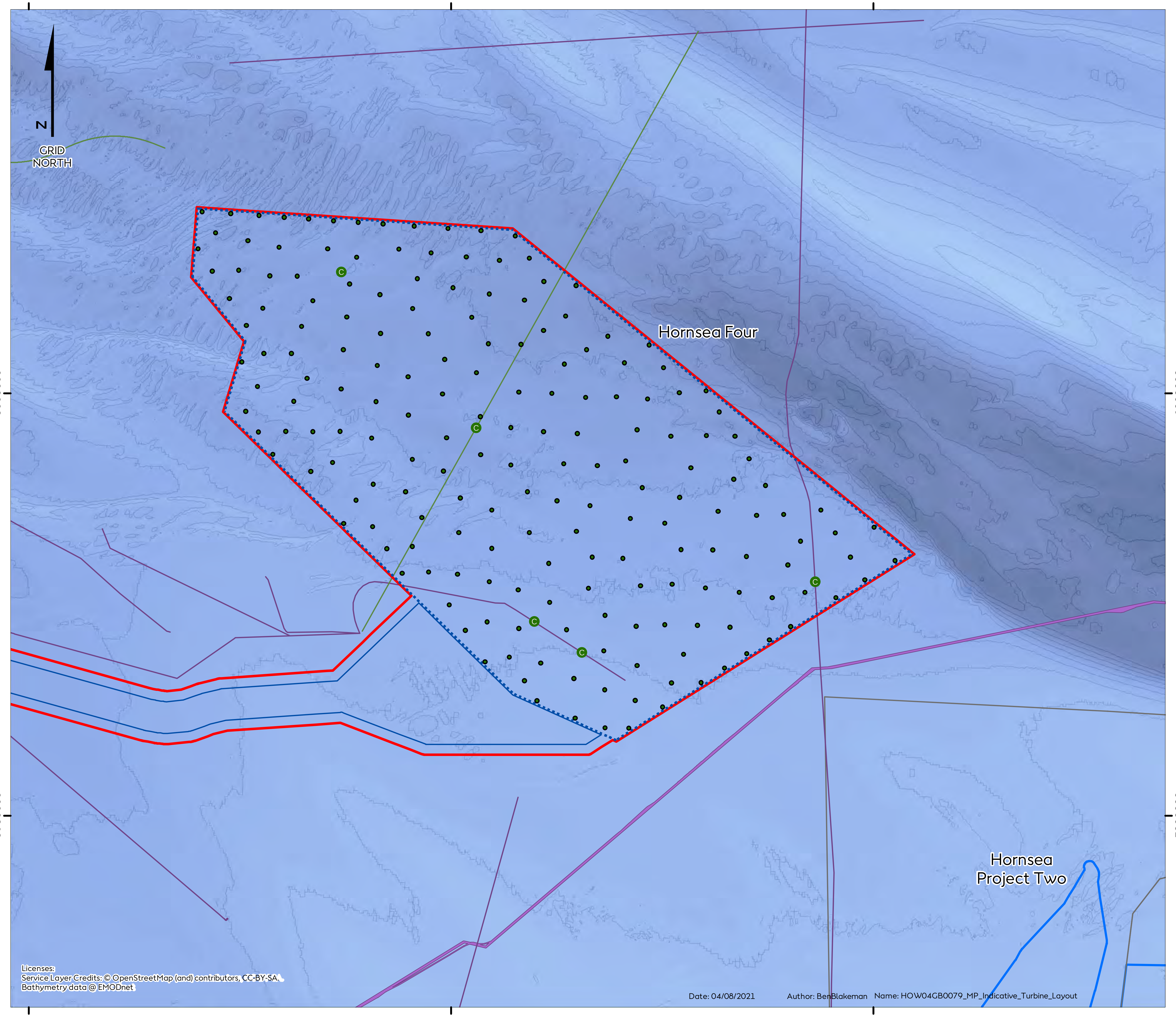
Table 21: Summary of MDS foundation options for scour protection in offshore array area.

Unit	Foundation type	Number	Base Width (m)	Scour protection area (m^2)
WTG	GBS	110	53	504,540
WTG	Monopile	70	15	296,881
OSS large	Box-type gravity base	3	150	120,000
OSS small	Box-type gravity base	6	75	150,000
Accommodation platform	Box-type gravity base)	1	75	25,000
Totals		**190**		**1,096,421**

4.5.4.3 The GBS (WTG-type) foundation is conical shaped with a base diameter of up to 53 m, comparable to the MDS case for Hornsea Three. The top section of the structure is a 15 m diameter pile. Scour protection is planned to extend up to 20 m around the base of this type of foundation and 30 m around the monopile foundation.

4.5.4.4 The effective base width for 75 and 150 m box-type GBS increases when the incident flow is at 45°, this leads to effective widths of 106 and 212 m, respectively. Scour protection is planned around the periphery of these foundations over a width of up to 50 m.

4.5.4.5 An indicative layout for the 190 foundations is presented in **Figure 42**. There is no final allocation of foundation type (e.g. WTG or OSS) at this stage. Spacings between foundations also remain indicative at this time, although a minimum distance of 810 m will be maintained between centres of all WTG (**Volume A4, Annex 4.7: Layout Principles**).



Hornsea Four

Figure 42

Indicative layout for 190 foundations across the offshore array

- Order Limits
- Array Area
- Offshore Export Cable Corridor
- Indicative Turbine Layout
- Crossing Point (Offshore)
- Existing Pipelines
- Proposed Pipelines
- Viking Link Cable
- Existing Licence Areas for Export Cables and Disposal Sites
- 5m Contour Intervals

Depth (m below LAT)
15
80

Coordinate system: ETRS 1989 UTM Zone 31N
Scale@A3: 1:175,000
0 4 8 Kilometres
0 2 4 Nautical Miles

REV	REMARK	DATE
...	First Issue	07/06/2019
A	Updated following PEIR consultation, for DCO	04/08/2021

Indicative Array Turbine Layout
Document no: HOW04GB0079
Created by: BPHB
Checked by: BC
Approved by: LK

GoBe
Ørsted

Sediment types

4.5.4.6 The surficial sediment types across the offshore array area are mainly sands with small patches with some gravel or fines. This sediment cover is generally > 1 m thick with a layer of firm to stiff clay of the Bolders Bank formation beneath (Gardline 2019a).

4.5.4.7 Sandwave crests are evident across much of the northern half of the offshore array. These crests are generally aligned perpendicular to the axis of tidal flows and indicate sediment mobility and net transport to the north-west, suggesting a live-bed regime.

Local hydrodynamic conditions

4.5.4.8 The most common sediment fraction across the offshore array area is medium sands (particle size in the range 0.25 to 0.50 mm) (Gardline 2019b). This sediment size requires flows in excess of 0.5 to 0.6 m/s to become mobilised, based on standard theoretical expressions (Soulsby 1997). Tidal mapping from the Atlas of UK Marine Renewable Energy Resources (DECC 2008a) suggests this magnitude is generally limited to peak flows during spring tides and is not attained during neap tides.

4.5.4.9 Water depths are sufficient to limit any wave affects acting on the seabed which could lead to sediment transport.

Scour assessment

4.5.4.10 Apart from monopiles for WTG, all other MDS foundation options exceed the case of slender piles. For these situations, flow separation is likely to occur around the leading edge of the foundation base which will be the main area prone to local scouring for situations prior to placement of scour protection.

4.5.4.11 The likely extent of local scour is taken to be less than the planned extent for scour protection. All foundations across the array are considered to be sufficiently separated to mitigate the chance of group scour.

4.5.4.12 The amount of material that may be scoured from any foundation base is likely to be lower than the quantities considered for seabed levelling at the same location. Once any scouring has removed the surface layer of mobile sands, deeper scour is likely to be moderated by the underlying till which is expected to have a much slower rate of scouring.

4.5.4.13 Any surface sands that become susceptible to being scoured will quickly assimilate into the wider sediment transport regime.

4.5.4.14 Scour protection material placed around foundations to mitigate local scour would have a maximum thickness of 2 m using rocks up to 1 m in diameter. Scour protection will therefore introduce a coarser substrate and seabed roughness than the baseline condition.

Evidence base

4.5.4.15 For the larger GBS box-type foundations a similar scour pattern is likely to occur to that described in **Section 4.5.3** for the HVAC Booster Station Search Area box-type GBS if no scour protection was present.

4.5.4.16 Hornsea Three considered scour development around a comparable 53 m diameter GBS. The predicted equilibrium scour depth under currents was 1.6 m. Based on the angle of repose for stable sediment slopes, the assumed extent of the scour hole was estimated as 2.5 m and produce a scoured volume of 347 m^3 per foundation (SMart Wind 2015c). These details remain equivalent for estimating scour depths, extents, and volumes for the GBS (WTG-type) being considered for Hornsea Four.

4.5.4.17 Hornsea Project Two also considered the potential resistance of stiff clay till using an Erodibility Index approach which indicated the underlying till would resist (rapid) scour development.

Summary

4.5.4.18 In the case that scour protection is placed after installation of foundations then some local scouring is likely to occur in the meantime. This would be a short-term effect until scour protection is placed. Full equilibrium scour depths are unlikely to be achieved in this period, especially where the underlying sediments are more resistant to erosion than any thin layer of surface Holocene sands.

4.5.4.19 The depth and extent of any local scouring will be minimised if scour protection was placed directly after installation or eliminated if either a filter layer or scour protection was placed prior to installation.

4.5.4.20 Any long-term effect will be due to the scour protection material placed around foundations to mitigate local scour. Scour protection would have a maximum thickness of 2 m using rocks up to 1 m in diameter introducing a coarser substrate and seabed roughness than the baseline condition.

4.5.4.21 The maximum total coverage of scour protection for all foundations across the offshore array area is very small relative to the whole area and is estimated to cover 1.10 km^2 within a total area of 468 km^2, equivalent to < 0.23 %.

4.6 Cable Protection

Overview

4.6.1.1 Rock armour is the MDS option for cable protection where this results in a change in profile of the seabed due to a rock berm (shallowing) and / or a change in substrate type (coarsening). Provisions for cable protection include:

During construction:
- Cable crossings (known locations across existing pipelines or cables); and
- Provisions for cable protection for up to 10 % of the total amount of cables where cable burial depths are not achieved (unknown locations).

During operation:
- Replenishment of rock protection (up to 25 % of original volume at known locations); and
- Locations where cables become exposed and need to be reburied (unknown locations).

4.6.1.2 Commitment Co188 ensures that no cable protection will be deployed within 350 m seaward of MLWS.

Cable crossings

4.6.1.3 Cable crossings are identified over existing and proposed assets (see **Volume A4, Annex 4.1: Offshore Crossing Schedule**).

4.6.1.4 **Volume A1 Chapter 4: Project Description** (Figure 4.11) provides an indicative example of a rock berm for a single crossing. Rock grading will generally have a typical rock size in the range of 90 to 125 mm and a maximum rock size up to 250 mm, although larger rocks (up to 500 mm in shipping corridors) may be necessary if protection from larger anchors is required.

4.6.1.5 Existing cables or pipelines will first be covered with a pre-lay rock berm of a typical length of around 25.3 m and 12.4 m in width and to a depth of around 0.3 m. The cable will be laid at right-angles over this material and then covered with a post-lay rock berm which is notionally 1.5 m high, up to 500 m in length and 10.4 m in width. The final profile of the rock berm will be a trapezium shape, typically up to 1.8 m above the seabed with a 3:1 gradient. For areas subject to the greatest risk of anchor strikes the rock berm would increase to 3.0 m high (0.3 + 2.7 m).

4.6.1.6 The potential environmental concerns for placing rock on the seabed are related to the change (coarsening) of ambient substrate type as well as the effects the height, length and orientation may have on interrupting sediment pathways, notably bedload.

4.6.2 Cable crossings: Offshore ECC

4.6.2.1 There will be up to six export cables (HVAC option) along the offshore ECC which will each need to cross existing cables and pipelines.

Offshore locations

4.6.2.2 **Table 7** identifies the locations along the offshore ECC (excluding two locations within the offshore array area) which require cable crossings. Apart from the Dogger Bank A and B export cable crossing, these sites are all distant from the coastline and in relatively deep water (> 40 m depth). Each crossing may locally modify the profile of the seabed but would not expect to interfere with wave energy transformation and have only a minor influence on near-bed tidal flows and sediment transport pathways. Some local "edge" scouring may also occur around the perimeter of rock berms, especially where mobile bedforms are present, such as the areas with megaripples east of the HVAC Booster Station Search Area (e.g. **Figure 21 b** where seabed scouring is visible along part of the Cleeton CP to Dimmlington pipeline which requires cable crossings).

Nearshore

4.6.2.3 **Table 7** includes the proposed nearshore cable crossing with the Dogger Bank A and B export cables at a location 2 to 3 km seaward of Smithic Bank and in water depths > 20 m below LAT (in line with commitment Co189, see **Volume A4, Annex 5.2: Commitments Register**). The expected environmental conditions at the crossing are:

- Water depth seaward of 20 m isobath;
- Tidal flows at this location broadly aligned with seabed contours east of Smithic Bank (approximately north to south);
- Indicative rock berm alignment is slightly offset to tidal flows (north-west to south-east); and
- Sandy gravel seabed (covering shallow glacial till beds).

4.6.2.4 Given that there are expected to be up to two pairs of export cables for the Dogger Bank A and B offshore wind farms and six export cables for Hornsea Four, this equates to 12 crossings, all relatively close together. The final arrangement of these crossings depends on many issues which are subject to further confirmation, not least the final alignment and separation between each of the export cables from Dogger Bank A and B. The full crossing arrangement is expected to cover an area of around 0.5 km^2 (up to 0.5 km wide and 1.0 km long) within which there will be six parallel rock berms orientated north-west to south east. The rock berms will create a locally raised seabed with an increased roughness due to a combination of the profile of the berms and the rock material which is expected to be coarser than seabed material. In relative terms, the berms could reduce local water depths at this location by up to 14 % (to around 18 m below LAT for the 3.0 m high berm, or 19.2 m below LAT for the 1.8 m high berm). The raised seabed and increased roughness have the potential to locally modify both waves and flows.

4.6.2.5 Net sediment transport pathways are deduced to be mainly tidally driven which enable sands to be moved to the south-west and onto Smithic Bank by the flood tide (**Figure 19**); peak flows during the flood phase are also greater than those during the ebb. These pathways span a wider area to the north and south of the rock berm, and only where flows pass the rock berm are there likely to be local scale modifications.

4.6.2.6 Flow modifications are expected to include areas of retardation where incident flows encounter the structure as well as over the top of the structures due to increased roughness. Flows are expected to accelerate around the structure. Sands in transport may initially build up in areas where flows are slowed but scouring may also occur around the structure in areas where flows are accelerated. Storm waves may also dissipate some energy on the berm prior to additional shoaling across the shallower profile of Smithic Bank. The overall effect on the nearshore sediment pathways related to Smithic Bank is expected to be minimal and not act a sufficient scale to disrupt supply to the bank, with only local scale interactions around the berm.

Modelling assessment of changes to nearshore tidal flows

4.6.2.7 Results from modelling changes in tidal flows due to the nearshore rock berm are presented in **Appendix C**. Four scenarios are considered to provide an envelope of possible effects related to variations in rock berm height and seabed roughness (to account for additional shallow water friction effects due to issues such as rock type).

4.6.2.8 Of the four scenarios, the maximum possible effect on tidal flows relates to a 3.0 m high rock berm with increased roughness. These effects become more pronounced during spring tides than neap tides and in proportion to the strength of flows. Figure B13 - upper shows the maximum extent of flow wakes (defined as leeward areas with a slight reduction in flow speeds) during different phases of the tide. The high water / flood tide wakes are generally larger (up to around 7 km) than those predicted at low water / ebb tide (up to around 5 km), confirming the greater influence of the flood tide at this location driving net sand transport. Figure B13 – lower provides a closer view of flow interactions around the berm demonstrating how incident flows are partially retarded against the berm, some flows diverted around the feature with increased flows and a slight reduction in flows formed as a leeward wake type feature. All flow reductions are within +/- 0.1 m/s and quickly dissipate away from the berm back to ambient conditions.

4.6.2.9 Although the local seabed comprises sandy gravel, and has an absence of distinct bedforms, this does not eliminate the possibility of some sands passing through this area and onto the southern extents of Smithic Bank, with local flows predicted to be capable of transporting fine and medium sands during periods of spring tide. The very localised and partial reduction of tidal flows due of the rock berm would not alter the general nearshore sediment transport pathways and the moderated flows still retain the capacity to transport medium and fine sands, albeit with slightly reduced rates where this material is within the proximity of the wakes.

4.6.3 Cable crossings: Offshore Array

4.6.3.1 Provisions for cable crossings are also required within the offshore array, these provisions may need to account for two new pipelines creating a provision for up to 32 cable crossings at separate locations. The likely area required to accommodate rock berms for all these crossings is estimated to be up to 204,000 m^2, or around 6,375 m^2 per crossing, on average. This total represents a little more than 0.04 % of the offshore array area.

4.6.3.2 The implication of up to 32 crossings in the offshore array area to marine processes is likely to be relatively minor. As an example of a comparable scaled surface feature, the Shearwater to Bacton gas pipeline is a surface laid asset running north to south within the eastern part of the offshore array area (**Figure 34**). The feature appears to have minimal influence on the wider seabed morphology, with areas of sandwaves and megaripples remaining present either side of the pipeline. Waves are not expected to be modified by the rock berms since water depths are already too deep for wave induced sediment transport.

4.6.3.3 The main environmental issue is likely to be the local-scale introduction of a coarser substrate (rock armour) onto a mainly sandy environment.

Evidence from Hornsea Project Two

4.6.3.4 Hornsea Project Two considered that comparable relatively low and narrow profile rock berms were not sufficient in height above the seabed to influence wave transformation significantly in deeper water (> 12 m). In addition, the likely extent of the cable protection measures does not constitute a continuous blockage along the cable route corridor (SMart Wind 2015d).

4.6.4 Cable re-burial and repairs

Overview

4.6.4.1 During the operation phase of Hornsea Four (anticipated to be a period of 35 years), there may be a requirement to undertake reactive maintenance to either re-bury exposed cables or undertake cable repairs (with the option for cable protection). In addition, a provision is included to replenish rock armour at sites with cable protection, should that become necessary. In general, the expectation for sediment disturbance effects during re-burial and repairs are the same as those during cable installation for the section of cable under consideration.

4.6.4.2 **Volume A1, Chapter 4: Project Description** makes the following remediation provisions for these activities over the operation phase.

Export cables

4.6.4.3 There is a provision for up to 14 km of cable to require reburial over the 35 year operational phase, with any single event up to 2 km in length. This provides for seven or more re-burial events, equivalent to once every five years or more, on average. During re-burial, up to 12,000 m^3 (i.e. 6 m^3 per metre of cable burial) of surficial seabed material (i.e. top 2 m to achieve burial depth) may be disturbed (by CFE or similar) over each 2 km length of cable, and up to 84,000 m^3 over the operational phase.

4.6.4.4 For cable repairs, the MDS option is based on full de-burial and re-burial of the relevant section of cable using jetting equipment (i.e. CFE or similar) with a provision for up to 23 repairs over the operational phase.

4.6.4.5 The consequence of any single cable re-burial or repair event along the export cable route in terms of sediment disturbance effects due to CFE is considered to be comparable to an equivalent section of trenching assessed for cable installation described in **Section 4.4.2**. The likelihood is each remediation event can be considered to be separate both in terms of either location or occurrence over the operational phase.

4.6.4.6 For replenishment of areas with existing rock armour, provision exists for up to 25 % of the original volume employed during the construction phase (i.e. 849,000 m^3) to be topped-up, an equivalent maximum volume of 212,250 m^3.

The consequence of rock armour replenishment along the export cable route, for deeper water locations, is considered to be comparable to the effects described in **Section 4.6.2** for installed rock armour at cable crossings. Replenishment intends to make sure the performance of rock armour protection is maintained; therefore, the profile of the rock berm would not expect to be greater than the original installation and therefore not have any greater effect.

Array cables

4.6.4.7 For re-burial of array cables, jetting equipment will be used (i.e. CFE or similar) to re-bury up to 2 km of cable per event, if and where required, to a total length of 42 km of cable over the operational phase. Depending on the final lengths to be re-buried in each event, this provides 21 or more re-burial events over 35 years, equivalent to once every two years or more, on average. During re-burial, up to 12,000 m^3 (i.e. 6 m^3 per metre of cable burial) of surficial seabed material (i.e. top 2 m to achieve burial depth) may be disturbed over each 2 km length of cable and up to 252,000 m^3 over the operation phase, if the full provision of 42 km is required.

4.6.4.8 For cable repairs, the MDS is based on full de-burial and re-burial of cables using jetting equipment (i.e. CFE or similar) up to ten times over the operational phase.

4.6.4.9 The consequence of any single cable re-burial or repair event within the array area in terms of sediment disturbance effects due to CFE is considered to be comparable to an equivalent section of trenching assessed for cable installation described in **Section 4.4.3**. The likelihood is each remediation event can be considered to be separate both in terms of either location or occurrence over the operational phase.

4.6.4.10 For replenishment of areas with existing rock armour, provision exists for up to 25 % of the original volume employed during the construction phase (i.e. 522,000 m^3) to be topped-up, an equivalent maximum volume of 130,500 m^3.

4.6.4.11 The consequence of rock armour replenishment within the array area is considered to be comparable to the effects described in **Section 4.6.3** for installed rock armour at cable crossings. Replenishment intends to make sure the performance of rock armour protection is maintained; therefore the profile of the rock berm would not expect to be greater than the original installation and therefore not have any greater effect.

Interconnector cables

4.6.4.12 For re-burial of interconnector cables, jetting equipment will be used (i.e. CFE or similar) to re-bury up to 2 km of cable per event, if and where required, to a total length of 7 km of cable over the operational phase. Depending on the final lengths to be re-buried in each event, this provides for four or more re-burial events over 35 years, equivalent to once every nine years or more, on average. During re-burial, up to 12,000 m^3 (i.e. 6 m^3 per metre of cable burial) of surficial seabed material (i.e. top 2 m to achieve burial depth) may be disturbed over each 2 km length of cable and up to 42,000 m^3 over the operation phase, if the full 7 km is required.

4.6.4.13 For cable repairs, the MDS is based on full de-burial and re-burial of cables using jetting equipment (i.e. CFE or similar) up to three times over the operational phase.

4.6.4.14 The consequence of any single re-burial or repair event for interconnector cables within the array area in terms of sediment disturbance effects due to CFE is considered to be comparable to an equivalent section of trenching assessed for cable installation described in **Section 4.4.3.** The likelihood is each remediation event can be considered to be separate both in terms of either location or occurrence over the operational phase.

4.6.4.15 For replenishment of areas with existing rock armour, where relevant, provision exists for up to 25 % of the original volume employed during the construction phase (i.e. 78,000 m^3) to be topped-up, an equivalent maximum volume of 19,500 m^3.

4.6.4.16 The consequence of rock armour replenishment for interconnectors is the same for array cables and comparable to the effects described in **Section 4.6.3** for installed rock armour at cable crossings. Replenishment intends to make sure the performance of rock armour protection is maintained; therefore the profile of the rock berm would not expect to be greater than the original installation and therefore not have any greater effect.

4.6.5 Cable protection and Smithic Bank

Baseline evidence

4.6.5.1 Smithic Bank represents a nearshore, shallow water location where cable protection measures may be required if planned burial depths of installed cables were not achieved or if cables became exposed during the operational period and need to be reburied with additional cable protection measures (e.g. by a drop in seabed levels due to sandbank morphology and / or cables being snagged by anchors). A cable burial risk assessment (CBRA) will apply to all cables to ensure appropriate burial depths are selected to de-risk exposure of cables, however, a low level of risk remains that cable protection might still be required.

4.6.5.2 SBP data has revealed that there is presently a depth of around 6 m of Holocene sands across the top of Smithic Bank (Figure 20). A planned cable burial depth of up to 3 m would seem highly achievable into this top layer suggesting a low likelihood to require any of the 10 % provision for initial cable protection (due to difficulties in burial).

4.6.5.3 Suitable data to examine the scale of past variation in seabed levels across Smithic Bank is fairly limited. Prior to the recent geophysical transects in 2019 the last known survey extending across the relevant part of Smithic Bank was a single beam hydrographic survey from 1979 (now incorporated into EMODnet bathymetry), essentially 40 years previously. In addition, there is partial coverage available from nearshore monitoring from 2011, based on a high resolution multi-beam survey. A comparison of the available data is presented in Figure 43 which suggests a generally flat and stable seabed, without sandwaves, and showing minimal overall variation in level. The depths across Smithic Bank in 1980 seem very comparable to those observed in 2011, despite several differences in survey methods. The maximum variation from present day surveys suggests the bank may have been up to 0.4 m shallower in 2011 and 1980.

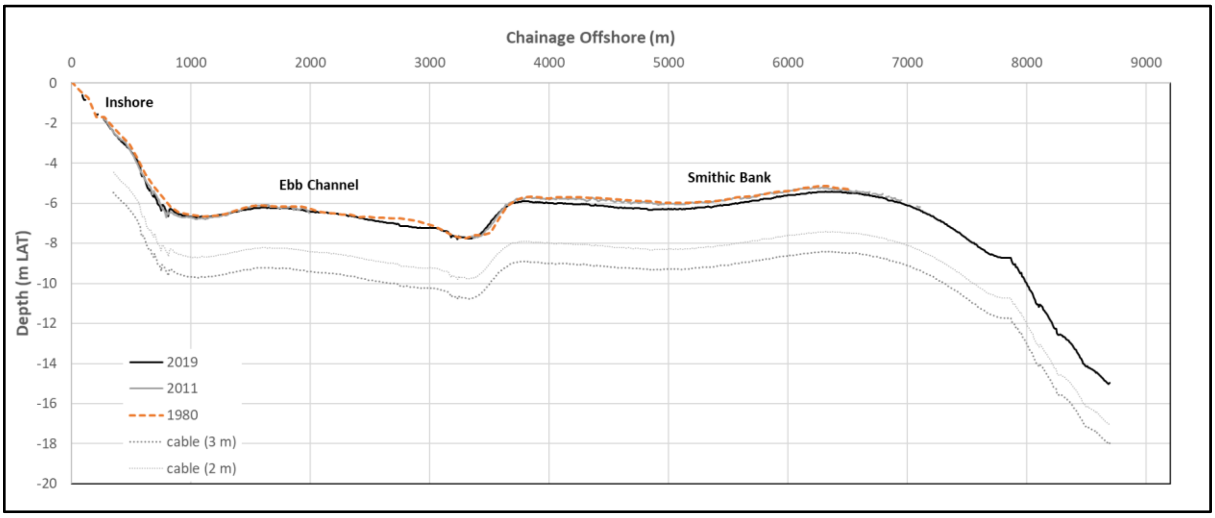


Figure 43: Seabed profiles across Smithic Bank along with hypothetical cable burial depth.

Cable burial

4.6.5.4 Figure 43 also shows conceptual cable burial depths at 2 and 3 m below the seabed. If the surface profile of Smithic Bank was to experience any morphological variation in line with evidence from the past 40 years then a cable burial depth at either 2 or 3 m would appear to be far beyond the risk of natural variation in seabed levels and cables would not expect to be exposed due to any such effect.

4.6.5.5 Achieving a specified burial depth may be affected by hard substrate or buried boulders, however, there are no reported SBP targets identified across the bank, so a design burial depth of 2 or 3 m would be expected to be achieved.

4.6.5.6 After burial, cables may be at risk from being dragged up by fishing gear (trawling) or ship anchors, however, a key reason for cable burial at 2 or 3 m is to place the asset beyond the anticipated risk of such interference.

4.6.5.7 The likelihood of cables becoming exposed across Smithic Bank during the operation period, either due to natural processes or man-made interference, is considered to be low to nil. However, a small chance will always remain that cables may need to be recovered for repairs and reburied, so provisions for requiring rock armour at such times cannot be completely ruled out (not all cable repairs would require use of cable protection).

4.6.5.8 If cables required reburial the maximum length involved would be up to 2,000 m per event. If cable protection was required then the rock armour would typically be up to 0.25 m in diameter (or up to 0.5 m for protection from anchor strike). Where a remedial rock berm is designed to protect from fishing gear a berm height of up to 1.5 m would be used, or in the case of protection from anchors, a berm height of up to 2.7 m, however, there is presently no evidence of either being a risk across Smithic Bank.

4.6.5.9 The shallowest part of the bank is between 5 to 6 m below LAT, inferring that the highest profile rock berm would occupy approximately 50 % of the water depth around the times of low water. This is considered an unlikely scenario due to reasons previously given. If a rock berm was installed along the alignment of a buried cable (largely perpendicular to flows) then the profile of the rock berm would act across the existing net sediment transport pathway to the south and south west. The expected response would be for some build-up of sediment against the berm on the updrift side and some sediments by-passing around the ends of the berm with the possibility of some local scouring. Whilst the rock berm may locally interfere with wave and tidal processes there would be not expected to be any change in the overall sediment budget of the bank. For a specific location, the scale of response to a rock berm is likely to be most sensitive to the height of the berm for a given length.

Laboratory Evidence

4.6.5.10 There is limited publicly available, observational evidence of the performance of rock berms in similar shallow water conditions to Smithic Bank, however, some laboratory studies on different arrangements of scaled rock berms still provide some useful observations. The laboratory tests were conducted at 1/32 scale for an equivalent prototype dimension of a rock berm of 1.8 m high in a water depth of 24 m deep. One of the conclusions from this investigation was scour due to the rock berm was shown to scale (positively) with berm height (Roulund et al. 2019).

Summary

4.6.5.11 Export cables from Hornsea Four are planned to be installed across the southern part of Smithic Bank. Hydrographic survey evidence for this location suggests the relatively flat profile of the bank has varied very little over the past 40 years, providing evidence of comparative stability and an indication that the bank is likely to remain stable over similar timescales into the future. Geophysical evidence would suggest cable installation to a design depth of 2 or 3 m should be successful and not impeded by any obstacles which might lead to a requirement to use cable protection. A cable buried at 2 or 3 m across Smithic Bank would not expect to be at risk from exposure due to natural variation, fishing activity or anchor drags. In the unlikely event that cables need to be reburied then provisions for using cable protection remain a possibility. As long as the profile of any rock berm is kept minimal the consequential effects on the bank would be expected to be low.

4.7 Turbulent Wakes

Overview

4.7.1.1 Turbulent wakes (rather than wakes that increase turbidity) are an extension of the near-field scour related blockage affects. Flow wakes occur on the leeward side of a foundation and are generally represented in hydrodynamic models as a localised reduction in the time-averaged flow speed. The distance and width shown to exhibit a reduced flow speed also provides a proxy for the area within which wake related turbulence effects can be considered to be greatest The intensity of turbulence within the wake is higher than the baseline which can lead to faster rates of dispersion and mixing. Where turbulent wakes occur in an area with fine sands or silts in an active boundary layer of sediment transport these situations can also develop turbidity plumes of locally increased suspended sediment concentration (e.g. Thanet Offshore Wind Farm).

4.7.1.2 The magnitude of turbulence along the wake centreline reduces exponentially with distance downstream from source. A relationship established by Rogan et. al. (2016), based on physical modelling of a scaled monopile, suggests that relative excess turbulence reduces to a comparable scale of ambient conditions at around 40 pile diameters. The work also suggests that across a wind farm, foundation wakes will generally act independently due to larger separation distances (in the alignment of the wake) and group effects are expected to be small.

4.7.2 Turbulent wakes at landfall area

4.7.2.1 Flow and wave related wakes will form locally around the (optional) temporary cofferdams used to protect offshore HDD exit pits, noting up to three cofferdams may be in place at any time and for periods up to three months. The precise form of these wakes remains dependent on the relative orientation of cofferdams to incident flows and waves and their relative spacing. The MDS arrangement is a 50 m length (cross-shore direction) and 18 m width (longshore direction) with a minimum separation of 50 m.

4.7.2.2 The potential for cofferdams to form scour around the base of cofferdams is discussed in **Section 4.5.2**.

4.7.2.3 Cofferdams could also cause some leeward reduction in wave energy reaching the shoreline. If up to three cofferdams were close together at the minimum spacing of 50 m then the combined longshore length could be around 154 m (including spacings). The likelihood is this configuration would not significantly interfere with longshore transport and with no greater effects than those from existing WWII tank traps already present along the foreshore.

4.7.2.4 Since the cofferdams are relatively small and temporary structures then their wake related effects are likely to be negligible over the period and cease once removed.

4.7.3 Turbulent wakes at HVAC Booster Station Search Area

4.7.3.1 Flow and wave related wakes will form locally around the three 75 m wide box-type gravity bases. Wave related effects are discussed in **Section 4.8**.

4.7.3.2 Due to the scale of these foundations, incident flows will be decelerated onto the face of each structure and then become separated to flow around the structure, most likely to create localised faster flows and separate vortices around edges. In the near-field, the flow related wakes will be responsible for scour development around the corners of the structure where the seabed is able to be locally eroded. The expectation is the turbulent flow wakes would quickly dissipate and decay in intensity thereafter along the axis of the tidal ellipse (north-west on the ebb and to south-east on the flood) with no further influences on the seabed. Ambient flows will also contain some turbulence and this may help the rate of dissipation of foundation related turbulence.

4.7.3.3 The precise form of these wakes remains dependent on the relative orientation of each foundation to incident flows and their relative spacing, noting that a minimum spacing of 100 m is possible.

Evidence from Hornsea Project Two

4.7.3.4 Hornsea Project Two considered the likely flow wakes from two GBS foundations required for HVAC reactive compensation substations along the ECC. The foundations were up to 50 m wide at the base. Given the depth of water (23 m below MSL), the principal changes in tidal flows were considered to remain localised to the structures, although it was predicted that wake effects could extend several kilometres to the north and south of the structure at times of peak tidal flows. The greatest changes were considered to be local to the foundation where the largest flow accelerations were expected to occur.

4.7.4 Turbulent wakes at offshore array

4.7.4.1 Flow and wave related wakes will form locally around the 190 foundations in the offshore array. All foundations will have a minimum separation of 810 m. The measurable distance of any wake is likely to be less than this distance. Wave related effects are discussed in **Section 4.8**.

4.7.4.2 There could be up to four types of foundations in the offshore array area which will develop different scales of wakes in proportion to their size and shape (and orientation to incident flows with respect to box-type GBS). The MDS combination for foundations across the array area is considered to be:

- Up to 110 GBS (WTG type), 53 m diameter base with a conical shape tapering to 15 m diameter upper section;
- 70 mono-suction bucket (WTG type), 40 m diameter bucket with up to 10 m above seabed with 15 m diameter upper section;
- Three large GBS box-type with 150 m width base (three OSS large); and
- Seven medium GBS box-type with 75 m width base (six OSS small and one accommodation platform).

4.7.4.3 A layout comprising of only WTG type foundations would expect to lead to individual wakes around each structure that would only interact if the ebb and flood wake alignments reached an adjacent foundation, however, separations between adjacent foundations are likely to be sufficient to limit this interaction, especially if their alignment also avoids the tidal axis.

4.7.4.4 The inclusion in the offshore array of large box-type foundations with greater widths and non-cylindrical shapes increases the potential for wake to wake interactions across parts of the array which are in the leeward path of these larger foundations. Wakes from these structures are likely to form initially with flow separations broadening the overall wake widths.

Flamborough Front

4.7.4.5 Based on detailed temperature modelling, and times when there is development of thermal stratification in the northern North Sea from spring to summer, Hornsea Four is shown to be within the area of stratification and around 11 km to the north-west (the direction of the ebb tide) of the Flamborough Front (at the closest point) (**Figure 36** and **Section 3.4.3.3**). On the flood tide, turbulent wakes from foundations located along the southern boundary of Hornsea Four would develop to the south-east with the front also advecting in the same direction and the two features would not interact. On the ebb tide, turbulent wakes would be developing to the north-west of each foundation and the frontal position would move towards the southern boundary. The likely maximum scale of advection can be assessed with reference to tidal excursions (**Figure 28**) which shows that the distance from the front established at this time to the southern boundary is larger than the tidal excursion during mean spring tides. Tidal ranges greater than mean springs would typically occur around the equinox periods and not during the summer when the front is established. These larger range tides would act to increase tidal mixing.

4.7.4.6 **Figure 37** shows that the frequency of occurrence of the front to be present within Hornsea Four is minimal during the summer period, hence the opportunity for the front to be influenced by turbulent wakes along the southern extent of Hornsea Four is expected to be low.

4.7.4.7 Increased seasonal mixing from autumn to winter, due to stronger winds, increased wave stirring effects, and surge related currents, act together to increase vertical mixing, de-stabilises the stratification in the northern North Sea and the front dissipates at these times.

4.7.4.8 Apart from potential interactions with the front, individual foundation wakes will add turbulent mixing into the water column which has the potential to locally influence thermal stratification across Hornsea Four from spring and summer and potentially make a small contribution to the destabilisation process during the autumn and winter period to create well-mixed conditions. Wakes will vary in magnitude between ebb and flood tidal phases and between spring and neap periods, so that their influence is not a constant effect.

Evidence of wake monitoring

4.7.4.9 The outcome from a review of current and wake monitoring at Barrow, Burbo Bank and Lynn & Inner Dowsing (all based on slender pile monopile foundations) demonstrated that the turbulent wake around a single foundation is directly influenced by the width (or diameter) of the structure and the incident current speed. In addition, provided foundations are located at a sufficient distance from one another, cumulative array-scale effects will not be an issue (MMO 2014).

Evidence from Hornsea Project One

4.7.4.10 Blockage effects on tidal flows have been modelled for Hornsea Project One as modifications to the time average flows, turbulence is not represented in the model; however the scale of wakes represented as a reduction in mean flows provides a proxy for the area within which turbulence effects can be considered to be greatest. Hornsea Project Two and Hornsea Three also referred to this evidence without modelling their respective layouts or alternative foundation sizes.

4.7.4.11 Hornsea Project One modelled the densest layout (Layout 1) comprising 332 WTG foundations, plus five HVAC collector substations, two offshore HVDC converter stations, two accommodation platforms and one offshore HVAC reactive compensation station (a total of 341 structures). All sites were represented with the same 50 m diameter GBS foundation. The separation between foundations in this case was 924 m.

4.7.4.12 Flows reduced slightly along a line of foundations which were also aligned with the tidal axis, indicating some wake to wake interactions. Flows increased slightly between rows. All changes in flows were shown to be less than 0.05 m/s.

4.7.4.13 Wakes generally remained within the boundary of the wind farm but some effects were still evident just beyond the array. The ebbing tide showed wakes extending from Hornsea Project One into Hornsea Project Two. The single HVDC station to the south of the array provides an indication of the scale of a wake from a box-type foundation which appears to be around 4 km on the ebb tide to the detectable limit of 0.01 m/s flow reduction.

4.7.4.14 For reference, Hornsea Project One is now built. The alignment of foundations along rows is comparable to Layout 1 but with an increased spacing. There are less WTG (174) and using a slender monopile foundation of 8.1 m diameter. On this basis, the actual scale of tidal wakes is likely to be substantially less than the conservative case presented from the modelling.

Evidence from Hornsea Three

4.7.4.15 Hornsea Three discussed the implications of changes to water column stratification and potential impacts to the Flamborough Front, although different information was used to assess the location and development of the front to that presented here for Hornsea Four. The considerations were offered in relation to water advecting past array foundations rather than a foundation developing a turbulent wake which passed beyond the array.

4.7.4.16 The assessment suggested a possibility that when stratification occurred the array foundations in the Hornsea Three may cause some minor decrease in the strength of water column stratification. Only a small proportion of water passing through the array area would interact with individual foundations, causing only partial and localised mixing of any stratification. Numerous passes through the array area would also be needed for an initially stratified body of water to become mixed; however, this was considered unlikely due to net displacement of the water body out of the array area over shorter time periods by residual tidal currents. On this basis, stratified water entering the Hornsea Three array area was considered unlikely to become fully mixed. Regional scale patterns of stratification in the North Sea would be unaffected and would continue to be subject to natural processes and variability. The location and physical characteristics of the Flamborough Front were not considered to become measurably affected for Hornsea Three and environmental conditions would remain within the range of natural variability (Orsted 2018a; 2018b).

4.7.4.17 In addition, all other proposed wind farms were considered to be located more than one tidal excursion from the Hornsea Three array area, so there was considered to be no potential for cumulative impacts from turbulent wakes on stratification.

Evidence from German Bight study

4.7.4.18 A theoretical investigation into the potential impacts of offshore wind farms on North Sea stratification, in the region of the German Bight, suggested that extensive development in deeper stratified water, leading to turbulent wakes with increased mixing from foundations, could theoretically impact large-scale stratification, although this was unlikely to be reached with the present scale of planned development which was considered to have very little impact (Carpenter et al. 2016).The work focused on potential large-scale destabilising effects on water stratification rather than effects on fronts.

4.7.4.19 A key parameter used in the investigation was the power consumption per unit area (P_{str}), adapted from Morrison's Equation. For the two wind farms considered (tripods for Bard 1 and Global Tech 1) the associated values of P_{str} were 0.0033 and 0.0053 mW/m^2 (low drag case, drag coefficient, C_D = 0.35) and 0.0094 and 0.015 mW/m^2 (high drag case, C_D = 1.0), respectively, and for wind farm length scales of around 8 km. A key (unproven) assumption in the approach is the power removed from flows due to drag forces exerted by a foundation is equivalent to the power introduced to local turbulence to increase mixing rates. An additional hypothetical large wind farm with a length scale of 100 km was included using a low-turbulent case of 0.0028 mW/m^2 and a high-turbulent case of 0.013 mW/m^2. No account is made on levels of ambient turbulence, the size and shape of wakes in which the increased turbulence and reduced flows exist since the effect is apportioned equally across the full width (or length) of the wind farm. Based on this approach, equivalent low and high turbulence values for Hornsea Four would be 0.0026 to 0.0075 mW/m^2 for monopiles and 0.0059 to 0.017 mW/m^2 for GBS WTG foundations (applying low and high estimates of C_D to help bound uncertainty). The associated length scales for Hornsea Four would be around 32 km along the axis of tidal flows and 18 km across.

4.7.4.20 Estimates for the relative reduction in stratification for arrays with a length scale of around 8 km varied from 1 % (low turbulence case) to 12 % (high turbulence case). For a large windfarm with a length scale of 100 km the relative reduction in stratification varied from 3 % (low turbulence case) to 100 % (high turbulence case). The range in results also greatly depended on which of three different mixing models was applied. N.b. the relative reduction in stratification expressed as a percentage change is not equivalent to a percentage change in sea surface temperature.

4.7.4.21 The main value of this theoretical investigation is considered to be in the comparative estimates in the reduction of stratification between different cases (e.g. foundation and wind farm sizes) rather than taking any values as absolute, given the various simplifications and assumptions made and the large variance in outcomes.

4.7.4.22 Although not included in their existing analysis, a further hypothesis was made that added drag forces from scour protection (and rock armour on cable crossings) may further exasperate the issue of turbulent mixing beyond the influence of foundations alone.

Summary

4.7.4.23 Hornsea Four will add up to 190 foundations across an area of 468 km^2. Each structure will form an individual turbulent flow wake which will reverse in direction between ebb and flood flows and increase and decrease in extent between spring and neap tides. The measurable extent of turbulent wakes is likely to be far less than the full tidal excursion.

4.7.4.24 Given the spacing and alignment of foundations in the indicative layout, most wakes are likely to remain independent of each other, however, for the ten box-type gravity base structures there remains a potential for larger scale wakes interacting with wakes from adjacent structures. Overall, there would appear minimal opportunity for individual turbulent wakes to form a larger array-scale wake affect.

4.7.4.25 During peak flood flows on a spring tide the maximum extent of wakes could extend around 600 m to the south-west from the southern boundary, however, tidal advection would also move the front away from these features along the same pathway meaning no interference to the Flamborough Front. On peak ebb flows the front would expect to advect towards Hornsea Four but the location of the array is considered to be sufficiently distant to the north-west to limit the opportunity of the front to pass into the array and interact with any foundation wakes. Only tides with larger excursions than a mean spring tide could reach the southern boundary of the array, and then most likely across the south-west corner. Large tides are typically limited to equinox periods outside of the period of frontal development and are periods with increased tidal mixing.

4.7.4.26 Apart from turbulent wakes, the addition of scour protection material could also locally increase seabed roughness, however, the MDS provision for scour protection around foundations (0.23 %) and at cable crossings (0.04 %) represent less than 0.27 % of the offshore array area.

4.7.4.27 Collectively, the influence of structures forming turbulent wakes, including scour protection, are considered to be limited to independent small-scale effects which are unlikely to be sufficient on their own to increase mixing to destabilise stratification across the offshore array or interfere with the Flamborough Front.

4.8 Changes to waves affecting coastal morphology

Overview

4.8.1.1 Waves acting on the coastline are an important mechanism for eroding the base of the cliffs and transporting sandy material along the beach as longshore drift. The oblique direction of waves arriving at the coastline determines if the longshore transport is to the north or south. The sheltering effect of Flamborough Head limits the influence of prevailing northerly waves at the landfall leaving the area more prone to infrequent southerly waves. Further to the south of the landfall the coastline is less sheltered by Flamborough Head and northerly waves have an increasing effect. This situation creates a longshore drift divide at the landfall.

4.8.1.2 Sands that are transported in a northerly direction provide a supply of sediment to help develop and maintain the profile of Smithic Bank. In turn, the profile of this sandbank also acts to dissipate some of the wave energy (due to shoaling effects) associated with large storms moving towards the coastline around Bridlington. South of the landfall area, sands are also transported in a net southerly direction along the Holderness Coast towards Spurn Head. Substantial modification to waves arriving at the coastline (in wave height or direction) has the potential to affect the balance in these nearshore processes.

4.8.1.3 There will always be some natural intra-annual and inter-annual variability in wave conditions. In addition, climate change may also modify the frequency, magnitude, and direction of storm tracks, although there is limited certainty at this time on the how these changes may be manifested.

4.8.1.4 Offshore structures can also interfere with the transmission of wave energy reaching the coastline through various forms of interaction, most notably through reflection and scattering off the vertical face and through drag forces (skin friction) as waves pass around structures. The added effect of diffraction depends on the relative scale of the obstacle versus the wavelength of the passing wave. For slender monopiles, the diameter of the obstacle is generally too small for diffraction to occur. When the (effective) diameter (D) is large relative to the incident wavelength (L) then diffraction effects become important. The criterion for diffraction is generally accepted to be when the ratio of $D/L > 0.2$ (Isaacson 1979). Collectively, the interactions between an incident wave and a structure are regarded as blocking type effects with a leeward change in wave energy possible and represented as a possible change in wave height, period, or direction. The leeward change in wave energy transmission may also be referred to as a (wave) wake effect.

4.8.1.5 Array scale blocking can also form when a foundation develops a wake that extends to a leeward structure which then adds to the incident wake. Wake recovery normally occurs beyond the array through dissipative effects with wave recovery also possible by further down-wind wind related stresses.

4.8.2 Changes to waves at HVAC Booster Station Search Area

4.8.2.1 The HVAC Booster Station Search Area is situated in the offshore ECC from around 35 to 41 km from the coast. Within this area there is an option for up to three 75 m wide box-type GBS foundations. If these structures were orientated at 45° to incident waves their effective width becomes 106 m. Water depths at this location are generally around 51 m below LAT.

4.8.2.2 The precise location, spacing and orientation of the three foundations remains unknown at this time; however, there is a stated minimum separation of 100 m between foundations.

4.8.2.3 Wave conditions at the HVAC Booster Station Search Area are likely to be similar to measurements further offshore since water depths are generally too deep to lead to any shoaling or refraction effects modifying wave energy transformation to this location and there are no additional sheltering influences from the coastline. Indicative wavelengths for most common wave periods in the range 4 to 8 s are 26 to 100 m. The ratio of D/L indicates diffraction of wave energy becomes important for these large structures.

4.8.2.4 The MDS for the HVAC booster station foundations on waves is the situation when their combined widths are aligned to become an effective barrier to waves which is estimated for a total width of 318 m. Waves would reflect and scatter off the incident faces of structures and diffraction would occur around the structures redistributing wave energy into the leeward shadow zone created by the structure.

Evidence from Hornsea Project One

4.8.2.5 A single offshore HVAC reactive compensation substation was included in the assessment of waves for Hornsea Project One. A worst-case GBS foundation option with a 50 m base diameter GBS was assessed for a location around 53 km offshore of Spurn Head in a water depth of around 24 m below LAT. This assessment concluded the following (SMart Wind 2013):

"Wave scattering around the structure will occur, and will be greatest for the GBF, but the effects will be spatially limited due to the single foundation. As the offshore HVAC reactive compensation substation is located in deep water offshore, it will not affect the wave climate at the shoreline."

Evidence from Hornsea Project Two

4.8.2.6 Two offshore HVAC reactive compensation substations were included in the assessment of waves for Hornsea Project Two. The worst-case foundation option was also the 50 m GBS. These structures were to be located alongside the Hornsea Project One structure with all three notionally 500 m apart along an alignment across the shared offshore ECC. The assessment for Hornsea Project Two concluded that they would not affect the wave climate at the coast (SMart Wind 2013).

Evidence from Hornsea Three

4.8.2.7 Hornsea Three considered up to four offshore HVAC booster stations halfway along the offshore cable corridor. The base dimension of these structures was 75 m for a box-type GBS. The layout and separation of these structures was not specified. The assessment concluded that they would not affect the wave climate at the shoreline (Orsted 2018a; 2018b).

Modelling assessment of changes to waves

4.8.2.8 Results from the modelling of the changes in waves due to the HVAC booster station foundations are discussed in **Section 4.8.3** along with effects from the offshore array area and Dogger Bank A and B export cable crossing. The main outcome is that local wave height reductions are discernible from the cluster of HVAC booster stations, but these modifications only extend a short distance and do not reach the coast or act in-combination with the Dogger Bank A and B export cable crossing.

Summary

4.8.2.9 The HVAC booster station foundation structures for Hornsea Four are comparable to those proposed for Hornsea Three but with only three structures. Whilst waves will undoubtably locally interact with these structures their distance offshore is considered to be sufficient for any wave modifications to be fully dissipated before a measurable effect reaches the coast.

4.8.3 Changes to waves at the offshore array area

4.8.3.1 There are up to four types of foundations in the offshore array area which will interact with waves. The type of interaction will depend on their size and shape, as well as the incident wave characteristics:

- Up to 110 GBS (WTG type), 53 m diameter base with a conical shape tapering to 15 m diameter upper section;
- 70 mono-suction bucket (WTG type), 40 m diameter bucket with up to 10 m above seabed with 15 m diameter upper section;
- Three large GBS box-type with 150 m width base (three OSS large); and
- Seven medium GBS box-type with 75 m width base (six OSS small and one accommodation platform).

4.8.3.2 Additional interaction of waves may occur across the array between adjacent foundations. This type of interaction depends on the relative spacing and orientation to incident waves that also allows a wake effect to reach a leeward foundation. The array scale interaction represents the aggregate effect of all foundation interactions and becomes the more relevant consideration for effects on far-field receptors, such as the adjacent coastline.

4.8.3.3 An initial comparison of the relative array-scale blockage for all projects within the former Hornsea Zone is offered based on the scale occupied by all foundation per array area (**Table 22**). Although this first order estimate of blockage ignores the shape of each array and the foundation layouts, the relative comparison between projects remains useful to indicate likely scales of effect on waves for comparable sized arrays.

Table 22: Comparison in scale of relative blockage for projects within the former Hornsea Zone.

Project	Status	Array Area (km^2)	Number of foundations	Footprint of all foundations (km^2)	Relative blockage for array (%)
Hornsea Project One	Consented	407	335	0.65	0.162
Hornsea Project One	Final	407	174	0.01	0.002
Hornsea Project Two	Consented	462	258	0.68	0.148
Hornsea Project Two	Final	462	165	0.01	0.003
Hornsea Three	Application	696	319	0.77	0.111
Hornsea Four	ES	468	190	0.44	0.093

4.8.3.4 The consented Hornsea Project One has the highest array scale blockage (resulting from the MDS case of 335 x 50 m diameter GBS) which would be expected to produce the greatest effect on waves for a comparable area. In this case, Hornsea Project One has now been built with a fewer number (174) of smaller (8.1 m) diameter monopile foundations which dramatically reduces the array scale blockage effect by a factor of 73. In addition, these smaller diameter piles would no longer expect to exceed the criterion for diffraction, further simplifying the type of wave interaction across this array.

4.8.3.5 The installed foundations for Hornsea Project Two also represent a similar reduction in number (258 to 165) and size of foundation (58 m diameter base GBS to 9.5 m diameter monopiles) which implies a reduction in array scale blockage by a factor of 58 from the consented MDS case. Similar to Hornsea Project One, this is a further important moderation to what was assessed for effects on waves for consent application and also for any cumulative impact concerns between these two projects as well as any adjacent projects.

Evidence from Hornsea Project One

4.8.3.6 A review of actual array blockage effects on waves has been completed based on the comparison between pre- and post-construction observations to the north and south of the Hornsea Project array. This review is reported in (Orsted 2020) and concluded no discernible changes in wave heights attributed to the presence of the monopile foundations now in place for Hornsea Project One. This is an important moderation to the assessment of waves based on the respective MDS case used for consent application of this project (SMart Wind 2013).

4.8.3.7 The approach for wave modelling was also assessed independently to be highly conservative in the way areas of foundations were represented in the far-field wave model (SWAN) by imposing wave transmission reductions across groups of 3 x 5 structures. This approach restricted waves from passing through the array unimpeded and gave the array a blanket effect of reducing all waves passing through the area. The method of determining wave transmission reductions was also biased by the apparent limitation of the near-field wave model not being capable of resolving short period waves typical of the area (assessed by measurements to be typically in the range 4 to 6 s, and up to 8 s in peak events) and instead was only applicable for wave periods between 8 to 16 s.

Evidence from Hornsea Three

4.8.3.8 Waves assessments were undertaken for Hornsea Three using various models, including the MIKE21 Spectral Wave model. Several configurations of wind farms were represented in the model (Orsted 2018a; 2018b):

a. Hornsea Project One and Two alone, based on their respective MDS configurations;
b. Hornsea Project One revised to the updated final configuration, and Hornsea Project Two and Hornsea Three using MDS configurations. This represented the likely MDS cumulative case at the time; and
c. Hornsea Three alone, for the MDS configuration.

4.8.3.9 **Figure 44** presents patterns of wave height reduction for these different configurations for the 50 % non-exceedance wave height which is taken to represent typical conditions rather than less frequent storm events. For this case, the equivalent offshore wave height was 1.1

m and wave period of 5 s for N, NE, and NNE wave directions. These directions are selected as they were the only directions with modified waves potentially reaching the coast around Suffolk. None of the scenarios showed reductions in wave conditions affecting the Holderness Coast.

4.8.3.10 Results for configuration (a.) are shown for completeness but are superseded by the final layouts for Hornsea Project One and Hornsea Project Two which now eliminate such effects.

4.8.3.11 Results for configuration (b.) introduce Hornsea Three but also modify Hornsea Project One to the final layout. This scenario lessens the amount of wave height reduction from this array and only the northerly scenario has wave height reductions reaching the coast. If Hornsea Project Two was also now updated to the final layout then no wave reduction effects would be expected to reach the coast when all three arrays are represented together.

4.8.3.12 Results for configuration (c.) are for Hornsea Three in isolation. No wave reductions reach the coast. The relative array blockage for the MDS case of Hornsea Three is also larger than that expected MDS case for Hornsea Four.

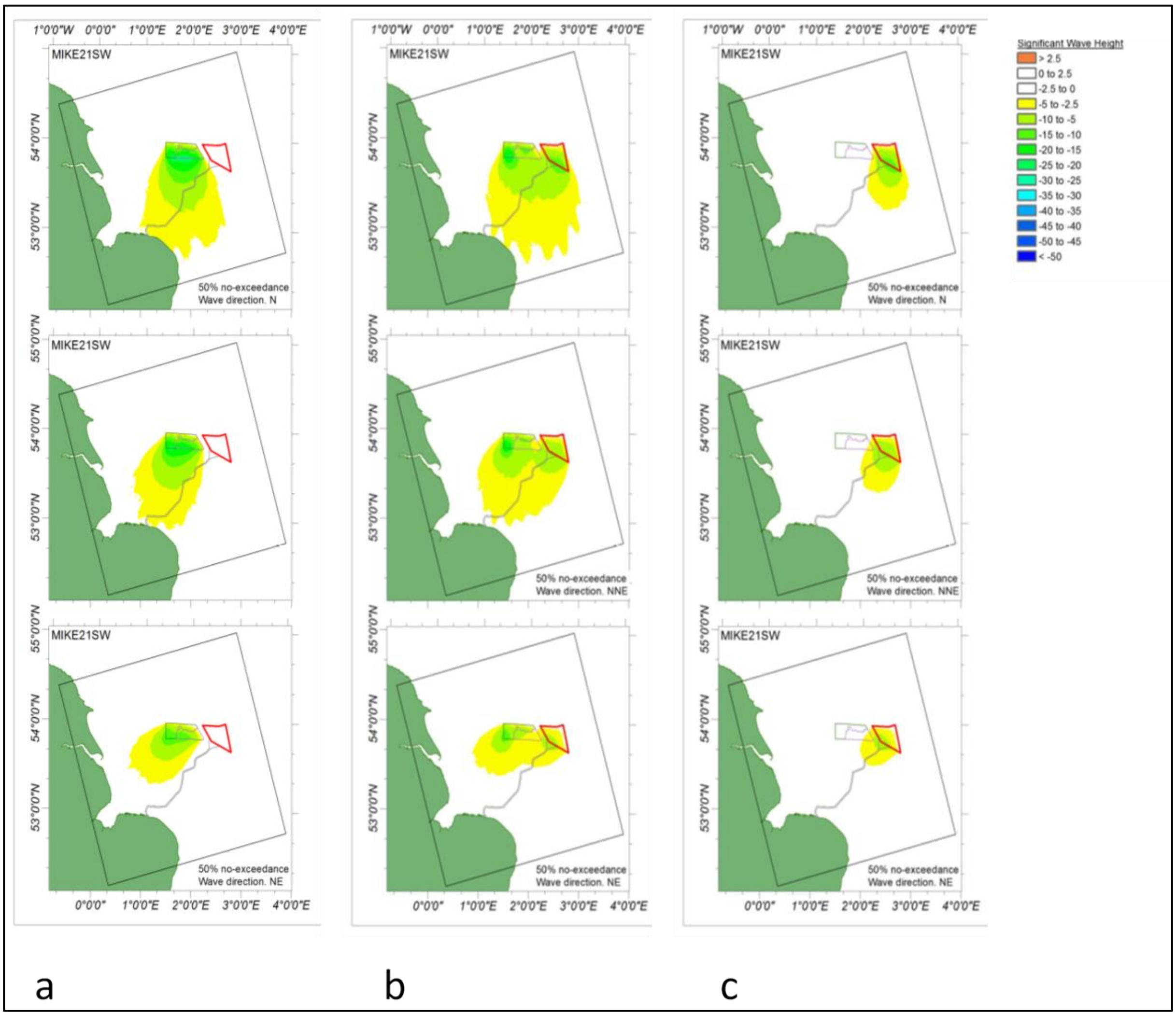


Figure 44: Wave model results for the 50 % non-exceedance percentage wave height reductions from N, NNE, and NE directions (from Orsted (2018a)).

Modelling assessment of changes to waves

4.8.3.13 An assessment of the potential effect of Hornsea Four on blocking wave energy transmission towards the Holderness coastline is investigated using wave modelling (**Appendix C**). The configuration of the wave model accounts for the influence of foundations in the HVAC Booster Station Search Area and the offshore array area, together with the raised profile of the nearshore rock berm crossing Dogger Bank A and B export cables. The maximum number of GBS-WTG foundations in the offshore array area will not exceed 110 locations (of 180 WTG) with the MDS case for the remaining 70 WTG foundations becoming the mono-suction bucket option. Since the final layout and distribution of WTG foundations remains unknown at this time then a conservative assumption has been adopted applying the GBS foundation option to all 180 WTG sites. The modelling also accounts for the final layout and foundation types for Hornsea Project One and Hornsea Project Two, along with MDS case for Hornsea Three as the maximum potential blockage representing an in-combination scenario across the former Hornsea Zone.

4.8.3.14 Results from the wave modelling are presented in **Appendix C** based on the same set of wave scenarios previously applied to investigate the influences of Hornsea Project One, Hornsea Project Two and Hornsea Three, but with the description of Hornsea Project One and Two now updated to represent their final layouts (i.e. the updated baseline) based on a fewer number of smaller diameter monopiles now installed.

4.8.3.15 The colour scale for determining any change in wave heights remains consistent to previous modelling (i.e. as shown in **Figure 44**). In this scale, changes in wave height in the range +/- 2.5 % of the baseline condition are not shown since this low level of change is considered to be insignificant to marine processes.

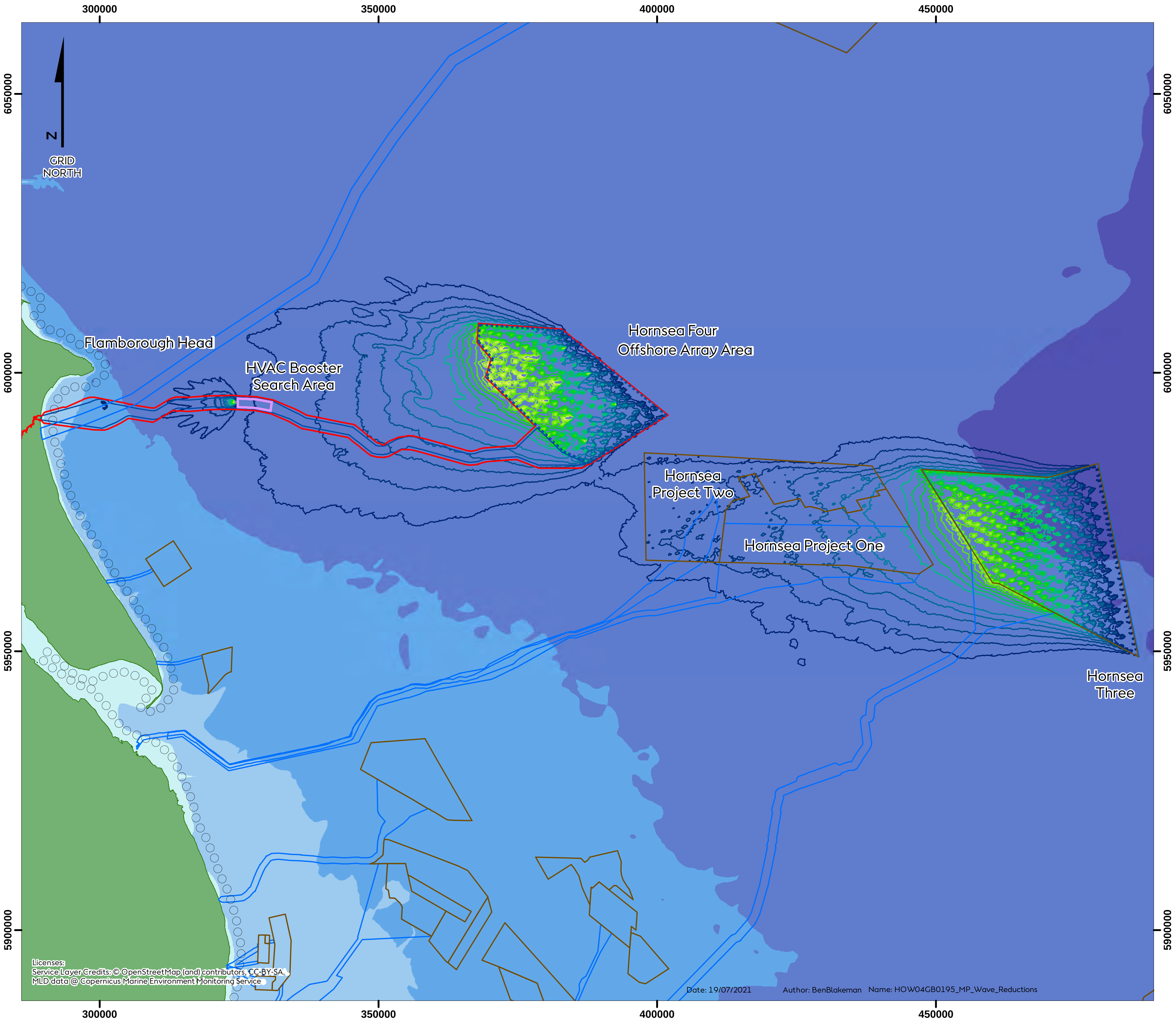
4.8.3.16 The largest percentage reductions in wave heights covering the largest area tend to be associated with 50 % non-exceedance cases rather than for more extreme cases, such as 0.1 to 100-year RP events. This is considered to be mainly as a function of differences in wave lengths, with the 50 % non-exceedance case having the smallest wave lengths which then develop the highest potential for diffraction type effects, whereas longer wavelengths minimise changes due to diffraction type influences. In addition, a small absolute change to a small wave height (e.g. 50 % non-exceedance case) is also likely to lead to a larger percentage change than a comparable small change on a larger wave height (e.g. 0.1 RP and above).

4.8.3.17 The most direct approach to the Holderness Coast, which also passes between all the offshore arrays, is for the E wave scenarios (Figure A10). Wave reductions in the range 2.5 to 10 % extend to the west of the offshore arrays but these effects also quickly dissipate over distance without reaching the coast. A small area of separate local reduction in wave heights is also evident down-wind of the HVAC Booster Station Search Area, these reductions also quickly dissipate over distance and do not extend into the nearshore.

4.8.3.18 Within the E scenarios, the largest absolute change in nearshore wave heights occurs for the 0.1 RP case (equivalent to general stormy behaviour occurring 10 times each year from this directional sector), noting remaining scenarios for other directions and higher RP may develop larger waves along the Holderness Coast but the associated reductions in wave height are far smaller. For reference, the E sector accounts for between 3 to 4 % of all waves, whereas the NNW sector accounts for around 23 % of all waves (see wave rose for Site L1, **Figure 30**).

4.8.3.19 **Figure 45** presents baseline wave heights (filled contours) for the 0.1 yr RP easterly scenario. Wave heights across the offshore are generally in the range 2 to 2.5 m until they approach the nearshore (defined here as shallower than 40 m below LAT) where initial reductions in wave height commence due to shoaling effects. As waves pass over Smithic Bank then further shoaling occurs reducing wave heights to 1.5 to 2.0 m, and across the shallowest part of the bank (North Smithic) there are additional reductions in wave heights to 1.0 to 1.5 m. Contours of wave height reduction (increments of -0.1 m) due to the effect of rock berm structures placed at the Dogger Bank A and B export cable crossing, and foundations located within the HVAC Booster Station Search Area and the offshore arrays (Hornsea Four, Hornsea Project One and Hornsea Project Two and Hornsea Three) are overlain.

4.8.3.20 The main areas of wave height reduction are related to Hornsea Three and Hornsea Four due to the presence of multiple larger diameter GBS foundations associated with their respective MDS options. Main areas of wave height reduction develop to the western margins of these arrays (for all easterly sectors of incident waves) which then quickly dissipate over distance. The separation between these two arrays mitigates for any larger scale of wave reduction developing cumulatively. The presence of three 75 m GBS box-type foundations at the western boundary of the HVAC Booster Station Search Area is evident with a further small area of wave height reductions that dissipate in in the down-wind direction within a distance of around 12 km to the west. The nearshore cable crossing with Dogger Bank A and B export cables is also evident as a small local reduction in wave heights. Wave height reductions at the HVAC Booster Station Search Area and the Dogger Bank A and B export cable crossing remain small and independent of other effects on wave heights. Importantly, all other wave scenarios for other RP and from other directions all demonstrate a lesser level of wave height reduction towards the coast.



Hornsea Four

Figure 45

Wave height reductions for 0.1 RP E scenario

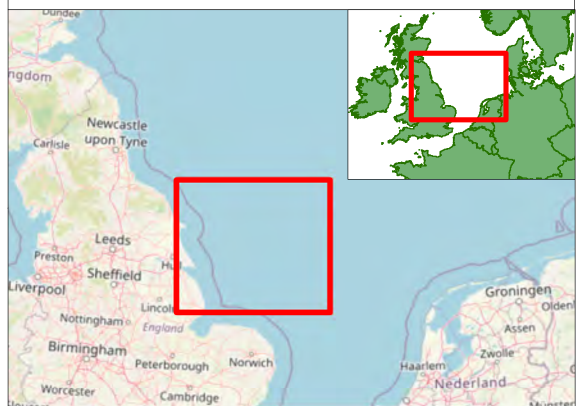
- Order Limits
- Array Area
- Offshore Export Cable Corridor
- HVAC Booster Station Works Area
- Existing Licence Areas for Export Cables and Disposal Sites
- Offshore Wind Farm Site Agreement (TCE)
- Coastal Wave Model Sample Locations

Wave Height Reduction (m)

-0.04	-0.10	-0.16
-0.05	-0.11	-0.17
-0.06	-0.12	-0.18
-0.07	-0.13	-0.19
-0.08	-0.14	-0.20
-0.09	-0.15	

Baseline Wave Height (m)

- 0 - 1
- 1 - 2
- 2 - 2.5
- 2.5 - 3
- 3 - 3.5



Coordinate system: ETRS 1989 UTM Zone 31N
Scale@A3: 1:650,000

0 10 20 Kilometres

0 5 10 Nautical Miles

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Wave reductions for 0.1 RP E scenario
Document no: HOW04GB0195
Created by: BPHB
Checked by: BC
Approved by: LK

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4.8.3.21 Additional analysis of changes in wave heights for all easterly sector scenarios is offered for nearshore locations (shown on **Figure 45**) from Flamborough Head (0 km chainage) to Spurn Head (75 km chainage) to confirm the scale of any effects reaching the Holderness Coast (waves arriving at these locations are responsible for driving longshore drift). **Figure 46** presents the comparison of wave heights from baseline scenarios (square markers) and the cumulative case (lines) of all offshore wind farms across the former Hornsea Zone, along with the HVAC Booster Station foundations the 3 m high rock berm option of the Dogger Bank A and B export cable crossing. Largest waves occur off Flamborough Head (0 km chainage) as this location has the deepest water in the nearshore. Wave heights then reduce to around 10 km chainage (Bridlington) confirming the shoaling effects across the shallowest part of Smithic Bank leading to leeward wave height reductions (additional sheltering from Flamborough Head is only relevant for northerly sectors). Wave heights then increase along the nearshore to around 25 km chainage since this frontage does not receive sheltering from Smithic Bank. At around 70 km chainage, waves reduce again due to shoaling across the shallow banks seaward of Spurn Head, known as The Binks, and a rapid re-orientation of the coastline.

4.8.3.22 The effect of wave blockage from offshore wind farms is not discernible on any baseline waves in the nearshore (demonstrated here for the easterly sector), noting all other sectors show a lesser change in wave heights. A nil effect on waves in the nearshore translates into a nil effect on any changes to wave driven longshore drift along the Holderness Coast.

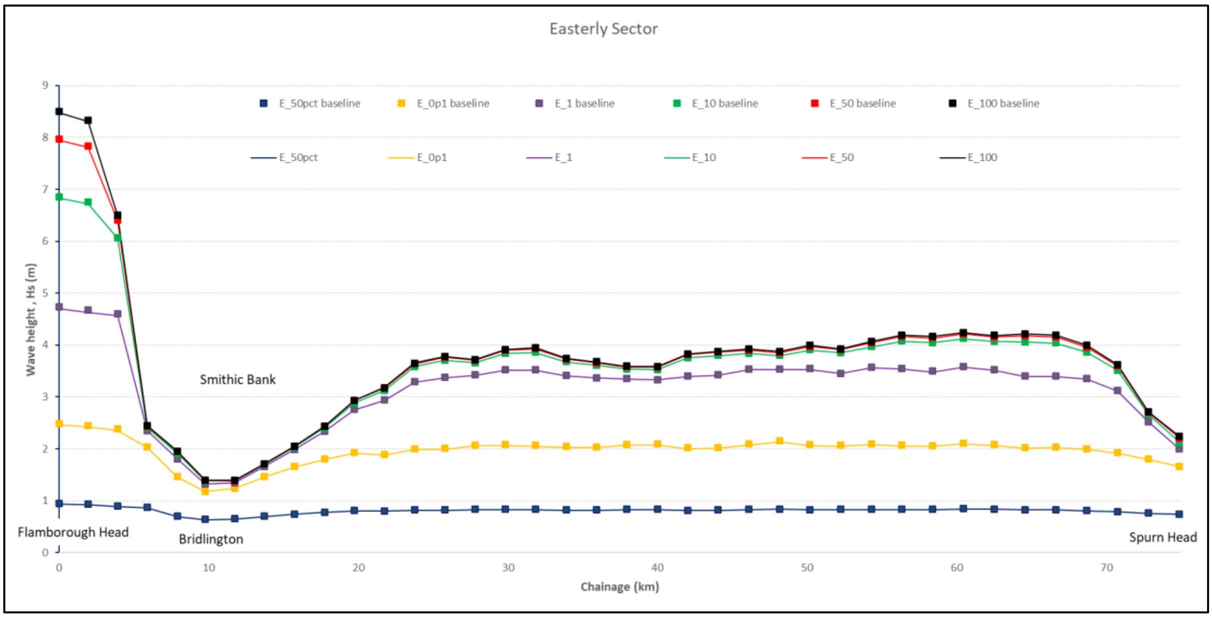

Figure 46: Nearshore wave conditions for easterly sector scenarios (derived from wave modelling).

<u>Summary</u>

4.8.3.23 Wave blockage effects are evident from the GBS profile foundations across Hornsea Three and Hornsea Four, as well as the HVAC Booster Station Search Area. Each of these areas appears to have an independent effect on waves (demonstrated by a reduction in wave height) with the separation between these areas sufficient to mitigate any larger cumulative wave height reduction effects. Wave height reduction effects are up to 10 % on the leeward side of each array which then quickly dissipate over distance away from the array with no effects reaching the adjacent coastline (**Figure 46**). The smaller profile monopile foundations represented in the modelling for Hornsea Project One and Hornsea Project Two do not appear to have any array scale affects which reduce wave heights, a finding which is also supported by the review of operational wave data for Hornsea Project One (Orsted 2020).

4.9 Changes to nearshore sediment pathways

Overview

4.9.1.1 The nearshore is considered here to be the area within the shelter of Flamborough Head with shallowing water depths, including Smithic Bank. The relevant activities that might lead to a change in nearshore sediment pathways are considered to include:

- Wave blockage effects from the offshore which propagate to the nearshore;
- Rock berms to manage cable crossings with Dogger Bank A and B export cables;
- Provisions for rock protection across Smithic Bank; and
- Requirements for remedial measures to rebury cables.

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4.9.1.2 The important nearshore sediment pathways are summarised on **Figure 19**. Cliff erosion by storm waves provides an primary source of beach material which is moved along the coast by longshore drift from waves with a southerly component. Some of this material is transported offshore into an ebb dominant tidal channel where the pathway moves material towards Flamborough Head. Flood flows reinforced by wave driven current from north of the headland maintain a one-way drift to the south which then forms a pathway for sands onto Smithic Bank. Waves help to moderate the profile of the bank with larger waves dissipating some of their energy onto the bank creating a southern section which is wider and smoother than the northern section of the bank. The northern section of the bank is dominated by stronger flows around Flamborough Head which help develop distinct sandwaves.

Short-term construction activities

4.9.1.3 Any landfall works and cable installation activities (i.e. access ramp, cofferdams, etc.) are considered short-term and small-scale and will not leave permanent structures on the beach or across the seabed which could modify nearshore sediment pathways.

Long-term installations

4.9.1.4 The cable crossing with Dogger Bank A and B export cable has been discussed in **Section 4.6.2**. Depending on the final length and profile of any rock berms, then some localised flow disruption might be expected with the pathways being diverted around the rock berms, however, these pathways are likely to reform in the lee of the structure.

4.9.1.5 The potential remains for cables to become unburied at any location during the operational period, including across the nearshore and Smithic Bank. For example, this may happen due to anchor dragging or a reduction in seabed levels across an area with a mobile seabed. Any rock armour protection required for re-burial will follow the alignment of the cable with a profile which may also be locally higher than the adjacent seabed, at least in the short-term. The rock armour may then initially act as a partial (low profile) barrier to bedload sediment transport along the length of the rock berm. Sediments in suspension are not expected to be affected by the berm. Depending on the situation, coarser grained mobile (bedload) sediments may initially build up against this partial barrier where flows are weakened, as well as bypass around the ends of any rock berm where flows may accelerate.

4.9.1.6 The situation for Smithic Bank is considered in further detail in **Section 4.6.5**.

4.10 Decommissioning effects

Sediment disturbance

4.10.1.1 Decommissioning issues include sediment disturbance events during removal of foundations as well as any exposed cables. Scour protection materials and buried cables are unlikely to be recovered.

4.10.1.2 All decommissioning activities are likely to have a comparable type (but lesser magnitude) of sediment disturbance than any activity described during construction for seabed preparation for foundations and cables. Accordingly, the level of any impacts from decommissioning can be considered smaller than those described for construction.

Blockage

4.10.1.3 Once foundations are removed their associated blockage effects will also cease. This returns the wave and tidal conditions back to a condition that represents a future baseline. Most blockage effects are remote from any receptors, so a potential reinstatement of a higher energy situation is unlikely to lead to any concern.

4.11 Cumulative Effects

Overview

4.11.1.1 Cumulative impacts result from the effect of Hornsea Four in combination with the effects from a number of different projects or activities, on the same single receptor/resource. For marine processes, the following projects and activities have been identified for potential cumulative impacts:

- Spoil disposal at HU015;
- Dogger Bank A and B export cable landfall works;
- Hornsea Project One, Hornsea Project Two and Hornsea Three potential blockage effects on waves reaching the Holderness Coast; and
- Endurance, proposed CO_2 storage facility comprising of pipelines, flow lines and seabed platforms.

4.11.2 Spoil disposal activities

4.11.2.1 Spoil site HU015 is used to dispose of maintenance dredgings from Bridlington Harbour. During these times, plumes will form at the disposal site as the silts are rapidly dispersed away. The use of the spoil site by Bridlington Harbour is expected to be relatively infrequent and on demand. **Paragraph 3.2.3.11** suggests the typical number of disposals expected each year. This varies year to year and month to month. HU015 is not a consideration for spoil disposal for requirements arising from Hornsea Four.

4.11.2.2 If Hornsea Four is releasing silts and fine sands in the nearshore from cable trenching by CFE during a period of ebbing tides at the same time as spoil disposal is occurring at HU015 then there is potential for some interaction and a larger overall sediment plume to form, however, this will also quickly disperse given the spoil site is located in an area of faster flows. The cumulative impact is considered to be negligible due to the low likelihood of occurrence and relatively short-term impacts.

4.11.3 Dogger Bank A and B export cable landfall works

4.11.3.1 The assumption is that all landfall works for Dogger Bank A and B export cable will already be completed and the area made good before similar landfall activities occur for Hornsea Four. On this basis there are not expected to be any larger cumulative effects on the integrity of the local beach.

4.11.4 Hornsea Project One and Hornsea Project Two

4.11.4.1 Hornsea Project One and Hornsea Project Two are a pair of offshore wind farms located to the south-east of Hornsea Four. The MDS consented foundation types for both Hornsea Project One and Hornsea Project Two assumed a large number of wide base GBS foundations that could potentially have led to measurable blockage effects on waves and flows which may then have acted cumulatively with Hornsea Four for certain directions. The moderation of this potential concern for blockage now exists because both Hornsea Project One and Hornsea Project Two are now developed with an alternative layout with a fewer number of smaller diameter foundations which dramatically reduces the effective magnitude of any blockage for both an individual foundation and for all foundations at the arrays scale. This moderation effect for reduced blockage for waves is demonstrated by the wave modelling discussed in **Section 4.8.3**.

4.11.4.2 Hornsea Three is considered to be less relevant to possible cumulative interactions for blockage because of the further distance from Hornsea Four and since the flow and sediment pathways do not pass between these two projects and waves are mainly from the northerly sector. However, for completeness, Hornsea Three is included in the modelling for wave blockage considerations.

4.11.5 Endurance

4.11.5.1 The Endurance reservoir is a proposed CO_2 storage facility targeting a site that overlaps with the northern part of the Hornsea Four array area, albeit using a large-scale saline aquifer at a depth below seabed of over 1,000 m. There are currently two planned Carbon Capture and Storage (CCS) projects that propose to make use of the Endurance reservoir, the proposed Net Zero Teesside (NZT) and Zero Carbon Humber (ZCH). At the present time, there is limited publicly available information on these projects due to their pre-planning status. The planned ZCH project may result in a crossing between the Hornsea Four offshore ECC and the CO_2 injection pipeline from Easington to Endurance. Consultation with National Grid Electricity Transmission has provided high-level project details which indicate approximately 40 smaller flowlines between manifolds and wells of which approximately 20 might be located within the Hornsea Four array area creating a potential requirement for additional cable crossing. There will also be a number of Brine Production Platforms which may target sites both within the array area as well as slightly to the north. The final siting of all structures remains dependent on completing site surveys and Front-End Engineering Design. The project is anticipated to start construction in early 2023 (subject to successful consenting) leading to first injection at the end of 2025 and becoming fully operational in late 2026.

4.11.5.2 The main components leading to in-combination blockage effects are considered to be the pipeline crossing to Easington, the possibility for additional cable crossings within the array area and the addition of a small number of Brine Production Platforms.

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Appendix A - Comparison of marine processes across the former Hornsea Zone

1. Introduction

The marine processes assessment for Hornsea Four is supported with an evidence-based approach where existing assessments from adjacent offshore wind farm developments are considered for comparable information to help determine scales of potential impacts. The basis of this approach is that comparable projects in comparable environmental settings can be expected to lead to comparable effects.

The justification of comparable environmental conditions is made by reviewing the similarities and differences of the baseline environmental setting of Hornsea Four with the adjacent offshore wind farms of Hornsea Project One and Hornsea Project Two, in particular, given their close proximity. The comparative review is offered for array areas in the main since the ECC and landfall location of Hornsea Four is geographically separate.

The following marine processes topics are considered:

- General setting;
- Bathymetry;
- Tidal levels;
- Flows and excursions;
- Waves;
- Surficial sediments;
- Bedforms; and
- Suspended sediment.

2. Primary evidence

In the main, comparisons between project areas are offered with reference to regional scale mapping; this includes EMODnet for bathymetry and surficial sediments, the UK Atlas of Marine Renewable Energy Resources for flows, tidal excursions and waves, and synoptic maps of SPM derived from satellites.

Where helpful, consideration is also made to the zonal metocean survey to help validate aspects of the regional scale information.

3. General setting

The former Hornsea Zone is being developed as four separate projects. The offshore wind turbine array areas are located as follows, from west to east;

- Hornsea Four is (relatively) closest to the Holderness coast, with Flamborough Head around 70 km to the west. The offshore array of Hornsea Four covers an area of 468 km^2.
- Hornsea Project Two is around 3.4 km to the south-west at the closest point of Hornsea Four and extends further eastward. This project covers around 462 km^2 of seabed.
- The northern and western borders of Hornsea Project One join up with Hornsea Project Two. This project covers around 407 km^2 of seabed.

- Hornsea Three is the most easterly project in the former Hornsea Zone and is also separated from Hornsea Project One by a shipping lane around 7.2 km wide. Hornsea Three is the most distant wind farm from Hornsea Four and is over 140 km from the coast, at the closest point. This project covers around 696 km^2 of seabed.

The four projects cover a distance of around 132 km from north-west to south-east. The similarities and differences between these areas are considered over this distance.

In their respective settings, all wind farm areas can be considered to be remote from the immediate influence of the adjacent coast and are subject to "offshore" type conditions. A further common association between all projects is that Outer Silver Pit defines the northern and north-eastern boundaries.

4. Water depths

Water depth is a consideration regarding the potential for waves to stir the seabed and influence sediment transport. In addition, the fate of dredgings falling to the seabed, and their capacity to be advected in this period, varies between shallow and deeper water for the same flow conditions.

The general water depths, neglecting any tidal contributions or presence of large bedforms, for each project area are summarised with reference to EMODnet bathymetry, as follows:

- Hornsea Project One is typically 30 to 35 m deep across the array;
- Hornsea Project Two is typically 30 to 40 m;
- Hornsea Three is typically 30 to 45 m with local deviations up to 70 m (e.g. Markham's Hole); and
- Hornsea Four is typically 40 to 55 m, sloping into deeper water to the north where there also larger bedforms.

All depth values reference metres below LAT.

4.1 Tidal influence

There is a slight variability in tidal levels across the zone with a small increase in amplitude with distance (to the west) from two tidal amphidromes in the southern North Sea. Hornsea Project One and Two are considered together in this comparison since they occupy a similar east-west position.

For mean spring tides, east to west;

- Hornsea Three: 2 to 2.5 m (Site L3 = 2.21 m);
- Hornsea Project One and Hornsea Project Two: 2.5 m to around 3 m (Site L2 = 2.67 m); and
- Hornsea Four: 3.1 to 3.6 m (Site L1 = 3.28 m, located around 5.4 km to the south-east).

For mean neap tides, the corresponding tidal range values are:

- Hornsea Three: 1 to 1.25 m (Site L3 = 1.09 m);
- Hornsea Project One and Hornsea Project Two: 1.25 m to around 1.5 m (Site L2 = 1.31 m); and
- Hornsea Four: 1.5 to 1.75 m (Site L1 = 1.61 m).

These tidal influences would all be in addition to the general water depths referred to previously, maintaining Hornsea Four as the deepest area overall and Hornsea Project One as the shallowest, in comparison.

5. Metocean Conditions

5.1 Overview

Metocean conditions are considered here for tidal flows, tidal excursion, and waves.

Tidal flows and excursion are relevant to the advection and dispersion of materials discharged into the marine environment such as dredged overspill and spoil disposal. The excursion provides an indication of both range and direction of advection over a tidal cycle.

Areas with higher flow speeds may be able to mobilise more sediment types more often than areas with weaker flows, a consideration for deposition and remobilisation of sediments in spoil.

Waves can influence sediment transport where their stirring effect reaches the seabed.

Waves and flows are also associated with the potential scale of blockage related effects. For tidal related blockage, the axis of any wake effects is likely to remain with the primary axis of the tidal ellipse.

5.2 Tidal flows

There is only a slight variability in tidal flows across the zone with a small increase to the west from Hornsea Three.

For mean spring tides, east to west, peak speeds of:

- Hornsea Three: 0.30 m/s;
- Hornsea Project One and Hornsea Project Two: 0.55 to 0.70 m/s; and
- Hornsea Four: 0.56 to 0.63 m/s.

For mean neap tides, the corresponding peak flow speeds are:

- Hornsea Three: 0.25 to 0.30 m/s;
- Hornsea Project One and Hornsea Project Two: 0.30 to 0.35 m/s; and
- Hornsea Four: 0.26 to 0.30 m/s.

5.3 Tidal excursion

The shape of the tidal ellipse changes from a rectilinear form across most of Hornsea Three to a more rotary form across Hornsea Four (east to west) with some transition between these two forms across Hornsea Project One and Hornsea Project Two.

The excursion distance for sites central to each project area are given in **Table A-1**.

Table A-1: Excursion distances for sites central to each project array area.

Tidal Range	Excursion (km)			
	Hornsea Three	Hornsea Project One	Hornsea Project Two	Hornsea Four
Mean spring	6.5	8.1	8.5	8.3
Mean neap	3.5	4.2	4.4	4.1

The axis (and relative flatness) of the tidal ellipse also slightly varies from Hornsea Three (in the east) to Hornsea Four (in the west).

5.4 Waves

Average winter wave heights may be slightly larger in Hornsea Three than the other project areas although this variability is unlikely to be important to any local sediment transport processes since water depths are the limiting condition on wave energy attenuation onto the seabed.

6. Suspended Sediments

In general, suspended sediment concentrations (using a proxy of surface SPM), are relatively low for all project areas. There is a slight increase from west to east with winter levels in Hornsea Four up to 2 mg/l increasing to 5 mg/l in Hornsea Three.

7. Surficial sediments

The main relevance of surficial sediments is in relation to sediment disturbance events and the relative content of finer sediment (fine sands, silts, and muds). In general, all offshore array sites can be considered as having coarser sediments with limited mud content. The relative content of gravels and sands shows more variability, but this size of material will generally all fall out of suspension when disturbed.

- Hornsea Four is mainly sandy with some patches of slightly gravelly sand;
- Hornsea Project Two is sandy in the north but slightly gravelly sand in the south;
- Hornsea Project One shows more gravel content, with some patches of sand, slightly gravelly sand, gravelly sand, and sandy gravel; and
- Hornsea Three has similar variability in surficial sediment as Hornsea One but with muddy sand in Markham's Hole.

8. Bedforms

Although sandwaves are found across all project areas, their prominence is greatest in the northern part of Hornsea Four where the features merge into a wider set of more dominant sand crests and sandbanks known as The Hills.

9. Geology

The underlying solid geology of the region is complex and is overlain by varying thicknesses of Quaternary sediments. These generally increase in thickness in an easterly direction and may be > 200 m thick in the east of the former Hornsea Zone. The geophysical survey from the former Hornsea Zone suggests the Bolders Bank Formation is extensive across the area surveyed, and it is generally mantled by varying thicknesses of recent seabed sediment (Holocene Sands).

10. Summary of environmental conditions

A regional scale comparison has been provided to demonstrate similarities and differences in environmental conditions between Hornsea Four and Hornsea Project One, Hornsea Project Two and Hornsea Three.

Similarities and difference occur between all four sites with some general trends in the parameters under consideration and mainly as spatial variance east to west.

Hornsea Project Two is most comparable, as might be expected due to the closest proximity to Hornsea Four. The environmental conditions across Hornsea Project One are similar to Hornsea Project Two.

In relative terms, Hornsea Three is the least comparable, due to the furthest distance from Hornsea Four. Main differences are in the water depth, flow speeds, and sediment types.

Accordingly, the application of the evidence base to support Hornsea Four focuses mainly on the information available from Hornsea Project One and Hornsea Project Two.

Appendix B - Data and Information

1. Primary evidence supporting marine processes

Table B-1 summaries of the key data and information which has informed the marine processes baseline understanding.

Table B-1: Key sources of marine processes data and information.

Source	Summary	Coverage
Site-specific geophysical survey	Multi-Beam Echo Sounder (MBES), SBP, Side-Scan Sonar (SSS), grab samples (see summary below).	**Offshore array:** partial coverage **Offshore ECC:** partial coverage
Zonal characterisation (ZoC) including metocean, geophysical and benthic surveys (SMart Wind 2012)	Initial broad-scale evaluation of the former Hornsea Zone to help establish areas for development. This work was supported by extensive baseline metocean, geophysical and benthic surveys.	**Offshore array**: metocean site L1 within the southern part of the AfL. Site L6 offers characterisation of the northern area but is slightly west of the AfL. Waves, tides, currents, OBS, ABS, temperature.
Existing wave and tidal models (SMart Wind 2015a, 2015b and 2015c) and (Orsted 2018)	Wave and tidal models previously calibrated against ZoC metocean survey data provide existing outputs offering an expanded view of baseline conditions as well as a quantified assessment of potential impacts. Existing model outputs support simplified assessment approaches for Hornsea Four.	**Landfall:** full coverage **Offshore array:** full coverage **Offshore ECC:** full coverage
Atlas of UK Marine Renewable Energy Resources (DECC 2008a)	Synoptic regional-scale description of waves, tidal levels, and currents to complement other baseline information.	**Offshore array:** full coverage **Offshore ECC:** full coverage
The European Marine Observation and Data Network (EMODnet) for thematic mapping of bathymetry, seabed substrate and geology	Baseline mapping of bathymetry, seabed substrate and sub-surface geology to provide a regional overview of seabed conditions, complementing site-specific surveys.	**Offshore array:** full coverage **Offshore ECC:** full coverage
GeoIndex	Database of analysed surficial sediment samples providing quantification of sand, gravels, and mud content, directly complements EMODnet seabed substrates.	**Offshore array:** full coverage with multiple samples **Offshore ECC:** full coverage with multiple samples
Southern North Sea Sediment Transport Study (HR Wallingford, Cefas / UEA, Posford Haskoning, and D'Olier B. 2002)	An in-depth review of the sediment transport regime across the Southern North Sea.	**Offshore ECC:** nearshore description of net sediment transport direction and indicators

Source	Summary	Coverage
Sand banks, sand transport and offshore wind farms (Kenyon & Cooper 2005)	Complements the Southern North Sediment Transport Study, offering a UK-wide and regional perspective of sediment pathways. Highlights relevance of sand transport issues to offshore wind farms.	**Offshore array:** check **Offshore ECC:** description of net sediment transport pathways
Suspended sediment mapping (Cefas 2016)	Synoptic description of baseline seasonal (monthly) variation in surface SPM across the study area derived from long-term satellite observations.	**Landfall:** sub-tidal only **Offshore ECC:** full coverage **Offshore Array:** full coverage
Temperature forecast modelling from Copernicus Marine Environmental Monitoring Service (Copernicus Marine)	Regional scale 3D forecasts of temperature structure to help describe development and location of Flamborough Front. Daily values obtained for 2018.	**Offshore ECC:** full coverage **Offshore Array:** full coverage
Seasonal averages of sea-surface temperature derived from satellite data (PML)	Regional maps of the frequency of occurrence of temperature fronts to complement data derived from modelling.	**Offshore ECC:** full coverage **Offshore Array:** full coverage
Nearshore seabed survey: Flamborough Head to Spurn Point (CCO 2014)	Detailed mapping of coastline, including LiDAR, multi-beam and European Nature Information System (EUNIS) habitat mapping.	**Landfall:** majority of area included **Offshore ECC:** partial coverage of nearshore, including parts of Smithic Bank
United Kingdom Hydrographic Office (UKHO)	Digital soundings across study area to augment other sources of bathymetry data.	**Offshore ECC:** partial coverage **Offshore Array:** partial coverage
Shoreline monitoring (ERYC)	Long-term monitoring of cliff recession and beach profiles to low water.	**Landfall:** intertidal areas
Dogger Bank A and B EIA	Particle size analysis of grab samples in the nearshore Nearshore geophysical survey.	**Offshore ECC:** partial nearshore coverage
British Oceanographic Data Centre (BODC)	Current meter records across the study area to augment other sources of flow information.	**Offshore ECC:** limited coverage **Offshore Array:** limited coverage

2. Summary of geophysical survey

Over the period 2018 to 2019, geophysical and benthic surveys were completed to inform the understanding of seabed properties across the Hornsea Four offshore wind farm array area and along the offshore ECC.

The survey coverage is shown in **Figure B-1** which presents the main survey lines and locations of sediment grab samples.

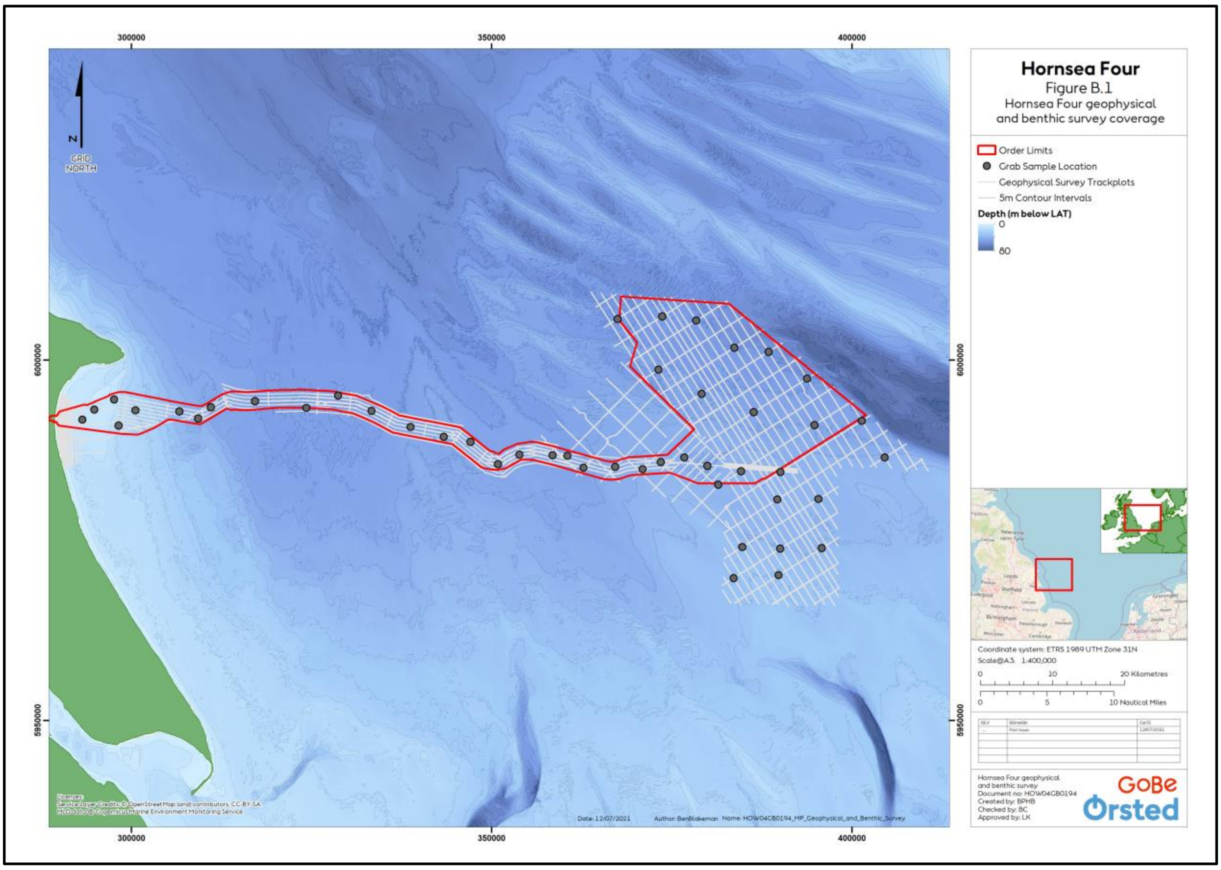

Figure B-1: Hornsea Four geophysical and benthic survey coverage.

Across the offshore array area, the main survey lines are typically 1.1 km apart and in a north-west to south-east orientation, with cross-lines spaced at around 3 km intervals. Some of the survey lines extended across the wider lease area which was still under consideration at the time of survey for the PEIR, notably the southern extent of the offshore array area.

Along the main part of the ECC, survey lines are around 0.5 km apart with cross-lines generally around 4 to 6 km apart. For the nearshore section, survey lines are around 1 km apart, with cross-lines at around 0.5 km spacing. In 2018, the very nearshore section of the ECC was surveyed in greater detail with a shore-parallel spacing of around 0.02 km. For around 1.4 km in the offshore direction this nearshore section achieved almost 100 % seabed coverage (see Figure 5).

Nine surficial sediment samples fall within the offshore array area with a further twelve across the wider lease area. Twenty-six sediment samples were collected along the offshore ECC.

2.1 Key parameters of interest to marine processes

- Multi-beam data at 0.5 m centres, resolving seabed depths and the profile of bedform features;
- Interpreted seabed lithology and morphology, including sandwave crests;
- SBP profiles up to 40 m deep along the ECC;
- Ultra-High Resolution Survey (UHRS) SBP geological interpretations based on pinger records; and

- Particle size analysis from seabed grab samples reported in intervals of 0.5 phi from 0.0 (very coarse sand) to 10.0 phi (clay size).

2.2 Utility of geophysical survey

The geophysical survey represents a detailed set of up to date information which describes key characteristics of the seabed along the offshore ECC and across the offshore array area. The data provides the primary information of bedform features, sediment type and sub-surface geology.

Whilst the bathymetry data does not offer 100 % coverage the partial coverage helps validate the utility of other data sources which are more complete. Partial coverage also implies that not all bedform features have been identified or fully resolved, especially where the orientation of the feature is not aligned with the survey transect.

Similarly, the grab samples from the geophysical survey are collated with comparable information on a consistent basis to offer a greater overall coverage and additional spatial detail.

Overall, the collated geophysical data from all sources represents sufficient coverage to support the assessment of bedform features and sediments.

2.3 Survey Reports

The geophysical surveys are reported in:

Gardline (2019). Hornsea 4 Offshore Wind Farm GP1A Survey. Processing and Interpretation Report. August – September 2018. Report Number 11201.2 (Rev 1). Orsted Wind Power A/S.

GeoSurveys (2019). 2D UHRS Hornsea 04 Windfarm Geophysical Survey. Interpretative Report. Document No.: REP83148. 8 March 2019.

Orsted (2019) Addendum/Notes to 2D UHRS Hornsea 04 Windfarm Geophysical Survey (2019) – UHRS 2D Interpretative Report (REP83148). August 2019.

Bibby Hydromap (2019). Hornsea 4 Offshore Wind Farm. Lot 7 GP1a Export Cable Corridor. Volume 3: Results Report. Project No. 2019-023A. February 2019.

Bibby Hydromap (2019). Hornsea 4 Offshore Wind Farm. Geophysical 1a Export Cable Corridor 2019. Volume 3: Results Report. Project No. 2019-005 and -005A combined. August 2019.

The associated benthic surveys which obtained surficial sediment grab samples are reported in:

Gardline. (2019) Hornsea 4 Offshore Wind Farm. Habitat Classification Report. Survey:14-Sep-2018 to 18-Sep-2018. Project Number: 11210. Client Reference: Lot 6 GP1a Array Area. Final.

Bibby Hydromap and Benthic Solutions (2019). Orsted Hornsea Four Wind Farm (HOW04). Pre-Construction Export Cable Route. Benthic Environmental Survey. Volume 4 - Combined Environmental Baseline Report and Habitat Assessment Survey. Project No. 2019-005. June 2019.

3. Sediment classification

Where possible, the synthesis of evidence to describe the composition of surficial sediment (from individual grab samples) across the study area adopts a consistent classification scheme of sediment type based on Folk (1954). This approach enables individual sediment samples with particle size data (collated from multiple data sources) to be coded with the same descriptions used in regional scale sediment maps based on the same classification scheme (e.g. from EMODnet or similar sources). This procedure also serves to provide local scale validation of these regional scale sediment maps against the individual sediment samples. Where validated, this also provides the means to infer other sediment properties to the regional maps, for example medium sands from the grab sample matching an area interpreted as sands on regional scale interpretations infers the mapped area of sands is also likely to comprise of medium sands.

Sediment descriptions offered in the ES, including any mapping, are generally based on the Folk descriptive classification scheme. Where necessary, information from particle size analysis of grab samples is also considered to provide additional quantification of grain sizes according to Wentworth (1922).

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Folk, R.L. (1954). The distinction between grain size and mineral composition in sedimentary-rock nomenclature. *Journal of Sedimentary Petrology, 62, 344-359.*

Wentworth, C.K. (1922). A scale of grade and class terms for clastic sediments. *The Journal of Geology, 30, No. 5, 377-392.*

Appendix C – Marine Processes Modelling

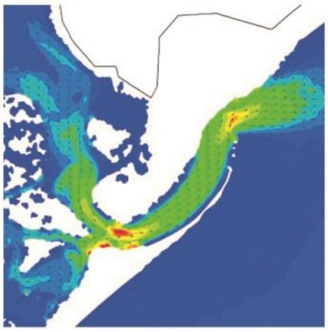
GoBe Consultants Ltd
(on behalf of Orsted Hornsea Project Four Limited)

Hornsea Project Four Offshore Wind Farm

Marine processes modelling

July 2021

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Hornsea Project Four Offshore Wind Farm

Marine processes modelling

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1 Introduction

1.1 Overview

1.1.1.1 ABPmer has been commissioned by GoBe Consultants, on behalf of Orsted Hornsea Project Four Ltd (hereafter the Applicant), to undertake numerical modelling to inform the Environmental Impact Assessment (EIA) for the proposed Hornsea Project Four Offshore Wind Farm(hereafter Hornsea Four). A range of numerical models have been developed and are used to address the following aims:

- How the various installed structures planned for Hornsea Four could affect the Holderness Coast (Flamborough Head to Spurn Head);
- How the cable crossing with the Dogger Bank A & B Offshore Wind Farm (Dogger Bank A & B) export cables could modify local tidal circulations around the sandbank feature Smithic Bank (hereafter Smithic Bank); and
- Characterising the nature of sediment plumes and deposits which might result from activities causing sediment disturbance.

1.1.1.2 This report presents information about the design and validation of the models used, the scenarios tested, and the results. This report does not directly consider the potential impacts or implications of any reported changes. Further interpretation of these results is presented in **Volume A2, Chapter 1: Marine Geology, Oceanography and Physical Processes**.

1.2 Topics of study

1.2.1.1 This study includes four distinct modelling types, which are described and reported separately in the following sections:

Section 2: Waves – Effect of Partial and Complete Construction of Hornsea Project One Offshore Wind Farm (Hornsea Project One).

Section 3: Waves – Effect of Hornsea Four In-Combination.

Section 4: Tidal Currents – Effect of Hornsea Four Cable Crossing Protection.

Section 5: Sediment Plumes – Effect of Activities Causing Sediment Disturbance.

1.2.1.2 A summary of each study is provided at the beginning of the corresponding section.

1.3 General approach to modelling

1.3.1.1 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.

1.3.1.2 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.

2 Waves – Effect of Partial and Complete Construction of Hornsea Project One

2.1 Overview

2.1.1.1 This section presents a study of the effect of partial and complete construction of Hornsea Project One wind turbine foundations, on the wave climate within and near to the Hornsea Project One array area, prior to, during and following the actual construction period in 2017/18. The study presented in this section relates to Hornsea Project One and does not provide any direct assessment of Hornsea Four. The purpose of this section is to provide validation of the wave model's ability to reproduce a range of baseline wave conditions and (indirectly) the model's ability to predict the magnitude of the effect of the as-built Hornsea Project One monopiles on waves. It provides a validation of the model which is then applied in Section 3 to assess the impact of Hornsea Four (alone and cumulatively) on waves.

2.1.1.2 Historical time series wave data are created for locations coincident with two wave buoys that were deployed at the north and south boundary of the Hornsea Project One array area throughout the construction period (shown in Figure 4 and Figure 5, and described in Section 2.4). Simulations with and without the offshore wind farm (OWF) infrastructure in place are created, to inform a separate study being undertaken to quantify the likely magnitude and pattern of actual effect at the two wave buoy locations, in this construction period.

2.1.1.3 The validation information provided in this section (for a range of historical conditions) also provides validation of performance for the same wave model used also in Section 3 for simulation of the potential effect of Hornsea Four and other wind farms during selected statistical extreme wave scenarios (for which no direct validation information is available).

2.2 Hindcast wave model design

2.2.1 Overview

2.2.1.1 A 'hindcast' wave model provides a continuous simulation of historical wave conditions. The hindcast wave model is built using the MIKE21 Spectral Wave (SW) module. MIKE21SW is a third-generation spectral wave model based on an unstructured mesh, which simulates the growth, decay and propagation of the swell and wind-generated waves in offshore and coastal areas.

2.2.1.2 Hornsea Project One and Hornsea Project Two Offshore Wind Farm (Hornsea Project Two) (both alone and in combination) have previously been modelled by HR Wallingford (HRW) using a calibrated SWAN (Simulating WAves Nearshore) spectral wave model (described in SMart Wind, 2013). An updated version of the HRW model using MIKE21SW was created for the assessment of Hornsea Project Three Offshore Wind Farm (Hornsea Three) (described in ABPmer, 2018).

2.2.1.3 For consistency, the MIKE21SW model developed for Hornsea Three (described in ABPmer, 2018), and used again here, utilises the same model extent, bathymetry, most setup parameters and baseline scenario definitions as the previous SWAN and MIKE21SW models. The MIKE21SW models were calibrated and validated against the baseline (extreme wave scenarios) and scheme impact results from the original SWAN models (described in ABPmer, 2018).

2.2.2 Model grid

2.2.2.1 The extent and resolution of the updated model grid is shown in Figure 1. The flexible mesh enables the grid resolution to vary throughout the domain, from approximately 2 km in offshore areas, reducing gradually to approximately 100 m in an area between the Holderness coastline and all OWFs in the former Hornsea Zone. This varying resolution aids computational efficiency and allows the application of finer resolution for accuracy around the areas of interest.

2.2.2.2 For the wider scope of the present study (including Sections 2 and 3 of this report), individual model grid elements have been centred on the actual locations of wind turbine and offshore substation foundations in Hornsea Project One, the planned locations in Hornsea Project Two, and the proposed locations in Hornsea Three and Hornsea Four.

2.2.2.3 The grid has also been locally aligned to the extent of the cable crossing area between export cables from Hornsea Four and Dogger Bank A & B, near to Smithic Bank. The mesh detail in this area is shown in Figure 2. The footprint of the cable crossing area, within which the effect of the installed infrastructure is applied in the model, is 770 m long and 500 m wide. Immediately outside of this footprint, the transitional slope from scheme to baseline conditions is contained within a narrow row of mesh elements, approximately 25 m length scale. This description of the scheme effect footprint is conservatively representative of the proposed design envelope. More information about the scheme effect applied within this area (in the wave model a reduction in water depth due to the presence of cable protection) is described in Section 3.4.

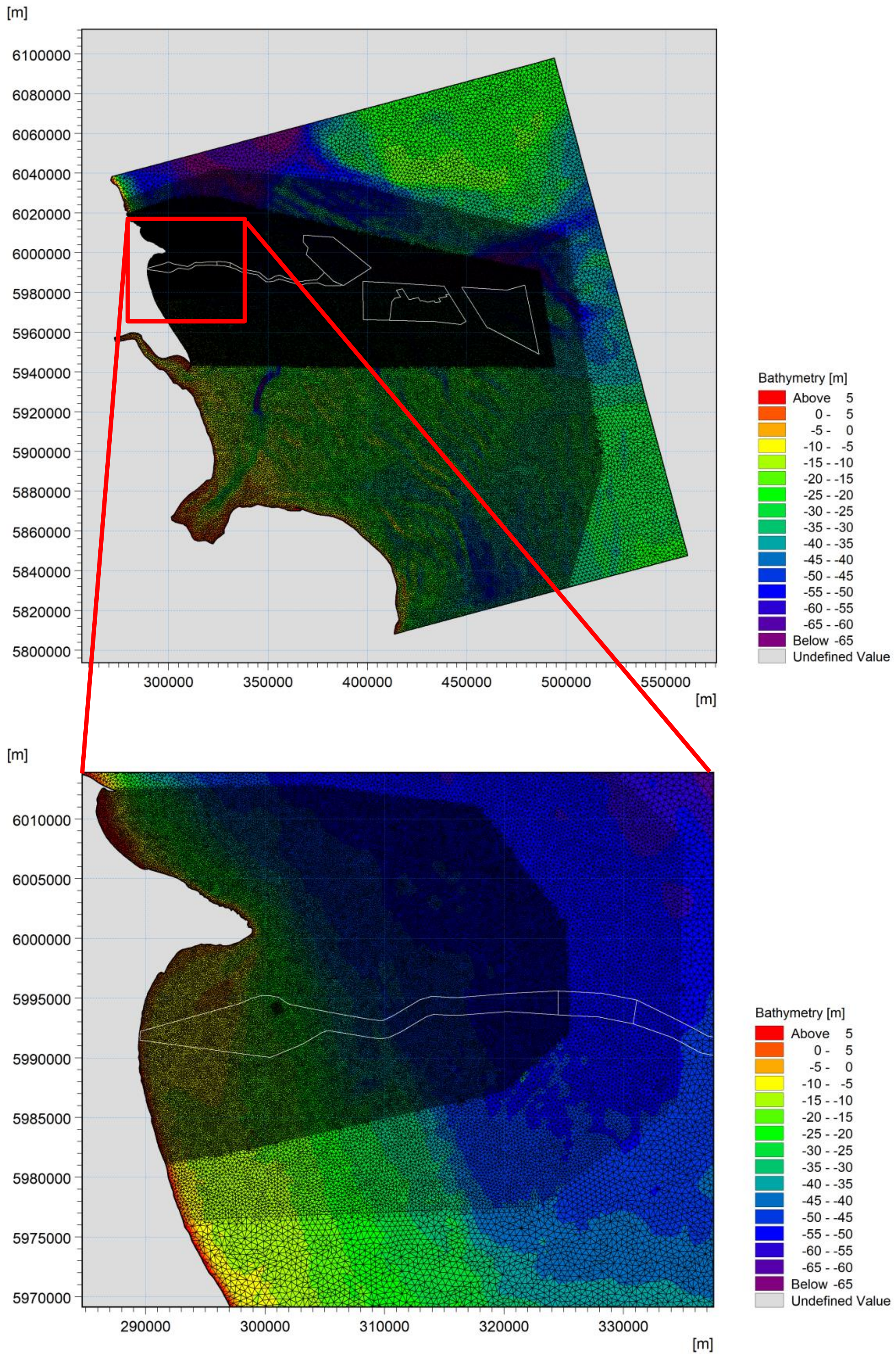

Figure 1. **Extent of the wave model mesh showing regional and locally enhanced resolution. Also showing outlines of the Hornsea Four array area and offshore ECC, and other offshore wind farm array areas in the former Hornsea Zone.**

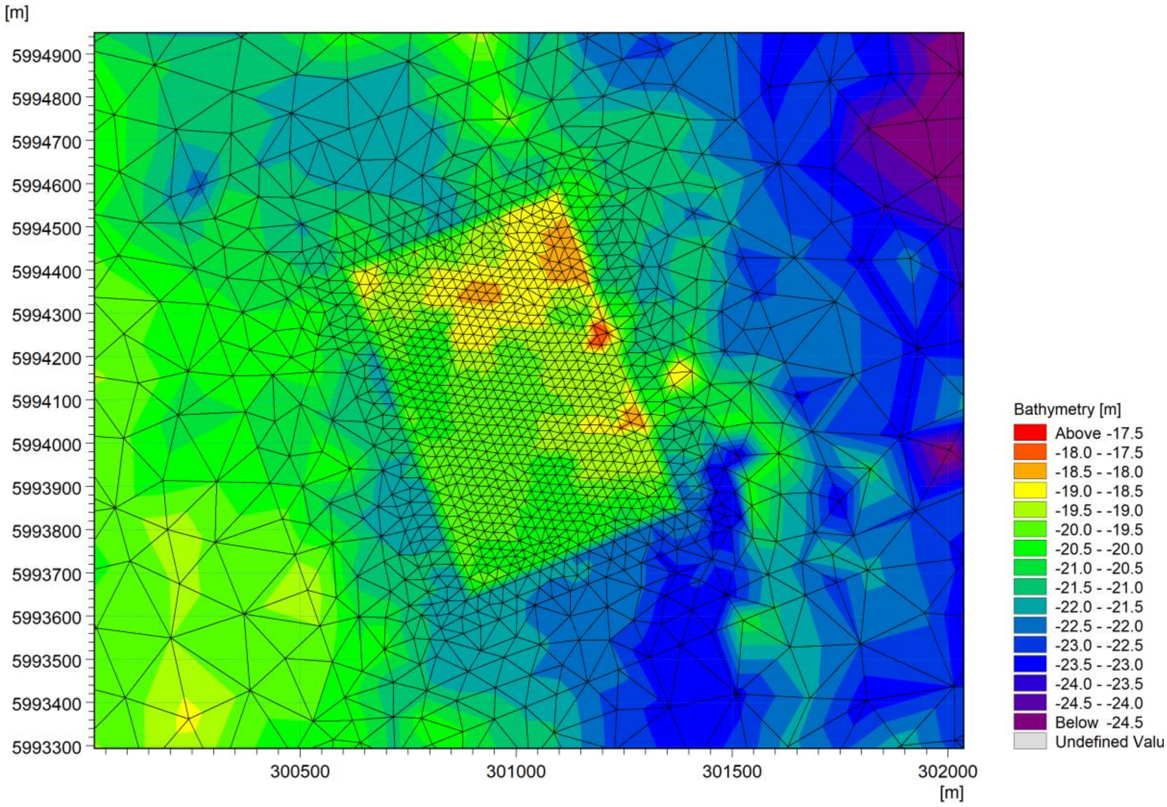

Figure 2. Local detail of the wave model mesh in the vicinity of the cable crossing area near to Smithic Bank. In this example, bathymetry within the footprint of the cable crossing scheme effect area is raised by 1.8 m above baseline values.

2.2.3 Model bathymetry

2.2.3.1 For consistency, the gridded bathymetry of the original SWAN model was interpolated directly onto the MIKE21SW wave model grid using a natural neighbour method (a method of spatial interpolation where surrounding data values are weighted according to their relative distribution and distance from the new location of interest). The resulting distribution of interpolated bathymetry is shown in Figure 1. All bathymetry in the mesh is referenced to Mean Sea Level (MSL).

2.2.3.2 The original bathymetry comprised regional scale data 'based on existing bathymetry files held by HRW that cover almost the entirety of the North Sea and the English Channel'. In addition, bathymetric survey data of the Hornsea Project One and array area (EMU, 2011) and the cable route close to the entrance to the Humber (Fugro, 2011) were also used by HRW to inform the original model.

2.2.3.3 The model bathymetry has been compared to the site-specific bathymetry data sets presently available to this study for Hornsea Three and Hornsea Four. No consistent large differences were found and so the model bathymetry is used without adjustment in these areas.

2.2.3.4 Additional higher resolution bathymetric survey data was obtained for the area around Flamborough Head, Smithic Bank and along the Holderness coast and is used to inform the grid bathymetry in these areas. The coverage, source and resolution of all the data sets used are outlined in Table 1. In areas of overlap, higher resolution data are locally prioritised during interpolation.

Table 1. Bathymetric data sets informing the wave model

Coverage	Source	Resolution
Whole domain	From the original Hornsea Project One and Hornsea Project Two Wave model, also used for Hornsea Three	200 m (1,000 m at outer edge of domain)
Spurn to Flamborough Head, offshore and nearshore, including Smithic Bank (1979)	UK Hydrographic Office (UKHO) Offshore single-beam survey bathymetry	50 m-120 m
Spurn to Flamborough Head, nearshore and intertidal areas (2011 - 2016).	Sourced from UKHO, collected originally by Channel Coastal Observatory (CCO). Subsampled by the UKHO from original multibeam and other high- and low-resolution survey bathymetry.	Areas of variable resolution including: 1, 10, and 100 to 200 m

2.2.4 Spectral and time formulations

2.2.4.1 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. Of the available choices, this formulation is considered to be the most accurate for the nature of the processes being simulated with respect to both general wave propagation and the effect of the wind farm foundations.

2.2.4.2 A quasi-stationary time formulation is used. Time is removed as an independent variable and a steady state solution is calculated at each time step (in this case corresponding to each timestep in the hindcast period). This choice is appropriate for the limited size of the model domain, within which waves are likely to achieve an equilibrium state with the input wave and wind boundary conditions during each (1 hour) timestep.

2.2.4.3 A logarithmic distribution of 25 spectral frequencies are resolved, equivalent to wave periods in the approximate range from 1.8 to 18 s, with smaller intervals at smaller wave periods (this is the default setting).

2.2.4.4 Directional calculations are made using 32 directional sectors (each sector covering a range of 11.25°). This is more than 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 wind farm infrastructure are included in the model. The baseline wave maps are largely unaffected by the difference.

2.2.4.5 Based on the available descriptions of model setup and the good level of agreement with results, from the new model (as described in ABPmer, 2018), the original SWAN modelling was likely also undertaken using a similar fully spectral quasi-stationary approach and a comparable frequency and directional parameterisation.

2.2.5 Model boundary conditions

Offshore wave boundaries

2.2.5.1 The wave model has open wave boundaries on its north, east and south edges (as shown in Figure 3). Wave boundary conditions are applied at each timestep, including: significant wave height (Hs), peak wave period (Tp), mean wave direction (DirM) and directional standard deviation (DSD).

2.2.5.2 To create the hindcast simulation, wave boundary data are obtained from ABPmer's validated regional-scale European Shelf SEASTATES Wave hindcast model, describing the temporally and spatially varying wave climate along each boundary during the period of interest. The design and performance of the regional model are described in a separate report (ABPmer, 2013).

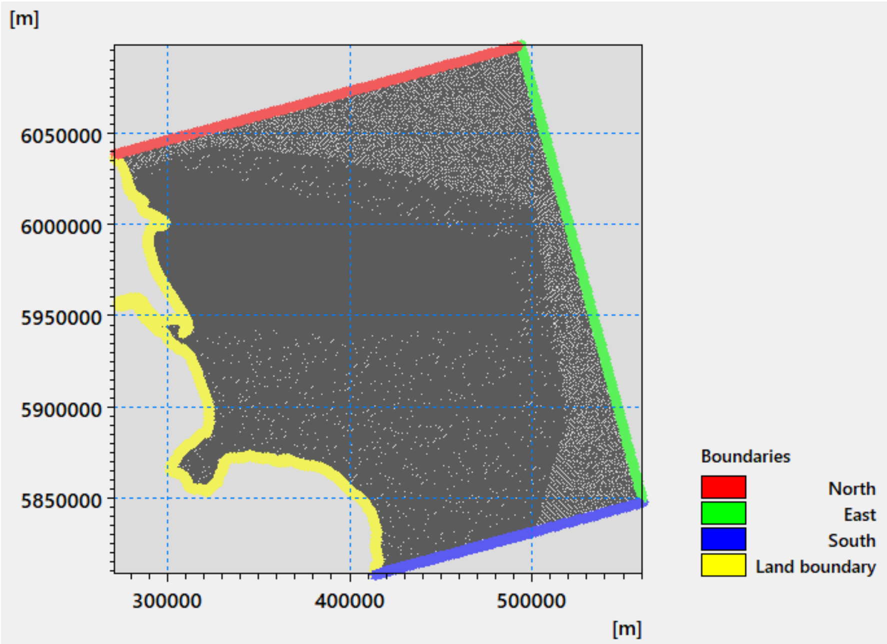

Figure 3. Wave model boundaries

Meteorological (wind) forcing

2.2.5.3 Hindcast wind boundary data were obtained from the NCEP (National Centers for Environmental Prediction) CFSv2 Climate Forecast System Reanalysis (CFSR) database (NOAA, 2019). The wind data describe the temporally and spatially varying wind speed and direction across the domain during the simulation period, at a spatial grid resolution of approximately 22 km, and with an hourly time timestep.

2.2.5.4 The local wave model was subject to sensitivity testing with respect to the magnitude of the wind speed and wave boundary conditions; a small number of other key model setup parameters (relating to the number of directional sectors and frequencies resolved by the model) were also considered. To optimise the overall comparison between the modelled and measured data, in the local MIKE21SW model the wind speed magnitude has been reduced by 10%.

Water levels

2.2.5.5 Water level was set to mean sea level (MSL) throughout the hindcast period. The total water depth in the offshore area in the vicinity of the two wave buoys is approximately 34 m relative to MSL and it is considered unlikely that the offshore wave conditions present during the simulation period would be measurably affected by small (tidally induced) differences in local water depth around this value.

2.2.6 Wave breaking, bottom friction and other wave transformation parameters

2.2.6.1 Wave breaking and bottom friction coefficients were varied from the default settings to those used in the previous SWAN model, in order to achieve consistency in setup and results.

2.2.6.2 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 both SWAN and MIKE21SW by standard equations that are scaled by a coefficient 'Gamma'. A constant Gamma value of 0.73 was used; the same value was used in the previous SWAN modelling.

2.2.6.3 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 hydrodynamic and sediment conditions. The settings used in the previous SWAN modelling were not explicitly reported. Sediment roughness is characterised in the MIKE21SW wave model by the Nikuradse Roughness length and the distribution of baseline wave heights in the domain was optimised in comparison to the results of the previous SWAN wave model by using a roughness length value of 0.01 m.

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

- White capping (Dissipation coefficients, constant Cdis = 4.5, constant DELTAdis = 0.5); and
- Quadruplet-wave interaction.

2.3 Hornsea Project One construction scenarios

2.3.1.1 The wind turbine foundations for Hornsea Project One were installed in two phases during 2017/18. The dates for the two phases of construction, and the pre- and post-construction periods where data collection was ongoing, are summarised in Table 2.

Table 2. Periods of construction during the data collection period of the wave buoys in Hornsea Project One

Period	From	To	Duration	Activity
Pre-construction	26-Sep-17	24-Jan-18	120 days	No foundation structures
Construction (Phase 1)	25-Jan-18	14-Apr-18	79 days	59 WTG foundations installed
Interval	15-Apr-18	13-Aug-18	120 days	No installations in period
Construction (Phase 2)	14-Aug-18	09-Nov-18	87 days	115 WTG foundations installed
Post-construction	10-Nov-18	19-Nov-18	9 days	Last date of data access

Consequently, three scenarios were simulated in the wave model:

- Pre-construction – no foundation structures present;
- Post-construction (Phase1) – 59 wind turbine foundations present; and
- Post-construction (Phase2) – 174 wind turbine foundations present.

2.3.1.2 The actual installed locations of the wind turbine foundations are used in the model. The post-construction (Phase1) scenario uses the locations of the 59 foundations installed at this time. Other foundations (e.g. offshore substations) are not included in these scenarios; however, the wind turbine foundations comprise the majority of the blockage within the array.

2.3.1.3 The wind turbine foundations installed in Hornsea Project One are monopiles with a diameter of 8.1 m. Individual foundations are simulated in the model by specifying a circular obstacle of 8.1 m diameter at each foundation location. The blockage presented by the foundation is interpreted by the model as the proportion of the area of the model grid cell in which it is located, which is used to determine an overall transmission coefficient for wave energy through that cell.

2.4 Hindcast wave model validation

2.4.1.1 The regional SEASTATES wave model largely controls the timing, magnitude and direction of the wave conditions entering and propagating through the local wave model domain. The regional model (which is also driven by the same wind data used in the local model) has been separately validated against wave buoy data in numerous locations around the European continental shelf (ABPmer, 2013).

2.4.1.2 In this section, the local wave model is further calibrated and validated against wave buoy data collected in Hornsea Project One, prior to, during and following the actual construction period in 2017/18. Two wave buoys (‘North’ and ‘South’) were deployed in the Hornsea Project One array area, from pre-construction through to post- Phase 2 construction. The entire period is utilised for both the model simulation and validation time frame. Figure 4 and Figure 5 show the two wave buoy locations relative to the installed wind turbine foundations. Observations from the buoys enable a direct comparison of modelled and measured significant wave height (Hs), peak wave period (Tp), mean wave period (Tm01), and mean wave direction (MDir), prior to, during and following the two phases of construction.

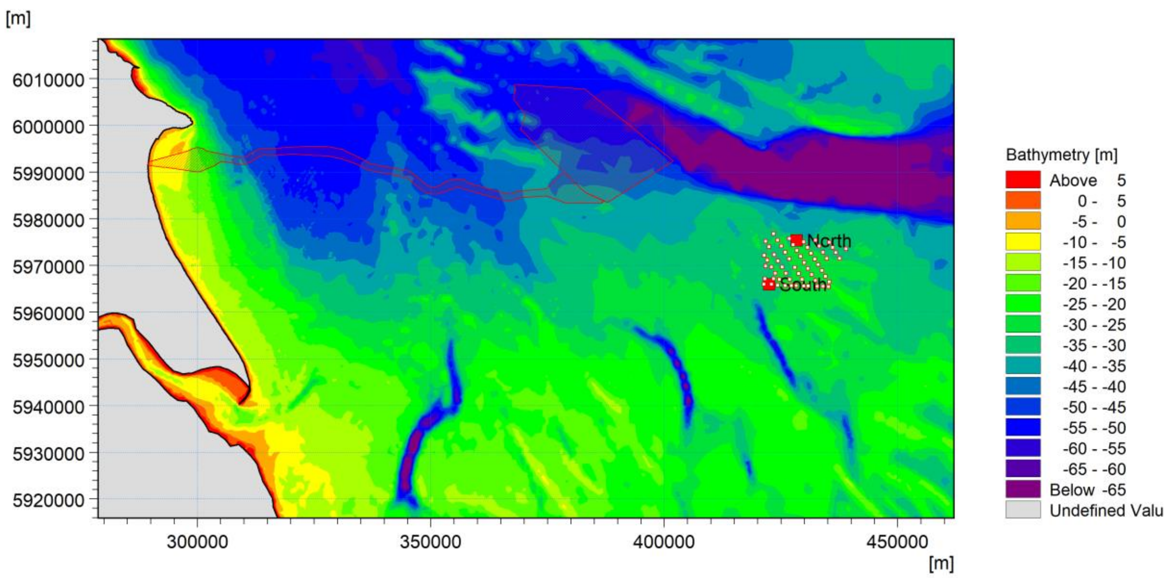

Figure 4. **Location of the North and South wave buoys and monopile foundations present in the Hornsea Project One ‘post-construction (Phase1)’ scenario. Also showing the location of the Hornsea Four array area and export cable corridor (ECC)**

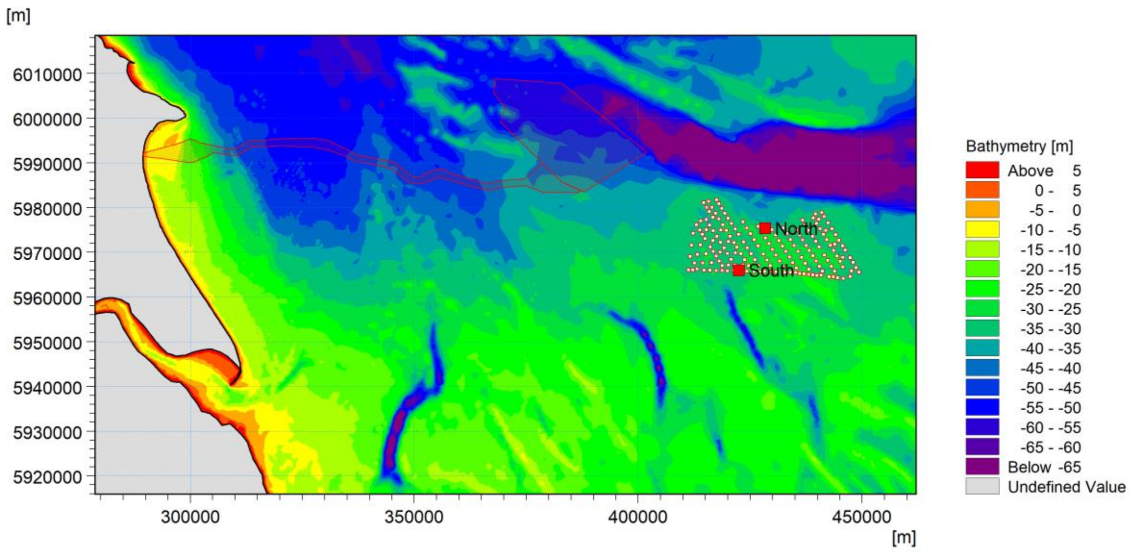

Figure 5. Location of the North and South wave buoys and monopile foundations present in the Hornsea Project One 'post-construction (Phase2)' scenario. Also showing the location of the Hornsea Four array area and ECC

2.4.1.3 Validation of model performance to provide a realistic hindcast of the key wave parameters is illustrated in Figure 6 and Figure 7 for the North wave buoy, and in Figure 8 and Figure 9 for the South wave buoy. The plots show that the model provides a good overall simulation of the magnitude and variation of both everyday conditions and occasional more energetic storm events. The relatively long duration of the simulation (approximately 15 months) is also shown to include a representative wide range of wave conditions with respect to wave height, period and direction; this range includes calm, intermediate and storm conditions, and all four seasons.

2.4.1.4 The accuracy of the model to simulate the effect of the installed foundations cannot be validated directly against measured data, as the effect of the foundations cannot be separated from the background wave condition in the observations. However, the following checks (of the spatial pattern of effect on wave height) demonstrate that the results of the modelling are consistent with those of previous studies for other wind farms, and the study for Hornsea Four presented in Section 3 of this report (Figure A6 to Figure A10).

2.4.1.5 Maps of the difference between modelled post-construction and pre-construction results were created. These plots are not shown here for the hindcast period but are similar to the spatial pattern of results shown for the selected extreme wave scenarios in Section 3. The plots confirm that the pattern of effect is consistent with previous studies, at an (expectedly) much lower magnitude of effect (discussed below).

2.4.1.6 The installed monopile foundations at Hornsea Project One create an array-scale pattern of reduction in wave height, gradually increasing from zero on the upwind edge typically to a maximum in the order of a few centimetres at the downwind edge. The reduction in wave height extends outside of the array area in a downwind direction, recovering to baseline (pre-construction) values within a relatively short distance (generally less than the array width). This characteristic spatial pattern and relatively smaller magnitude of effect is as expected for a relatively lower density array of small diameter monopiles, in comparison to a relatively higher density array of relatively larger cross-section foundations usually considered for EIA.

2.4.1.7 The results of the timeseries comparisons at the two wave buoys (described in more detail below) consistently show a similar small magnitude of effect (in the order of a few centimetres) at the locations of the wave buoys. The possibility of any measurable effect is realistically limited to the buoy(s) located downwind of the array, and the magnitude of any effect will be limited by the distance waves must travel through the array to the location of the buoy.

2.5 Hindcast wave model results

2.5.1.1 The effect on key wave parameters (Hs, Tp, DirM), of partial and complete installation of wind turbine foundations in the Hornsea Project One array area, is also illustrated in Figure 6 to Figure 9. The following comparison relates to the relative difference between the three model results only – the (dark blue line) observed data should be ignored.

2.5.1.2 The effect of the installed foundations on waves is shown to be very small in absolute terms (see below) – so small that the three model scenario results (light blue line ‘Pre-Construction’, red line ‘Post-Construction (Phase1)’ and orange line ‘Post-Construction (Phase2)’) are almost exactly superimposed and only the uppermost (orange line ‘Post-Construction (Phase2)’) result remains visible in all of the Figures.

2.5.1.3 Differences in modelled Hs (top panels in the figures) at any given point in time (between the three model scenarios) are typically in the order of a few centimetres. Associated differences in Tp (middle panels) are typically less than 0.1 s and in DirM (bottom panels) are less than 0.5°. Such small magnitude differences are within the uncertainty of the modelling process and are much smaller than the naturally present temporal and spatial variability in these parameters (as shown in the figures). Such small magnitude differences would also not be reliably measurable in practice.

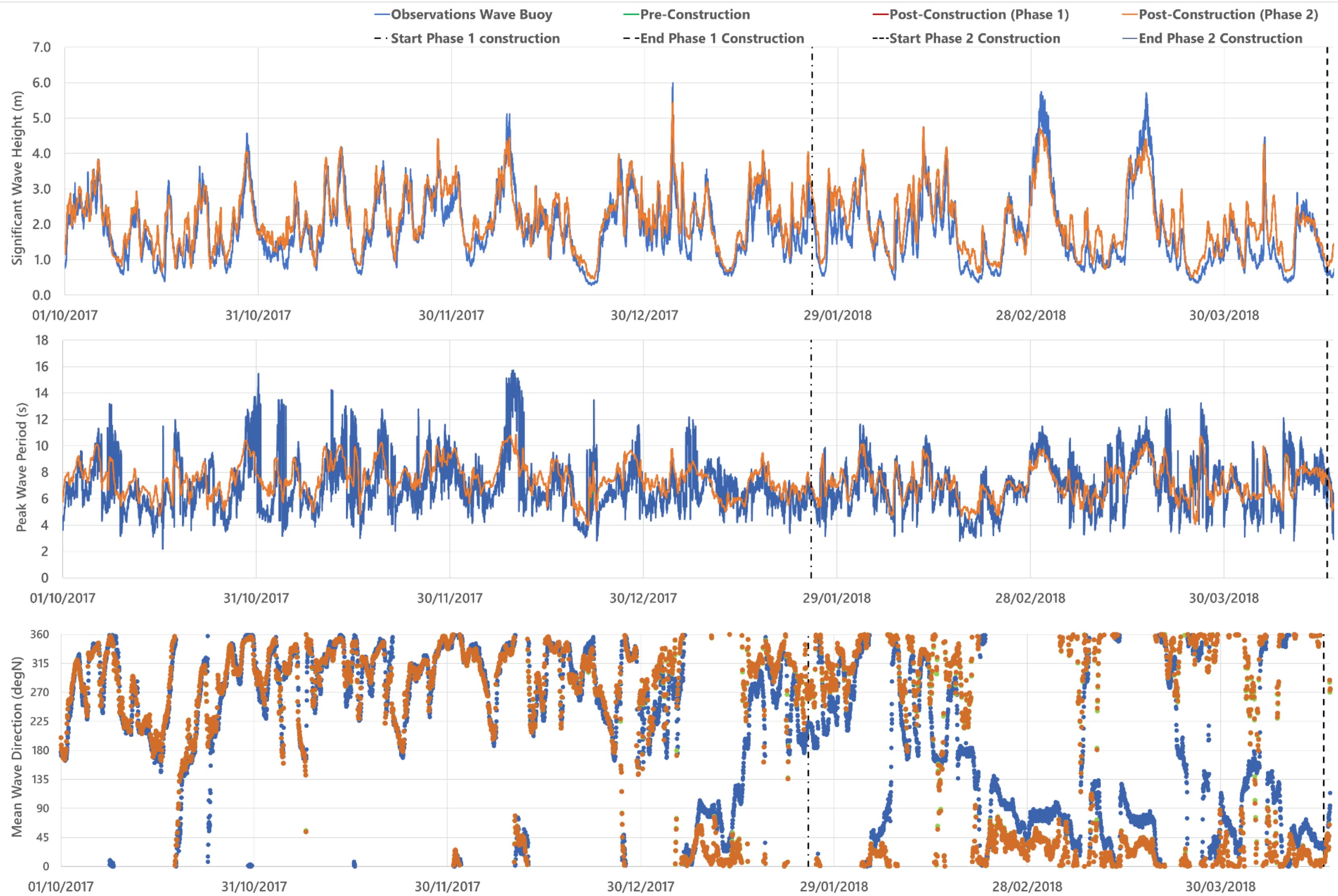

Figure 6. North wave buoy – observed and modelled wave conditions (pre-construction to the end of Phase 1 construction)

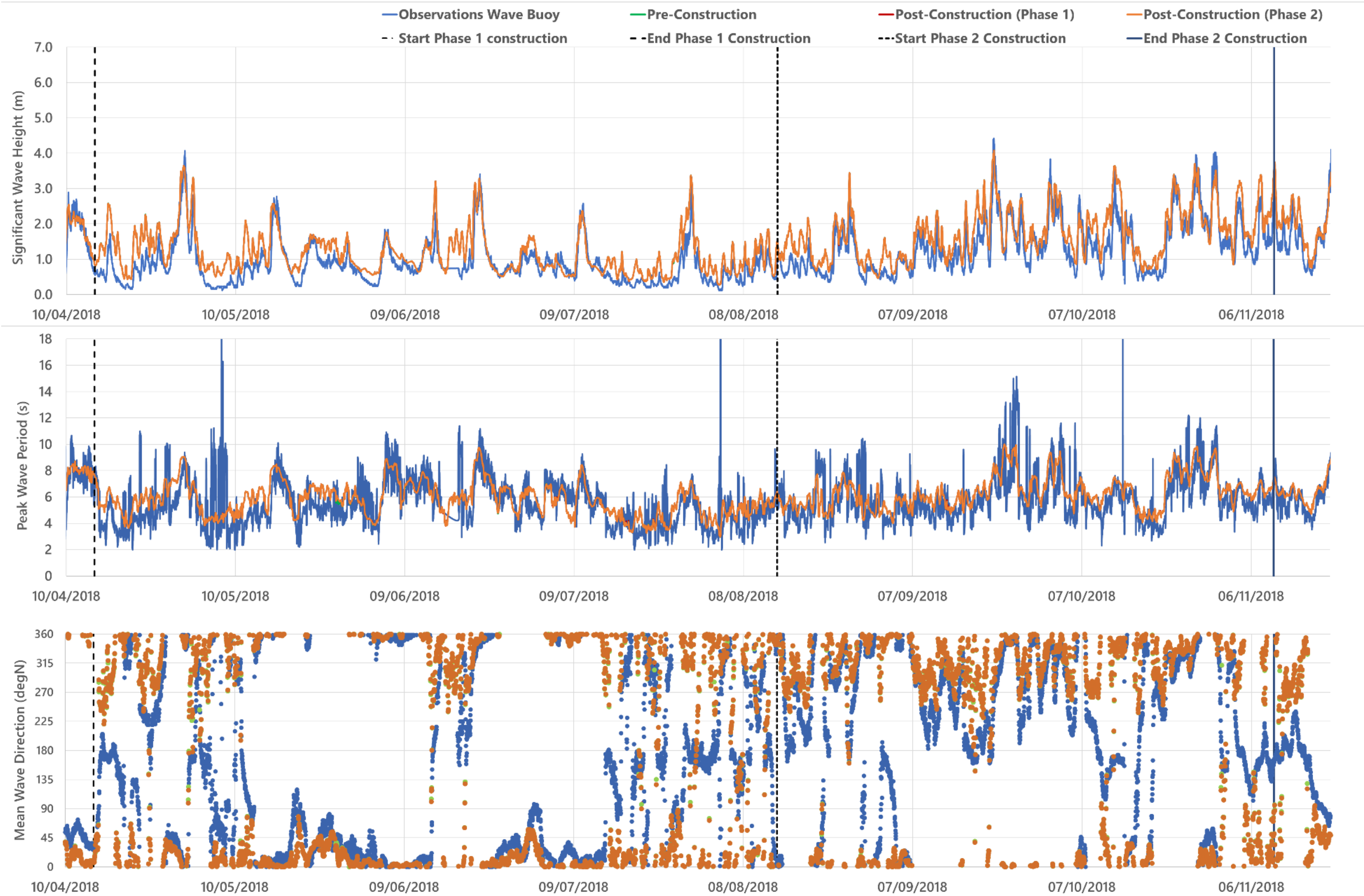

Figure 7. North wave buoy – observed and modelled wave conditions (end of Phase 1 construction to the end of Phase 2 construction)

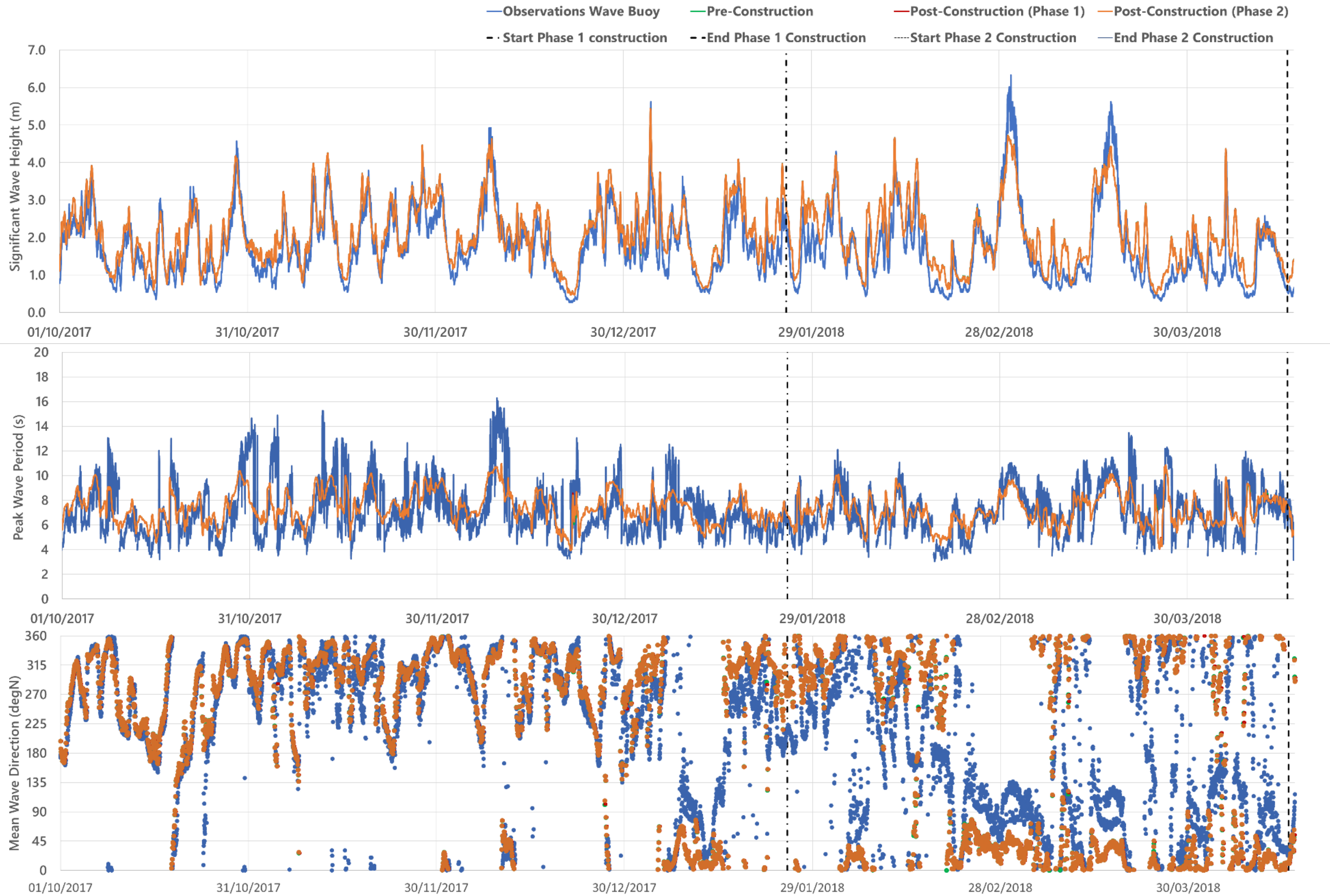

Figure 8. South wave buoy – observed and modelled wave conditions (pre-construction to the end of phase 1 construction)

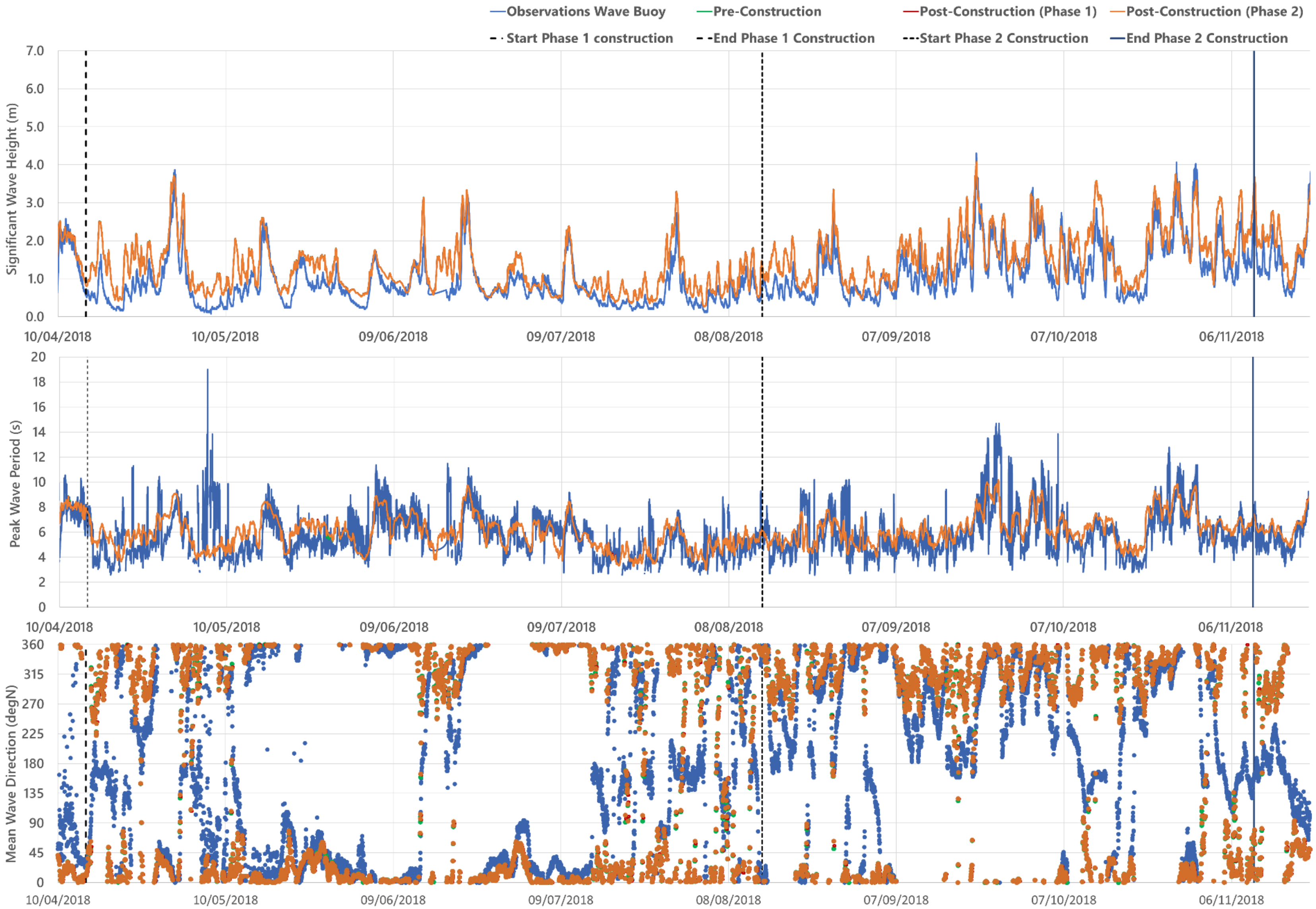

Figure 9. **South wave buoy – observed and modelled wave conditions (end of phase 1 construction to the end of phase 2 construction)**

3 Waves – Effect of Hornsea Four In-Combination

3.1 Overview

3.1.1.1 This section presents a study of the potential effect of OWF infrastructure associated with development in Hornsea Four, and elsewhere in the former Hornsea Zone, on a range of extreme wave conditions.

3.1.1.2 Maps of potential effect on wave height are produced for a development scenario including Hornsea Four in combination with Hornsea Project One, Hornsea Project Two and Hornsea Three. The simulated infrastructure (foundation locations, type and dimensions) are representative of the maximum design scenarios (MDS) for Hornsea Three and Hornsea Four and of the final approved designs for Hornsea Project One and Hornsea Project Two, respectively (described in Section 3.4).

3.1.1.3 The infrastructure simulated for Hornsea Four includes the foundations for wind turbine generators, small and large substations and an accommodation platform in the offshore array area, High Voltage Alternating Current (HVAC) booster substations in the ECC, and an area of cable protection associated with a cable crossing at the proposed Dogger Bank A & B export cables offshore of Smithic Bank, close to the adjacent coastline.

3.2 Extreme wave model design

3.2.1 Overview

3.2.1.1 The 'extreme' wave model provides discrete simulations of selected extreme wave conditions (return period and direction). The extreme wave model is the same as the hindcast wave model used in the present study, described in Section 2.2, with the exception of the wave and wind boundary conditions used (as described below).

3.2.2 Model boundary conditions

3.2.2.1 The model is driven by wave forcing at the three offshore wave boundaries at the north, east and south extent of the model grid (see Figure 3), and a constant wind forcing applied over the whole domain as applicable to each extreme condition. The wave and wind boundary conditions used in the MIKE21SW wave model are the same as those applied in the previous SWAN model (with only minor adjustment of wind speed to optimise results) and were derived by HRW from analysis of a long timeseries of hindcast offshore wave and wind conditions from the UK Met Office (UKMO) European Wave Model (described in SMart Wind, 2013 and 2015). The data and methods used in the original determination of baseline boundary conditions by HRW have been reviewed and found to remain suitable for application in the new MIKE21SW wave model.

3.2.2.2 Directional spectral wave conditions are applied uniformly along the three offshore wave boundaries, defined by significant wave height (Hs), peak wave period (Tp), mean wave direction (DirM) and directional standard deviation (DSD). The directional return period values of Hs, Tp and mean wave direction used are shown in Table 3. The shortest return period is the wave condition not exceeded 50% of the time, representing a relatively common wave condition; other return periods are expressed in years, representing progressively more severe infrequent events. As would be expected, the values are different for each coming direction and return period. The DSD value used in the previous SWAN modelling was not explicitly reported; a value of 23.3° (corresponding to the suggested default value in MIKE21SW) was therefore used for all scenarios in the MIKE21SW wave model.

3.2.2.3 Wind boundary conditions are applied uniformly across the whole domain area. The directional return period values of wind speed (at 10 m above sea level) and direction used are also shown in Table 3. In order to fully optimise the comparison between the SWAN and MIKE21SW directional return period baseline condition results (due to small differences in the underlying details of the modelling packages), wind speed inputs (only) were modified slightly (in the range ±5%) from the originally used values. The wind speed values provided in Table 3 reflect these adjustments.

Table 3. Wave and wind boundary conditions for each of the directional return period conditions

Directional Sector	Case (Return Period)	Significant Wave Height (Hs, m)	Peak Wave Period (Tp, s)	Mean Wave Direction (°N)	Wind Speed @10 m (m/s)	Wind Direction (°N)
N	50% no exc	1.10	5.0	0.0	4.32	0.0
	0.1 yr RP	2.90	8.1	0.0	10.40	0.0
	1 yr RP	4.15	9.6	0.0	16.06	0.0
	10 yr RP	5.39	11.0	0.0	21.68	0.0
	50 yr RP	6.23	11.8	0.0	24.50	0.0
	100 yr RP	6.58	12.2	0.0	25.77	0.0
NNE	50% no exc	1.10	5.0	22.5	4.52	22.5
	0.1 yr RP	2.40	7.4	22.5	9.52	22.5
	1 yr RP	3.91	9.4	22.5	17.17	22.5
	10 yr RP	5.35	11.0	22.5	23.24	22.5
	50 yr RP	6.34	11.9	22.5	26.30	22.5
	100 yr RP	6.76	12.3	22.5	27.19	22.5
NE	50% no exc	1.10	5.0	45.0	4.15	45.0
	0.1 yr RP	2.70	7.9	45.0	10.74	45.0
	1 yr RP	4.00	9.6	45.0	17.53	45.0
	10 yr RP	5.05	10.7	45.0	22.12	45.0
	50 yr RP	5.67	11.4	45.0	23.96	45.0
	100 yr RP	5.92	11.6	45.0	24.79	45.0
ENE	50% no exc	1.20	5.2	67.5	5.00	67.5
	0.1 yr RP	2.90	8.1	67.5	9.61	67.5
	1 yr RP	4.72	10.4	67.5	14.69	67.5
	10 yr RP	6.21	11.9	67.5	18.41	67.5
	50 yr RP	7.16	12.8	67.5	20.20	67.5
	100 yr RP	7.56	13.1	67.5	20.86	67.5
E	50% no exc	1.30	5.4	90.0	6.02	90.0
	0.1 yr RP	3.20	8.5	90.0	11.24	90.0
	1 yr RP	4.69	10.3	90.0	17.46	90.0
	10 yr RP	5.91	11.6	90.0	22.14	90.0
	50 yr RP	6.66	12.3	90.0	24.50	90.0
	100 yr RP	6.96	12.5	90.0	25.43	90.0

3.3 Extreme wave model validation

3.3.1.1 The local MIKE21SW wave model was extensively validated in ABPmer (2018) to provide an accurate and consistent reproduction of the original HRW extreme wave scenario modelling results, with respect to:

- Baseline (extreme) wave conditions (maps of Hs within the model domain); and
- The magnitude and spatial pattern of reduction in wave height caused by the MDS wind turbine foundations in Hornsea Project One and Hornsea Project Two.

3.3.1.2 The detail of this validation is not repeated here. The validated model was then used in ABPmer (2018) to make further assessments of impacts associated with Hornsea Three, both alone and in combination with Hornsea Project One and Hornsea Project Two. The same baseline model setup and extreme wave scenario boundary conditions are used in the present study for Hornsea Four.

3.3.1.3 Section 2.4 of this report also demonstrates that the local wave model, in conjunction with suitable boundary conditions, is able to adequately reproduce a continuous historical timeseries of measured wave conditions within the model domain, including the final approved design foundations for Hornsea Project One.

3.4 Offshore wind farm design scenario

3.4.1.1 The following design scenario is tested:

- MDS for Hornsea Four in combination with the MDS for Hornsea Three and the final approved designs for Hornsea Project One and Hornsea Project Two.

3.4.1.2 The following design parameters are considered:

- Hornsea Four MDS
  - 180 wind turbine generator foundations in the array area. Round gravity base, diameter 53 m reducing to topside monopile diameter 15 m (at LAT), equivalent monopile diameter 34 m (see text below for definition of the term 'equivalent monopile diameter').
  - 3 large offshore substation foundations in the array area. Square gravity base, length scale 150 m, equivalent monopile diameter 212 m (maximum diagonal cross section).
  - 6 small offshore substation foundations + one accommodation platform foundation in the array area. Square gravity base, length scale 75 m, equivalent monopile diameter 106 m (maximum diagonal cross section).
  - 3 small offshore substation foundations in the HVAC booster station search area in the ECC. Square gravity base, length scale 75 m, equivalent monopile diameter 106 m (maximum diagonal cross section).
  - Increase in seabed level by 1.8 m and 3.0 m (two scenarios) to conservatively represent rock berms within the extent of the cable crossing area offshore of Smithic Bank.

- Hornsea Three MDS
  - 319 wind turbine generator foundations in the array area. Round gravity base, diameter 43 m, monopile diameter 15 m, equivalent monopile diameter 29.4 m.

- Hornsea Project Two final approved design
  - 165 wind turbine generator foundations in the array area. Round monopiles, diameter 9.5 m.

- Hornsea Project One final approved design

- 174 wind turbine generator foundations in the array area. Round monopiles, diameter 8.1 m.

3.4.1.3 The individual foundations are described in the model as circular obstacles with a representative diameter. The effect of each foundation is to reduce the magnitude of the wave energy passing through the mesh element in which it is contained. The rate of reduction is determined as the ratio of the area of the foundation footprint (determined by the diameter), to the area of the mesh element in which it is contained. In the case of gravity base foundations, where the diameter of the obstacle varies through the water column, a representative 'equivalent monopile diameter' is determined as the average diameter from seabed to the water surface. This approach provides a conservative representation of the gravity base foundation as wave energy is concentrated at and near the water surface (the depth of penetration depending on the wave length) and will normally interact mainly with the relatively narrower profile of the foundation higher in the water column.

3.5 Extreme wave model results

3.5.1 Overview

3.5.1.1 The following results are provided as images in Appendix A:

- Results for each of 2 design scenarios (increase in seabed level by 1.8 m or by 3.0 m in the cable crossing area near to Smithic Bank, in conjunction with all other wind farm infrastructure described in Section 3.4).
- Results for each wind and wave condition.
- Baseline maps of wave height.
- Difference maps (Scheme minus baseline values) for wave height.

3.5.2 Summary of the effect of Hornsea Four in combination with other wind farms

3.5.2.1 The results for the two design scenarios (1.8 m berm height, Figure A6 to Figure A10; or 3.0 m berm height, Figure A11 to Figure A15) are very similar and so are summarised collectively below. The local effect of the different cable protection scenario heights is summarised in more detail below.

3.5.2.2 As shown in Figure A6 to Figure A15, the effect of the wind farm infrastructure is to cause an array scale reduction in wave height in proportion to the overall blockage density presented by the wind turbine and substation foundations. The magnitude of the effect gradually increases with distance downwind from the upwind edge of each array area. The effect then extends downwind of the array, gradually recovering to background values with distance. A more quantitative discussion is provided below.

3.5.2.3 As shown in Figure A6 to Figure A15, the greatest relative magnitude of effect of Hornsea Four and Hornsea Three is between 5 and 10% of the baseline wave height within and immediately downwind of these array areas for the 50% exceedance return period scenario for all of the wave directions tested. The magnitude of effect reduces to 2.5 to 5% within a distance similar to the width of the individual array areas relative to the wave direction. Potentially measurable effects on wave height (more than 2.5 to 5%) do not extend to any of the adjacent coastlines.

3.5.2.4 As shown in Figure A6 to Figure A15, the relative magnitude and extent of the effect is greatest for the 50% exceedance return period scenario (the lowest energy wave height condition considered), progressively decreasing for higher return period scenarios for all of the wave directions tested. This pattern occurs because wave energy is proportional to the product of the wave height and the square of the wave period. A reduction in wave energy at higher energy levels will therefore result in a smaller proportional reduction in wave height. For a given return period, the relative magnitude and extent of the effect is similar for the range of wave directions simulated.

3.5.2.5 In comparison to the effect of MDS gravity base foundations in Hornsea Four and Hornsea Three, the effect of final approved design monopiles in Hornsea Project One and Hornsea Project Two is very small in both absolute and relative terms. As described in Section 2.5, the absolute magnitude of effect of the relatively low density of smaller monopile wind turbine foundations installed in the Hornsea Project One array area was in the order of less than 0.05 m for a range of wave conditions over a 15 month period. The effect of Hornsea Project One and a similarly low density of similarly slender monopiles in the Hornsea Project Two array area is correspondingly small in this simulation also. The relative magnitude of effect is less than 2.5% of the baseline wave height both within and outside of these two wind farm array areas for all of the wave direction and return period conditions tested.

3.5.2.6 The greatest overall potential for cumulative effects on wave height is when waves come from the east (Figure A10) and all four array areas are broadly aligned to the wave direction. Under this condition, measurable effects from Hornsea Three overlap with Hornsea Project One and Hornsea Project Two, but still do not extend as far as Hornsea Four.

3.5.2.7 The Hornsea Four HVAC booster substations also cause a local reduction in wave height of small magnitude (between 2.5% and 5% locally) that is limited to an area only up to 200 m immediately downwind. Although there may realistically be a more complete wave shadow immediately behind a large gravity base foundation in practice, wave heights are expected to recover rapidly due to wave energy spreading laterally into the shadow from the surrounding area.

3.5.2.8 The relatively small difference in local water depth due to the Hornsea Four cable crossing berms causes no measurable change in wave height (greater than 2.5% of the baseline condition) either within or outside of the footprint of the cable crossing area for either the 1.8 m berm height (Figure A6 to Figure A10) or 3.0 m berm height (Figure A11 to Figure A15) scenario. This is likely because the cable crossing area is sufficiently deep (approximately 20 m) in relation to the wave action penetration depth, that the small relative change of water depth does not cause measurable changes to the baseline patterns of wave breaking or wave propagation.

4 Tidal Currents – Effect of Hornsea Four Cable Crossing Protection near to Smithic Bank

4.1 Overview

4.1.1.1 This section presents a study of the potential effect of cable protection associated with an area of cable crossing with the proposed Dogger Bank A & B export cables, near to and offshore of Smithic Bank.

4.1.1.2 Maps of potential effect on current speed and direction are produced for development scenarios including two potential protection heights (a reduction in water depth over the crossing area of 1.8 m and 3.0 m), both with and without additional allowance for an associated change to bed roughness.

4.1.1.3 The potential cumulative effect of other OWF foundation infrastructure (e.g. foundations in the HVAC booster station search area or array area) is not included in these simulations. Modelling studies and field observations consistently demonstrate that the effect of such foundations on currents is characterised by a narrow wake of locally reduced current speed extending downstream, up to the width of the foundation, recovering rapidly to ambient current speed over a distance in the order of 10- to 100-times the obstacle width. No other OWF foundation infrastructure is located upstream of the cable crossing area or Smithic Bank, and so there is no potential for cumulative effects on Smithic Bank.

4.1.1.4 The flow field data from the tidal model also provides the basis for the sediment plume model described in Section 5.

4.2 Tidal model design

4.2.1 Overview

4.2.1.1 The tidal model provides a timeseries simulation of tidal water levels and depth averaged current speed and direction throughout the model domain. The tidal model is built using the MIKE21FM Hydrodynamic (HD) module, which simulates the propagation of the tidal wave and associated movements of water volume in offshore and coastal settings.

4.2.1.2 The tidal 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 study area. The design and performance of the regional model are described in a separate report (ABPmer, 2017).

4.2.2 Model grid

4.2.2.1 The tidal model grid 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 10.

4.2.2.2 The resolution of the mesh is increased within the study area to approximately 100 m along the Holderness coastline and in a broad corridor from the coastline to the array area of Hornsea Four.

The resolution of the mesh is increased further to approximately 50 m on the south side of Flamborough Head, including the area on and around Smithic Bank. The increased resolution provides a more detailed description of the key bathymetric and coastal features affecting flow patterns in these areas, including Smithic Bank and the cable crossing protection area. The higher resolution is also relevant to the resolution of outputs from the sediment plume model described in Section 5.

4.2.2.3 The grid is locally aligned to the extent of the cable crossing area between export cables from Hornsea Four and Dogger Bank A & B, near to Smithic Bank. The mesh detail in this area is the same as shown for the wave model in Figure 2. The footprint of the cable crossing area, within which the effect of the installed infrastructure is applied in the model, is 770 m long and 500 m wide. Immediately outside of this footprint, the transitional slope from scheme to baseline conditions is contained within a narrow row of mesh elements, approximately 25 m wide. This description of the scheme effect footprint is conservatively representative of the proposed design envelope. More information about the scheme effect applied within this area (in the tidal model a reduction in water depth and an increase in bed roughness due to the presence of cable protection) is described in Section 4.4.

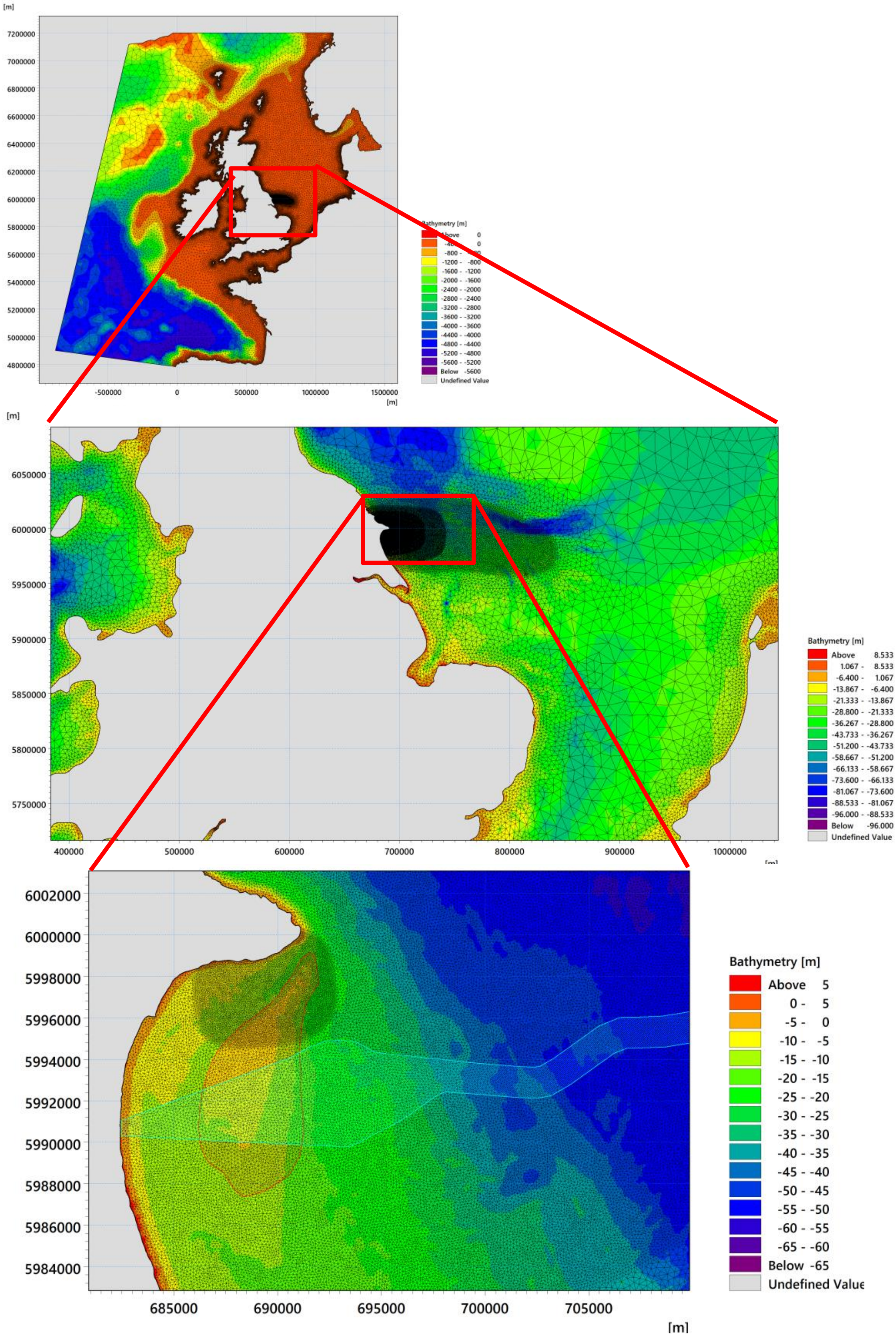

Figure 10. Extent of the tidal model mesh, showing regional and locally enhanced resolution. Lower plot also shows the Hornsea Four ECC and outline of Smithic Bank

4.2.3 Model bathymetry

4.2.3.1 The majority of the tidal model bathymetry is the same as used by the original ABPmer SEASTATES European Shelf Tide and Surge model. The regional bathymetry data is sourced from EMODnet (https://www.emodnet-bathymetry.eu/), which is a freely available and generally reliable data source. The good level of validation achieved by the model with respect to water levels and currents (ABPmer, 2017) provides indirect validation of the bathymetry data source.

4.2.3.2 The regional model bathymetry has been compared to the site-specific bathymetry data sets presently available to this study for Hornsea Four. No consistent large differences were found and so the model bathymetry in this area is used without adjustment.

4.2.3.3 Additional higher resolution survey bathymetry from the UKHO and CCO are used in the area of increased model resolution the vicinity of Flamborough Head, Smithic Bank, and along the Holderness coastline (previously described in Table 1). The bathymetry sets were carefully aligned with the highest resolution having priority over any coarser data that shared coverage.

4.2.3.4 Spatially varying adjustments are made to convert bathymetry data from LAT at source, to MSL for use in the model. Adjustments are made using a combination of VORF (UCL and UKHO, 2005) and tidal water level statistics for tide gauges elsewhere in Europe.

4.2.4 Model boundary conditions

Offshore tidal boundaries

4.2.4.1 The tidal model has four open water level boundaries (shown in Figure 11).

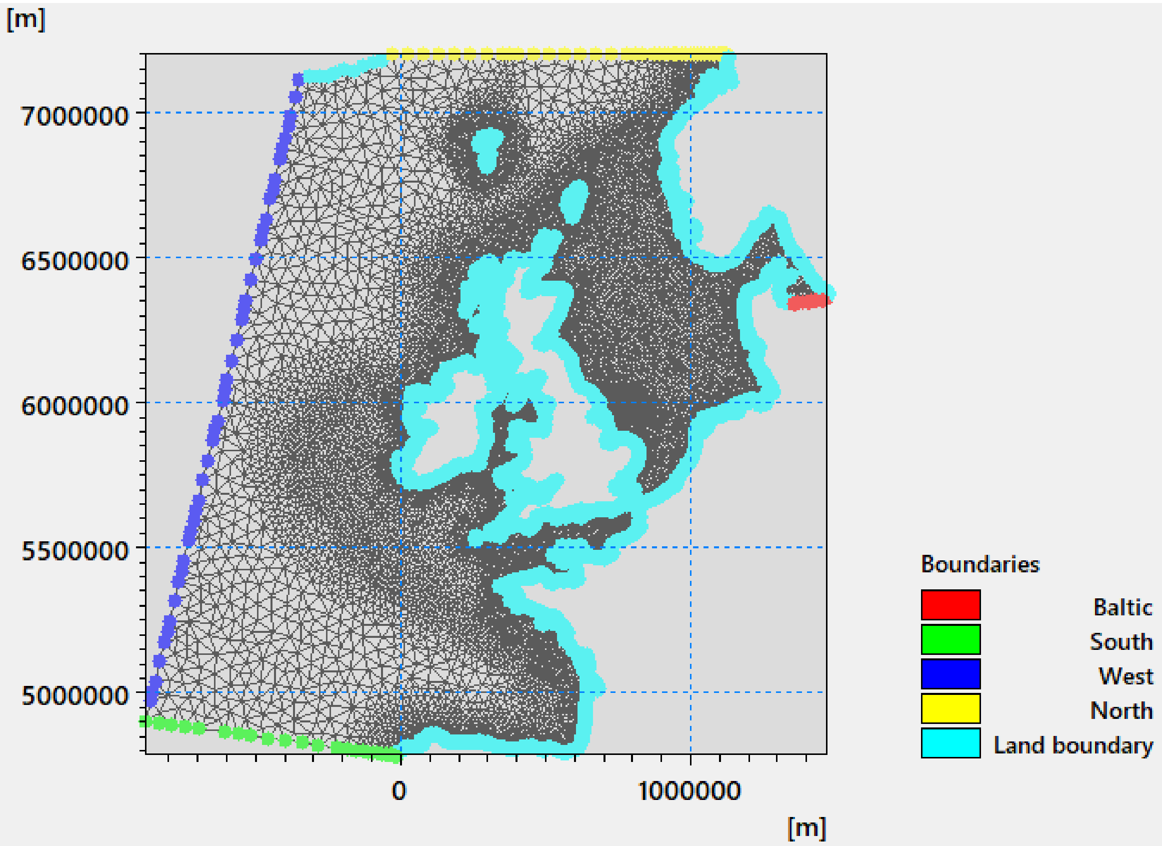

Figure 11. Tidal model boundaries

4.2.4.2 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 DTU10 (DTU, 2010) database of harmonic constituents. The good level of validation achieved by the model with respect to water levels and currents (ABPmer, 2017) provides indirect validation of the tidal boundary data source.

Meteorological boundaries

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

4.2.5 Bed roughness

4.2.5.1 Bed roughness in the model describes the friction from the seabed 'felt' by moving water. Changing the magnitude of bed roughness locally affects 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.

4.2.5.2 The ABPmer SEASTATES European Shelf Tide and Surge model utilises a bespoke spatially varying map of bed roughness, 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), which provides indirect validation of the bed roughness values.

4.2.5.3 The same validated spatially variable bed roughness distribution is applied in the present study. Bed roughness is locally modified (roughness is increased) in the footprint of the cable crossing area in some scenarios to represent the additional roughness of the cable protection material and berm features (as described in Section 4.4).

4.3 Tidal model validation

4.3.1.1 The regional SEASTATES tide model largely controls the timing, magnitude and direction of water levels and currents entering and propagating through the local study area. The regional model has been separately validated against tide gauge and current meter data in numerous locations around the European continental shelf (ABPmer, 2017).

4.3.1.2 The tidal model has also been locally validated against project specific survey and other historical observations of water levels and currents. Observations of water levels and profiles of current speed and direction were collected in 2010/11 at six locations in the former Hornsea Zone using Acoustic Wave And Current (AWAC) profilers. Three of the locations closest to the Hornsea Four array area and ECC (L1, L5 and L6, shown in Figure 12) have been selected to inform the model validation. Two older historical single point current meter records from the British Oceanographic Data Centre (BODC) archives that are located closer inshore in close vicinity to the Hornsea Four ECC have also been used.

4.3.1.3 Measured and modelled water levels, depth-averaged current speed and direction from the more recent metocean survey at Locations L1, L5 and L6 are directly compared over a representative spring-neap cycle in Figure 13 to Figure 15, respectively. Measured depth-specific current speed and direction from the BODC1 and BODC2 data records are compared with harmonically re-predicted depth-averaged currents based on the more recent modelled time period in Figure 16 and Figure 17, respectively. Some allowance is made for small difference introduced by the harmonic re-prediction process, and for the single point nature of the devices used in the BODC data.

4.3.1.4 The plots generally show that the tide model provides a good representation of the magnitude, timing and variance of water levels, current speed and direction at these locations in the offshore part of the study area. Variance in peak current speed between adjacent flood/ebb tides is important for the realistic simulation of local tidal asymmetry and drift (e.g. affecting sediment plume advection and dispersion). The model is shown to simulate a similar pattern of asymmetry in peak current speed; the nature and strength of this asymmetry appears variable in time and between the three measurement locations. The main axis and direction of rotation of tidal currents is also well represented by the model.

4.3.1.5 Smaller differences lasting from hours up to a 1 to 2 days are likely to be explained by some additional (small) surge influence in the measured data that is not included in the tide only model prediction.

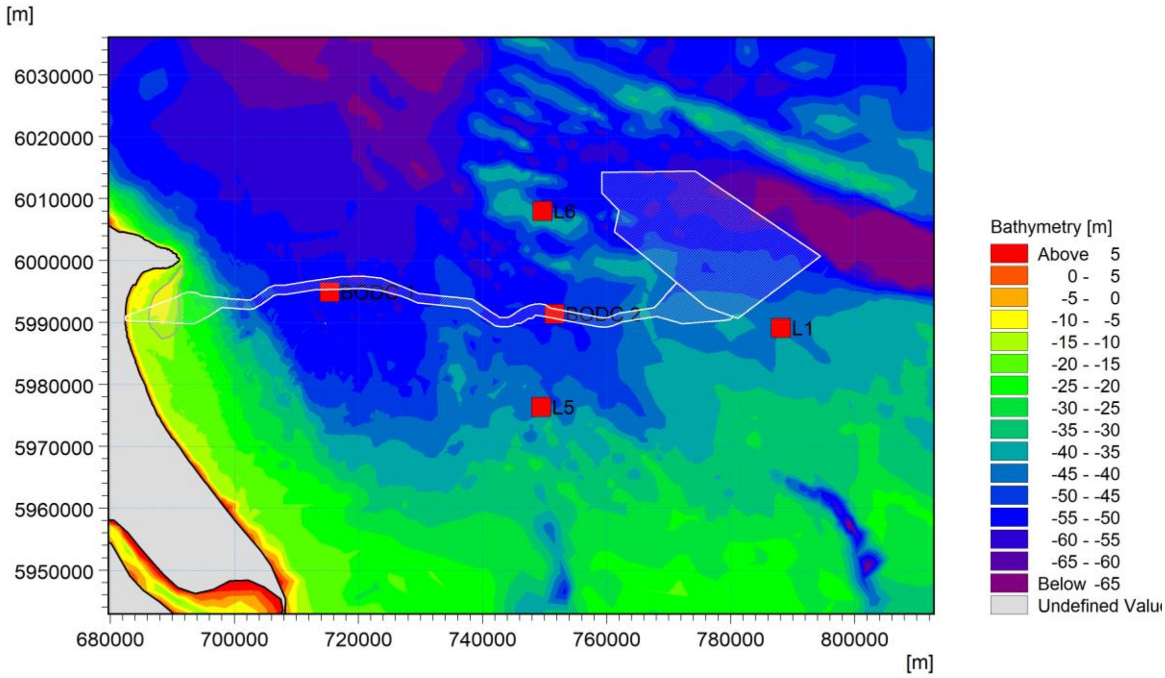

Figure 12. Locations of survey instruments L1 (east), L5 (south), L6 (north), BODC1 (west) and BODC2 (central) used for tidal model validation in relation to the maximum design scenario locations of wind turbine foundations in the Hornsea Four array area

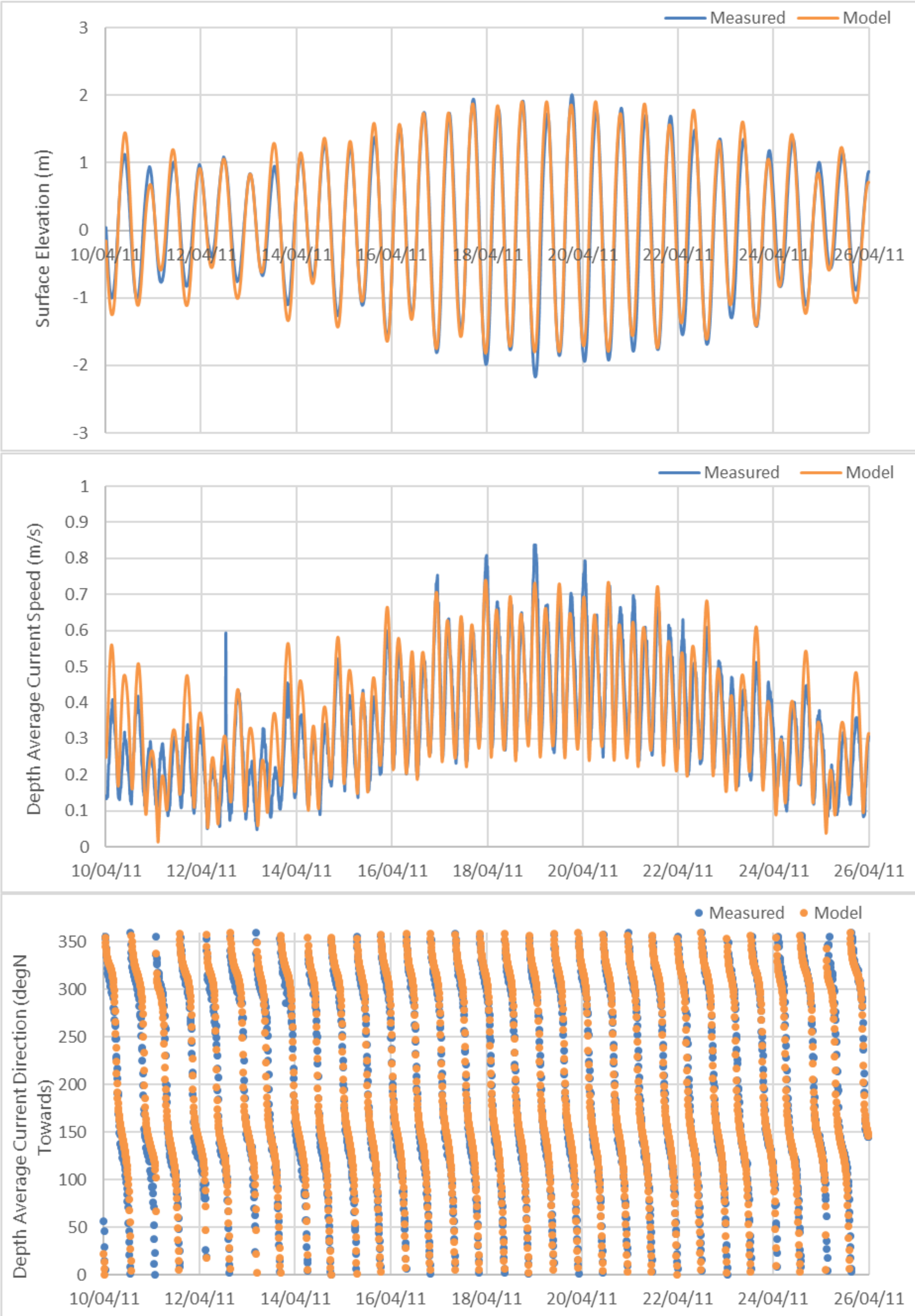

Figure 13. **Local validation of the tidal model (Location L1)**

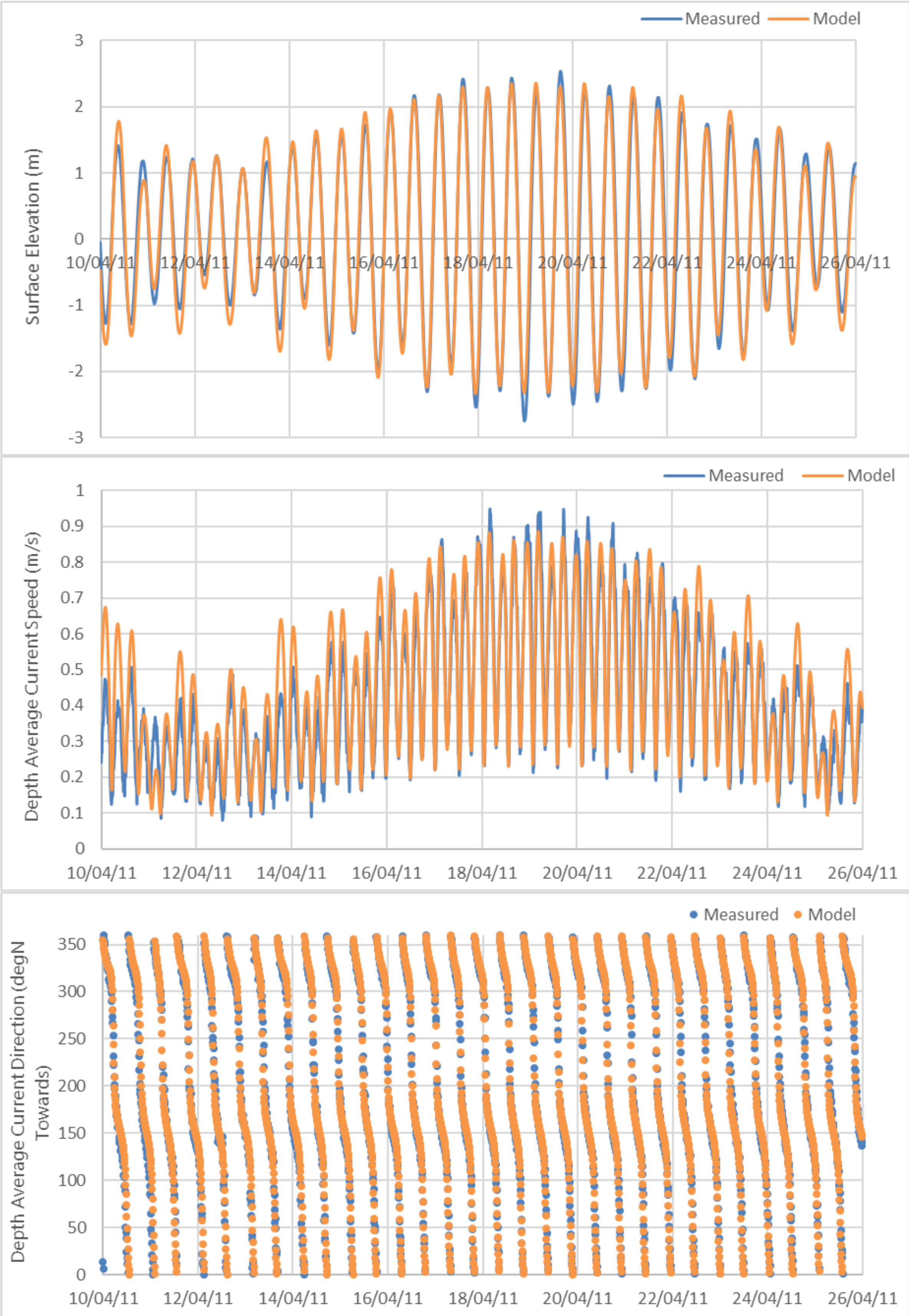

Figure 14. Local validation of the tidal model (Location L5)

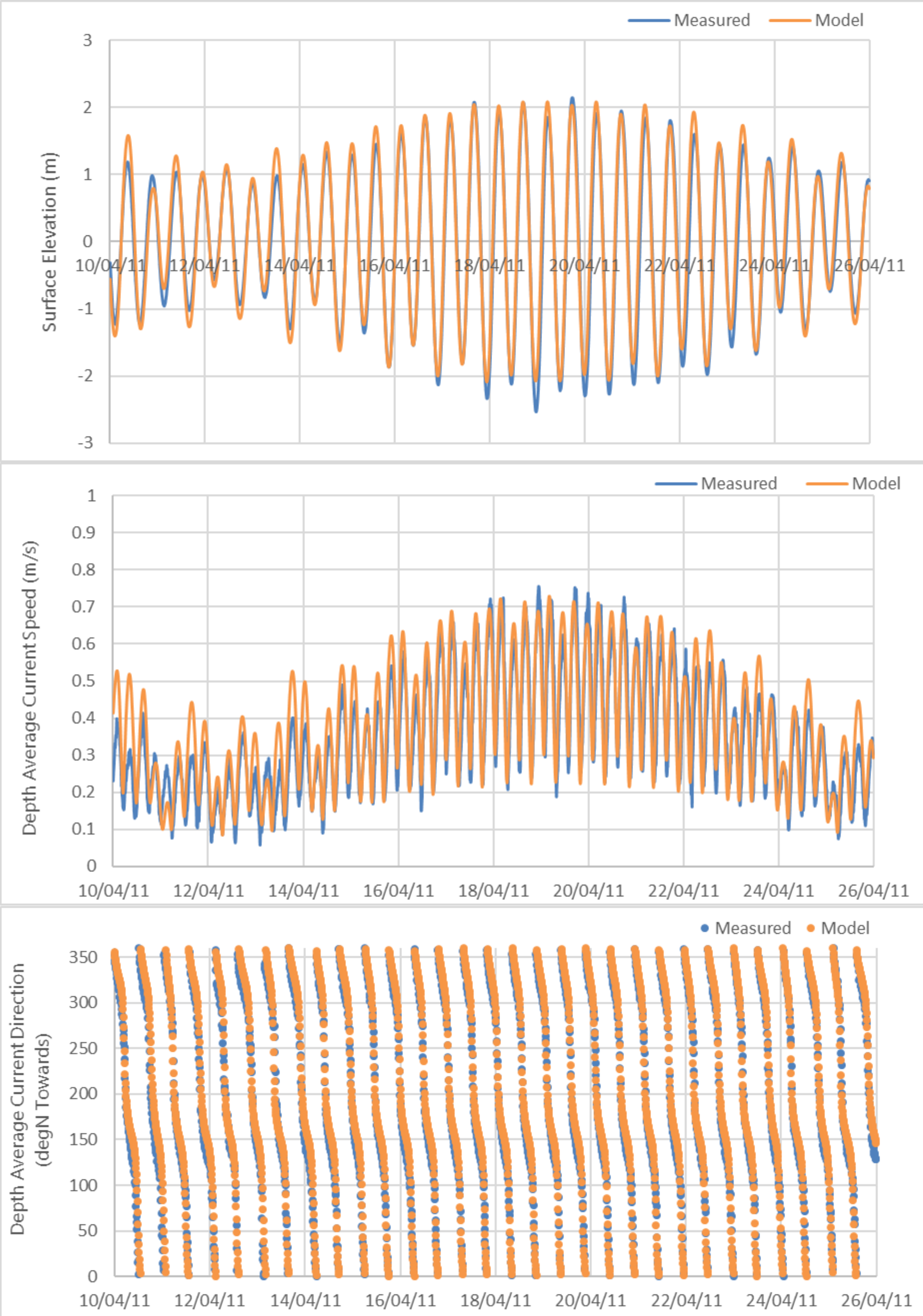

Figure 15. Local validation of the tidal model (Location L6)

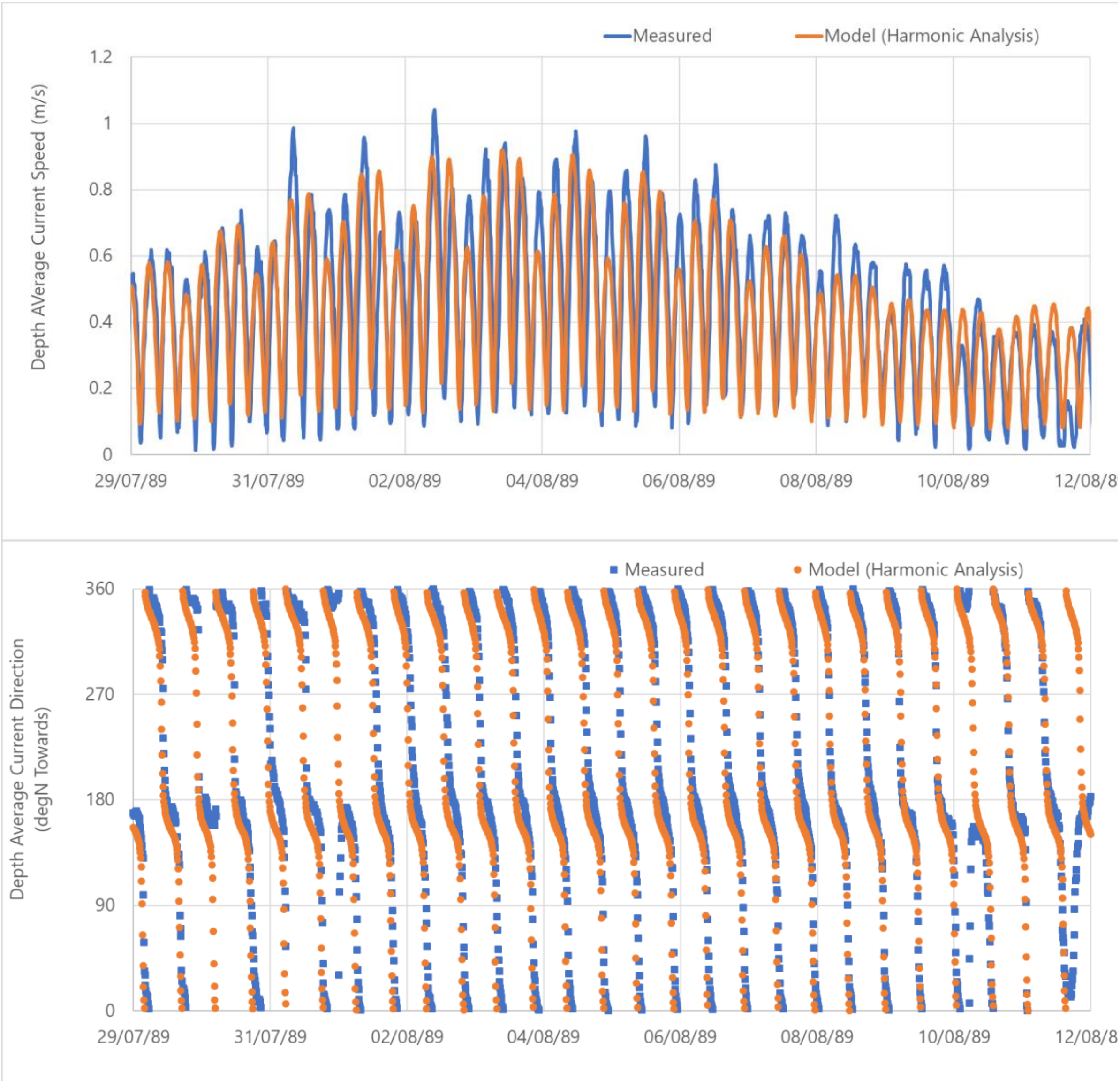

Figure 16. Local validation of the tidal model (Location BODC1)

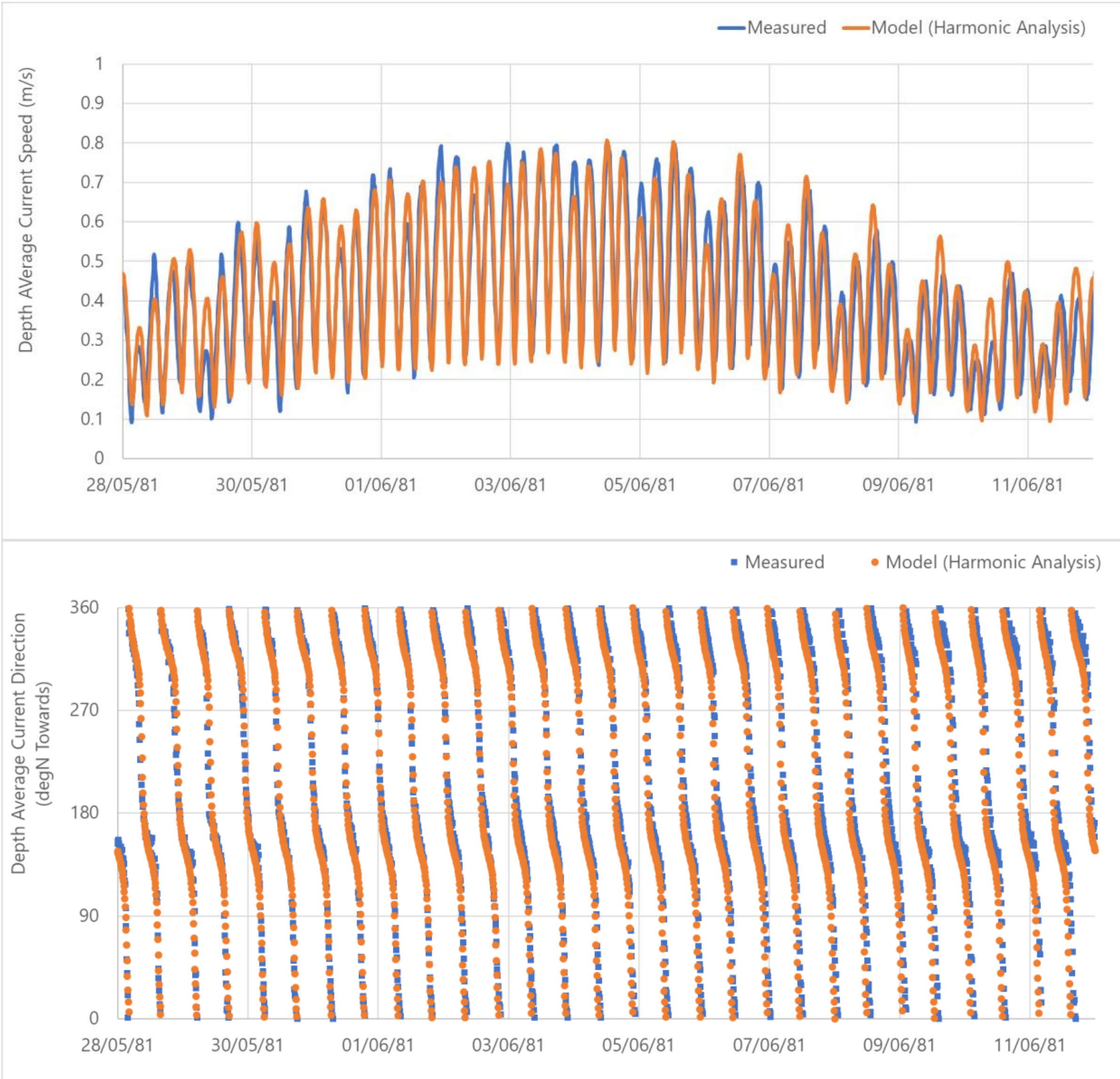

Figure 17. Local validation of the tidal model (Location BODC2)

4.4 Cable crossing protection scenarios

4.4.1.1 This model is used to investigate the potential effect of export cable crossings between Hornsea Four (up to 6 cables) and Dogger Bank A & B (4 cables). The configuration of the crossings creates the potential for up to 24 individual crossings within a relatively local area which is just seaward of Smithic Bank. The combined height and width of the cable protection material proposed for these crossings is included in the tidal model as a local reduction in water depth and a local increase in bed roughness.

4.4.1.2 Five model scenarios are considered:

- Baseline (no cable crossing protection).
- Scheme (reduction in water depth by 1.8 m).
- Scheme (reduction in water depth by 1.8 m and increase in bed roughness).
- Scheme (reduction in water depth by 3.0 m).
- Scheme (reduction in water depth by 3.0 m and increase in bed roughness).

4.4.1.3 Each scenario is modelled throughout a representative spring-neap cycle, containing discrete tides that are of mean-neap and mean-spring range (based on the modelled water levels at Bridlington tide gauge and with reference to the Admiralty tide tables for that location).

4.4.1.4 The baseline scenario uses the model bathymetry and bed roughness without modification.

4.4.1.5 The MDS height for 80% of the length of cable protection is 1.8 m above the seabed level. There is an allowance for up to 20% of all cable protection to be up to 3.0 m for additional anchor strike protection at select locations, which might also be applied in the cable crossing area. In practice, the cable protection will follow the individual cables and positions of cable crossings. As such, the maximum design height will likely only be reached locally on the crest of individual cables and cable crossings in some locations; cable protection is likely to be lower or absent in other locations within the cable crossing area. In the model, the maximum local reduction in water depth is conservatively represented by a uniform increase in seabed level of 1.8 m or 3.0 m over the whole footprint of the cable crossing area (an area approximately 500 by 770 m, not just the crests of cable protection within that area).

4.4.1.6 The size of the cable protection material (assumed here to be rock material) will likely be relatively small (typically no larger than 25 cm in diameter, and up to 50 cm in diameter where anchor strike protection is required), which will have minimal direct effect on friction at the seabed. However, the linear cable protection features they create may result in an undulating topography (up to the maximum design height but with spacing of tens of metres), that may present measurable additional friction to flow through the cable crossing area. In the model, the local increase in bed roughness is represented by a uniform increase in bed roughness from Mannings M≈35 (theoretically representing smooth to rippled sand), to Mannings M=25 (theoretically representing a coarse seabed with clasts diameter approximately 0.5 m) over the whole footprint of the cable crossing area. This roughness value was considered to fairly represent the additional roughness effect over the whole area; any greater roughness effect in combination with the full effect of the berms on seabed level was considered likely to be unnecessarily conservative. Increasing roughness in this way will have an omni-directional effect on currents passing through the cable crossing area. In practice, the orientation of the cable protection features to the ambient current direction may locally reduce the actual effect of form-roughness on flows. It is noted that the Hornsea Four cables are closely (although not completely) aligned to the local tidal axis, however, the proposed DBCB export cables being crossed are nearly perpendicular to the tidal axis.

4.5 Tidal model results

4.5.1 Overview

4.5.1.1 The following results are provided as images in Appendix B:

- Results for each of 4 design scenarios (increase in seabed level by 1.8 m or by 3.0 m in the cable crossing area near to Smithic Bank, with and without an additional increase in bed roughness, as described in Section 4.4).
- Results for representative mean-neap and mean-spring tides.
- Results for times of high-water and low-water (at Bridlington) and peak-flood and peak-ebb (current speed at the cable crossing area).
- Baseline maps of current speed and direction.
- Difference maps (Scheme minus Baseline values) for current speed and current direction.

4.5.2 Summary of relevant baseline conditions

4.5.2.1 Patterns of baseline current speed and direction are shown in Figure B1 and Figure B2 for neap and spring tide conditions, respectively.

4.5.2.2 During the flood tide, currents are generally towards the south. During the ebb tide, currents are generally towards the north.

4.5.2.3 During the mean spring tide, the peak current speed in the cable crossing area is approximately 0.90 m/s on the flood, and 0.75 m/s on the ebb. During the mean neap tide, the peak current speed in the cable crossing area is approximately 0.4 m/s on the flood, and 0.45 m/s on the ebb.

4.5.2.4 There are complex but repeatable patterns of current speed and direction around Flamborough Head and over Smithic Bank that evolve during the tidal cycle. These include the formation of recirculation and channelized flow features caused by flow interaction with Flamborough Head, Smithic Bank and the adjacent coastlines.

4.5.2.5 At the cable crossing site, peak flood and ebb current speeds occur approximately 2 hours before high and low water at Bridlington, respectively. Local high and low waters are not associated with a regional slack water condition. The local occurrence and timing of slack water and flow reversal is highly variable across the wider area due to the evolution of the flow features described above.

4.5.3 Summary of the effect of the cable crossing as a local reduction in water depth

4.5.3.1 Patterns of change to current speed and direction are shown in Figure B3 to Figure B6 for a 1.8 m reduction in water depth, for neap and spring tide conditions, respectively.

4.5.3.2 Patterns of change to current speed and direction are shown in Figure B7 to Figure B10 for a 3.0 m reduction in water depth, for neap and spring tide conditions, respectively.

4.5.3.3 The effect of the cable crossing, when described as a conservative local reduction in water depth (with no change to bed roughness), is to cause only slight and localised modification to current speed and direction.

4.5.3.4 In all of the result figures for these scenarios, currents are shown to continue to pass over the cable crossing area with a speed and direction very similar to the baseline condition. Compared to the baseline direction, the flow diverges slightly, at or near the upstream edge of the cable crossing area, converging again at a similar rate at or near the downstream edge. Logically, current speed is being slightly increased within the footprint of the cable crossing area as the flow is vertically constricted locally.

4.5.3.5 The greatest magnitude of the modelled effect is in the order of 0.05 m/s increase in current speed (up to 0.1 m/s locally) and 3° current direction for the (higher) 3.0 m berm on a (faster) mean spring tide (Figure B9 and Figure B10).

4.5.3.6 The spatial pattern remains similar, but the magnitude of absolute effect is relatively less for the other cable protection height and tidal condition scenarios tested. In descending order of absolute magnitude of effect: the 3.0 m cable protection on a mean neap tide (Figure B7 and Figure B8); and the 1.8 m cable protection on mean spring and neap tides (Figure B3 to Figure B6).

4.5.3.7 For the (smaller) 1.8 m height, effects greater than a representative very small magnitude ±0.01 m/s and ±1 degree are largely contained within the footprint of the cable crossing area during mean spring conditions. For the (larger) 3.0 m height, effects of this magnitude may also extend up to 500 m downstream.

4.5.4 Summary of the effect of the cable crossing as a local reduction in water depth and increase in bed roughness

4.5.4.1 Patterns of change to current speed and direction are shown in Figure B11 to Figure B14 for a 1.8 m reduction in water depth and increase in bed roughness, for neap and spring tide conditions, respectively.

4.5.4.2 Patterns of change to current speed and direction are shown in Figure B15 to Figure B18 for a 3.0 m reduction in water depth and increase in bed roughness, for neap and spring tide conditions, respectively.

4.5.4.3 The effect of the cable crossing, when described as a conservative local reduction in water depth and increase in bed roughness, is to cause a modification to current speed and direction both within the footprint of the cable crossing area and in a wake area extending both laterally and downstream.

4.5.4.4 In all of the result figures for these scenarios, currents are shown to continue to pass over the cable crossing area with a speed and direction broadly similar to the baseline condition. Compared the baseline direction, the flow diverges at or near the upstream edge of the cable crossing area, however, in this scenario the flow direction does not converge again at the downstream edge.

4.5.4.5 Current speed is locally reduced in an area upstream of the cable crossing and in a wake feature extending downstream, aligned with the central axis of the area, relative to the orientation of the tidal current. The current speed reduction is greatest immediately downstream of the cable crossing area and recovers with distance downstream. Current speed within the footprint of the cable crossing area is reduced to a lesser extent than the wake features outside.

4.5.4.6 Current speed is also increased slightly in areas over the lateral corners and downstream from these areas, to the side of the cable crossing area. These features are consistent with the acceleration and (slight) deflection of water over and around the cable crossing area, where its passage is (slightly) restricted by the reduction in water depth and increase in local bed friction.

4.5.4.7 The greatest magnitude of the modelled effect (increase and/or decrease in flow speed) is in the order of 0.10 m/s current speed (increase on the lateral corners of the area and decrease in the downstream wake) and 3° current direction (in the area of deflection upstream) for the (higher) 3.0 m cable protection on a (faster) mean spring tide (Figure B17 and Figure B18)n

4.5.4.8 The spatial pattern remains similar, but the magnitude of absolute effect is relatively less for the other cable protection height and tidal condition scenarios tested. In descending order of absolute magnitude of effect: the 3.0 m cable protection on a mean neap tide (Figure B15 and Figure B16); and the 1.8 m cable protection on mean spring and neap tides (Figure B11 to Figure B14).

4.5.4.9 As shown in all of the result figures for these scenarios, effects greater than ±0.01 m/s and ±1 degree can extend up to 7 km downstream of the cable crossing area during mean spring or neap conditions. The magnitude and extent of effect appears relatively greater on the flood (flow to the south) than the ebb.

5 Sediment Plumes – Effect of Activities Causing Sediment Disturbance

5.1 Overview

5.1.1.1 This section presents a study of the likely nature of sediment plumes (footprint, concentration, duration) and associated sediment deposits (footprint and thickness) as a result of MDS sediment disturbance during the construction of Hornsea Four (described in Section 5.4).

5.1.1.2 Maps of potential increase in suspended sediment concentration (SSC) and thickness of sediment deposition are produced for various sediment disturbance and tidal scenarios. The MDS' include use of a controlled flow excavator (CFE) tool at the seabed for trenching and cable burial and the sudden release of dredge spoil at the water surface, as dredged material resulting from sandwave clearance is deposited.

5.2 Sediment plume model design

5.2.1 Overview

5.2.1.1 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 a series of discrete particles.

5.2.2 Model grid, bathymetry and hydrodynamic inputs

5.2.2.1 The sediment plume model utilises the same model grid and the flow field timeseries generated by the validated MIKE21HD model described in Section 4. The model is therefore able to consider a range of tidal conditions over a representative spring neap cycle. A relatively high level of spatial resolution is used in the area of the proposed sediment releases.

5.2.3 Sediment types, settling, dispersion and erosion rates

5.2.3.1 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 4.

Table 4. Sediment grain size fractions used

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

5.2.3.2 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 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.

5.2.3.3 Once deposited to the seabed, sediment in the model is made unable to be eroded and will remain *in situ*. In practice, sediment in a plume that has been deposited to a similar area of seabed will 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 with more detail.

5.3 Sediment plume model validation

5.3.1.1 Section 4.3 provides validation of the current speed and direction data from the tidal model controlling advection in the particle tracking model. The representative rate of dispersion is controlled by the model settings but can be variable depending on other environmental conditions (e.g. wave conditions) in practice. The definition of the sediment release and the analysis of results is determined by an experienced modeller. Although objective quantitative validation is not possible in this case (or normally) due to a lack of similar site-specific plume observations, this type of modelling approach, in conjunction with validated hydrodynamic inputs, is generally accepted to provide a realistic description of sediment plumes in the marine environment.

5.4 Sediment disturbance scenarios

5.4.1.1 The following MDS sediment releases were considered:

- Two activity types:
  - Trenching using a CFE tool at the seabed; and
  - Spoil release from a dredger at the water surface representing disposal from sandwave clearance / seabed levelling;
- At three locations;
- Occurring (separately) on and around mean spring and mean tides.

5.4.1.2 The subsequent plume settlement and dispersion is simulated over a three day period following the end of the sediment disturbance.

5.4.1.3 Table 5 provides a summary of the sediment plume scenarios, the location of each release, the mass of sediment and the type of sediment at each site. The following notes apply for each of the three locations:

- The location of the release in Scenarios 1 to 4 is approximately central in the Hornsea Four array area. The CFE is represented as a moving source over a 21 hour period, moving from south to north at a rate of 300 m/hr (moving 6.3 km during the simulation period).

- The location of the release in Scenarios 5 to 8 is nearby to the proposed location of HVAC booster substations in the Hornsea Four ECC. The CFE is represented as a moving source over a 21 hour period, moving from east to west at a rate of 300 m/hr (moving 6.3 km during the simulation period).
- The location of the release in Scenarios 9 to 12 is nearby to the proposed location of the cable crossing offshore of Smithic Bank in the Hornsea Four ECC. The CFE is represented as a moving source over a 21 hour period, moving from east to west at a rate of 300 m/hr (moving 6.3 km during the simulation period).
- The location of the release in Scenarios 13 to 14 follows the inshore part of the cable route, west of Smithic Bank in the Hornsea Four ECC. The CFE is represented as a moving source over a 21 hour period, moving from east to west at a rate of 125 m/hr (moving 2.6 km during the simulation period).

Table 5. Sediment disturbance scenarios

Scenario Number	Mean Tidal Condition	Activity	Location of Release (UTM31N)	Mass Released	Grain Size Fractions (% of Total)
1	Neap	CFE	X 386365 Y 5992769	875 kg/s for 21 hours	Medium sand (95.3%) Silt (4.7%)
2	Spring				
3	Neap	Spoil release	X 386365 Y 5991769	1,749,000 kg sudden release*	
4	Spring				
5	Neap	CFE	X 324560 Y 5994709	1,060 kg/s for 21 hours	Coarse sand (13.26%) Fine sand (51.31%) Silt (35.43%)
6	Spring				
7	Neap	Spoil release	X 324647 Y 5993663	1,749,000 kg sudden release*	
8	Spring				
9	Neap	CFE	X 301327 Y 5993488	930 kg/s for 21 hours	Gravel (59.07%) Medium sand (39.86%) Silt (1.07%)
10	Spring				
11	Neap	Spoil release	X 301327 Y 5991488	1,749,000 kg sudden release*	
12	Spring				
13	Neap	CFE	X 293268 Y 5992068	438 kg/s for 21 hours	Gravel (7%) Medium sand (71%) Silt (22%)
14	Spring				

At 1 hour after peak flood current speed (to the south).

5.4.1.4 The mass of sediment disturbed per second by an active CFE tool was estimated by GoBe based on the MDS trench cross section dimensions, the speed of progress of the tool, and the bulk density of the local sediment type at each of the three locations. All of the disturbed sediment is initially released at 3 m above the local seabed level. In practice, an CFE will also displace some proportion of sediment from the trench to the adjacent seabed through liquefaction and near-bed gravity flow (rather than necessarily putting sediment into suspension higher into the water column). This scenario therefore provides a conservative representation of the nearfield effect of the CFE process.

5.4.1.5 The mass of sediment placed into suspension by a spoil release scenario is estimated as follows:

- A representative large hopper sediment volume of 11,000 m^3 is released suddenly (within a single 10 minute timestep in the model).
- The total mass of sediment released is estimated as 11,000 m^3 sediment x 0.6 solidity ratio x 2,650 kg/m^3 solid density = 17,490,000 kg.

- The majority (90%) of the sediment volume is realistically assumed to descend directly to the bed in the 'active phase' of the plume as a single mass of sediment, which does not contribute to the more diffuse SSC effects considered by the plume model.
- The remaining 10% of sediment (10% of 17,490,000 kg =1,749,000 kg) is assumed to be dispersed into the water column at the point of release, allowing sediment grains to remain in suspension for longer, forming the 'passive phase' of the plume.
- It is assumed that the sediment is sufficiently mixed by the dredging process that the proportion of sediment fractions in the active and passive phases are the same as the original seabed sediment.

5.4.1.6 The proportion of sediment assumed to be in the passive and active phases is a conservatively representative value that may vary in practice. The chosen value (up to 10% in the passive phase) is consistent with recent studies on this topic by Becker *et al*. (2015).

5.4.1.7 The sediment type at each location is based on grab sample results from the recent benthic survey conducted for Hornsea Four along the ECC (Bibby Hydromap, 2019) and across the offshore array area (Gardline, 2019). The proportion of sediment mass in each grain size fraction is accounted for the in the number and mass of the individual particles released at each timestep.

5.5 Sediment plume model results

5.5.1 Overview

5.5.1.1 The following results are provided as images in Appendix C:

- Results for each model scenario in Table 5.
- Maps of SSC at the end of sediment disturbance, and one and three days later.
- Maps of instantaneous maximum SSC at any time throughout the model simulation period.
- Timeseries of SSC at a central location in the area of sediment disturbance (centre of the CFE route or at the location of the spoil disposal).
- Maps of settled sediment thickness at the end of the model simulation period.

5.5.1.2 Results for SSC describe an increase in SSC relative to the ambient naturally occurring condition.

5.5.1.3 Sediment in the model is not subject to erosion or further transport following deposition to the seabed. In practice, sediment in the plume that has been deposited to a similar area of seabed will re-join the natural sedimentary environment and will be mobilised again when the local conditions are suitable to cause erosion of that sediment type. The sediment will be naturally eroded at the same time and rate as all other similar naturally present sediment in that location, contributing to the ambient naturally occurring levels of SSC and any resulting deposition.

5.5.2 Summary of results: SSC of plumes from trenching (moving point source over multiple flood/ebb cycles)

5.5.2.1 Maps of SSC associated with CFE trenching, for all sediment types together, are shown in Figure C1 and Figure C3 for the Hornsea Four array area, Figure C9 and Figure C11 for the HVAC booster station search area, Figure C17 and Figure C19 for the nearshore cable crossing area, and in Figure

C25 and Figure C27 for the inshore cable route area, for neap and spring tidal conditions, respectively.

5.5.2.2 Maps of SSC associated with CFE trenching, for only the finer silt sized sediments that are advected over longer distances, are shown in Figure C2 and Figure C4 for the Hornsea Four array area, Figure C10 and Figure C12 for the HVAC booster station search area, Figure C18 and Figure C20 for the nearshore cable crossing area, and in Figure C26 and Figure C28 for the inshore cable route area, for neap and spring tidal conditions, respectively.

5.5.2.3 The following summary provides a general description and characterisation of the more detailed results for each location shown in the figures listed above. See the individual figures for site and scenario specific details of SSC and plume dimensions.

5.5.2.4 The plume feature resulting from continuous trenching activities is characterised as a long, relatively thin plume extending downstream from the point of active trenching. The path of active trenching in the simulation period is visible in the results images as a line of higher maximum instantaneous SSC.

5.5.2.5 Gravels and sands will settle relatively rapidly towards the seabed (see Table 4, settling velocities from 0.01 to 0.5 m/s). From the maximum expected height of initial suspension (3 m above bed), sediment of these grain sizes is likely to resettle to the seabed (no longer contributing to an increase in SSC) within 1 to 5 minutes. At a representative higher current speed of 0.9 m/s on spring tides, these sediment grades will settle to the bed (and not cause any effect on SSC) within 5 m (gravel) to ~250-300 m (finer sands) from the trench. This distance will be proportionally reduced during periods of lower current speed (e.g. times other than peak flow speed and generally around neap tides).

5.5.2.6 The level of SSC caused by all sediment types together is realistically expected to be locally very high at the location of active trenching (where sediment is being put into suspension at a rate of the order 800 to 1,000 kg/s). Within 5 m of the activity, SSC might be millions of mg/l or more locally, i.e. more sediment than water in parts of the local plume. The effect is very localised and would last only while the CFE is active over that section of the trench. As sediment in the plume is redeposited and dispersed both vertically and horizontally with distance and time downstream, SSC is expected to reduce to thousands or high hundreds of mg/l within tens to low hundreds of metres. These detailed nearfield processes are only relatively coarsely resolved in the model (at a resolution of 50-100 m).

5.5.2.7 From the relatively low height of initial suspension from the trench, only silt sized sediments are likely to persist in suspension for long enough to cause any effect on SSC beyond approximately 5 m for gravels, 30 m for coarse sand, 90 m for medium sand, and ~250-300 m for finer sands, from the trench.

5.5.2.8 The width of the plume of finer material (silt) is initially in the order of 10 to 50 m (within 10 to 20 minutes of release, up to 500 to 1,000 m downstream). The SSC in this section of plume is relatively high (up to 1,000 mg/l for all sediment types and up to 100 mg/l for silts alone).

5.5.2.9 During the first half tidal cycle (~6 hours), the width of the plume increases through dispersion to 50-100 m, all non-silt sediments have settled to the seabed, and SSC consequentially reduces rapidly to 5-10 mg/l.

5.5.2.10 After 3 days, the width of the measurable plume spreads to 250-500 m wide and SSC reduces to 1-2 mg/l as a result of ongoing sediment dispersion and settlement.

5.5.2.11 The magnitude of SSC associated with silt is shown to be relatively higher in the HVAC booster station search area scenarios (Figure C9 and Figure C11). This is due to the higher proportion of silt in the seabed sediment being disturbed (approximately 35%, see Table 5), and so a higher release rate of this sediment type. The proportion of silt is lower in the array area (5%) and lowest in the nearshore cable crossing area (1%), leading to proportionally lower SSC in the plume in these areas, generated by otherwise similar activities causing sediment plumes.

5.5.2.12 During spring tidal conditions, the disturbed sediment is carried away from the working area at a faster rate, dispersing the sediment mass over a larger area and water volume, and so the resulting SSC in the plume is relatively lower than on a comparable neap tide.

5.5.2.13 During slack water (on both neap and spring tides), water is not moving sediment away from the area of disturbance, resulting in suspended sediment accumulating in a local area of relatively higher SSC (approximately 100-200 m across, order of 5 to 10 mg/l). This local area of higher SSC is subsequently advected by the tide and may take longer to reduce to background levels than other parts of the plume generated during non-slack water conditions.

5.5.2.14 The limited width/footprint of the plume feature means that specific locations will only be affected by the described increase in SSC for the limited duration it takes for the plume to be advected past by the tide.

5.5.2.15 The path followed by the tidal ellipse is not the same on every tide, so it is unlikely that the same area of seabed will be affected by higher SSC more localised plume for more than one or two consecutive tides.

5.5.3 Summary of results: SSC of plumes from spoil disposal

5.5.3.1 Maps of SSC associated with the passive phase of the plume created by spoil disposal, for all sediment types together, are shown in Figure C5 and Figure C7 for the array area, Figure C13 and Figure C15 for the HVAC booster station search area, and in Figure C21 and Figure C23 for the nearshore cable crossing area, for neap and spring tidal conditions, respectively.

5.5.3.2 Maps of SSC associated with the passive phase of the plume created by spoil disposal, for only the finer silt sized sediments that are advected over longer distances, are shown in Figure C6 and Figure C8 for the array area, Figure C14 and Figure C16 for the HVAC booster station search area, and in Figure C22 and Figure C24 for the nearshore cable crossing area, for neap and spring tidal conditions, respectively.

5.5.3.3 The following summary provides a general description and characterisation of the more detailed results for each location shown in the figures listed above. See the individual figures for site and scenario specific details of SSC and plume dimensions.

5.5.3.4 The passive phase plume feature resulting from a spoil disposal event is characterised as an isolated circular plume, initially with higher concentration in the centre, decreasing with radial distance outwards.

5.5.3.5 Gravels and sands will settle relatively rapidly towards the seabed (see Table 4, settling velocities from 0.01 to 0.5 m/s). From the maximum expected height of initial suspension (50 m above bed within the Hornsea Four array area), sediment of these grain sizes is likely to resettle to the seabed (no longer contributing to an increase in SSC) within 2 to 85 minutes. At a representative higher current speed of 0.9 m/s on spring tides, these sediment grades will settle to the bed (and not cause any effect on SSC) within approximately 90 m for gravel, 450 m for coarse sand, 1,500 m for medium sand and 4,500 m for finer sands, from the trench. This distance will be proportionally reduced during periods of lower current speed (e.g. times other than peak flow speed and generally around neap tides).

5.5.3.6 Fine sand and silt sized sediments persist in suspension for longer than relatively coarser sediment grain sizes (i.e. medium sand, coarse sand and gravels) and so control the majority of the effect on SSC beyond the above durations/distances.

5.5.3.7 The magnitude of SSC associated with silt is shown to be relatively higher in the HVAC booster station search area scenarios (Figure C13 and Figure C15). This is due to the higher proportion of silt in the seabed sediment being disturbed (approximately 35%, see Table 5), and so a higher release rate of this sediment type.

5.5.3.8 The proportion of silt in the seabed sediment being disturbed is lower in the array area (5%) and lowest in the nearshore cable crossing area (1%), leading to proportionally lower SSC in the plume in these areas, generated by otherwise similar activities causing sediment plumes.

5.5.3.9 The dimensions of the plume is realistically expected to be in the order of tens of metres in diameter at the point of release (not resolved directly by the model).

5.5.3.10 The plume model indicates that dispersion will increase the width of the plume to approximately 1 to 2 km after one tidal cycle (approximately 12 hours), 3 km after one day and to approximately 5 km after 3 days, with an associated reduction in SSC.

5.5.3.11 The level of SSC associated with all sediment fractions is realistically expected to be locally very high at the location of the spoil release (millions of mg/l within 5 m of the activity, i.e. more sediment than water in the local plume. This level of detail is not resolved directly by the sediment plume model, which indicates a more dispersed initial concentration of 1,000 to 10,000 mg/l.

5.5.3.12 Due to ongoing dispersion and the settlement of non-silt sediment to the seabed during the first half tidal cycle, the level of SSC associated with the remaining silt in the advected plume will reduce with time from 50 to 100 mg/l in central parts of the plume after one day, to less than 2 mg/l after 3 days.

5.5.3.13 The limited width/footprint of the plume feature means that specific locations will only be affected by the described increase in SSC for the limited duration it takes for the plume to be advected past by the tide. The limited width of the spoil disposal plume also means that only locations closely aligned to the disposal location along the tidal axis are likely to be measurably affected.

5.5.3.14 The path followed by the tidal ellipse is not the same on every tide, so it is unlikely that the same area of seabed will be affected by higher SSC more localised plume for more than one or two consecutive tides.

5.5.4 Summary of results: Settlement thickness resulting from plumes from CFE trenching

5.5.4.1 Estimates of the footprint and thickness of sediment deposition from CFE trenching are provided based on:

- The results of the sediment plume model (for all sediment types and for silts alone); and
- Direct estimates (for all sediment types).

5.5.4.2 The sediment plume model results provide the more reliable description of settlement thickness in the far field, i.e. for sediments that are subject to advection and dispersion over timescales greater than 1 hour and distances greater than 500 to 1,000 m.

5.5.4.3 The direct estimates provide a more generalised but demonstrably realistic range of potential deposition area/thickness combinations in the nearfield, i.e. for sediment of any type that is deposited more rapidly to the seabed in timescales less than 1 hour and distances less than 500 to 1,000 m. Such direct estimates can provide a more reliable description of details in the nearfield that are not resolved spatially or temporally by the sediment plume model.

CFE - sediment plume model estimates of settlement thickness

5.5.4.4 Maps of settlement thickness for all sediment types together, and for only the finer silt sized sediments that are advected over longer distances, are shown in Figure C29 and Figure C30 for the Hornsea Four array area, in Figure C31 and Figure C32 for the HVAC booster station search area in the ECC, Figure C33 and Figure C34 for the nearshore cable crossing area offshore of Smithic Bank, and in Figure C35 and Figure C36 for the inshore cable route area, respectively.

5.5.4.5 The following summary provides a general description and characterisation of the more detailed results for each location shown in the figures listed above. See the individual figures for site and scenario specific details of settlement thickness and extent.

5.5.4.6 The results show the thickness of sediment following initial deposition. The same sediment may be subsequently re-eroded and resettled elsewhere as part of the ongoing natural sediment transport regime.

5.5.4.7 The predicted thickness of settlement accounting for all sediment types is limited. The coarser sand and gravel fractions at each site settle to the seabed within a limited time of release (from seconds up to 5 minutes, i.e. within the 10 minute timestep of the sediment plume model) and so tend to be deposited within a relatively small footprint (from metres up to 270 m), resulting in a relatively greater local thickness of 115 to 130 mm in the Hornsea Four array area (Figure C31), 100 to 120 mm in the cable crossing area, and 130 to 140 mm in the inshore cable route area . The predicted thickness of settlement for only the finer sediments dispersed more widely in the passive phase plume at these locations is very limited, in the order of <1 mm in all sites, over a dispersed area of effect.

5.5.4.8 In the HVAC booster station search area, the maximum local settlement thickness is relatively smaller (50 to 70 mm) because the majority of non-silt sediment is fine sand, which is dispersed slightly more widely before settlement. The settlement thickness from silt alone might be relatively greater (8 to 10 mm) near to the trenching activity because of the higher proportion of silt in the sediment being released.

5.5.4.9 Sediment accumulation of this magnitude would not cause a measurable change in bed level or sediment type in practice. Fine sediments that do settle are also likely to experience further erosion and dispersion during subsequent tides. The area and thickness of sediment settlement from the active phase and coarser sediments in the passive phase of the plume which are not resolved in detail by the plume model are considered below.

CFE - direct estimates of settlement thickness

5.5.4.10 As discussed in Section 5.5.2, coarser sediments (gravels and sands) will settle form the maximum height of disturbance (3 m) relatively rapidly towards the seabed and so the distance of advection and dispersion is realistically limited to distances within 5 m (gravel) to ~250-300 m (finer sands) downstream from the trench during representative stronger tidal current conditions (0.9 m/s). Distances will be proportionally less at times of lower current speed. The plume model does not resolve spatial details less than the resolution of the model mesh (between 50 and 100 m) and tidal current speed varies widely over flood and ebb, and spring and neap cycles. The following method provides a range of realistic direct estimates.

5.5.4.11 The volume of sediment displaced from the trench is finite and proportional to the trench cross section (up to 6 m^2) and so it is possible to estimate the maximum average sediment thickness for a range of realistic downstream dispersion distances. Results are presented in Table 6. This calculation assumes that the downstream dispersion is approximately perpendicular to the trench axis (which is applicable to most of the Hornsea Four ECC). Where the current direction is more oblique to the trench, the perpendicular distance from the trench to the edge of the deposit might be reduced, with a proportional increase in average thickness. In all cases, a larger footprint or extent of effect for any reason will result in a proportionally smaller average thickness of deposition, and *vice versa*.

Table 6. Maximum average sediment deposit thickness for a range of realistic downstream dispersion distances

Downstream Dispersion Distance (m)	Maximum Average Thickness of Sediment Accumulation (mm) for Varying Trench Cross Sections		
	4 m^2	5 m^2	6 m^2
5	800	1,000	1,200
10	400	5,00	600
25	160	2,00	240
50	80	100	120
100	40	50	60
150	27	33	40
200	20	25	30
250	16	20	24
300	13	17	20

5.5.5 Summary of results: Settlement thickness resulting from plumes from spoil disposal

5.5.5.1 Estimates of the footprint and thickness of sediment deposition from dredge spoil disposal are provided based on:

- The results of the sediment plume model for the passive phase of the plume only (for all sediment types and for silts alone).
- Direct estimates for the passive phase of the plume only (for all sediment types); and
- Direct estimates for the active phase of the plume only (for all sediment types).

5.5.5.2 The sediment plume model results provide the more reliable description of settlement thickness in the far field, i.e. for sediments that are subject to advection and dispersion over timescales greater than 1 hour and distances greater than 500 to 1,000 m.

5.5.5.3 The direct estimates provide a more generalised but demonstrably realistic range of potential deposition area/thickness combinations in the nearfield, i.e. for sediment of any type that is deposited more rapidly to the seabed in timescales less than 1 hour and distances less than 500 to

1,000 m. Such direct estimates provide a more reliable description of details in the nearfield that are not resolved spatially or temporally by the sediment plume model.

5.5.5.4 The results from the plume model relate only to the sediment in the passive phase of the plume (i.e. 10% of the total sediment volume/mass being deposited). Results for the passive and active phases of the plume should be considered together in order to describe the full effect of the dredge spoil release.

Spoil disposal passive phase - sediment plume model estimates of settlement thickness

5.5.5.5 Maps of settlement thickness for all sediment types together, and for only the finer silt sized sediments that are advected over longer distances, are shown in Figure C29 and Figure C30 for the Hornsea Four array area, in Figure C31 and Figure C32 for the HVAC booster station search area in the ECC, and in Figure C33 and Figure C34 for the nearshore cable crossing area offshore of Smithic Bank, respectively.

5.5.5.6 The following summary provides a general description and characterisation of the more detailed results for each location shown in the figures listed above. See the individual figures for site and scenario specific details of settlement thickness and extent.

5.5.5.7 The results show the thickness of sediment following initial deposition. The same sediment may be subsequently re-eroded and resettled elsewhere as part of the ongoing natural sediment transport regime.

5.5.5.8 The predicted thickness of settlement accounting for all sediment types in the passive phase plume is limited. The coarser sand and gravel fractions at each site settle to the seabed within a limited time of release (from minutes to 1 hour) and so tend to be deposited within a relatively small footprint (200-300 m diameter or less), resulting in a relatively greater local thickness of 30 to 40 mm in the Hornsea Four array area (Figure C31), and 60 to 100 mm from the cable crossing area. The predicted thickness of settlement for only the finer sediments dispersed more widely in the passive phase plume at these locations is very limited, in the order of <1 mm in all sites, over a dispersed area of effect.

5.5.5.9 In the HVAC booster station search area, the maximum local settlement thickness is relatively smaller (3 to 4 mm) because the majority of non-silt sediment is fine sand, which is dispersed more widely before settlement. The settlement thickness from silt alone is however relatively greater (2.5 to 5 mm) near to the trenching activity because of the higher proportion of silt in the sediment being released.

5.5.5.10 Sediment accumulation of this magnitude would not cause a measurable change in bed level or sediment type in practice. Fine sediments that do settle are also likely to experience further erosion and dispersion during subsequent tides. The area and thickness of sediment settlement from the active phase and coarser sediments in the passive phase of the plume which are not resolved in detail by the plume model are considered below.

Spoil disposal passive phase – direct estimates of settlement thickness

5.5.5.11 As discussed in Section 5.5.3, coarser sediments (gravels and sands) in the passive plume will settle from the water surface (up to 50 m above the seabed in the array area) relatively rapidly towards the seabed and so the distance of advection and dispersion is realistically limited to distances within 90 m (gravel) to ~4,500 m (finer sands) downstream from the disposal site during representative stronger tidal current conditions (0.9 m/s on spring tides). Distances will be proportionally less at times of lower current speed (and during neap tides). The plume model does not resolve spatial details less than the resolution of the model mesh (between 50 and 100 m) and tidal current speed varies widely over flood and ebb, and spring and neap cycles. The following method provides a range of realistic direct estimates.

5.5.5.12 As noted in Section 5.4, the total volume of sediment in the passive phase of the plume is limited (10% of 11,000 m^3 = 1,100 m^3) and so it is possible to estimate the maximum average sediment thickness for a range of realistic dispersion footprint dimensions. Results are presented in Table 7. These estimates conservatively assume that all sediment in the passive phase is deposited to the seabed, however, the silt fraction (comprising up to 5 to 35% of the sediment mass in the passive phase, depending on the location, see Table 5) will remain in suspension for longer (as described by the plume model results above) and will not contribute to these estimates.

Table 7. Maximum average sediment deposit thickness as a result of the passive plume for a range of realistic downstream dispersion distances

Downstream Dispersion Distance (m)	Maximum Average Thickness of Sediment Accumulation (mm) for Varying Dispersion Widths.		
	50 m	100 m	200 m
100	220	110	55
250	88	44	22
500	44	22	11
750	29	15	7
1,000	22	11	6
2,000	11	6	3
3,000	7	4	2
4,000	6	3	1
5,000	4	2	1

Spoil disposal active passive phase – direct estimates of settlement thickness

5.5.5.13 The active phase of the plume will descend rapidly and directly to the seabed, where it will spread laterally, initially with the force of impact and then under gravity. The final shape or dimensions of the deposit therefore cannot be predicted in detail. The volume of sediment in the active phase of the plume is also limited (90% of 11,000 m^3 = 9,900 m^3) and so it is also possible to estimate the maximum average sediment thickness for a range of realistic dispersion footprint areas. Results are presented in Table 8.

Table 8. Maximum average sediment deposit thickness for a range of realistic active phase deposit dimensions and areas

Deposit Length Scale (m)	Deposit Footprint Area (m^2)*	Maximum Average Thickness of Sediment Accumulation (mm)
50	2,500	3,960
100	10,000	990
150	22,500	440
200	40,000	248
222	49,500	200
315	99,000	100
445	198,000	50

* Deposit footprint area] = [Deposit length scale^2

5.5.6 Tidal excursion distance and plume advection

5.5.6.1 The local extent of the sediment plume at any given time describes the instantaneous local magnitude and extent of elevated SSC. As described in Sections 5.5.2 and 5.5.3, the plume is being almost continuously moved (advected) by the ambient currents. This section considers the distances and directions that the plume might be displaced from the source before it is dissipated to near background concentrations, and therefore the overall spatial extent that any local plume effects might be (temporarily) experienced.

5.5.6.2 The sediment plume is mainly advected from the source of the sediment disturbance by the ambient tidal currents. The relative motion (local speed and direction) of the plume at any given time in the tidal cycle will vary depending not only on the relative time in the flood ebb cycle, but also the spatially varying flow characteristics along the path of advection.

5.5.6.3 In open water, plume advection typically describes an elliptical path, which may or may not be closed, i.e. returning to approximately the same position at the end of the tidal cycle. In areas of more complex flow, the path may be more complex, e.g. following coastline or bathymetric features, and the path may not be necessarily closed. The distance that the plume is advected from the disturbance source (both along the tidal axis and laterally across it) describes the area over which any effects on SSC are likely to occur. Conversely, areas beyond the tidal excursion distance and footprint are unlikely to experience any effect on SSC from the plume.

5.5.6.4 The displacement of the plume features by tidal currents provides a proxy measure of the tidal excursion distance from each of the three release locations for representative neap and spring range conditions. The path of the plume (including changes in flow speed and direction elsewhere in the model domain) provides a 'Lagrangian' estimate. In areas of more complex flow (e.g. near to Smithic Bank and Flamborough Head), this provides a more realistic measure than the alternative 'Eularian' estimate (based on the net displacement of water past a particular location).

5.5.6.5 The tidal excursion distance is the approximate distance over which a package of water (or a section of plume with elevated SSC is advected during one flood or ebb tide.

5.5.6.6 The values below were determined based on the observed advection of the plumes features in the sediment plume model results, over multiple flood and ebb cycles, during representative mean neap and mean spring tidal range conditions. There can be variation in the peak current speed between consecutive flood and ebb tides (see Figure 13 to Figure 17), therefore, a small range of tidal excursion distances are presented for tidal ranges representative of mean neap and mean spring conditions.

5.5.6.7 The tidal excursion distance varies in proportion to the peak current speed during particular flood or ebb cycles. As such, the distance may also be smaller than the mean neap conditions (on smaller than mean neap tidal ranges) and occasionally larger than the mean spring condition (on larger than mean spring tidal ranges).

5.5.6.8 In the Hornsea Four array area:

- On neap tides, the tidal excursion distance is between ~4-7 km, depending on the peak flow speed during that half tidal cycle.
- On spring tides, the tidal excursion distance is between ~8-10 km, depending on the peak flow speed during that half tidal cycle.
- There was minimal residual advection evident over a 3 day period in this location on these tides.

5.5.6.9 In the HVAC booster station search area of the Hornsea Four ECC:

- On neap tides, the tidal excursion distance is between ~5-7 km, depending on the peak flow speed during that half tidal cycle.
- On spring tides, the tidal excursion distance is between ~9-12 km, depending on the peak flow speed during that half tidal cycle.
- There is minimal (slight southerly) residual advection over a 3 day period.

5.5.6.10 In the cable crossing area of the Hornsea Four ECC, just offshore of Smithic Bank:

- On neap tides, the tidal excursion distance is ~6 km.
- On spring tides, the tidal excursion distance is ~14 km.
- Further offshore, there is minimal (slight southerly) residual advection over a 3 day period.
- Closer inshore, there is significant residual advection also affecting plume advection and dispersion over a 3 day period, associated with the large scale complex flow features associated with Flamborough Head and Smithic Bank.

5.5.6.11 In the inshore cable area of the Hornsea Four ECC, west of Smithic Bank:

- On neap tides, the tidal excursion distance is ~4 km to the south and ~6 km to the north.
- On spring tides, the tidal excursion distance is ~6 km to the south and ~10 km to the north.
- Further offshore, there is minimal (slight southerly) residual advection over a 3 day period.
- The orientation of the streamlines in inshore areas (approximately 1 km or more from the coast) during the flood tide to the north (see Figure B1 and Figure B2) cause the path of the plume to diverge from the coastline in order for the flow to pass around Flamborough Head. Any remaining effect of plumes originating in inshore areas that is present at or north of Flamborough Head at the turn of the tide are likely to be subsequently be directed south, east of Smithic Bank, remaining further offshore (rather than back along the adjacent coastline).

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7 Nomenclature

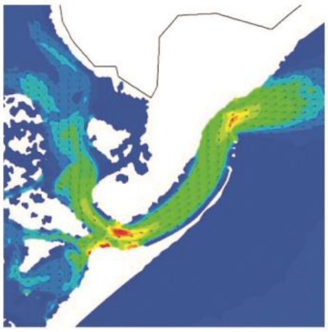
AWAC	Acoustic Wave and Current Meter
BODC	British Oceanographic Data Centre
CCO	Channel Coastal Observatory
CFE	Controlled flow excavator
CFS	Climate Forecast System
CFSR	Climate Forecast System Reanalysis
DHI	Danish Hydraulic Institute
DirM	Mean wave direction
DSD	Directional standard deviation
DTU	Danish Technical University
ECC	Export Cable Corridor
EIA	Environmental Impact Assessment
EMODnet	European Marine Observation and Data Network
FM	Flexible Mesh (MIKE21FM model)
GoBe	GoBe Consultants Ltd
HD	Hydrodynamic (MIKE21FMHD model)
HRW	Hydraulics Research, Wallingford
Hs	Significant wave height
HVAC	High Voltage Alternating Current
LAT	Lowest Astronomical Tide
MDir	Mean Wave Direction
MDS	Maximum Design Scenario
MSL	Mean Sea Level
NCEP	National Centers for Environmental Prediction
NOAA	National Ocean and Atmospheric Administration
OWF	Offshore Wind Farm
PT	Particle tracking (MIKE21FMPT model)
RP	Return Period
SSC	Suspended Sediment Concentration
SW	Spectral Wave (MIKE21SW model)
SWAN	Simulating WAves Nearshore (wave model)
Tm01	Mean wave period
Tp	Peak wave period
UCL	University College London
UK	United Kingdom
UKHO	United Kingdom Hydrographic Office
UKMO	United Kingdom Met Office
UTM	Universal Transverse Mercator
VORF	Vertical Offshore Reference Frames
WTG	Wind Turbine Generator

Cardinal points/directions are used unless otherwise stated.

SI units are used unless otherwise stated.

Appendices




Innovative Thinking - Sustainable Solutions

A Results from the Extreme Wave Model

A.1 Baseline Wave Conditions

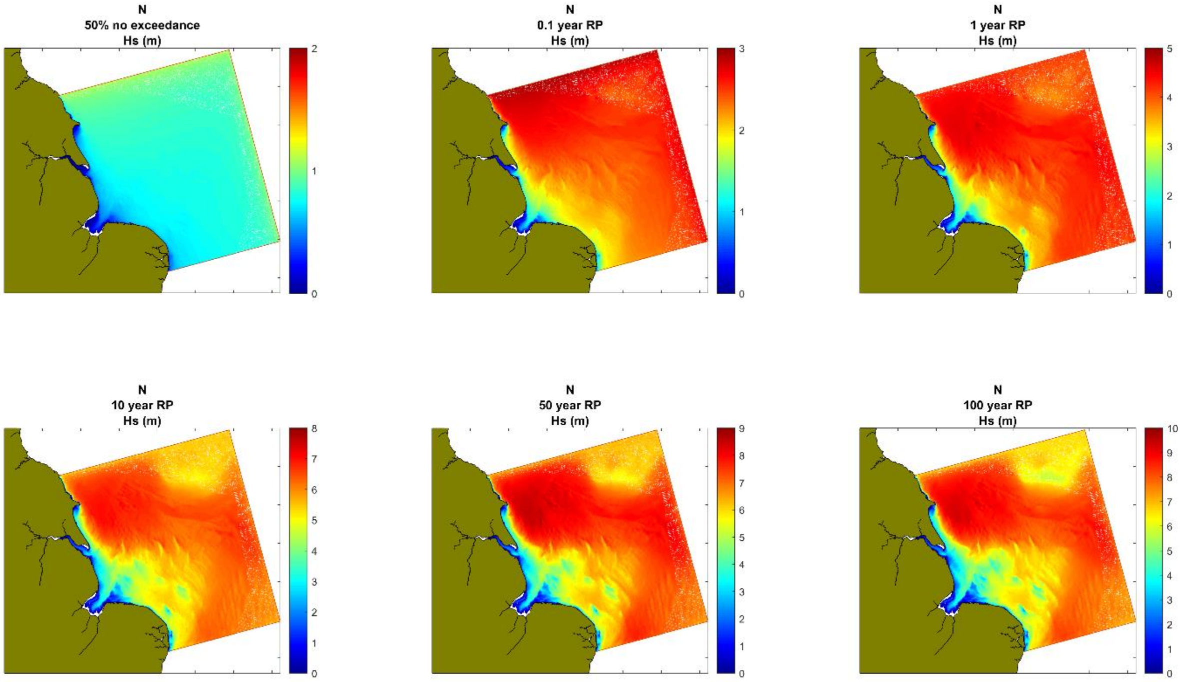


Figure A1. Baseline significant wave height, waves from the north, all return periods

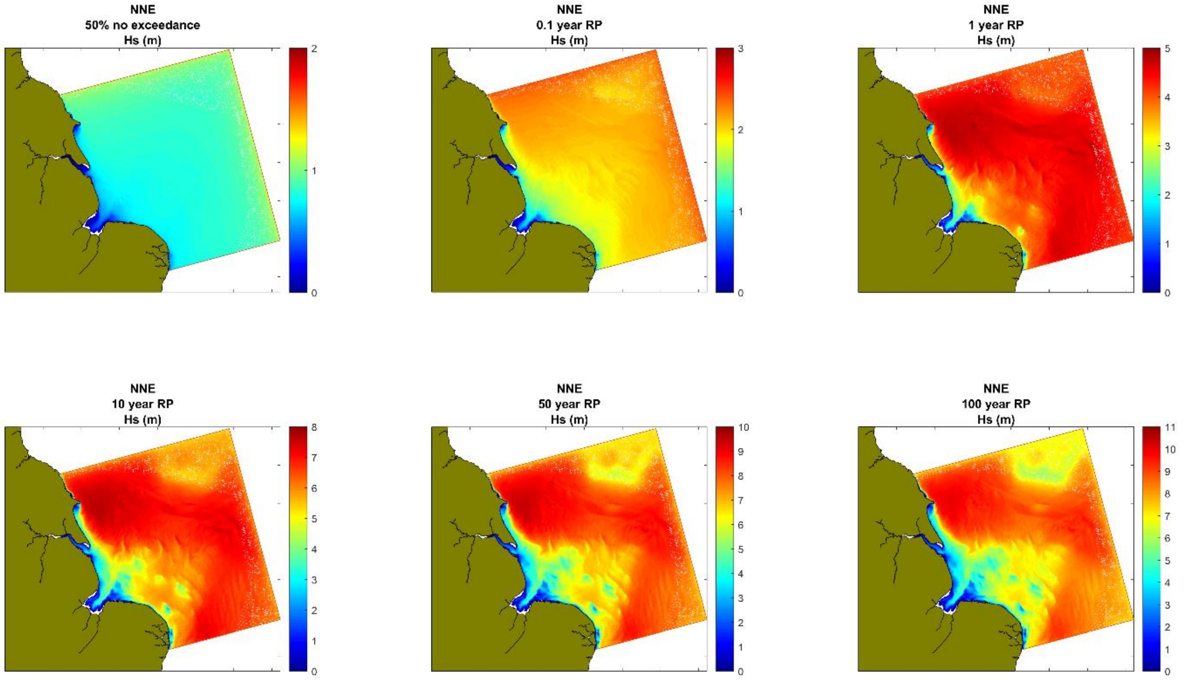


Figure A2. Baseline significant wave height, waves from the north-north-east, all return periods

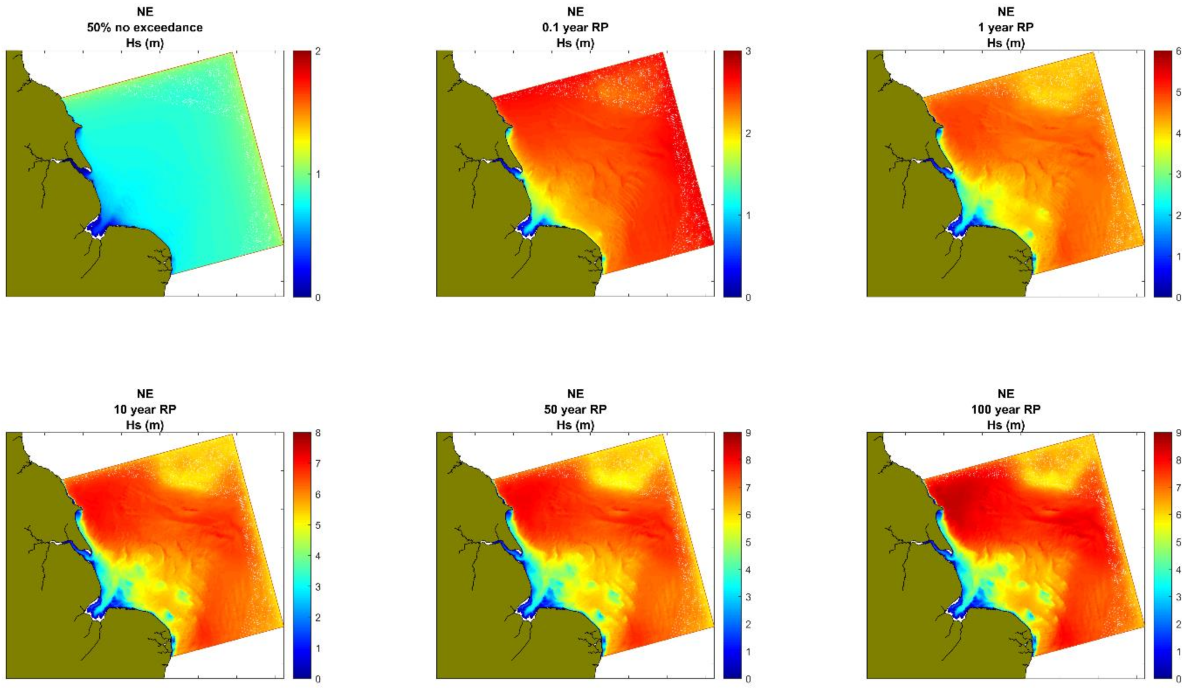


Figure A3. Baseline significant wave height, waves from the north-east, all return periods

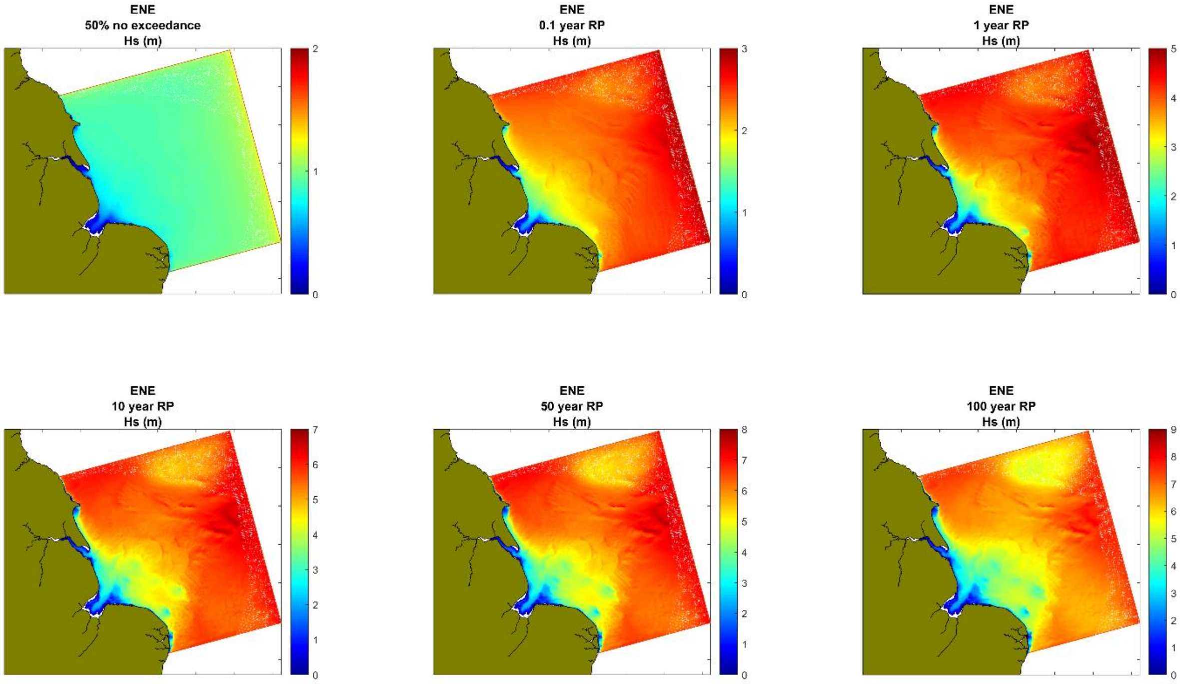


Figure A4. Baseline significant wave height, waves from the east-north-east, all return periods

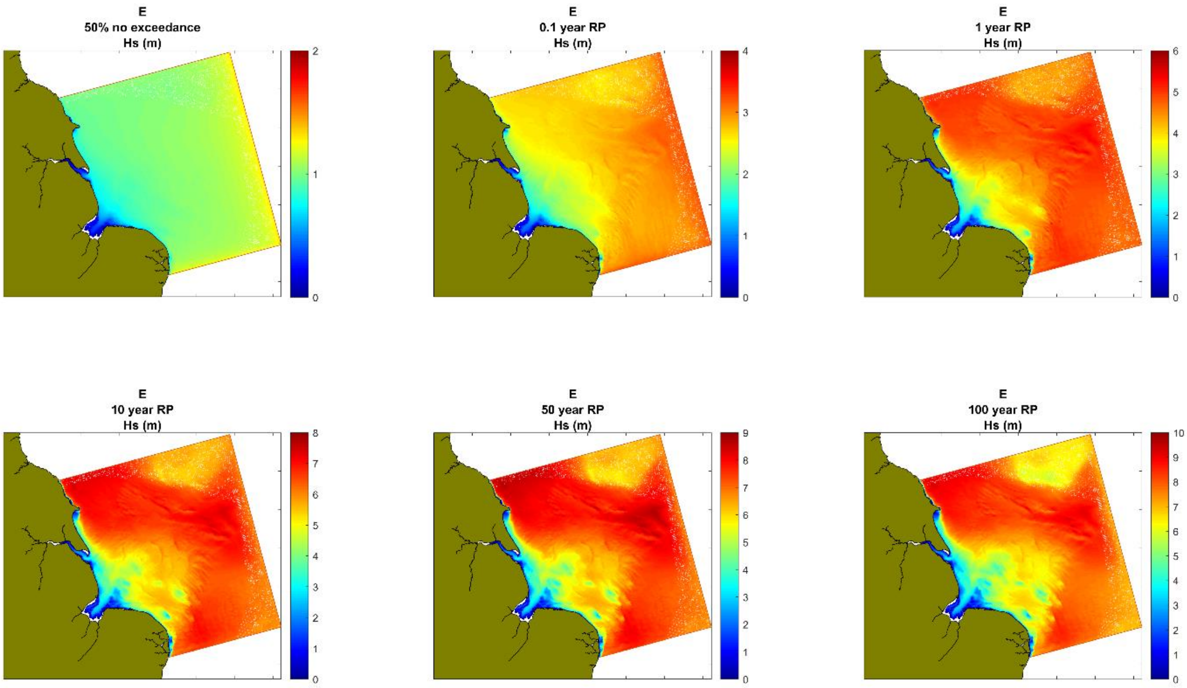


Figure A5. Baseline significant wave height, waves from the east, all return periods

A.2 Hornsea Four In Combination With Other Offshore Wind Farms (reduction in water depth 1.8 m at cable crossing area near Smithic Bank)

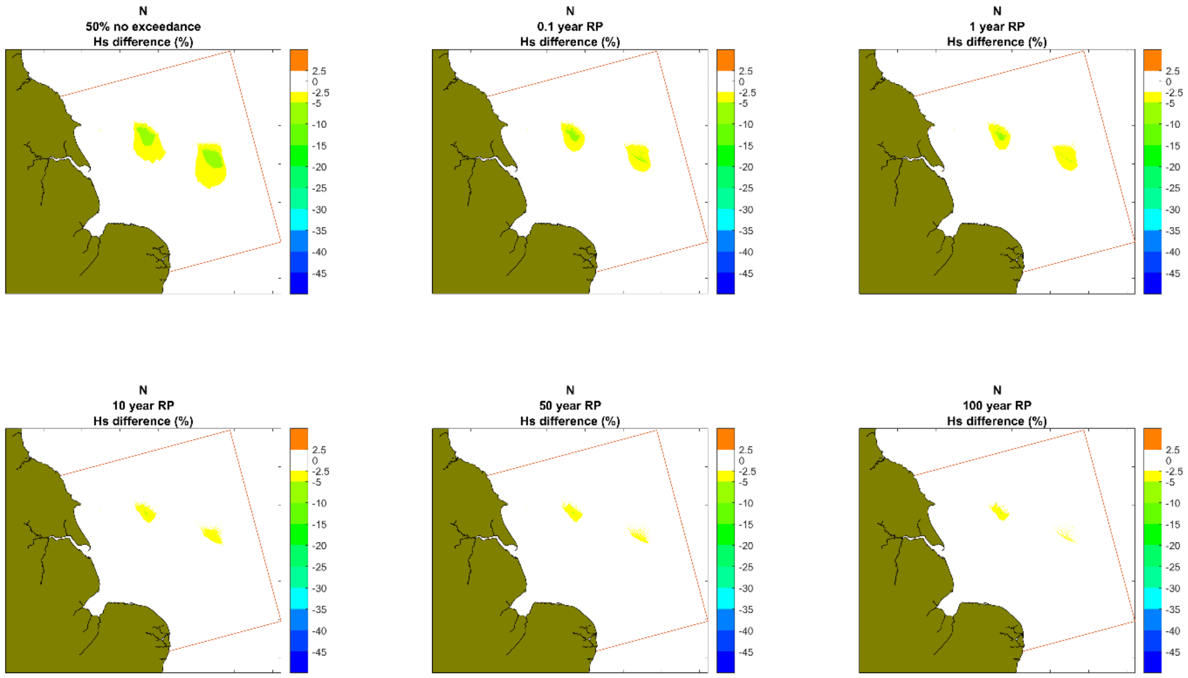


Figure A6. Percentage difference in significant wave height (scheme minus baseline as a proportion of baseline values), operational phase, waves from the north, all return periods. Negative values are a reduction in wave height as a result of the installed infrastructure. 1.8 m reduction in water depth in the cable crossing area

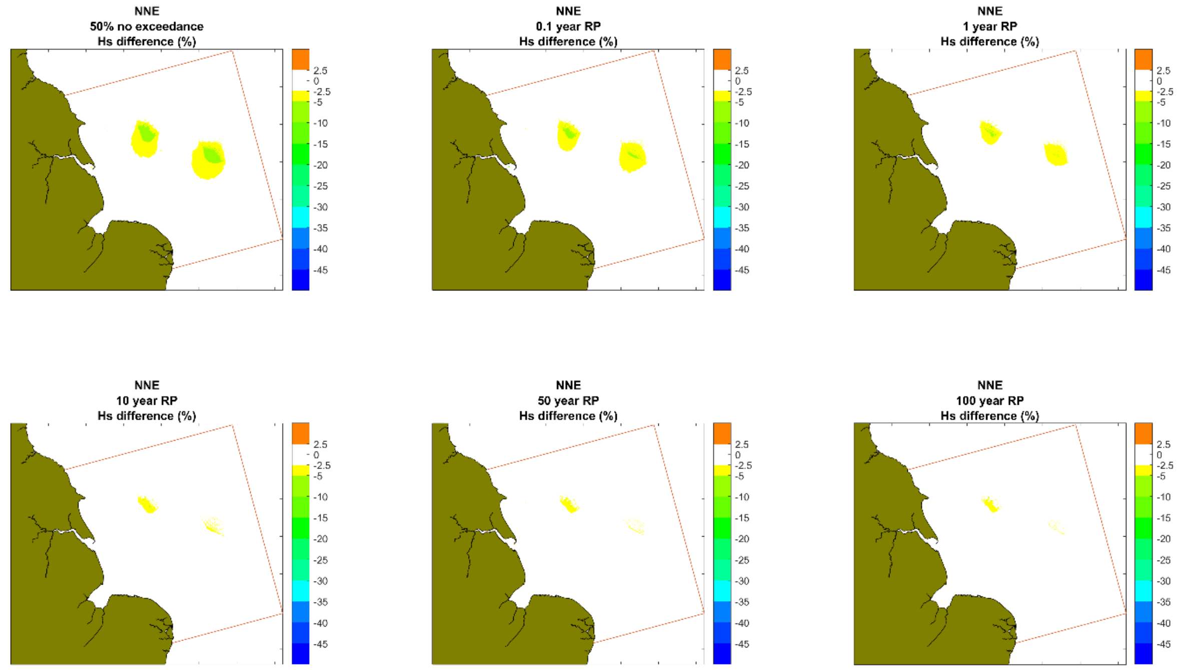


Figure A7. Percentage difference in significant wave height (1.8 m scheme minus baseline as a proportion of baseline values), operational phase, waves from the north-north-east, all return periods. Negative values are a reduction in wave height as a result of the installed infrastructure. 1.8 m reduction in water depth in the cable crossing area

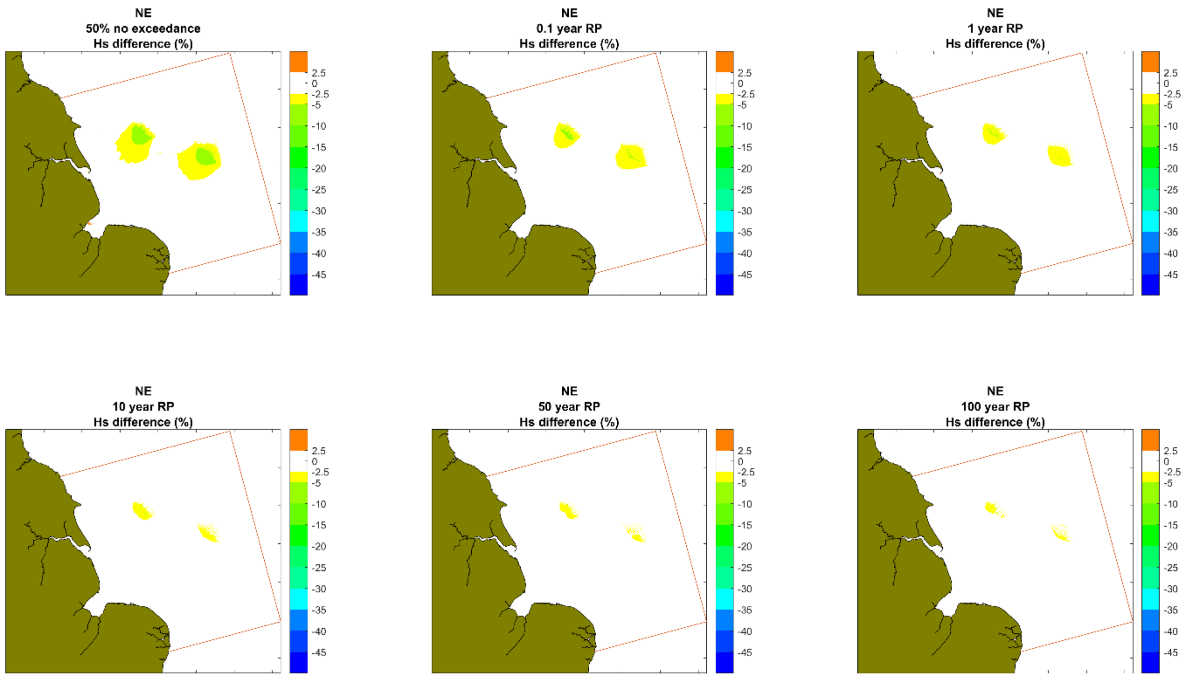


Figure A8. Percentage difference in significant wave height (1.8 m scheme minus baseline as a proportion of baseline values), operational phase, waves from the north-east, all return periods. Negative values are a reduction in wave height as a result of the installed infrastructure. 1.8 m reduction in water depth in the cable crossing area

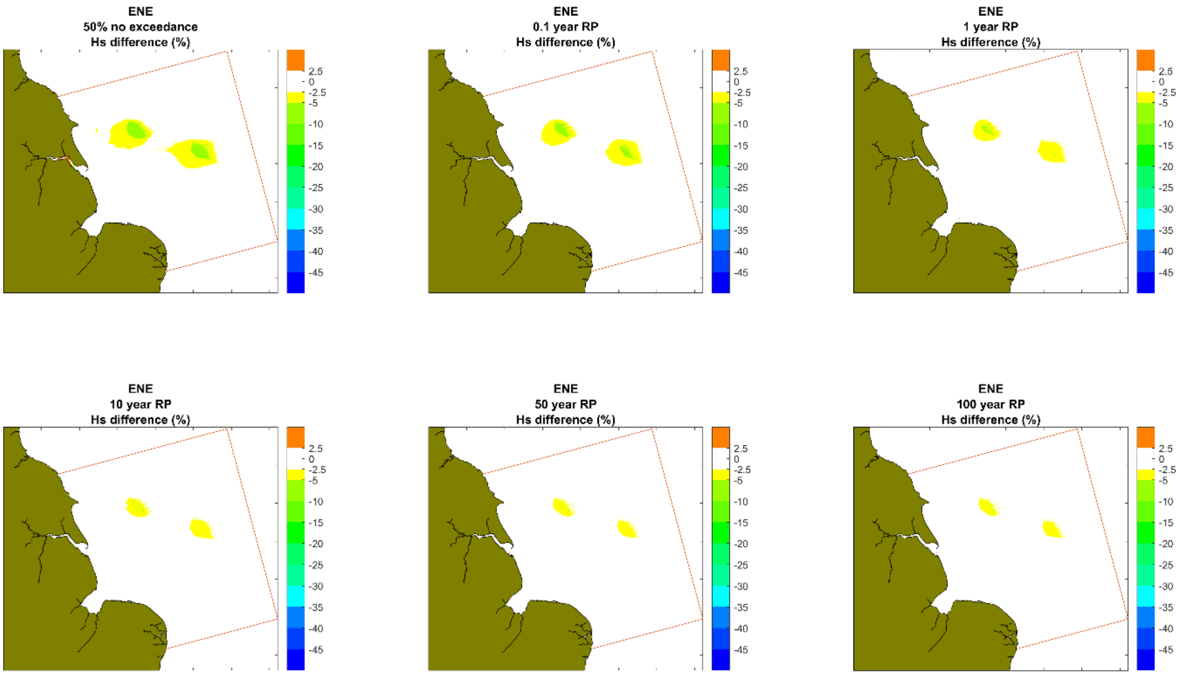


Figure A9. Percentage difference in significant wave height (1.8 m scheme minus baseline values), operational phase, waves from the east-north-east, all return periods. Negative values are a reduction in wave height as a result of the installed infrastructure. 1.8 m reduction in water depth in the cable crossing area

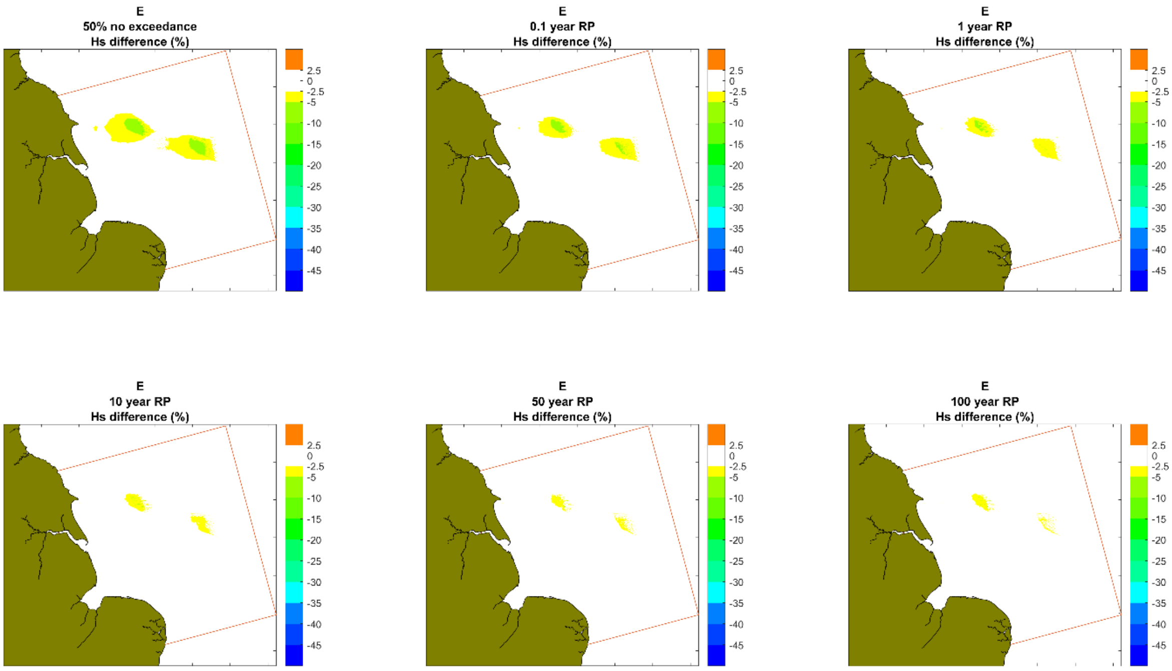


Figure A10. Percentage difference in significant wave height (1.8 m scheme minus baseline as a proportion of baseline values), operational phase, waves from the east, all return periods. Negative values are a reduction in wave height as a result of the installed infrastructure. 1.8 m reduction in water depth in the cable crossing area

A.3 Hornsea Four In Combination With Other Offshore Wind Farms (reduction in water depth 3.0 m at cable crossing area near Smithic Bank)

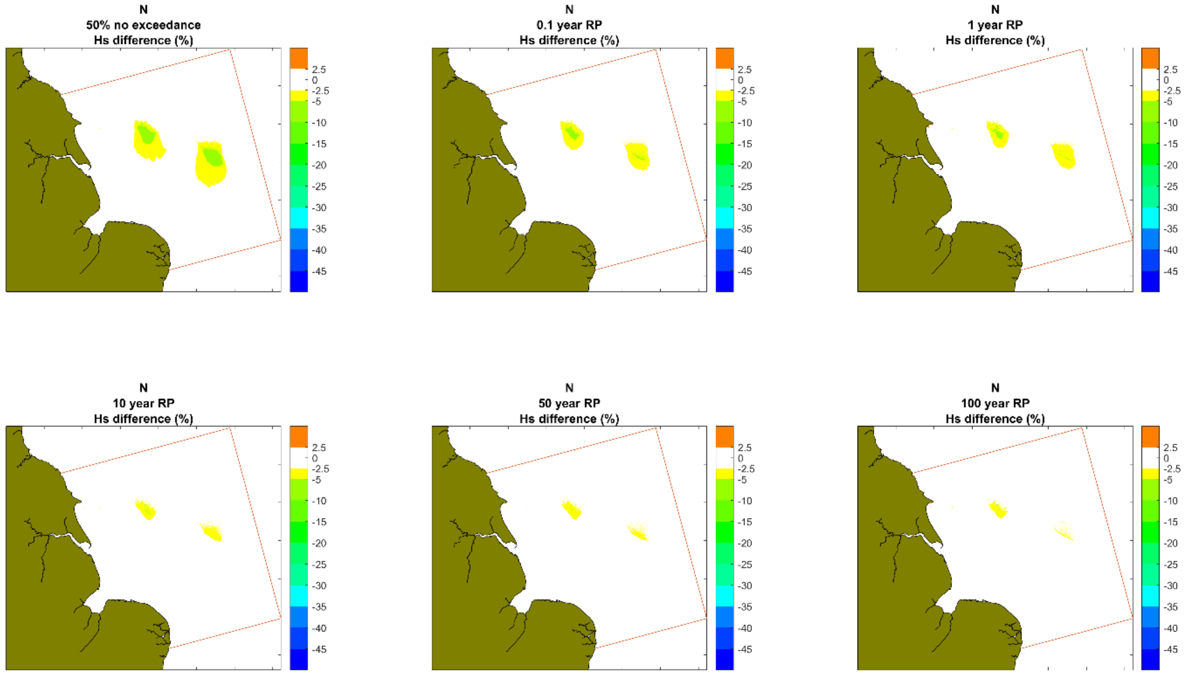


Figure A11. Percentage difference in significant wave height (scheme minus baseline as a proportion of baseline values), operational phase, waves from the north, all return periods. Negative values are a reduction in wave height as a result of the installed infrastructure. 3.0 m reduction in water depth in the cable crossing area

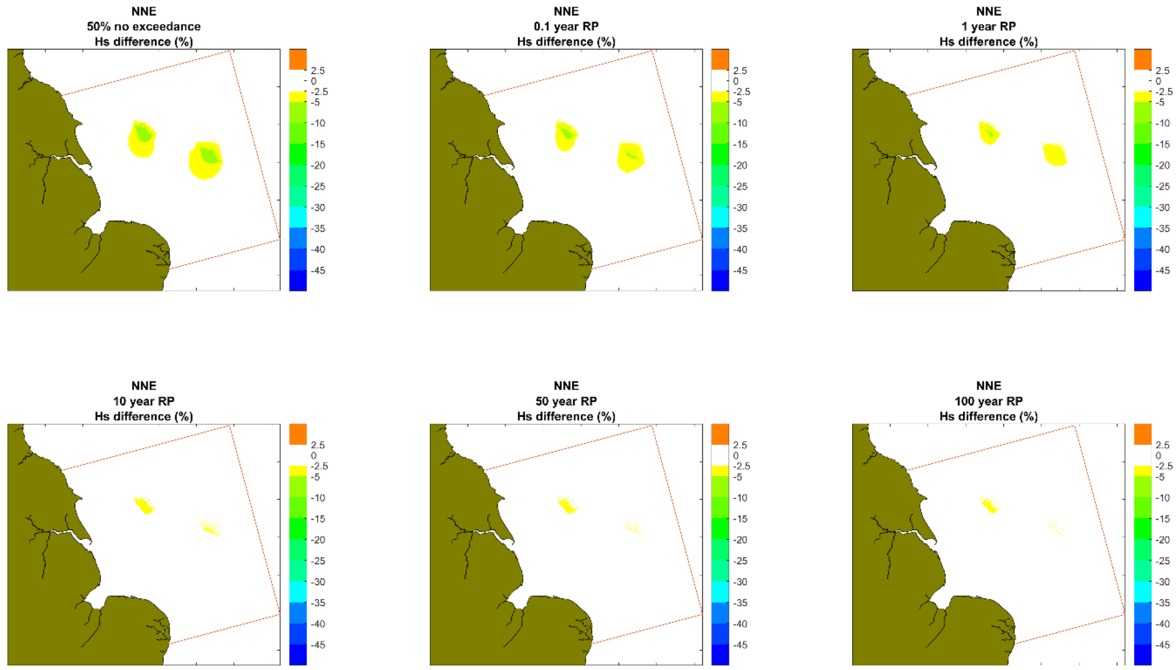


Figure A12. Percentage difference in significant wave height (scheme minus baseline as a proportion of baseline values), operational phase, waves from the north-north-east, all return periods. Negative values are a reduction in wave height as a result of the installed infrastructure. 3.0 m reduction in water depth in the cable crossing area

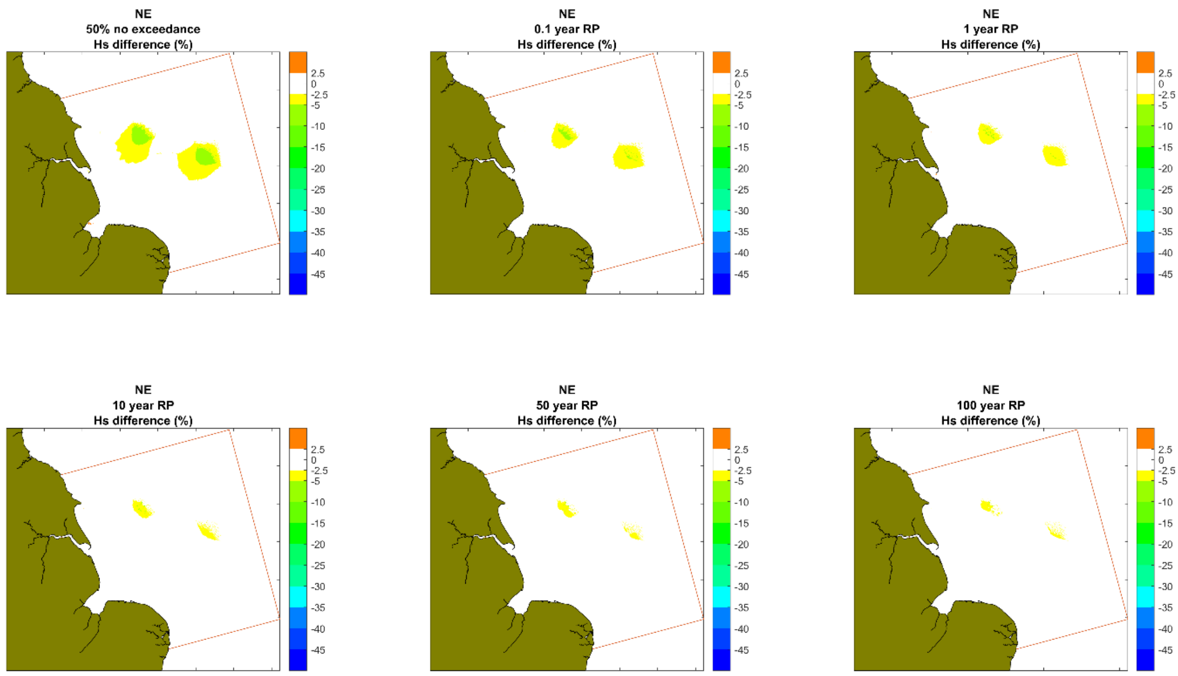


Figure A13. Percentage difference in significant wave height (scheme minus baseline as a proportion of baseline values), operational phase, waves from the north-east, all return periods. Negative values are a reduction in wave height as a result of the installed infrastructure. 3.0 m reduction in water depth in the cable crossing area

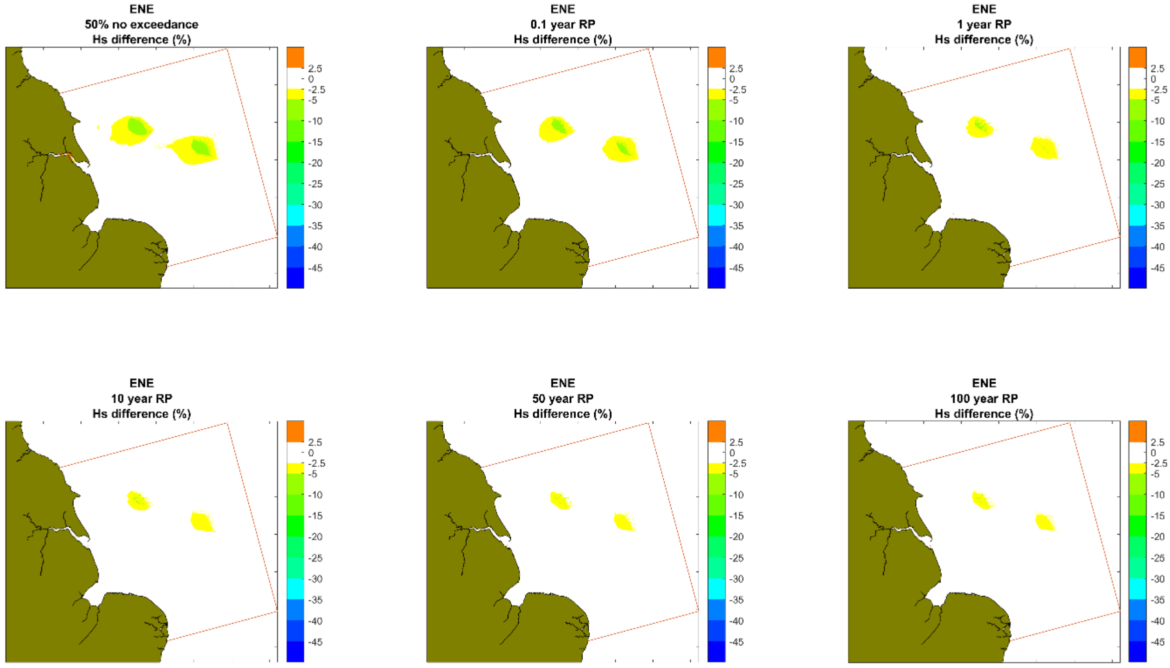


Figure A14. **Percentage difference in significant wave height (scheme minus baseline as a proportion of baseline values), operational phase, waves from the east-north-east, all return periods. Negative values are a reduction in wave height as a result of the installed infrastructure. 3.0 m reduction in water depth in the cable crossing area**

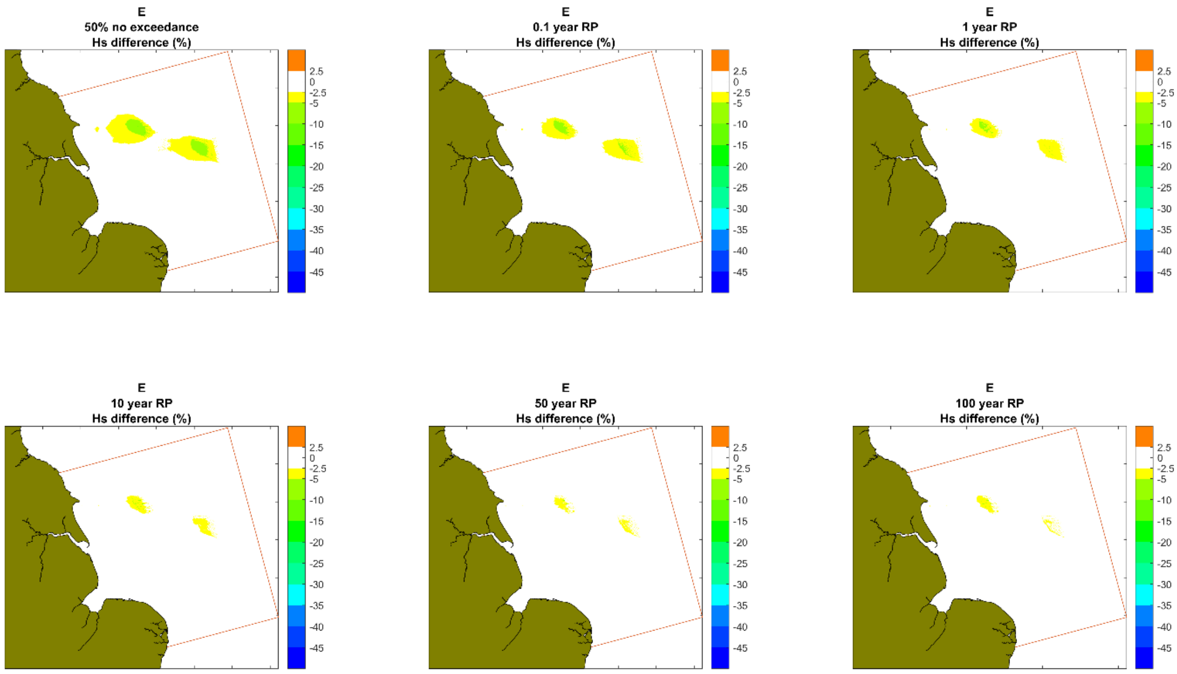


Figure A15. **Percentage difference in significant wave height (scheme minus baseline as a proportion of baseline values), operational phase, waves from the east, all return periods. Negative values are a reduction in wave height as a result of the installed infrastructure. 3.0 m reduction in water depth in the cable crossing area**

B Results from the Tidal Model

B.1 Baseline Tidal Conditions

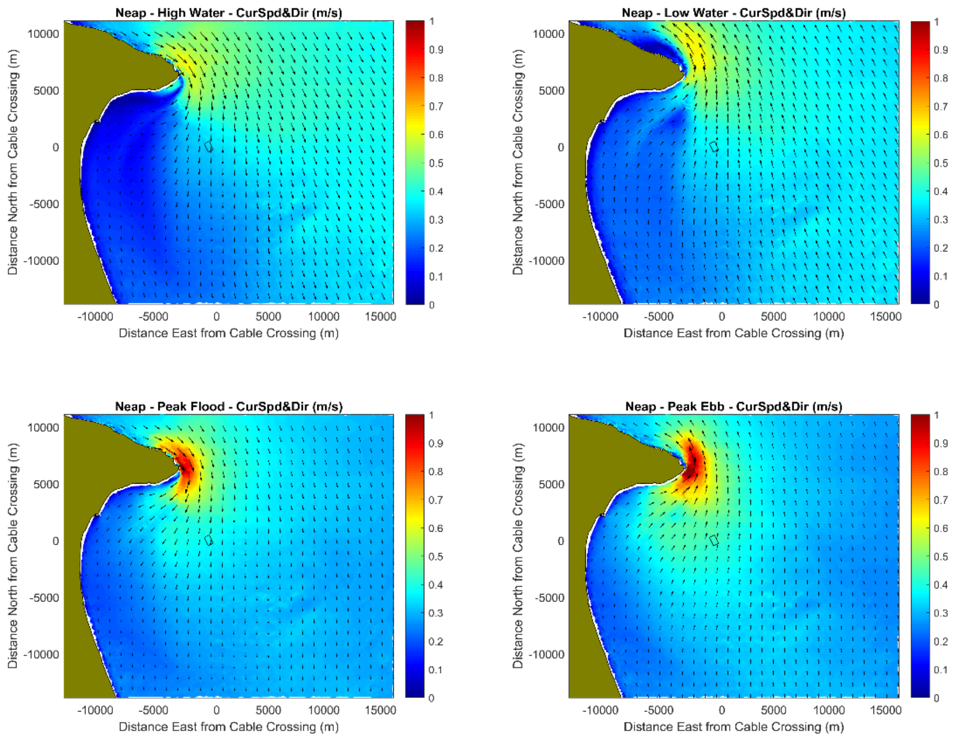


Figure B1. Baseline tidal current speed and direction. Mean neap tide

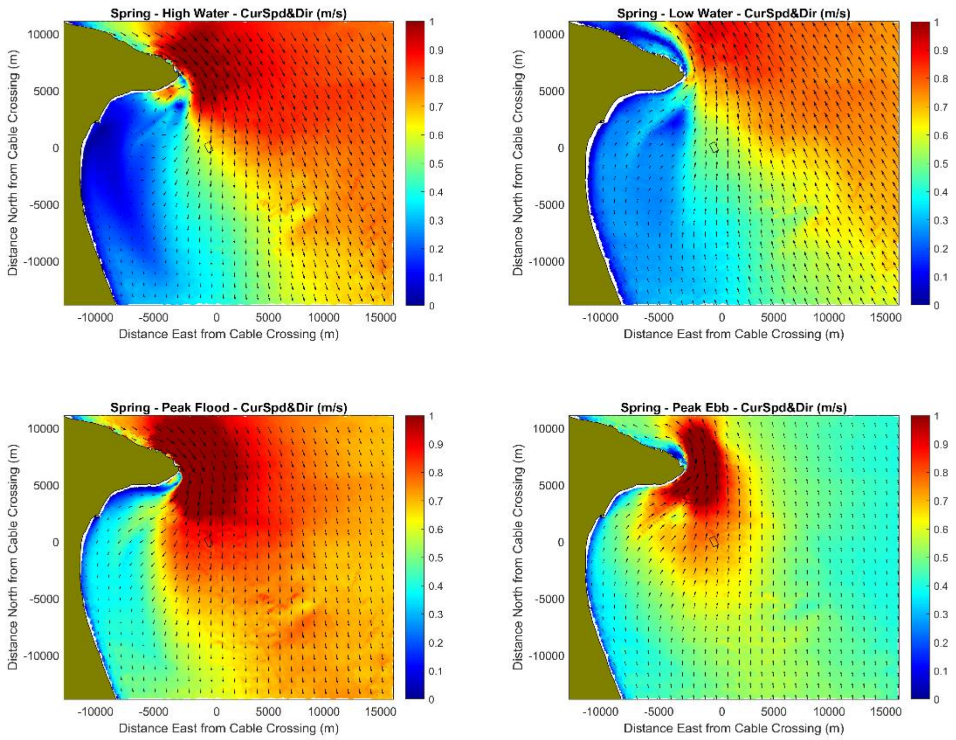


Figure B2. Baseline tidal current speed and direction. Mean spring tide

B.2 Scheme (reduction in water depth by 1.8 m)

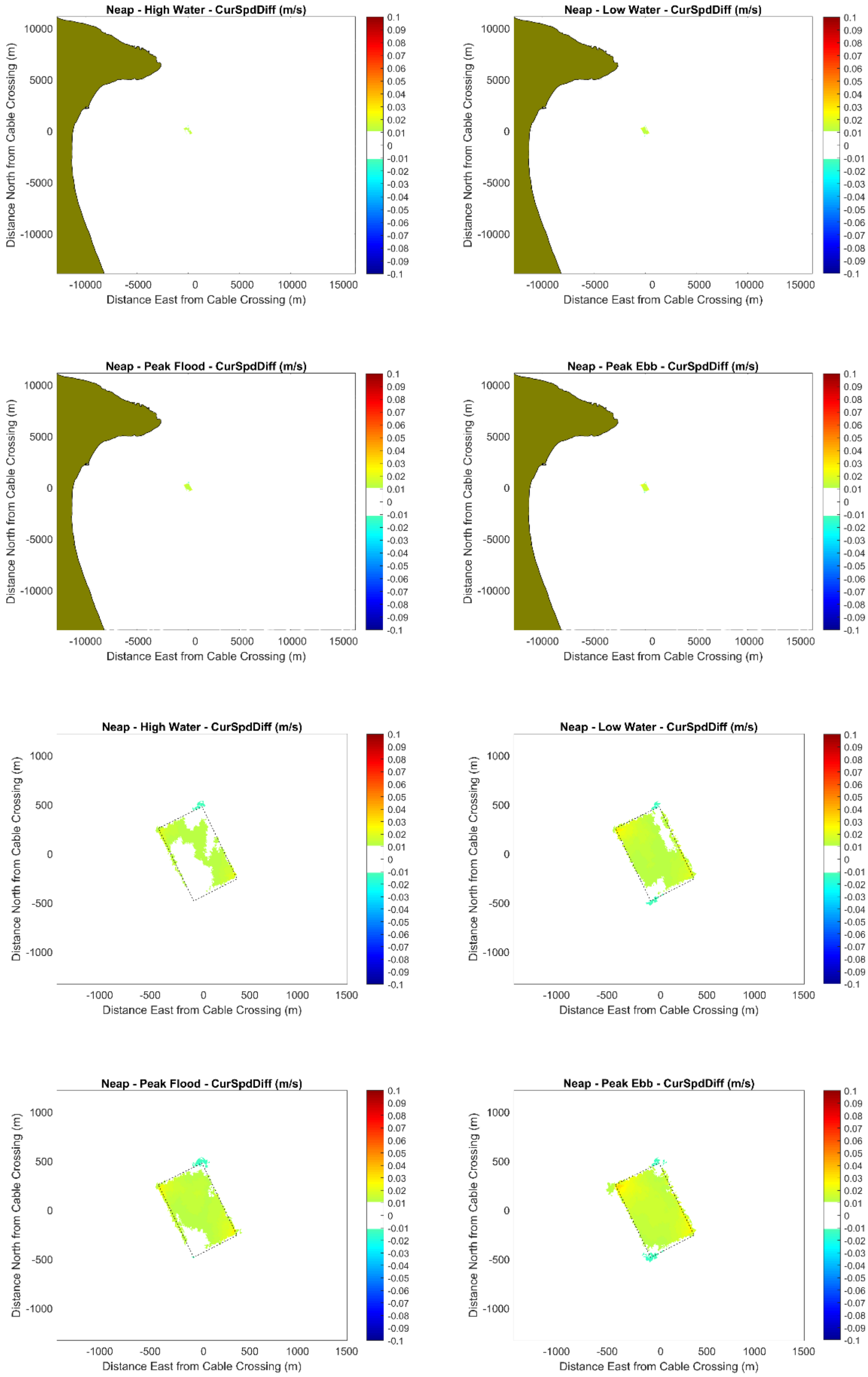


Figure B3. Absolute difference in current speed (scheme minus baseline values). Scheme (reduction in water depth by 1.8 m). Mean neap tide. Positive values are an increase in current speed as a result of the installed infrastructure (and *vice versa*)

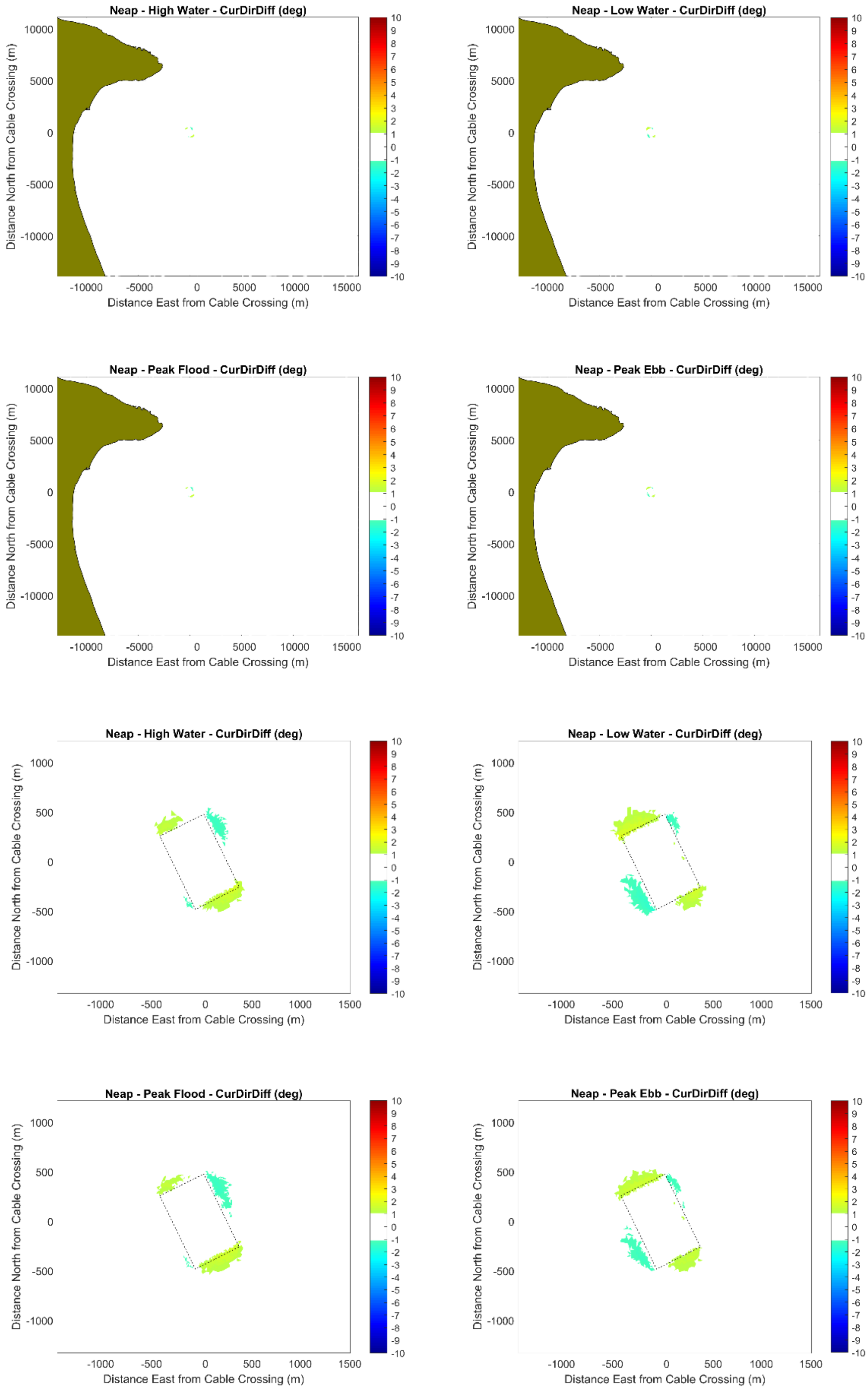


Figure B4. **Absolute difference in current direction (scheme minus baseline values). Scheme (reduction in water depth by 1.8 m). Mean neap tide. Positive values are a deflection in current direction to the right as a result of the installed infrastructure (and *vice versa*)**

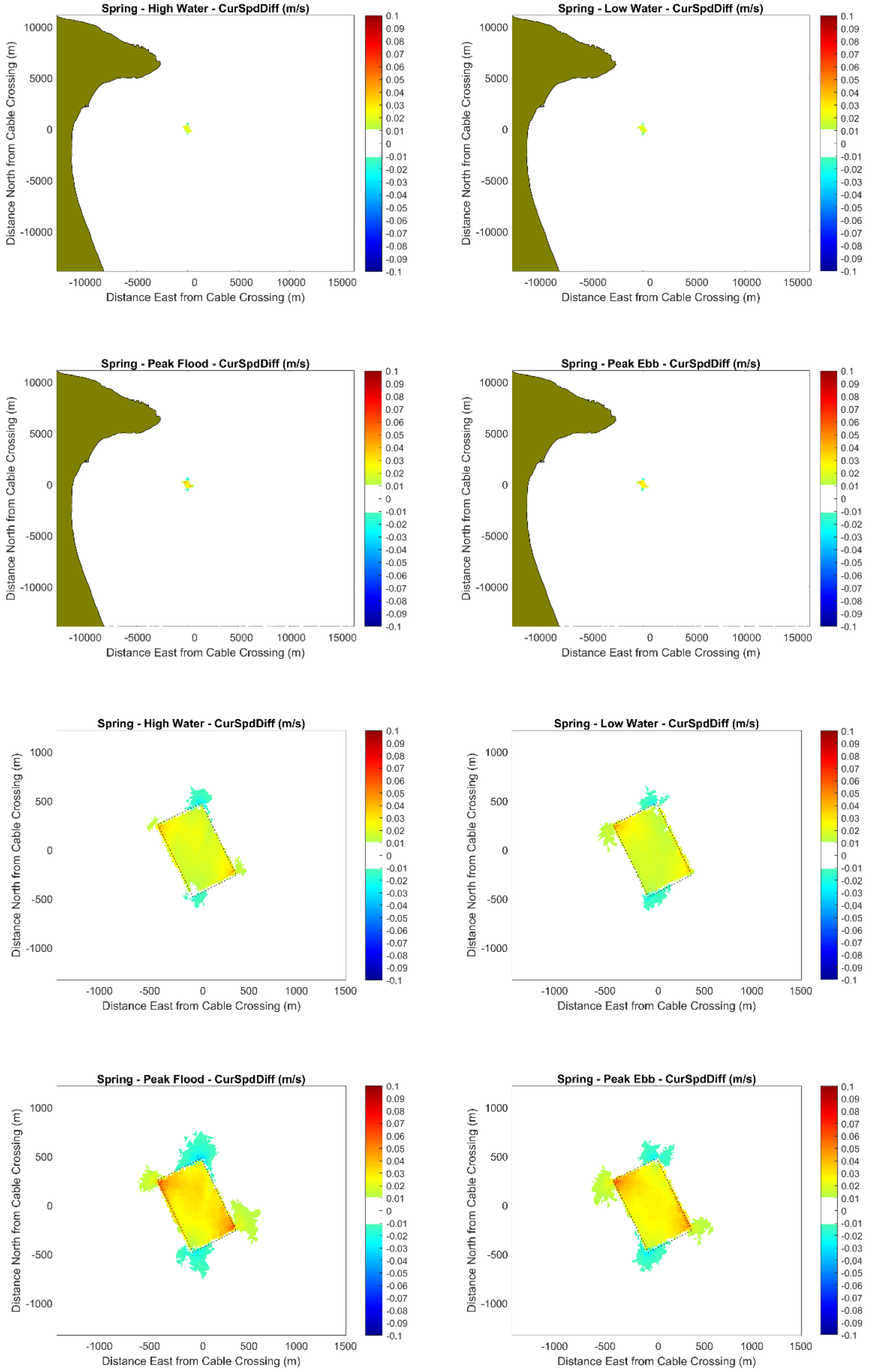


Figure B5. **Absolute difference in current speed (scheme minus baseline values). Scheme (reduction in water depth by 1.8 m). Mean spring tide. Positive values are an increase in current speed as a result of the installed infrastructure (and *vice versa*)**

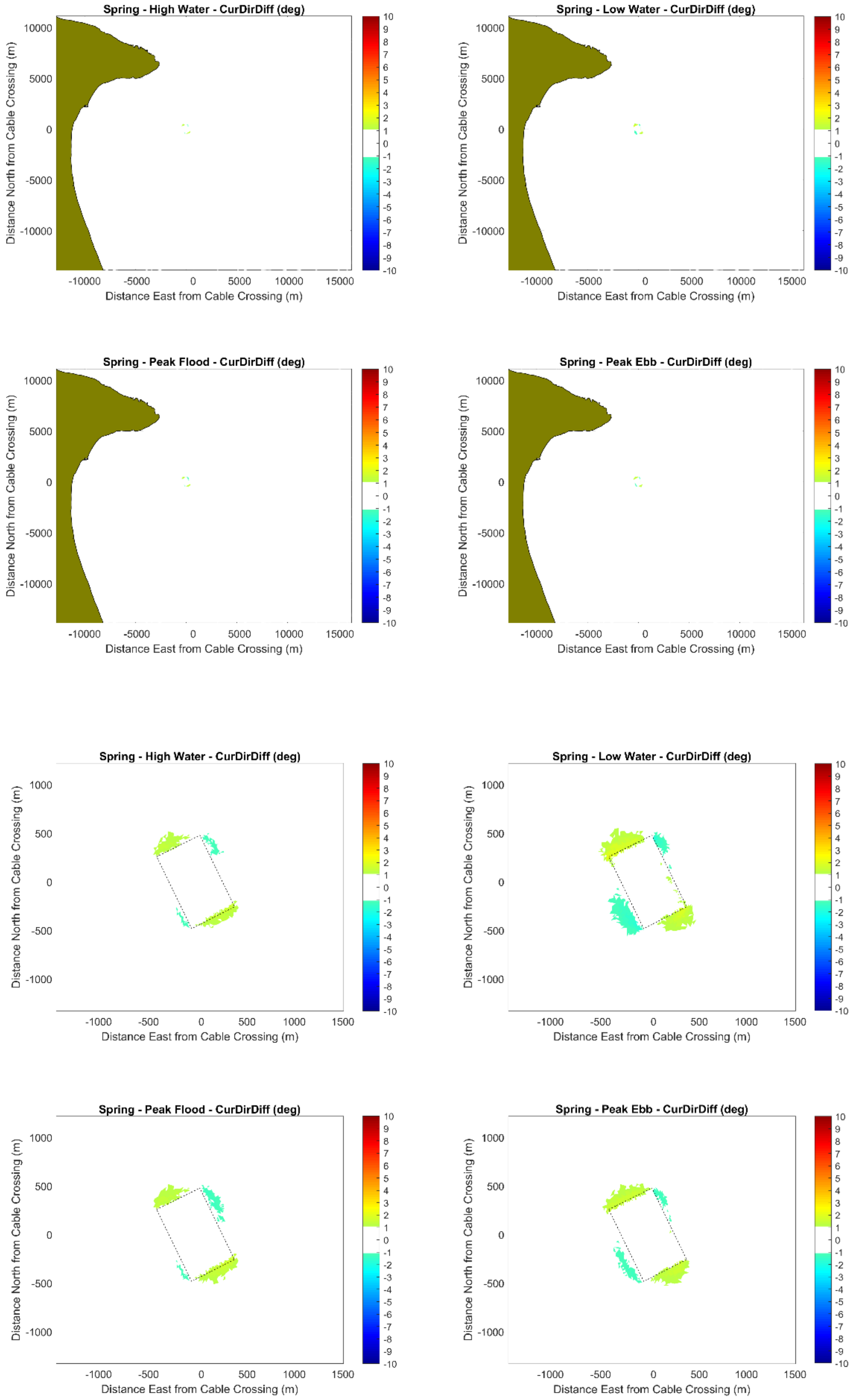


Figure B6. **Absolute difference in current direction (scheme minus baseline values). Scheme (reduction in water depth by 1.8 m). Mean spring tide. Positive values are a deflection in current direction to the right as a result of the installed infrastructure (and *vice versa*)**

B.3 Scheme (reduction in water depth by 3.0 m)

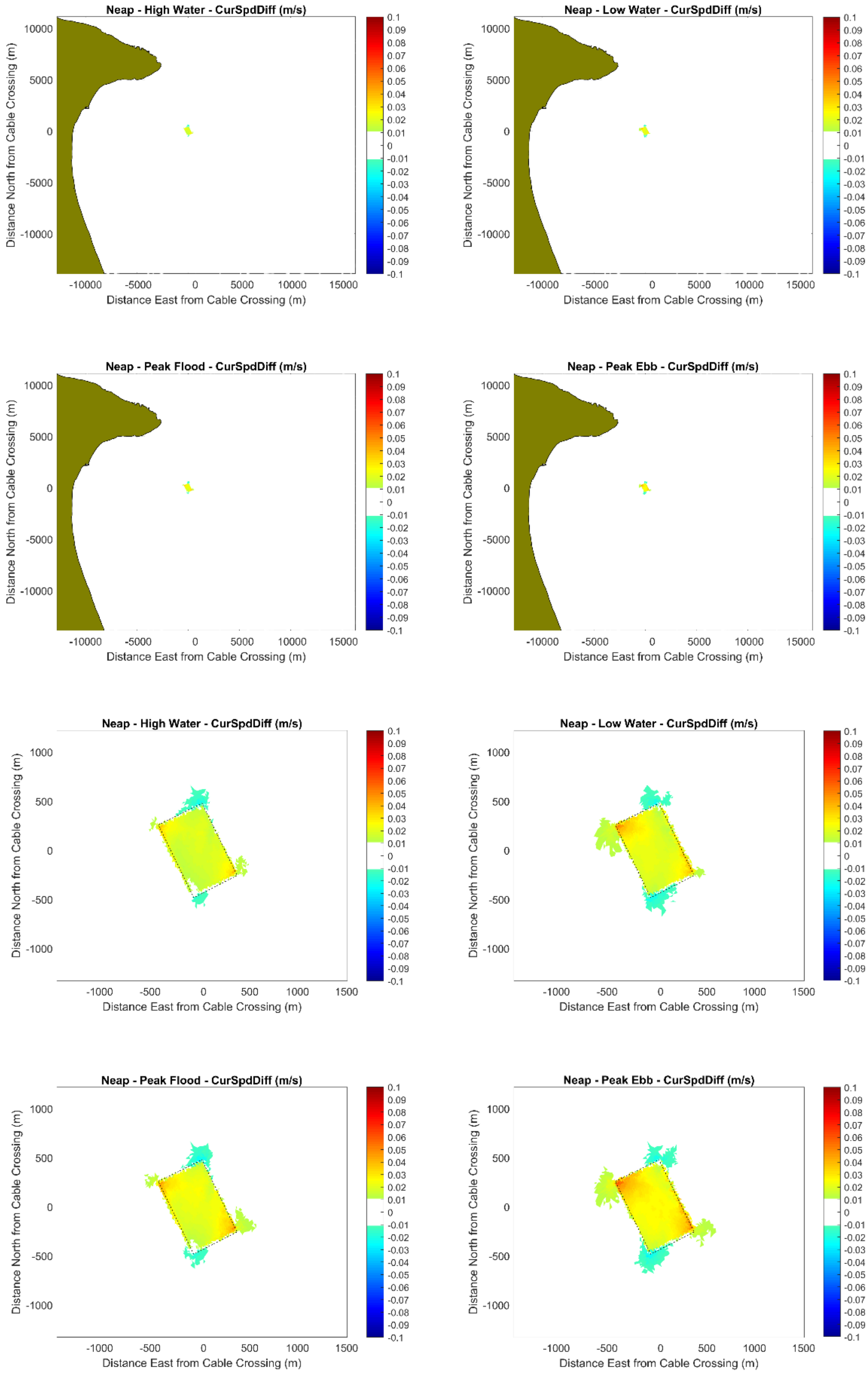


Figure B7. Absolute difference in current speed (scheme minus baseline values). Scheme (reduction in water depth by 3.0 m). Mean neap tide. Positive values are an increase in current speed as a result of the installed infrastructure (and *vice versa*)

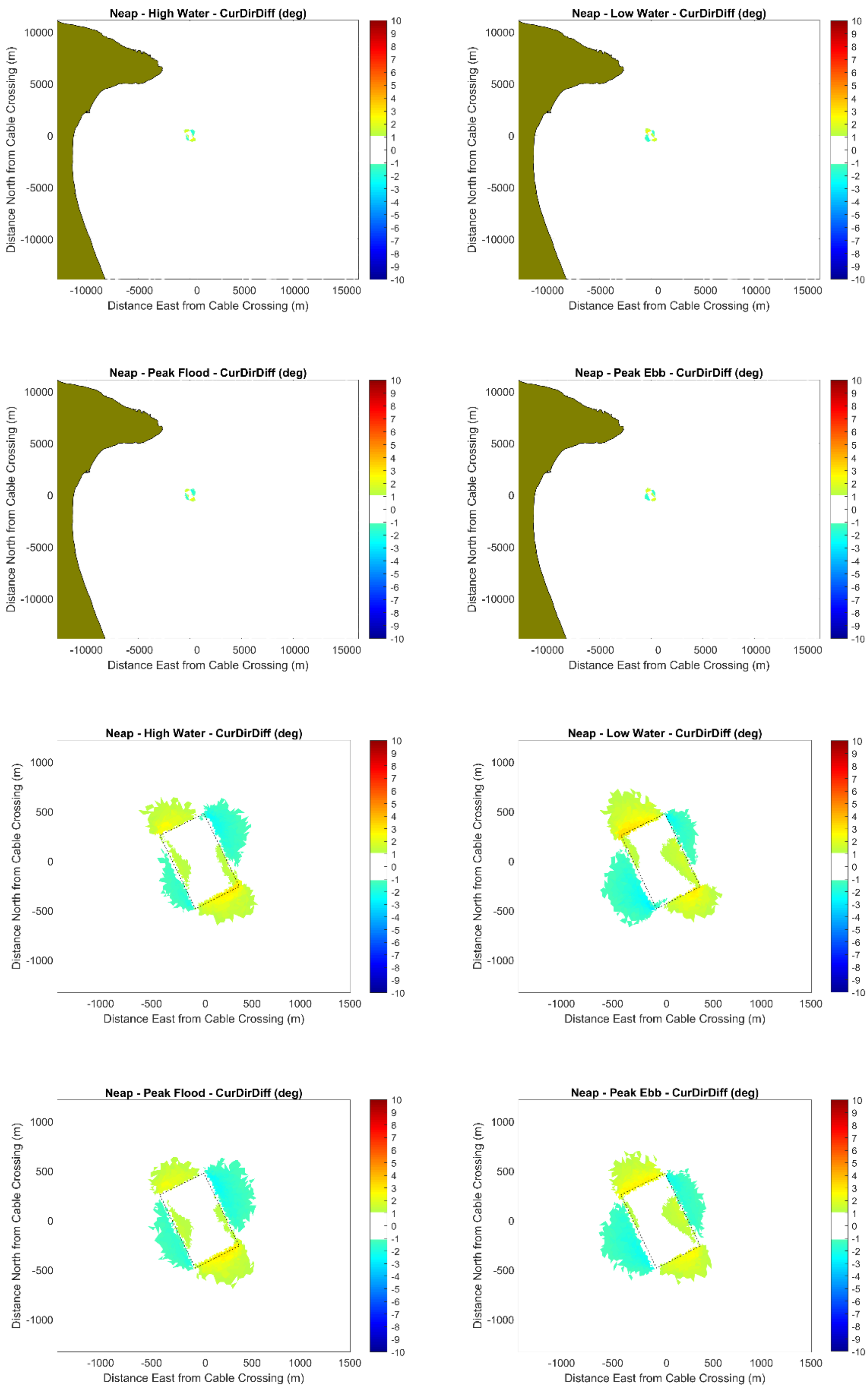


Figure B8. **Absolute difference in current direction (scheme minus baseline values). Scheme (reduction in water depth by 3.0 m). Mean neap tide. Positive values are a deflection in current direction to the right as a result of the installed infrastructure (and *vice versa*)**

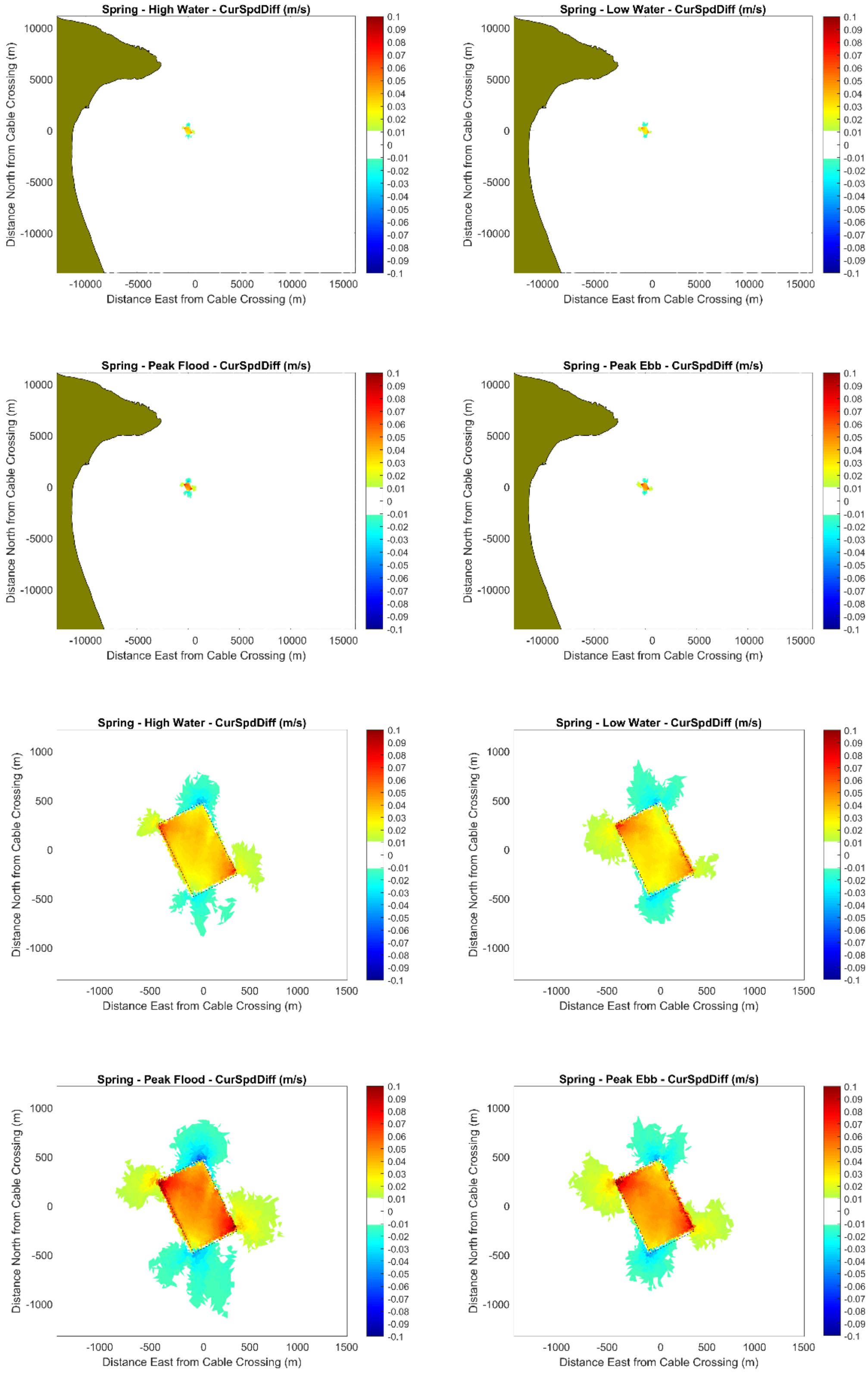


Figure B9. **Absolute difference in current speed (scheme minus baseline values). Scheme (reduction in water depth by 3.0 m). Mean spring tide. Positive values are an increase in current speed as a result of the installed infrastructure (and *vice versa*)**

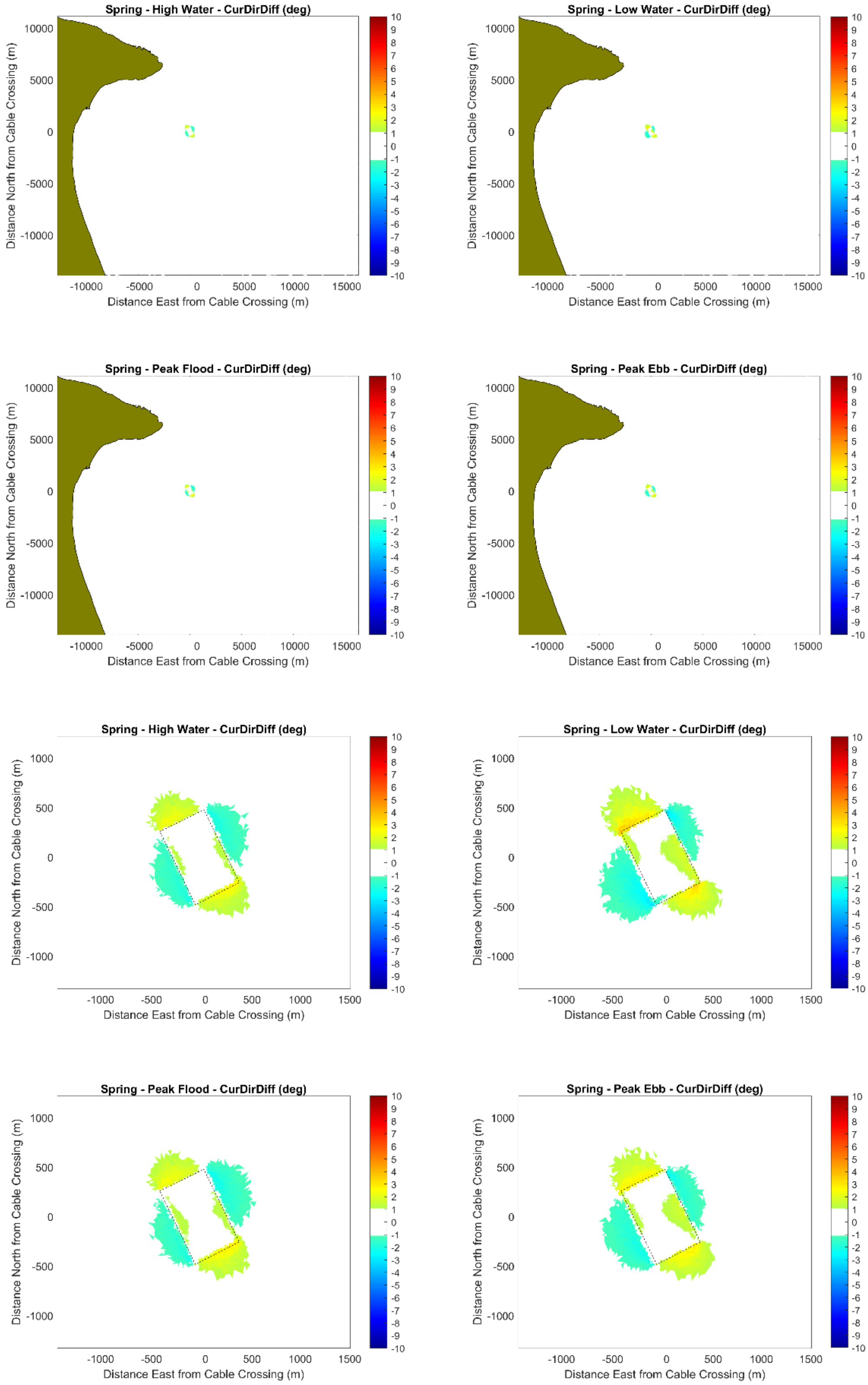


Figure B10. **Absolute difference in current direction (scheme minus baseline values). Scheme (reduction in water depth by 3.0 m). Mean neap tide. Positive values are a deflection in current direction to the right as a result of the installed infrastructure (and *vice versa*)**

B.4 Scheme (reduction in water depth by 1.8 m and increase in bed roughness)

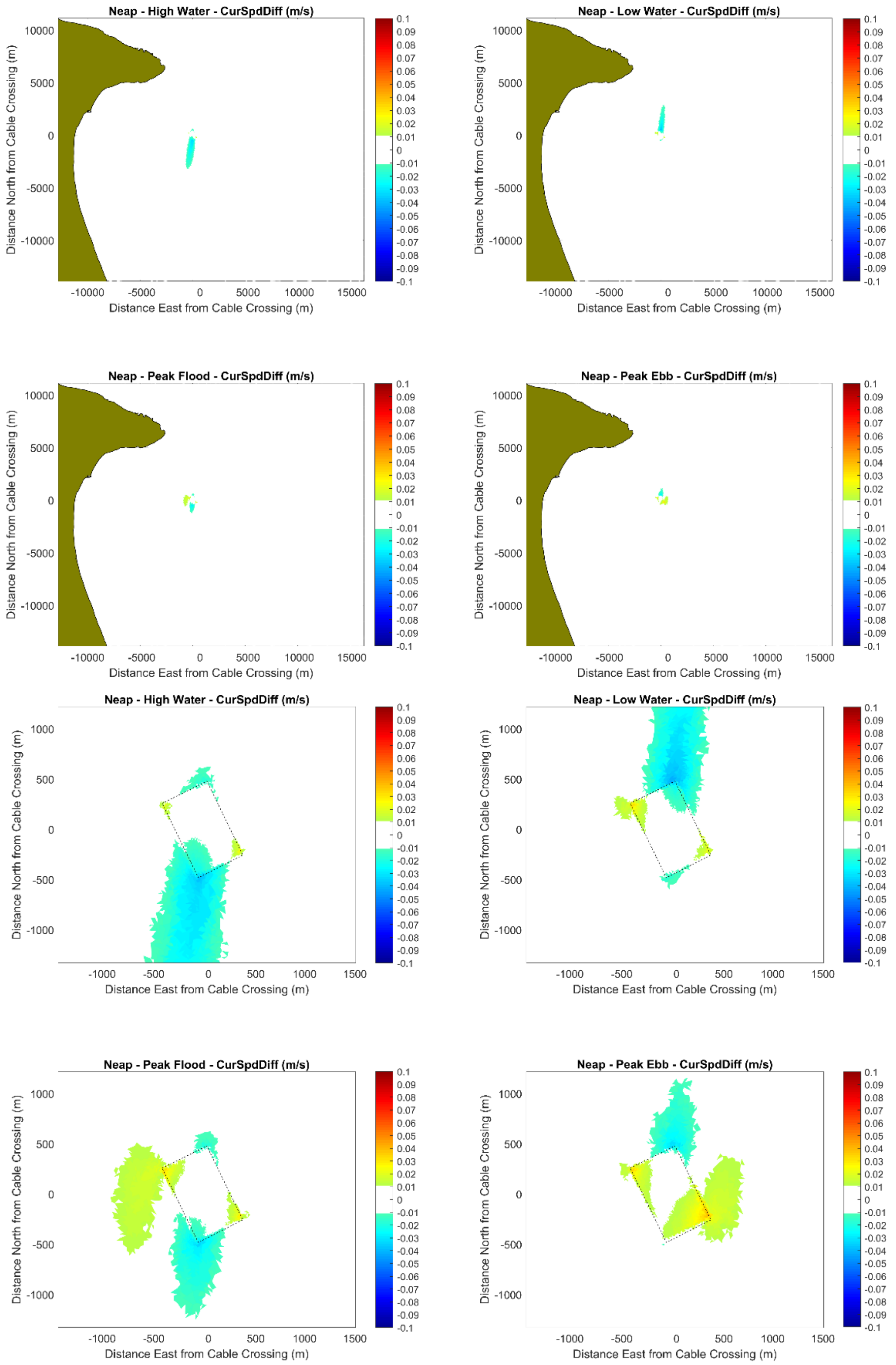


Figure B11. **Absolute difference in current speed (scheme minus baseline values). Scheme (reduction in water depth by 1.8 m & additional roughness). Mean neap tide. Positive values are an increase in current speed as a result of the installed infrastructure (and *vice versa*)**

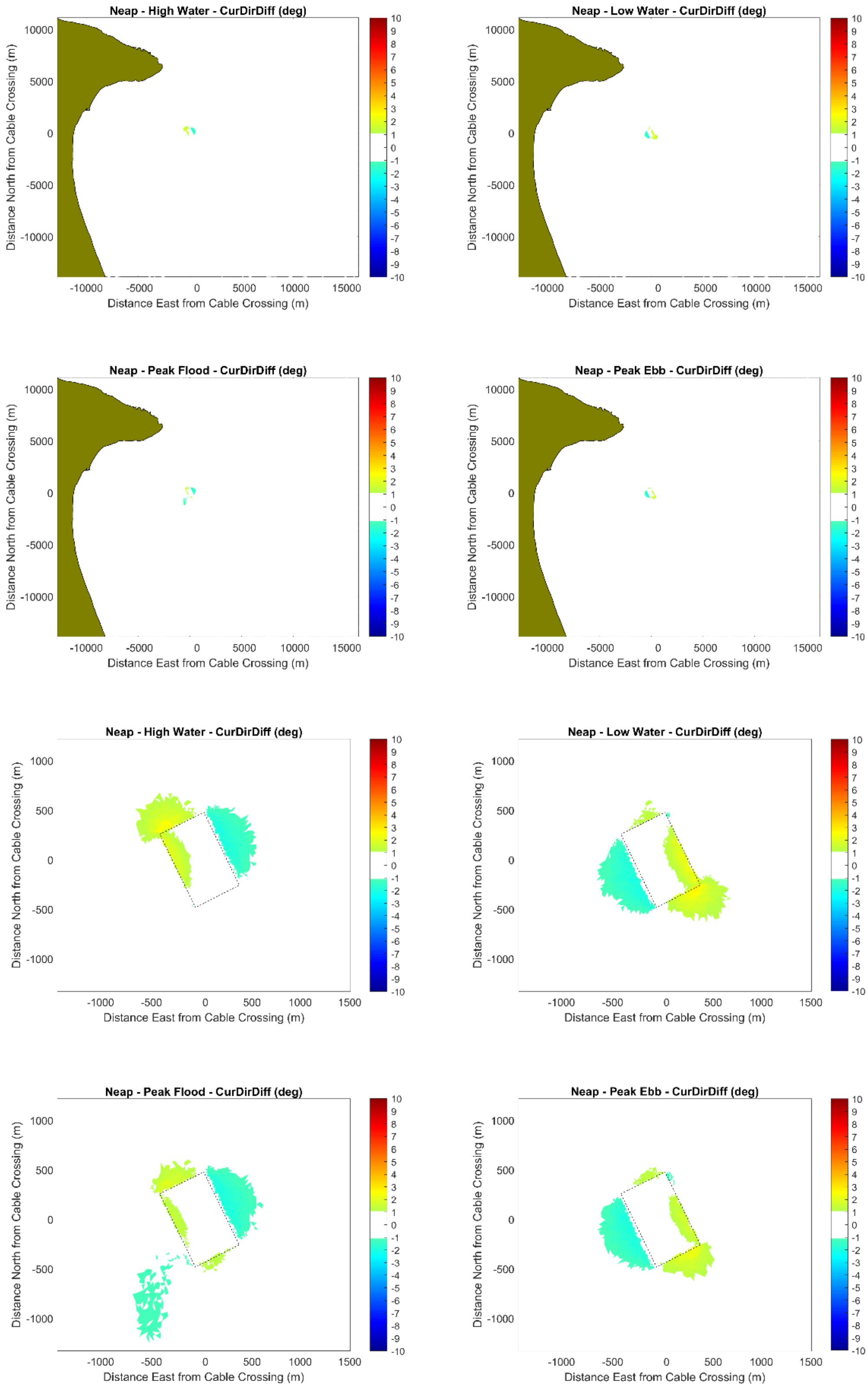


Figure B12. **Absolute difference in current direction (scheme minus baseline values). Scheme (reduction in water depth by 1.8 m & additional roughness). Mean neap tide. Positive values are a deflection in current direction to the right as a result of the installed infrastructure (and *vice versa*)**

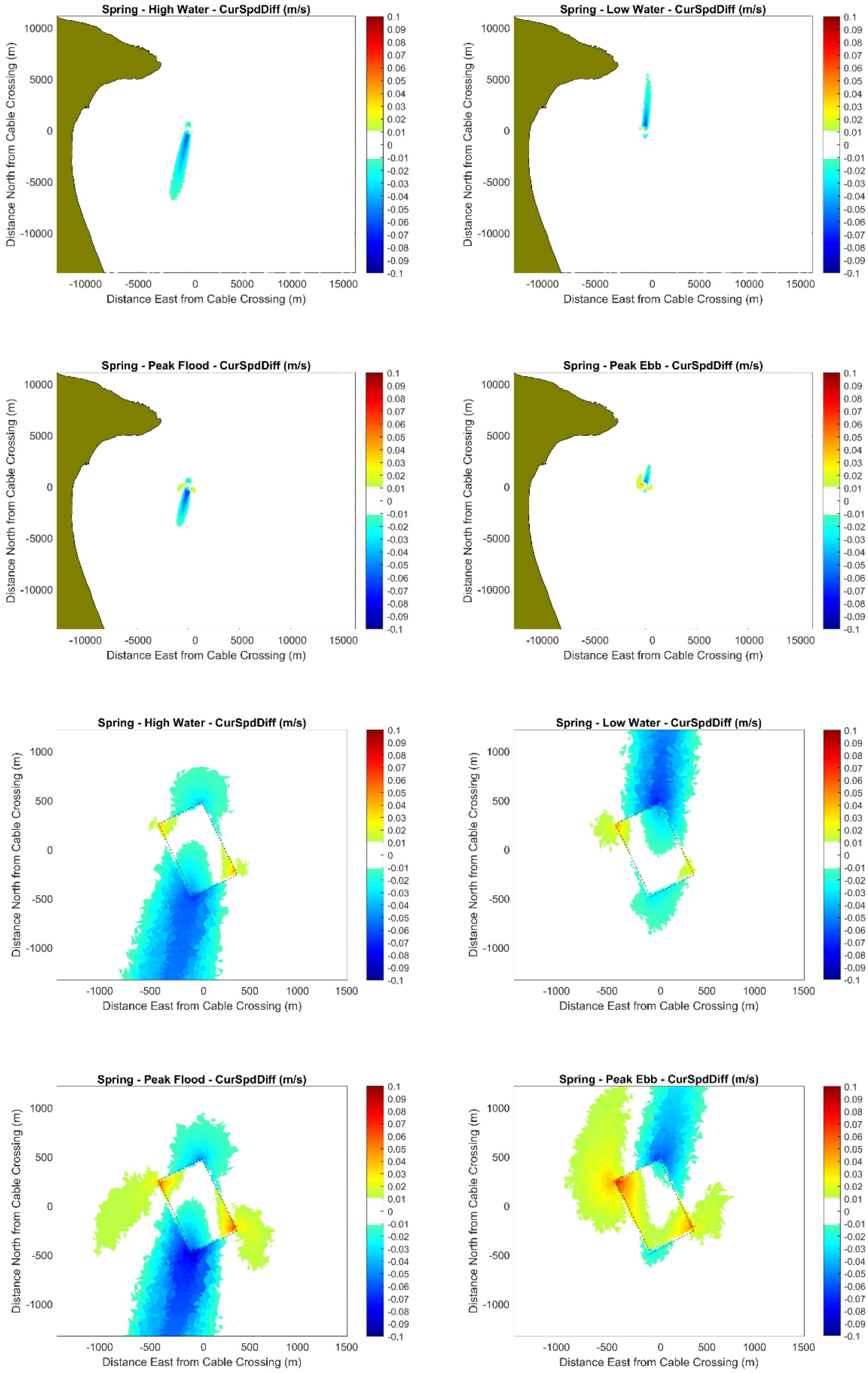


Figure B13. **Absolute difference in current speed (scheme minus baseline values). Scheme (reduction in water depth by 1.8 m & additional roughness). Mean spring tide. Positive values are an increase in current speed as a result of the installed infrastructure (and *vice versa*)**

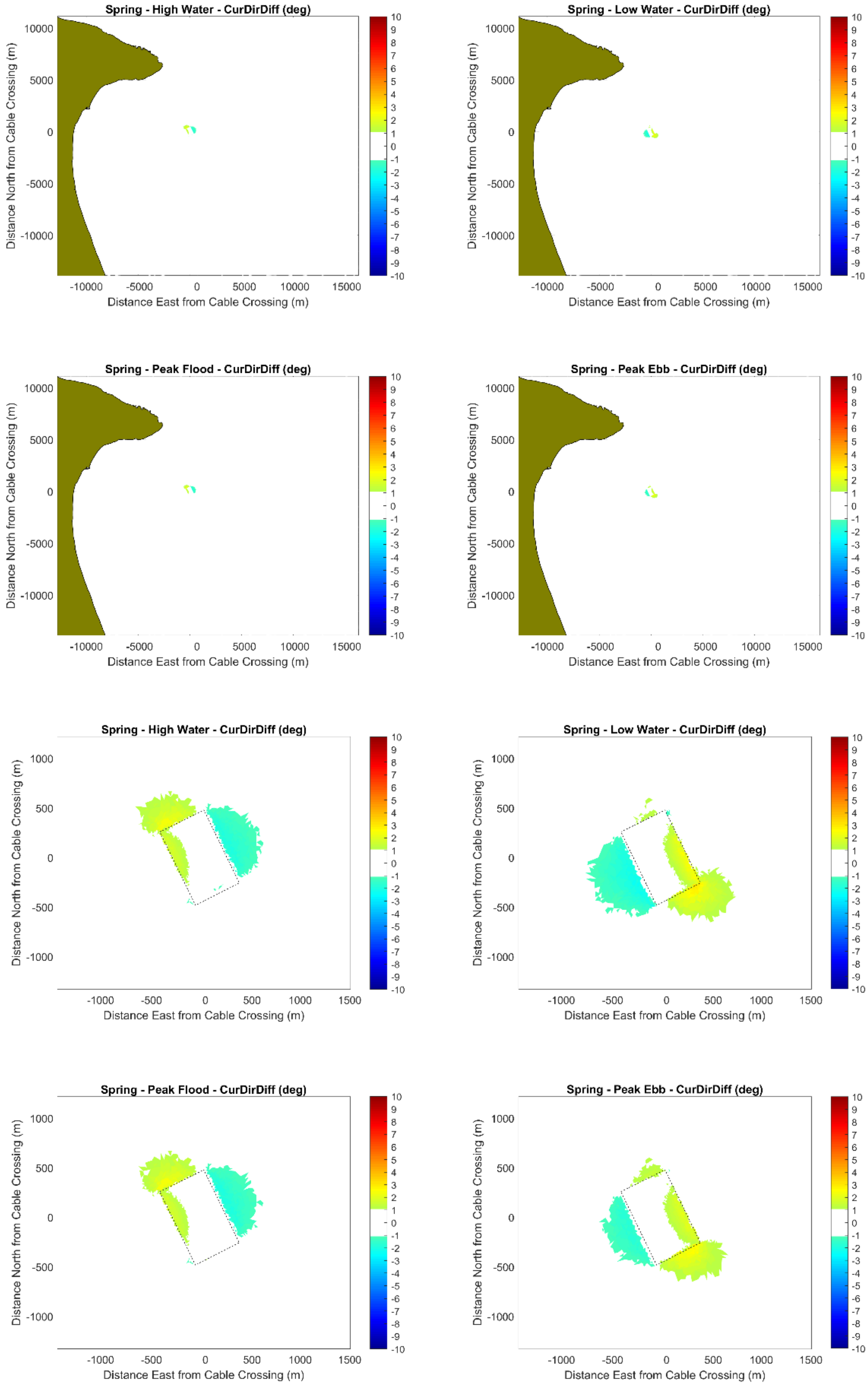


Figure B14. **Absolute difference in current direction (scheme minus baseline values). Scheme (reduction in water depth by 1.8 m & additional roughness). Mean spring tide. Positive values are a deflection in current direction to the right as a result of the installed infrastructure (and *vice versa*)**

B.5 Scheme (reduction in water depth by 3.0 m and increase in bed roughness)

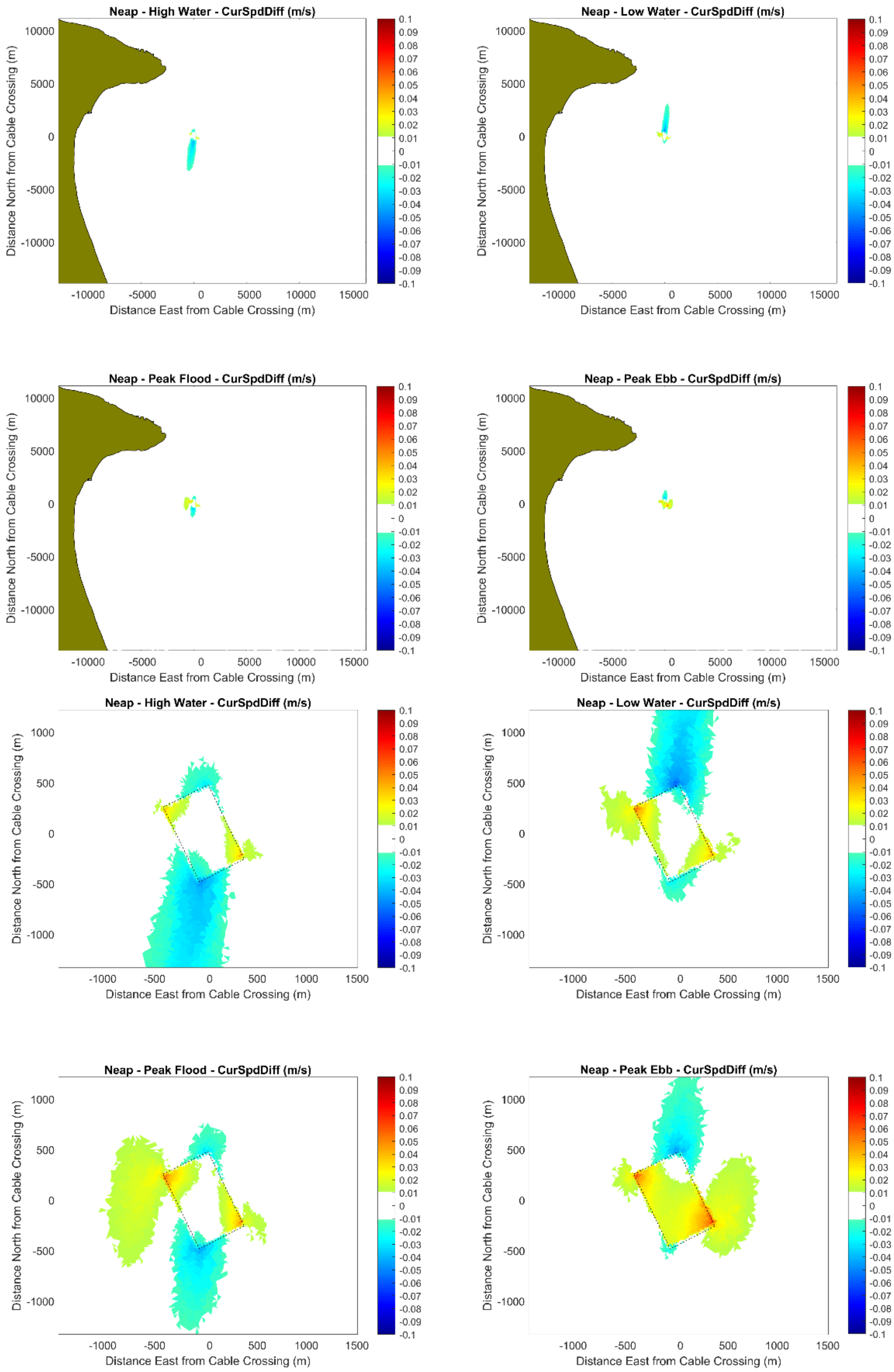


Figure B15. **Absolute difference in current speed (scheme minus baseline values). Scheme (reduction in water depth by 3.0 m & additional roughness). Mean neap tide. Positive values are an increase in current speed as a result of the installed infrastructure (and *vice versa*)**

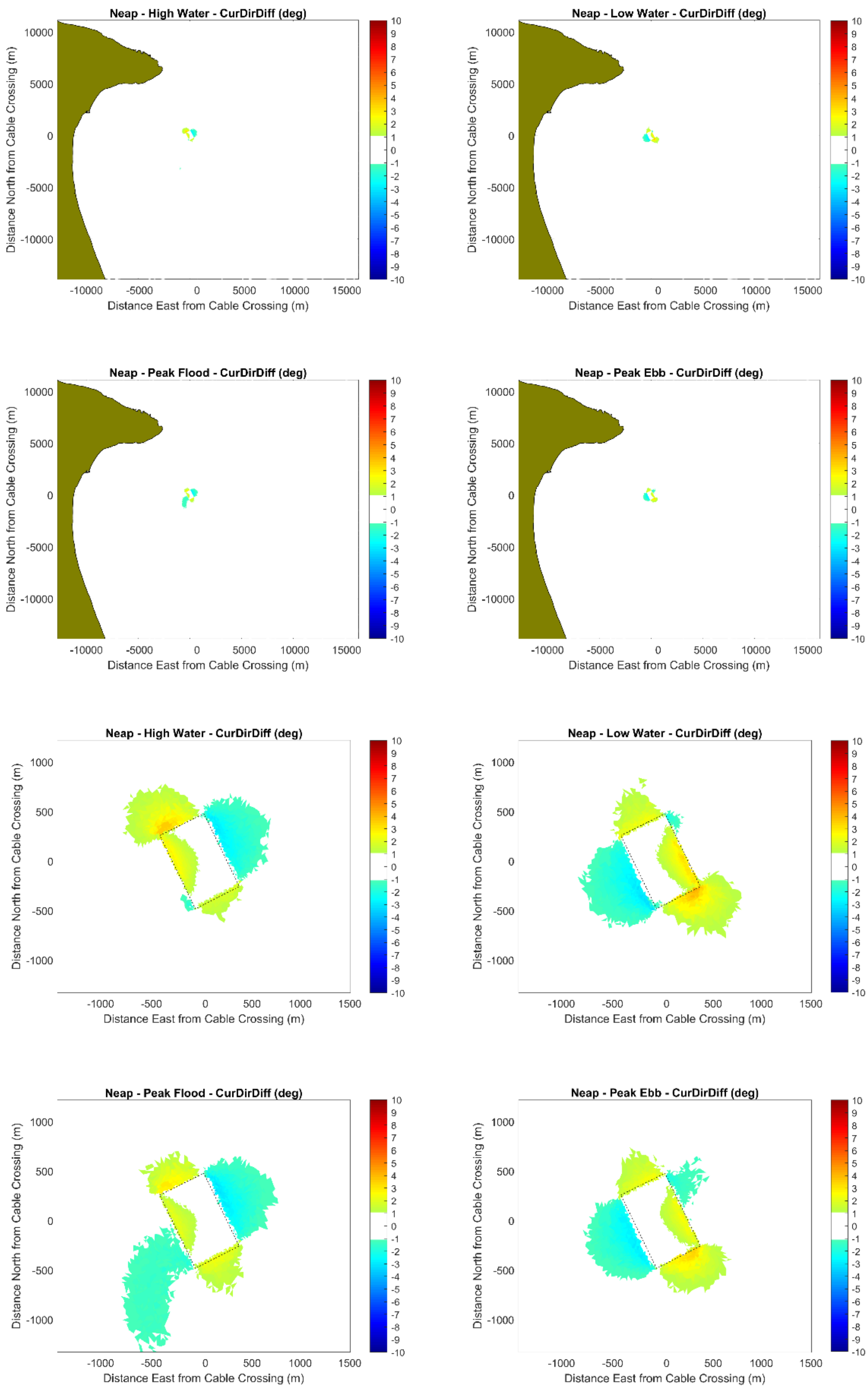


Figure B16. **Absolute difference in current direction (scheme minus baseline values). Scheme (reduction in water depth by 3.0 m & additional roughness). Mean neap tide. Positive values are a deflection in current direction to the right as a result of the installed infrastructure (and *vice versa*)**

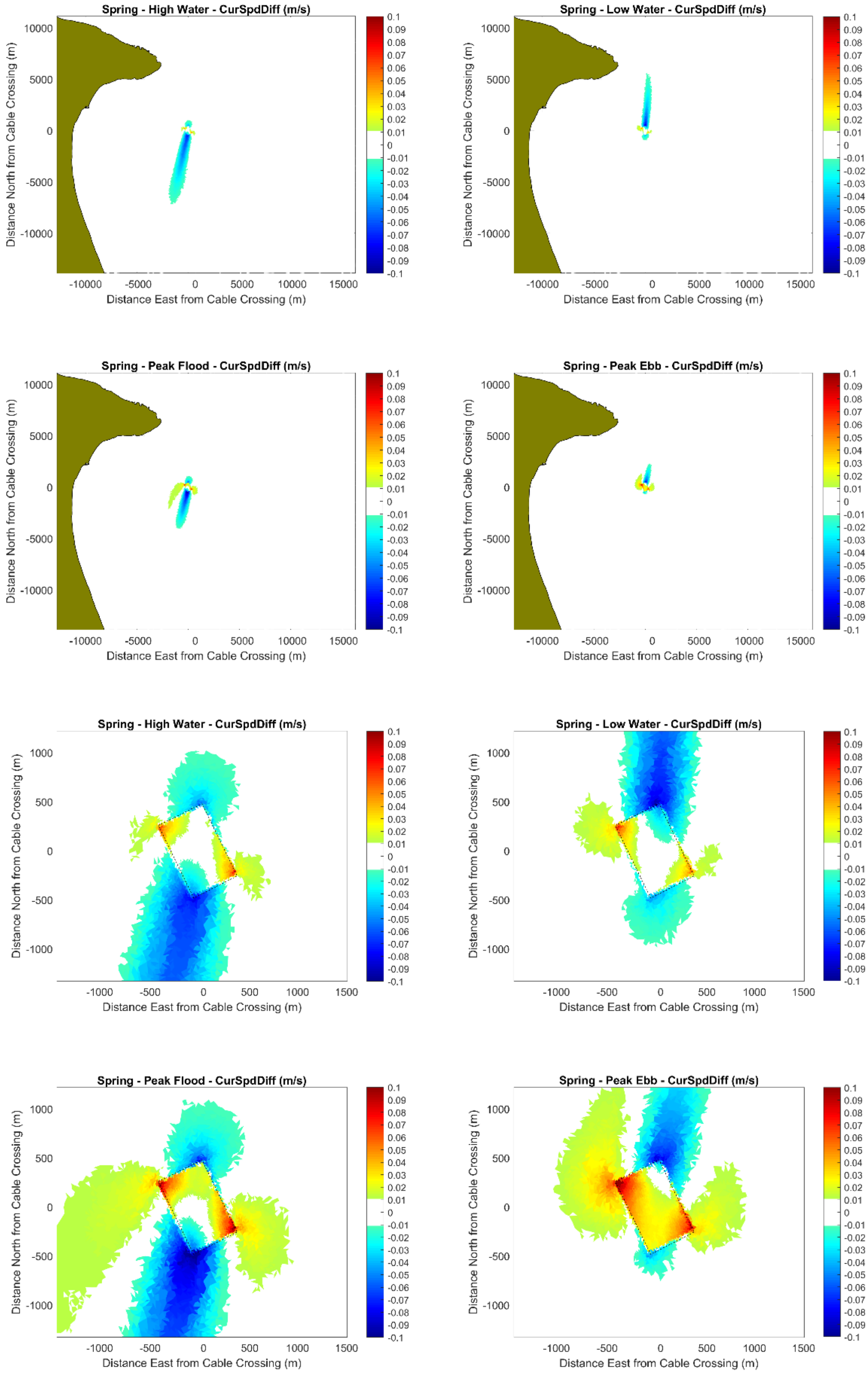


Figure B17. **Absolute difference in current speed (scheme minus baseline values). Scheme (reduction in water depth by 3.0 m & additional roughness). Mean spring tide. Positive values are an increase in current speed as a result of the installed infrastructure (and *vice versa*)**

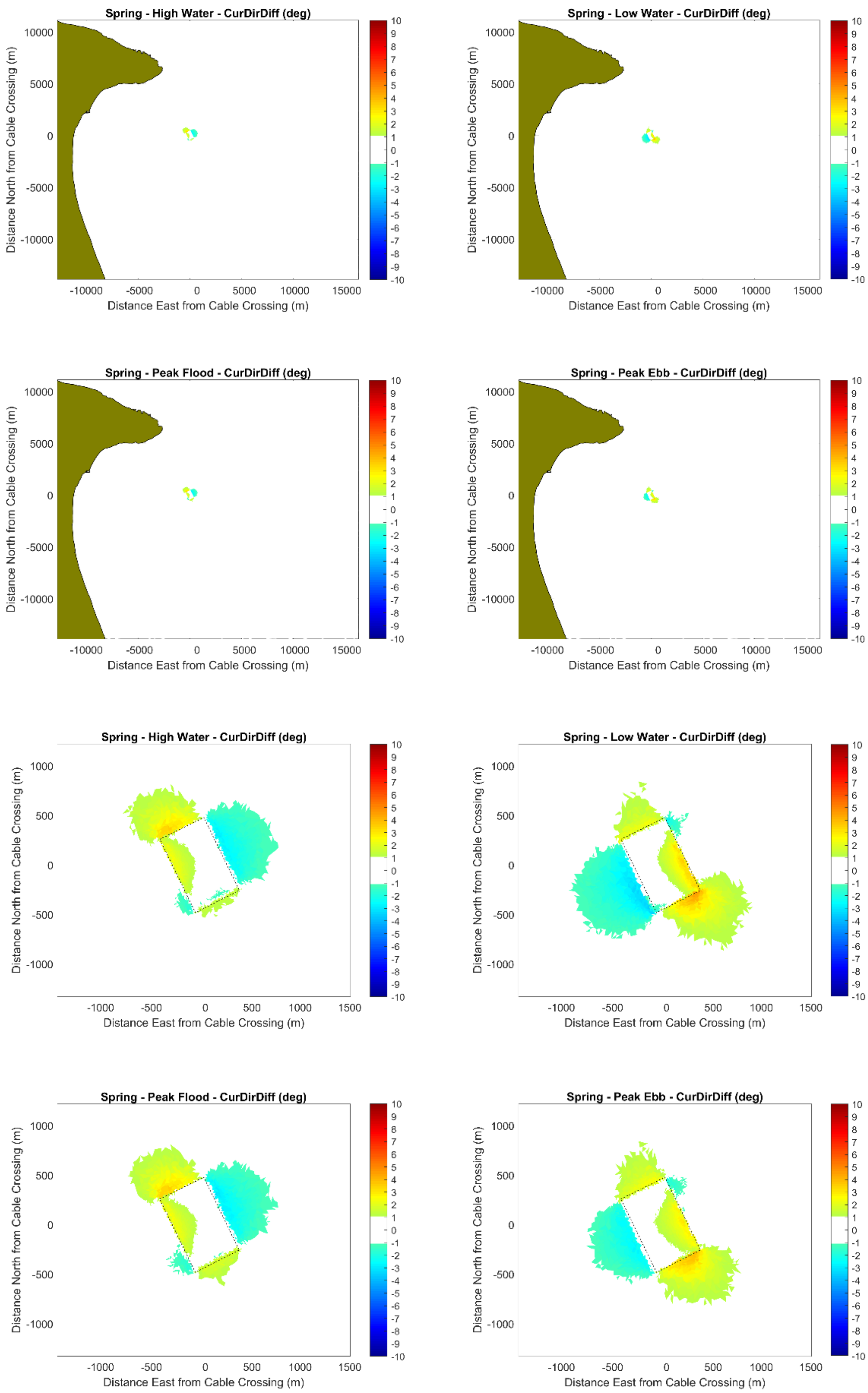


Figure B18. **Absolute difference in current direction (scheme minus baseline values). Scheme (reduction in water depth by 3.0 m & additional roughness). Mean spring tide. Positive values are a deflection in current direction to the right as a result of the installed infrastructure (and *vice versa*)**

C Results from the Sediment Plume Model

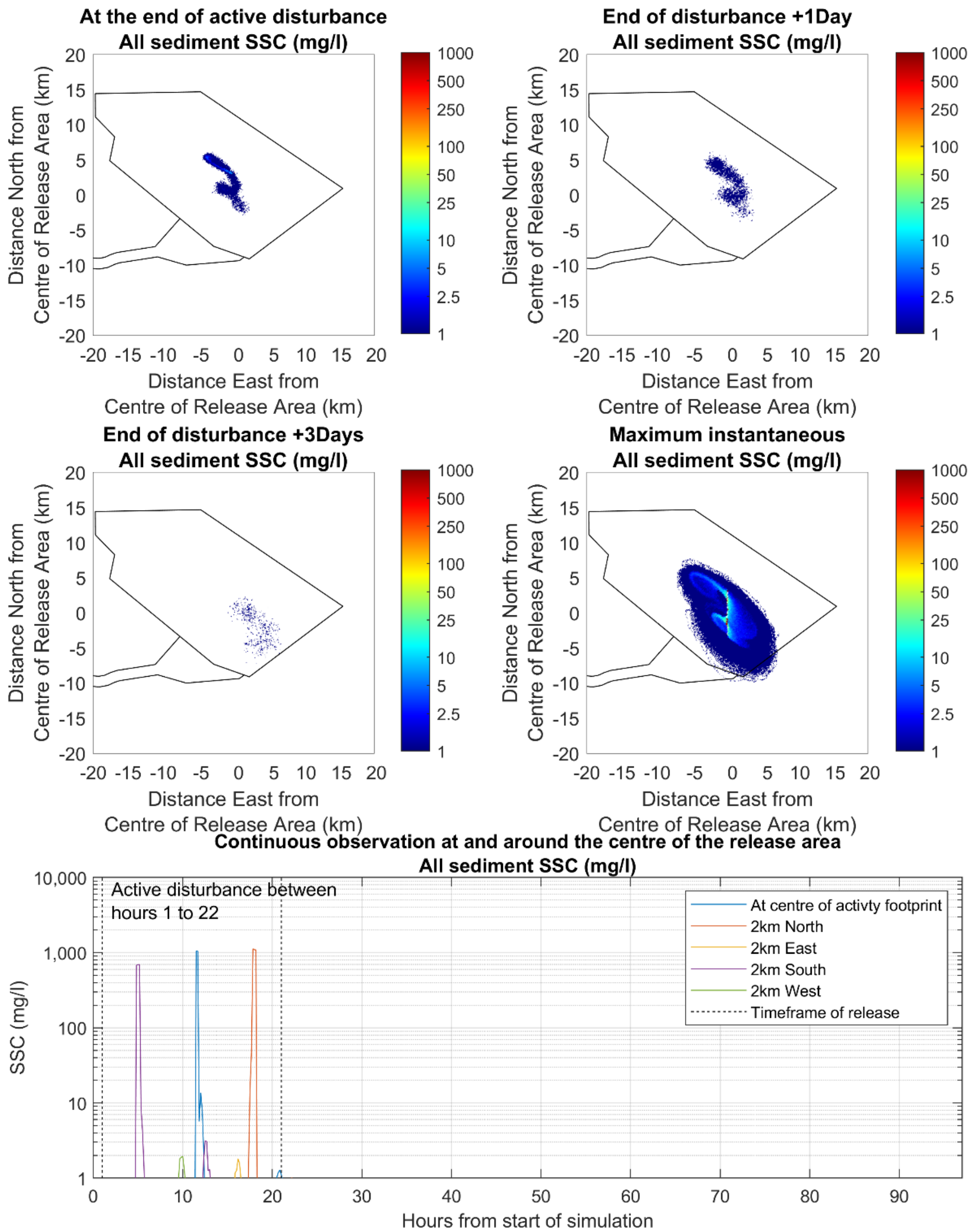


Figure C1. Suspended sediment concentration (all sediment types) as a result of CFE dredging in the Hornsea Four array area. Mean neap tide

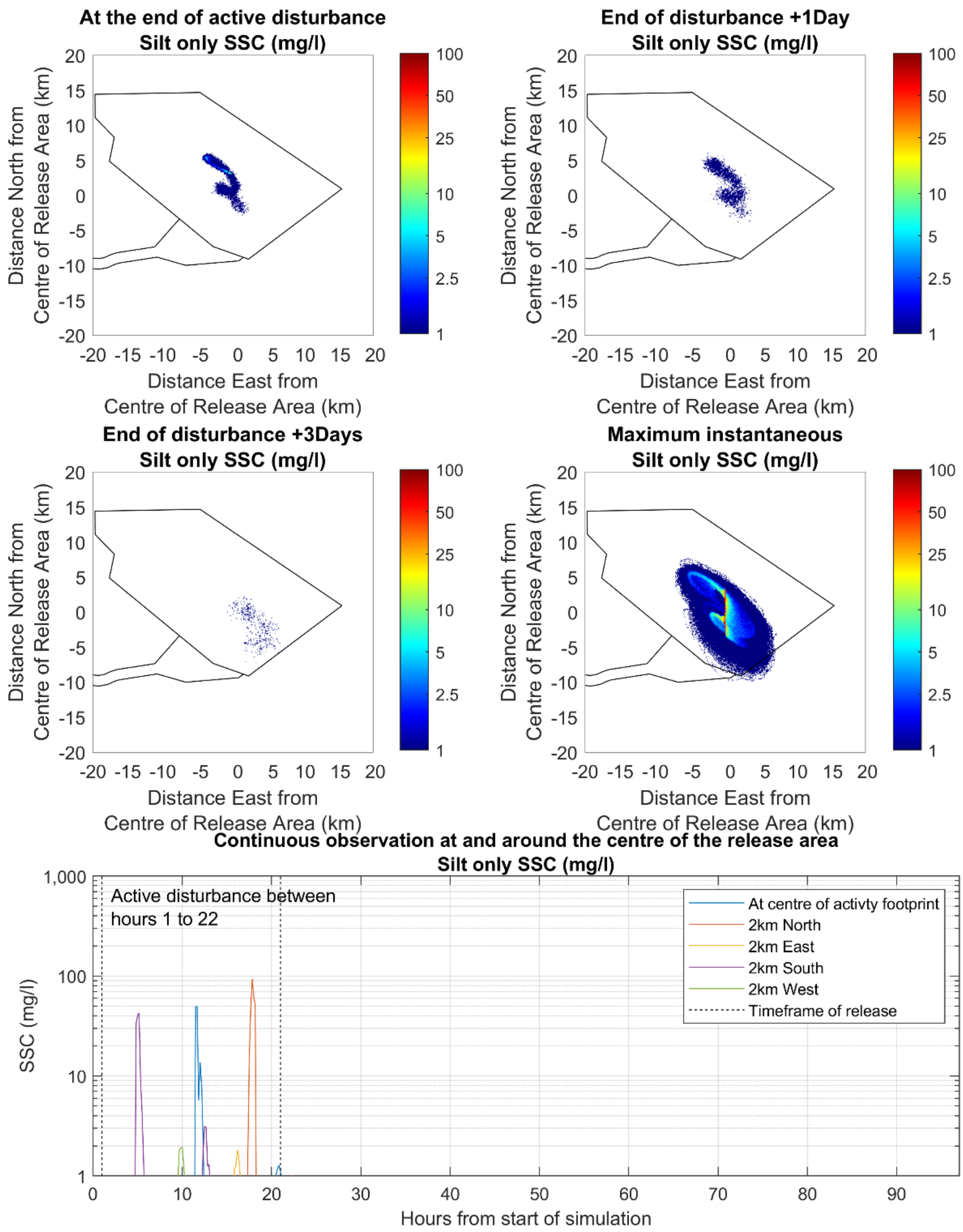


Figure C2. Suspended sediment concentration (silt fraction only) as a result of CFE dredging in the Hornsea Four array area. Mean neap tide

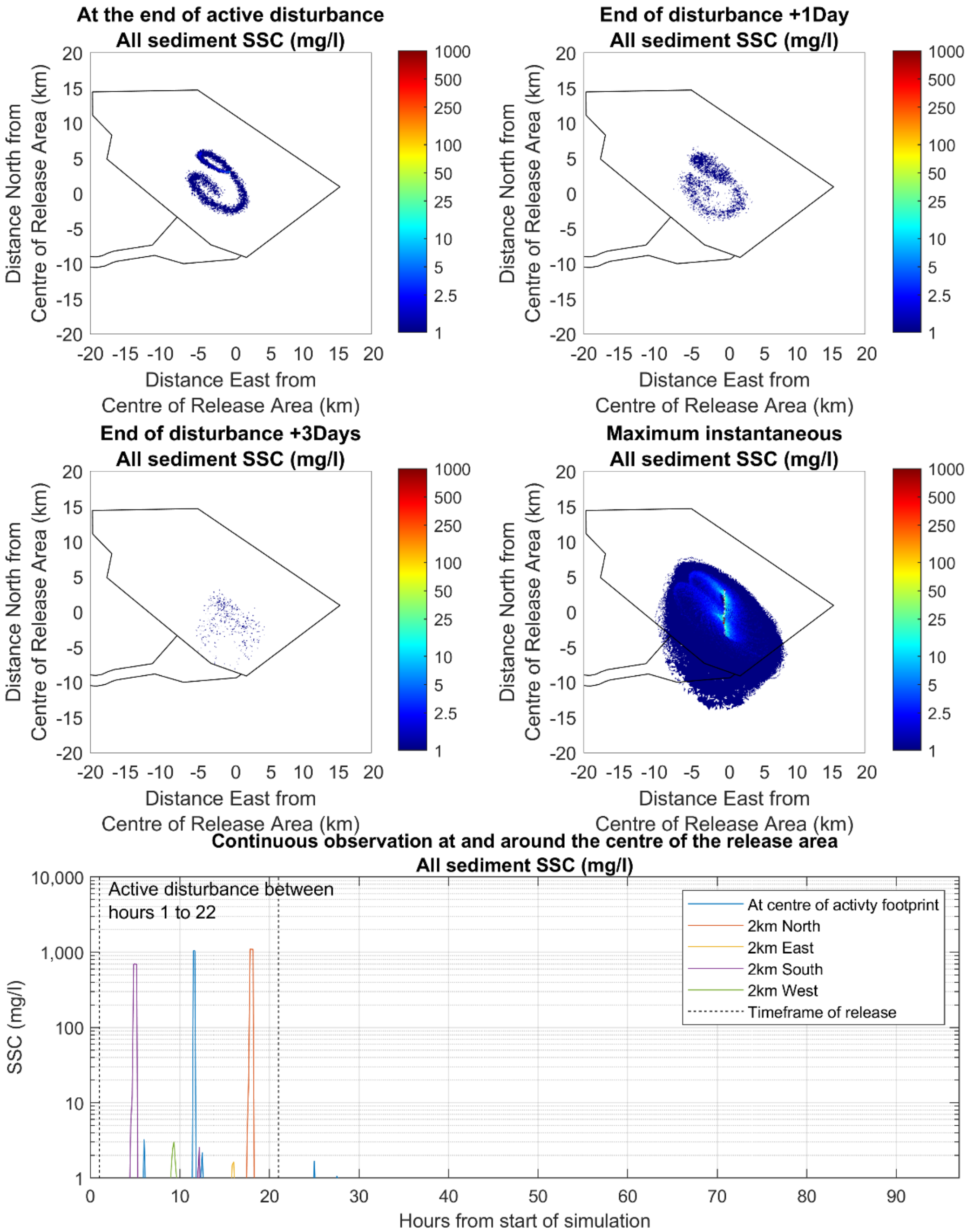


Figure C3. **Suspended sediment concentration (all sediment types) as a result of CFE dredging in the Hornsea Four array area. Mean spring tide**

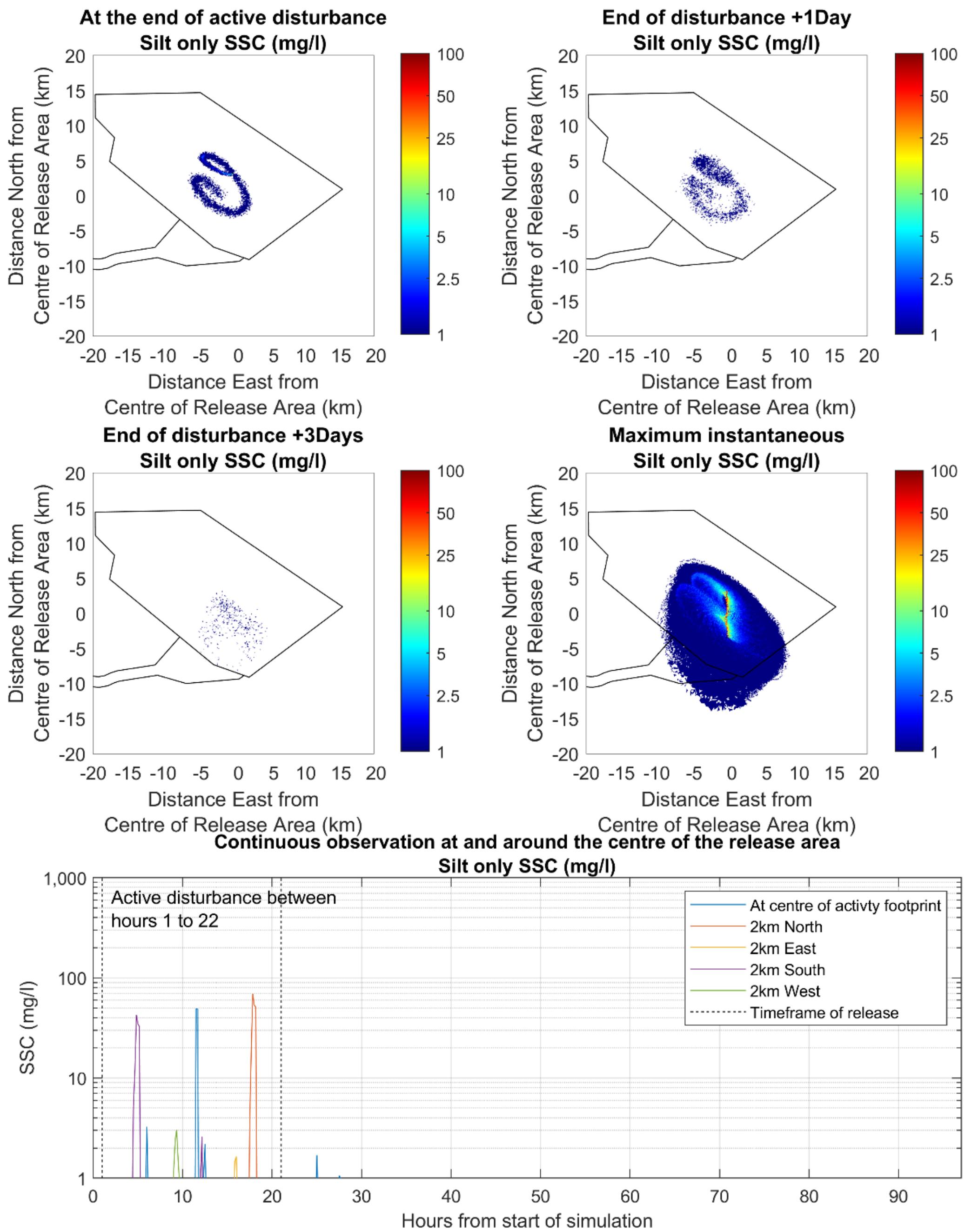


Figure C4. Suspended sediment concentration (silt fraction only) as a result of CFE dredging in the Hornsea Four array area. Mean spring tide

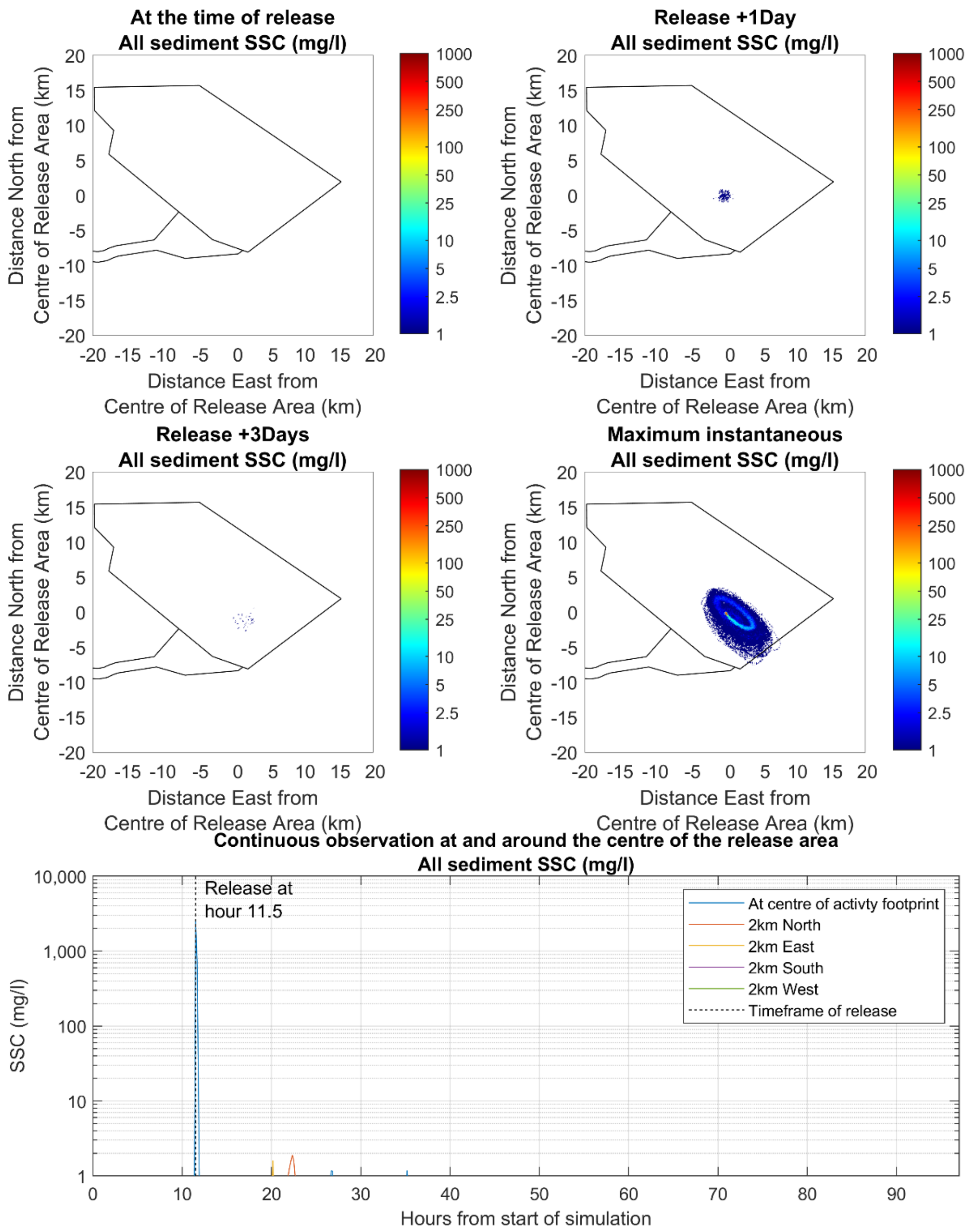


Figure C5. **Suspended sediment concentration (all sediment types) as a result of the passive phase plume from dredge spoil disposal in the Hornsea Four array area. Mean neap tide**

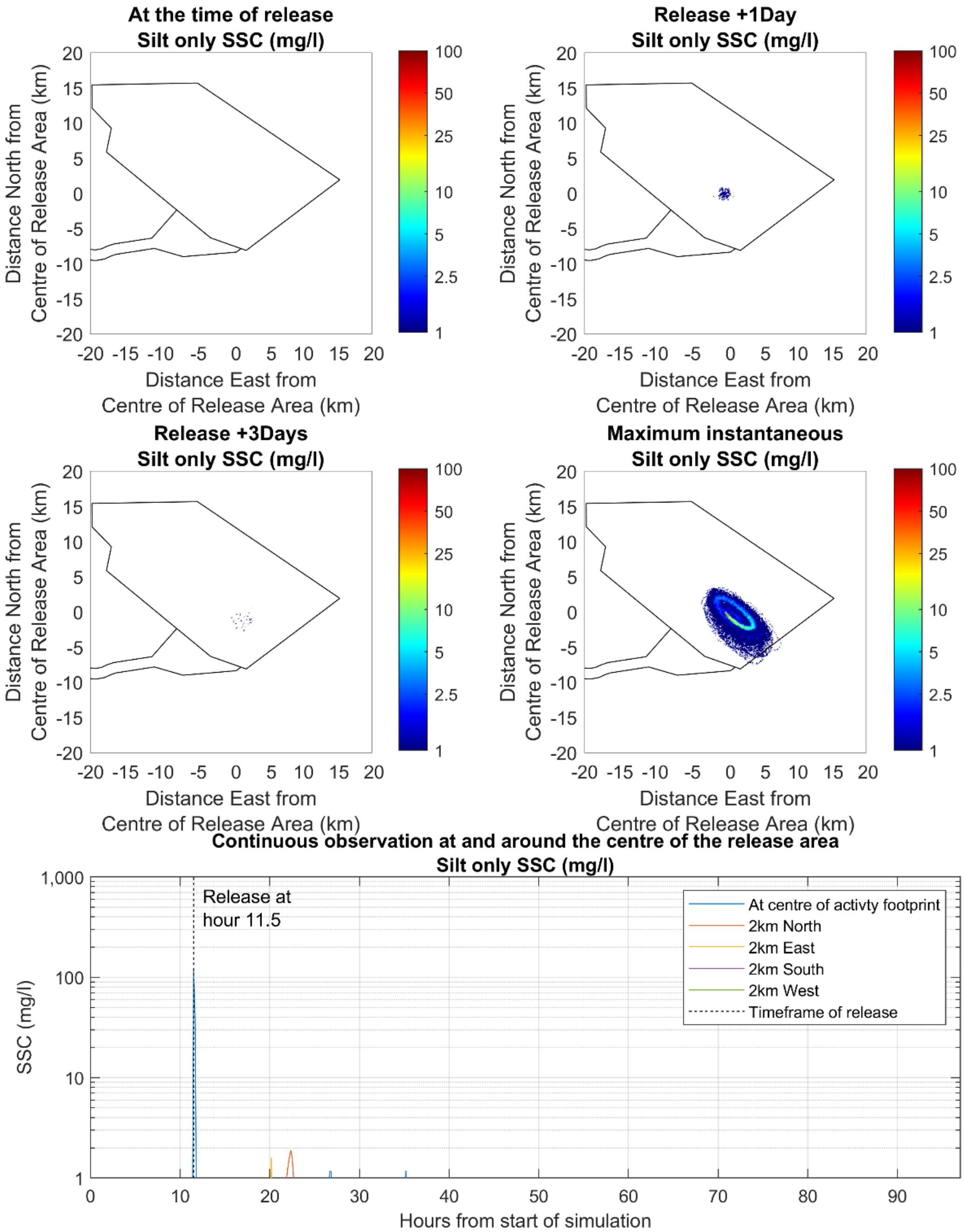


Figure C6. **Suspended sediment concentration (silt fraction only) as a result of the passive phase plume from dredge spoil disposal in the Hornsea Four array area. Mean neap tide**

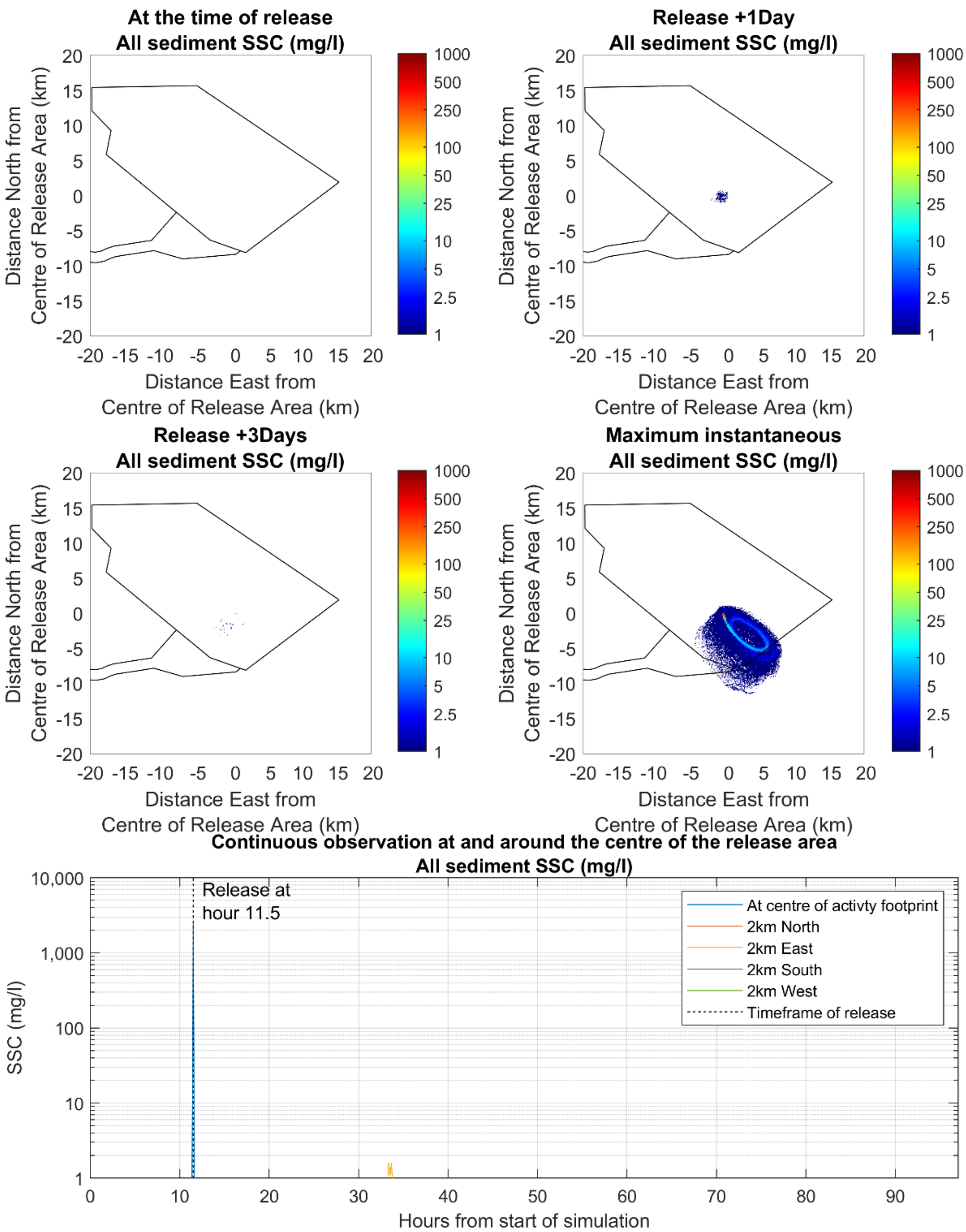


Figure C7. **Suspended sediment concentration (all sediment types) as a result of the passive phase plume from dredge spoil disposal in the Hornsea Four array area. Mean spring tide**

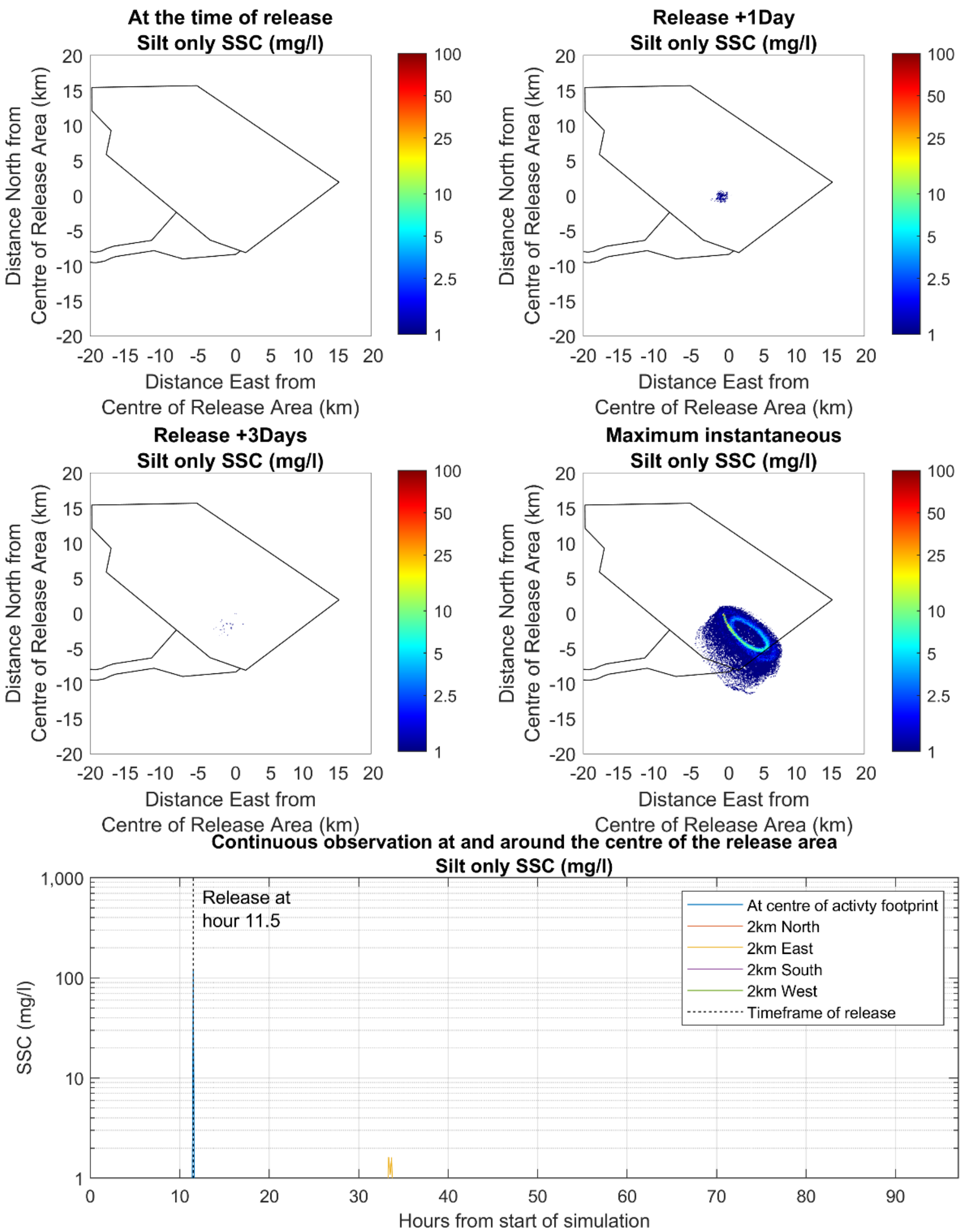


Figure C8. **Suspended sediment concentration (silt fraction only) as a result of the passive phase plume from dredge spoil disposal in the Hornsea Four array area. Mean spring tide**

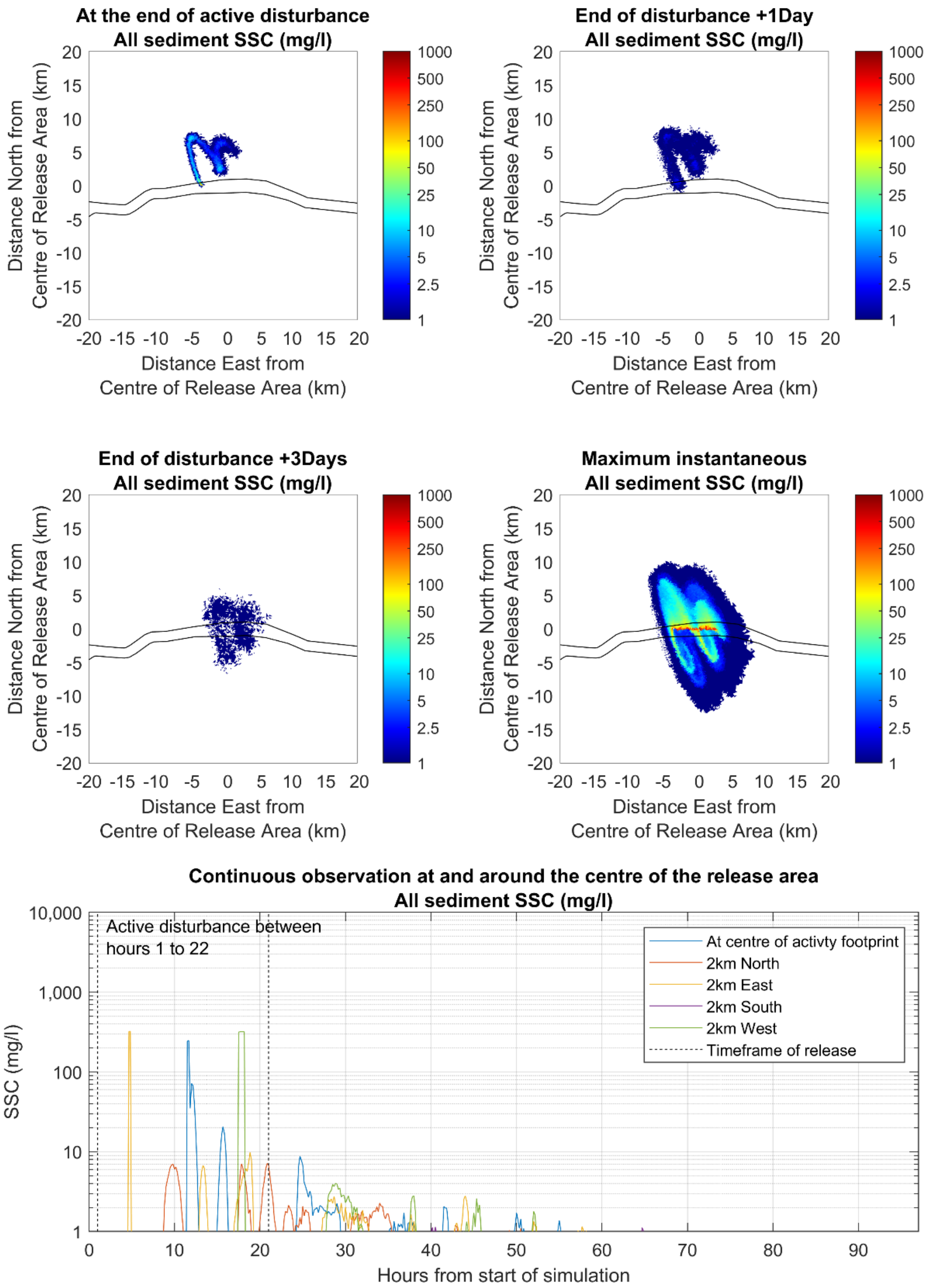


Figure C9. **Suspended sediment concentration (all sediment types) as a result of CFE dredging in the HVAC booster station search area. Mean neap tide**

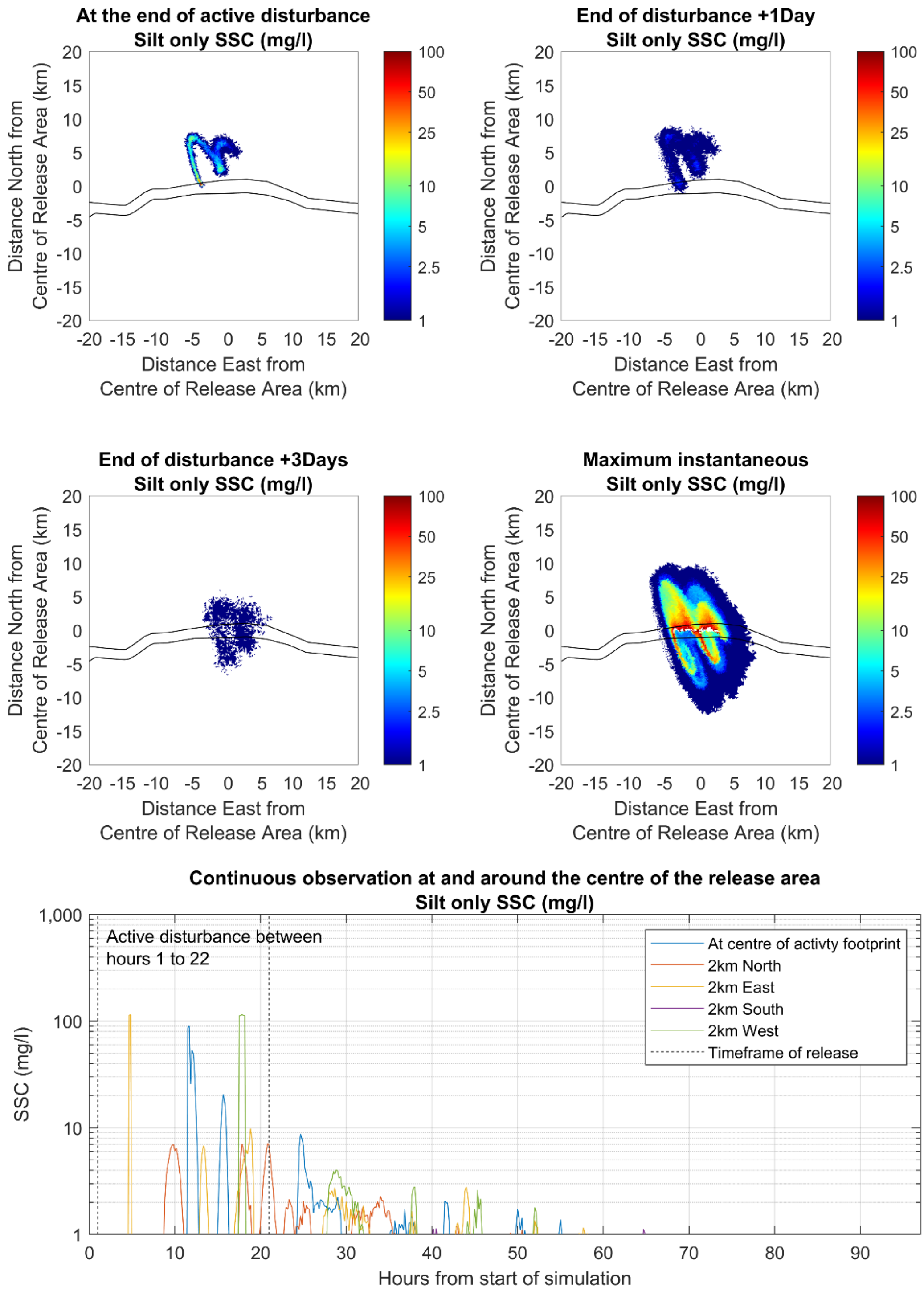


Figure C10. Suspended sediment concentration (silt fraction only) as a result of CFE dredging in the HVAC booster station search area. Mean neap tide

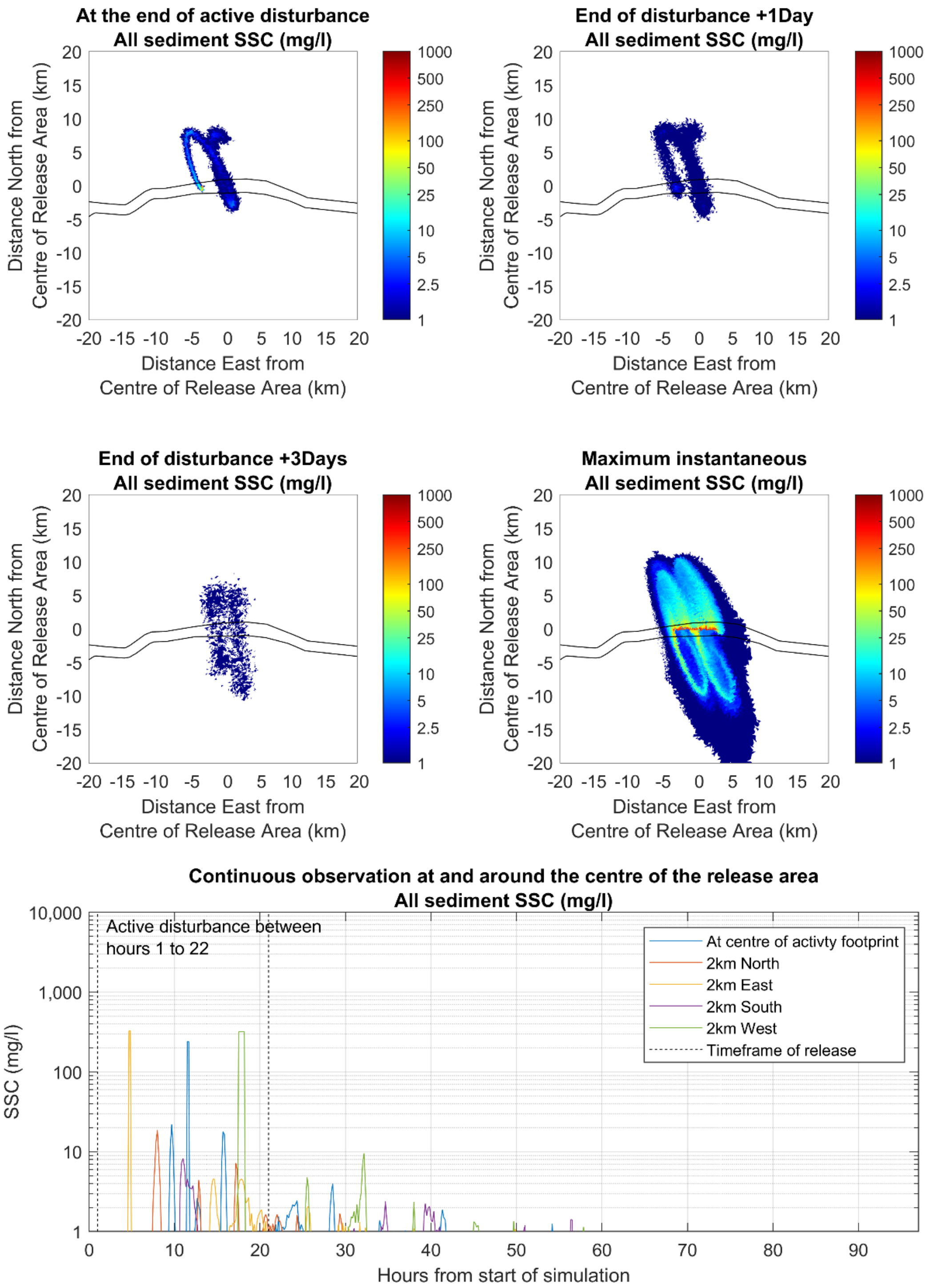


Figure C11. **Suspended sediment concentration (all sediment types) as a result of CFE dredging in the HVAC booster station search area. Mean spring tide**

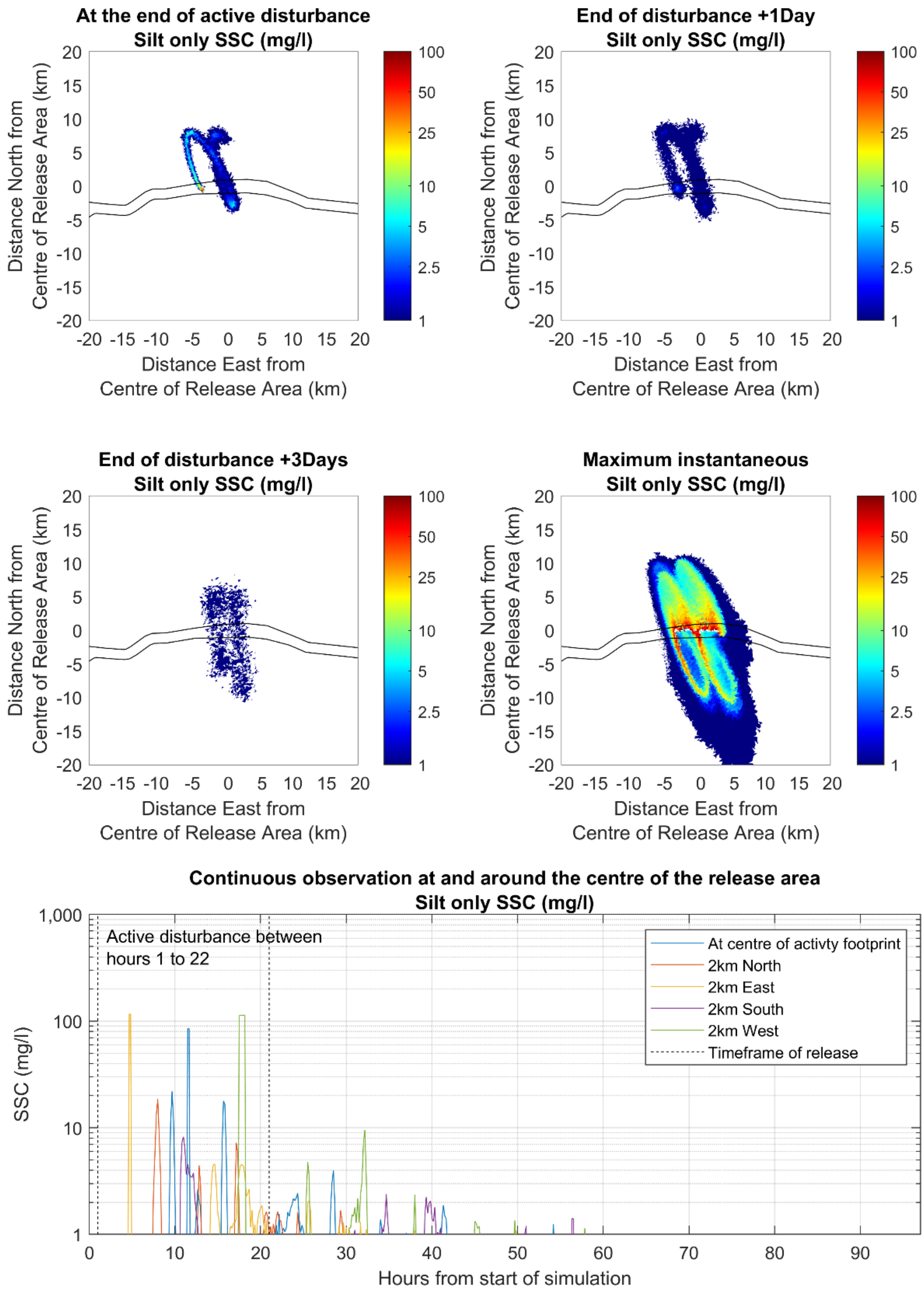


Figure C12. Suspended sediment concentration from (silt fraction only) as a result of CFE dredging in the HVAC booster station search area. Mean spring tide

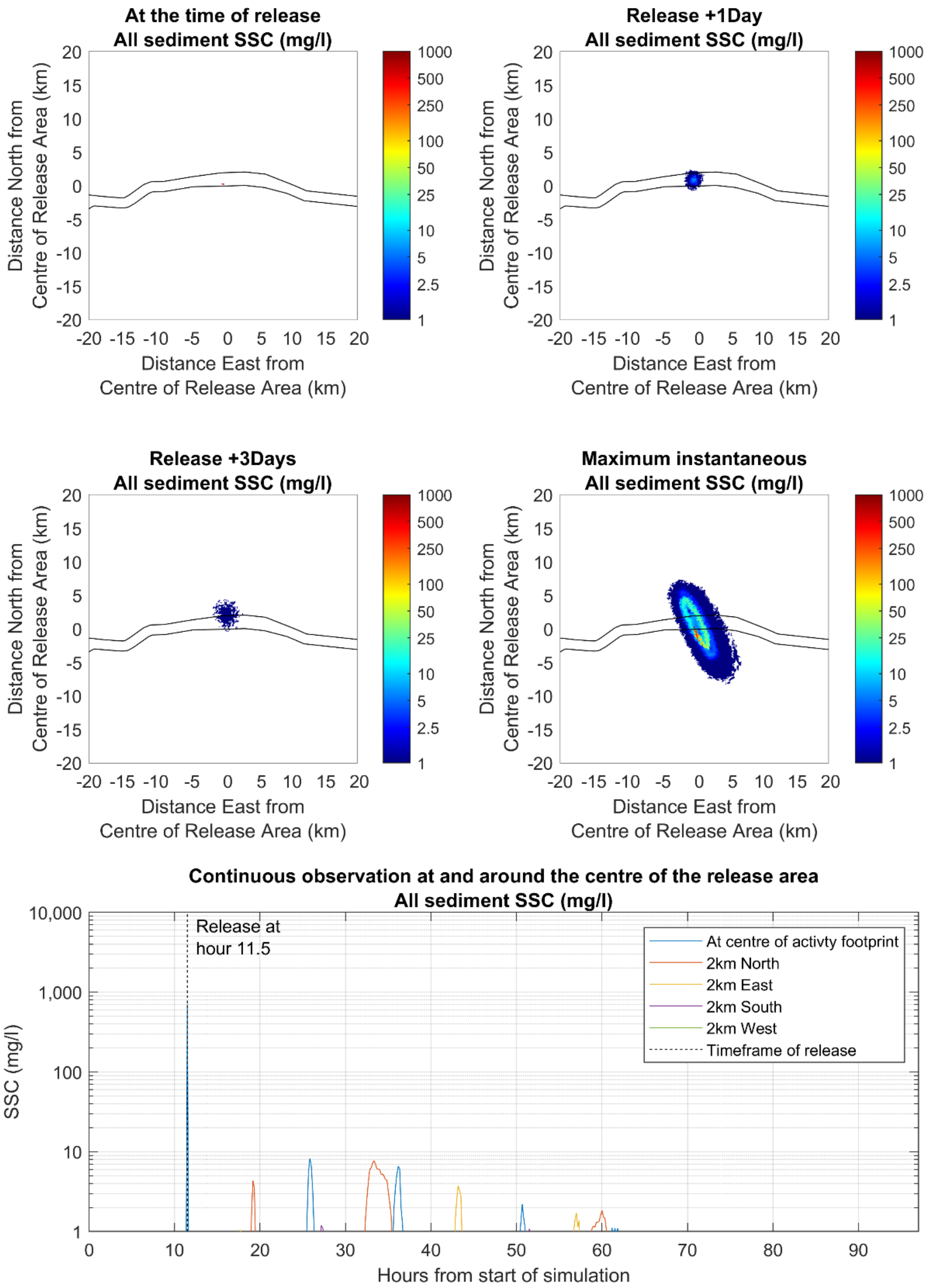


Figure C13. **Suspended sediment concentration (all sediment types) as a result of the passive phase plume from dredge spoil disposal in the HVAC booster station search area. Mean neap tide**

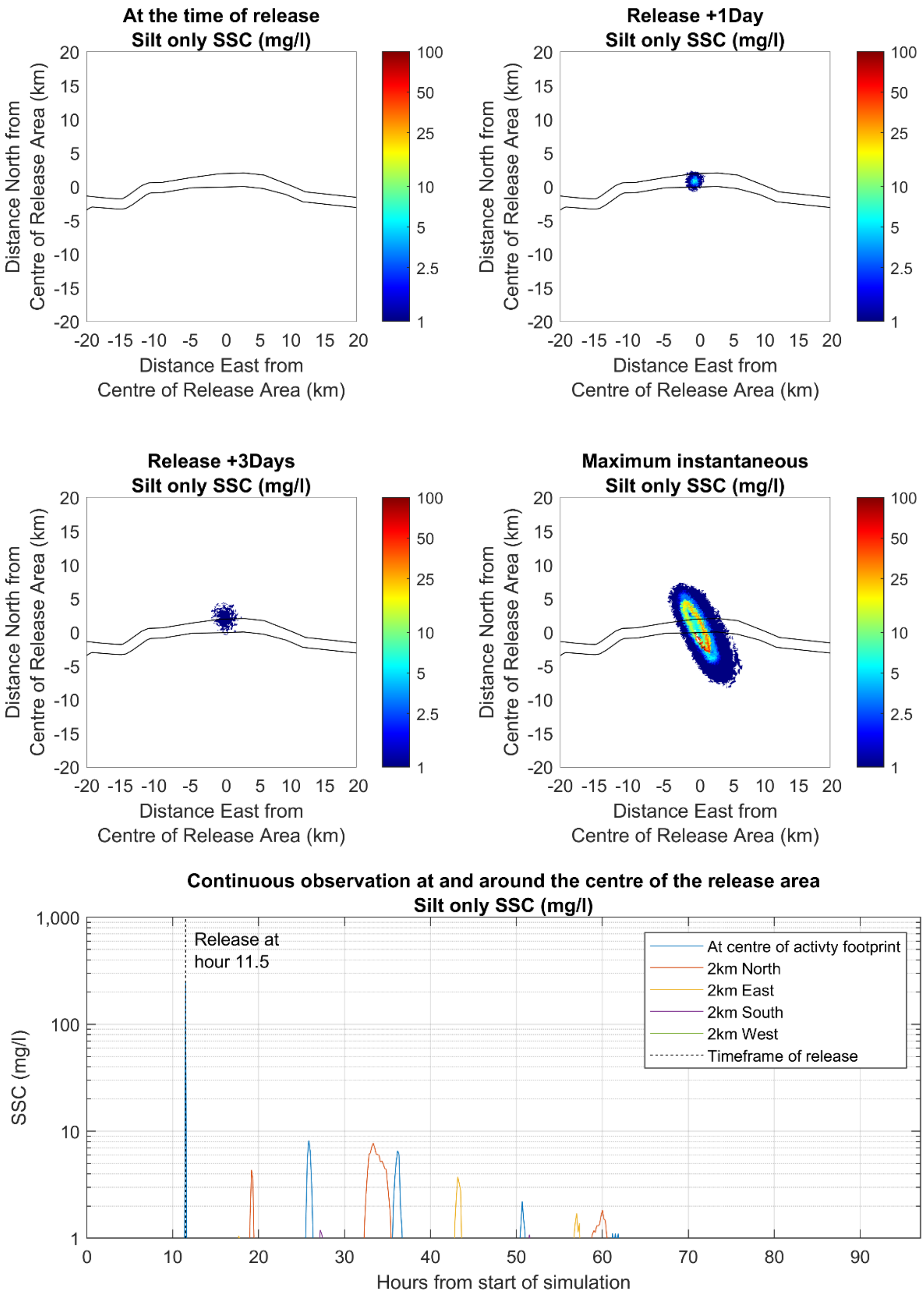


Figure C14. **Suspended sediment concentration (silt fraction only) as a result of the passive phase plume from dredge spoil disposal in the HVAC booster station search area. Mean neap tide**

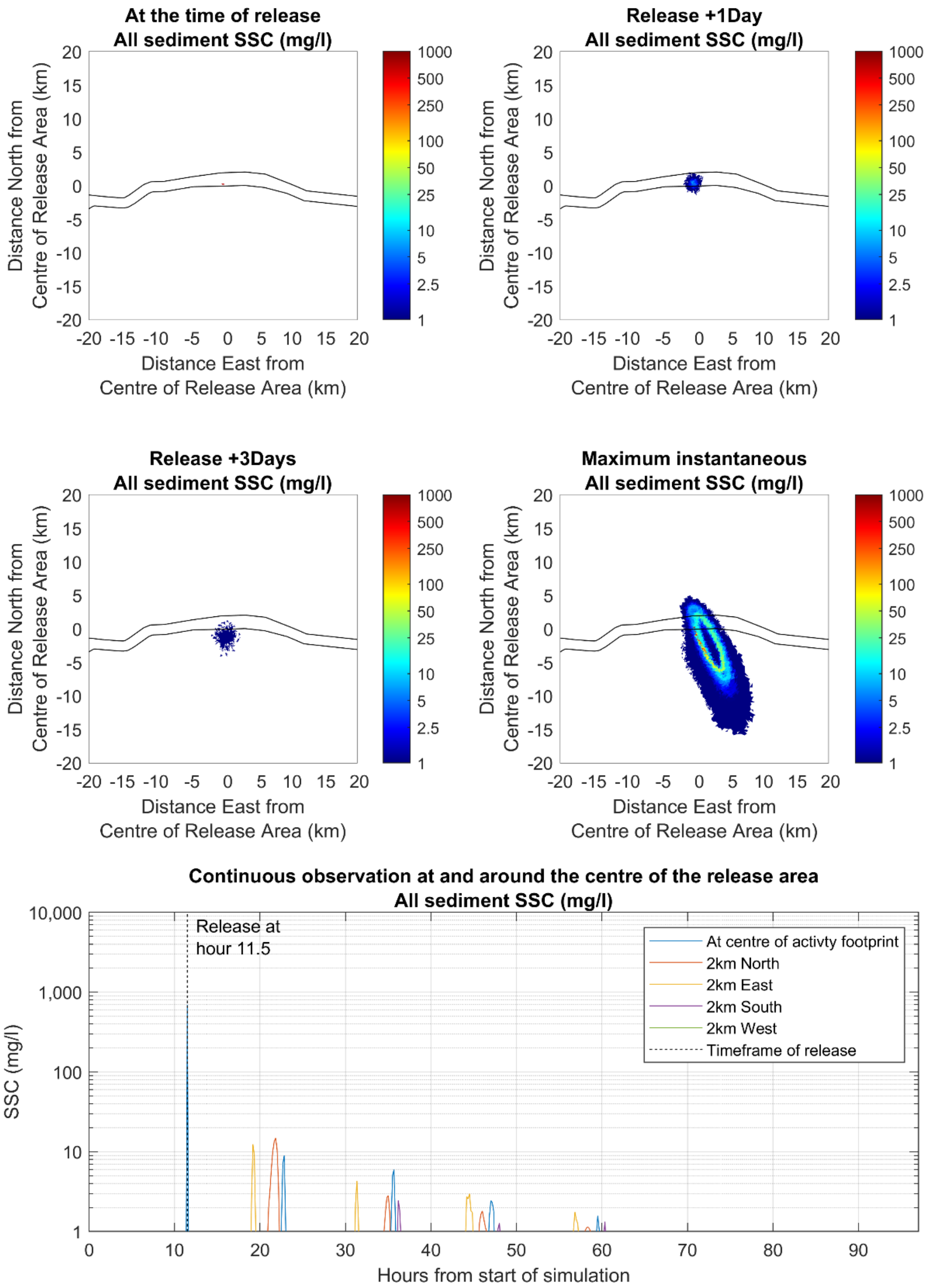


Figure C15. **Suspended sediment concentration (all sediment types) as a result of the passive phase plume from dredge spoil disposal in the HVAC booster station search area. Mean spring tide**

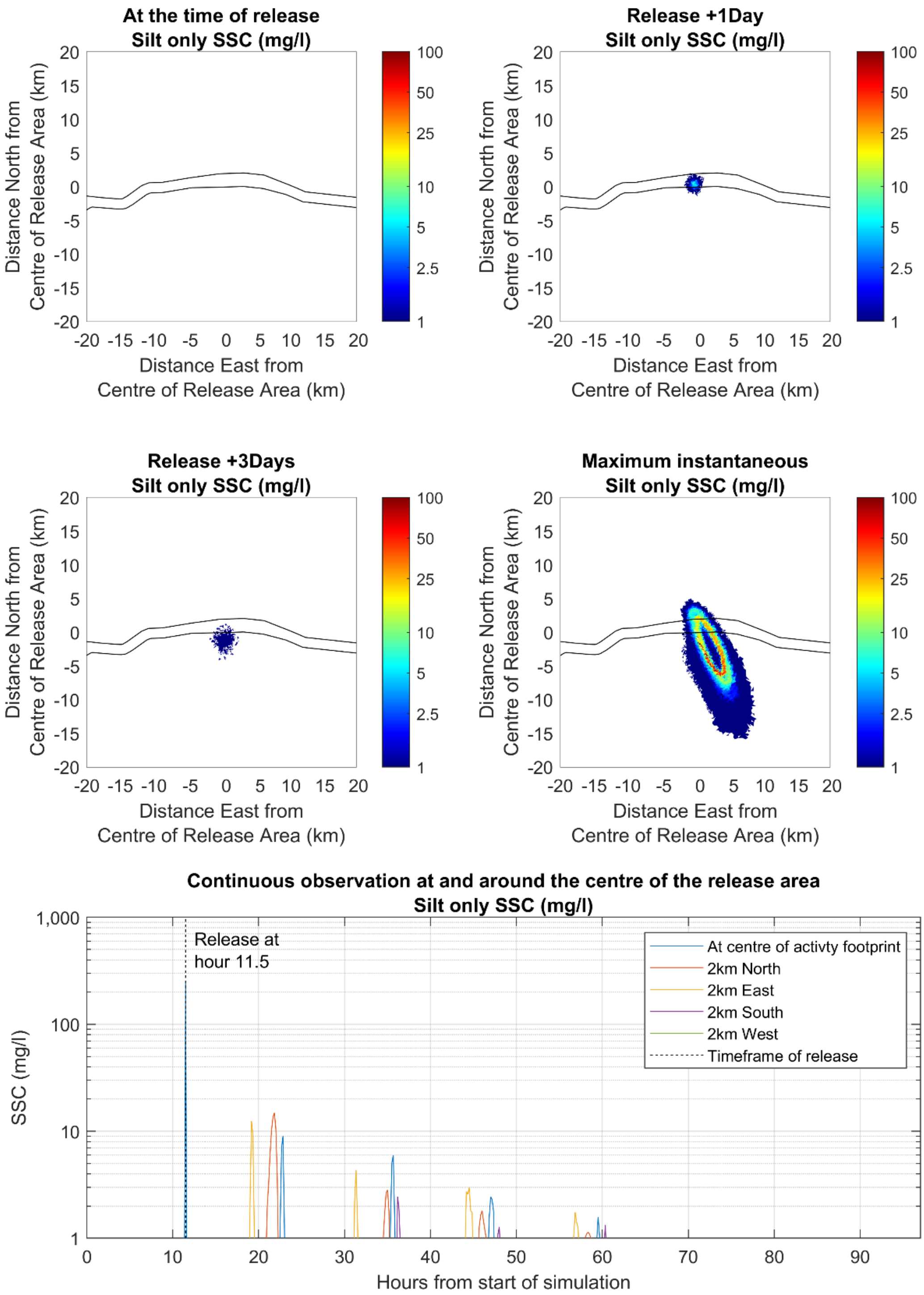


Figure C16. Suspended sediment concentration (silt fraction only) as a result of the passive phase plume from dredge spoil disposal in the HVAC booster station search area. Mean spring tide

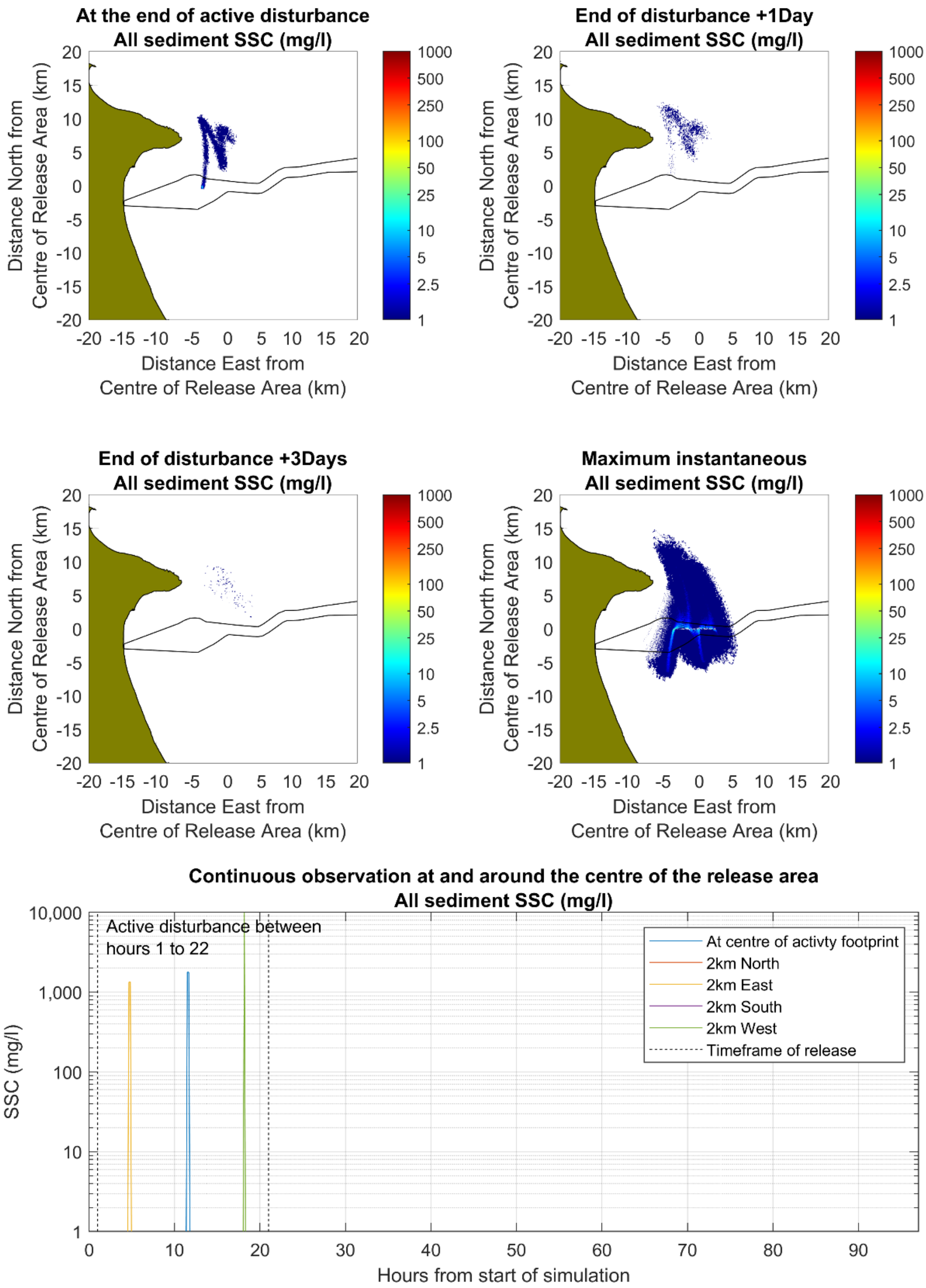


Figure C17. Suspended sediment concentration (all sediment types) as a result of CFE dredging in the nearshore cable crossing area offshore of Smithic Bank. Mean neap tide

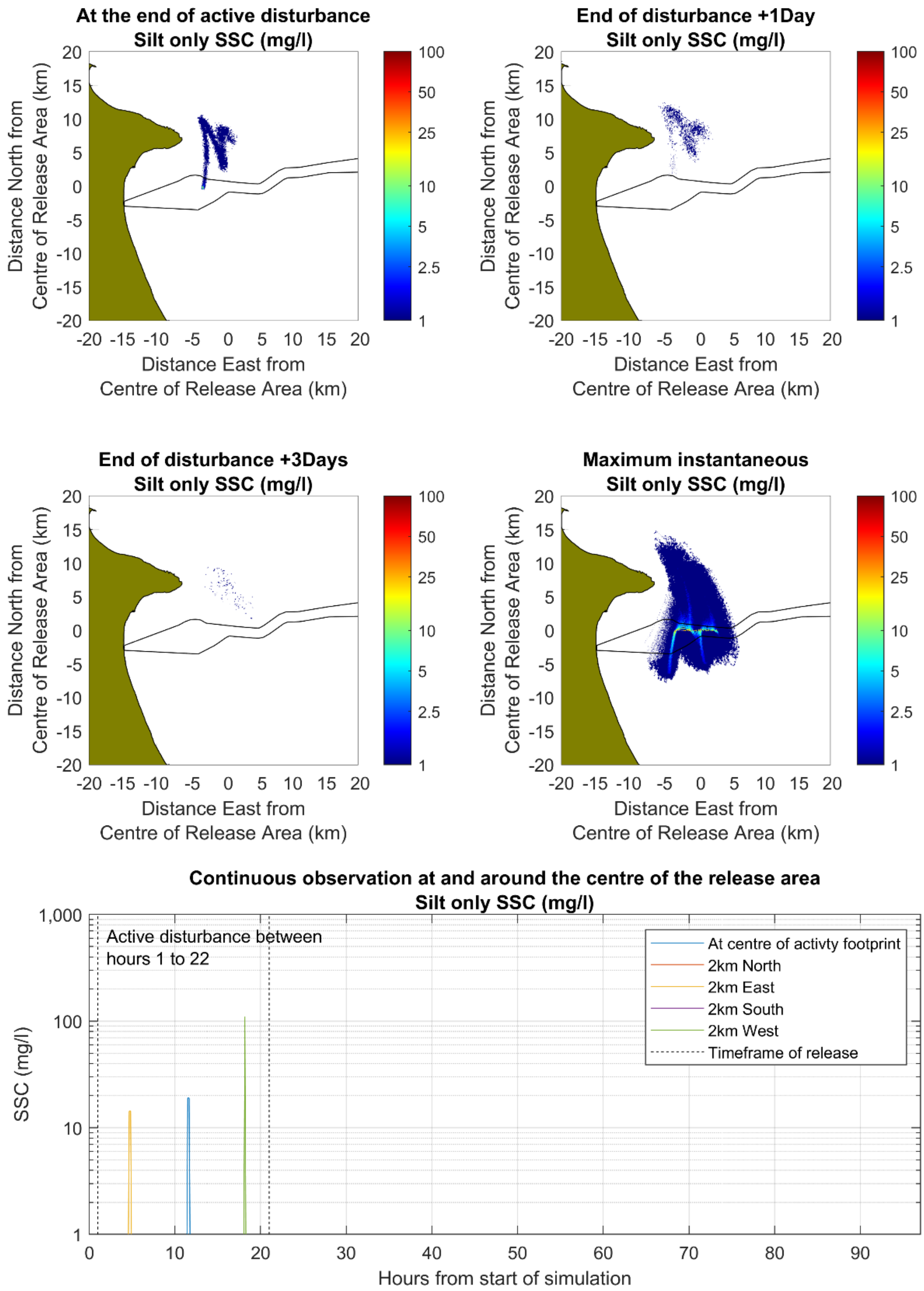


Figure C18. **Suspended sediment concentration (silt fraction only) as a result of CFE dredging in the nearshore cable crossing area offshore of Smithic Bank. Mean neap tide**

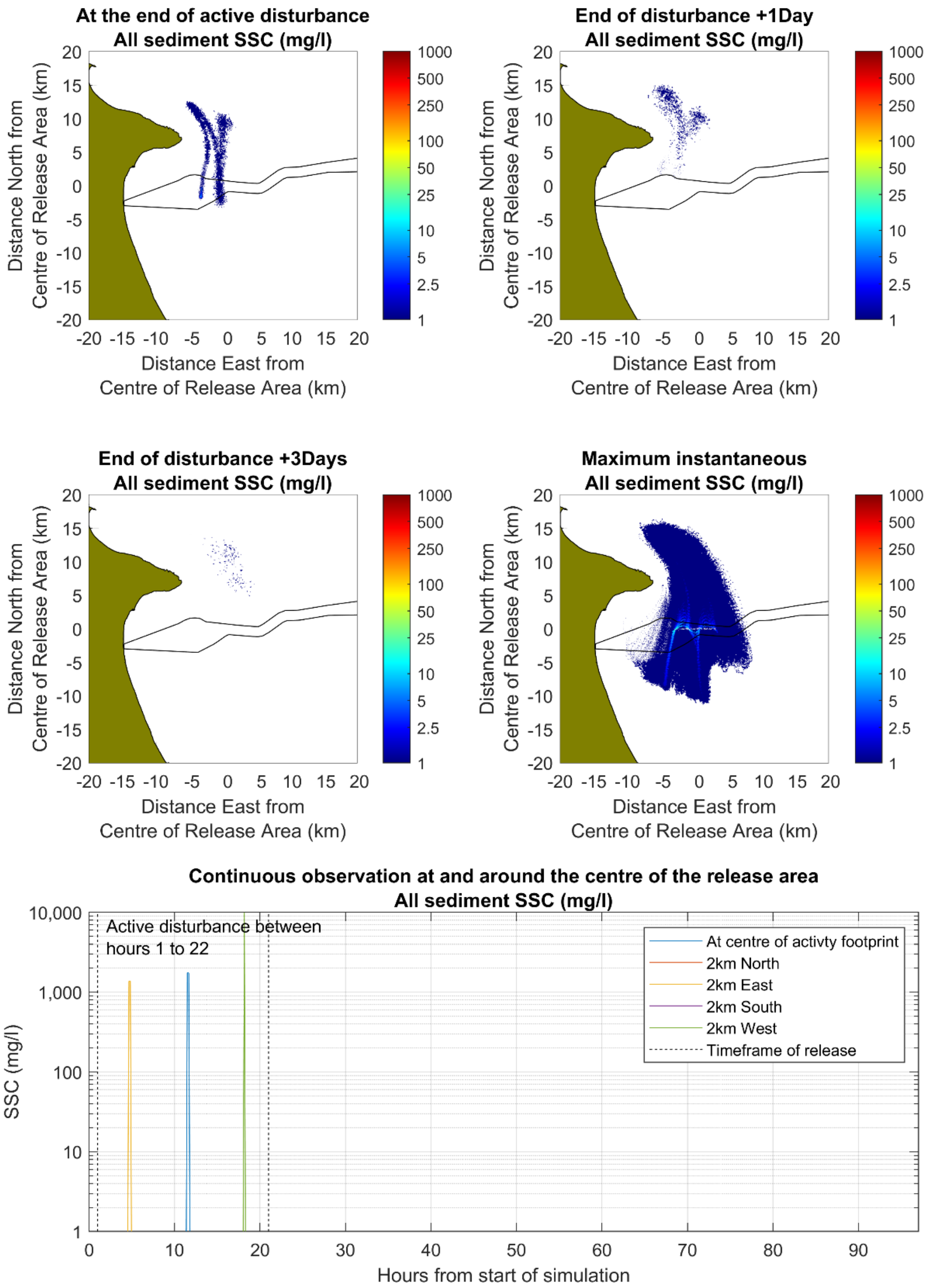


Figure C19. **Suspended sediment concentration (all sediment types) as a result of CFE dredging in the nearshore cable crossing area offshore of Smithic Bank. Mean spring tide**

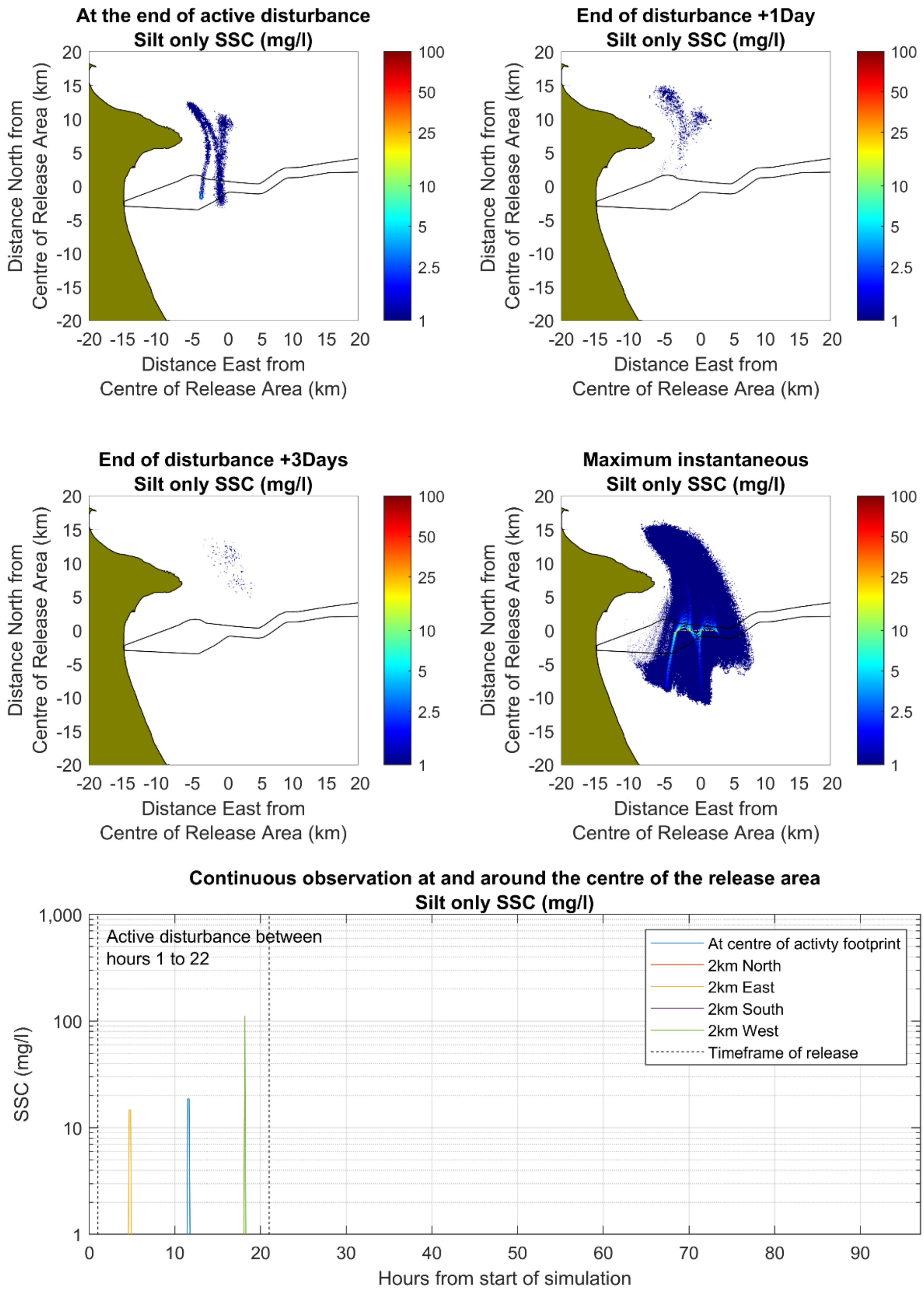


Figure C20. **Suspended sediment concentration (silt fraction only) as a result of CFE dredging in the nearshore cable crossing area offshore of Smithic Bank. Mean spring tide**

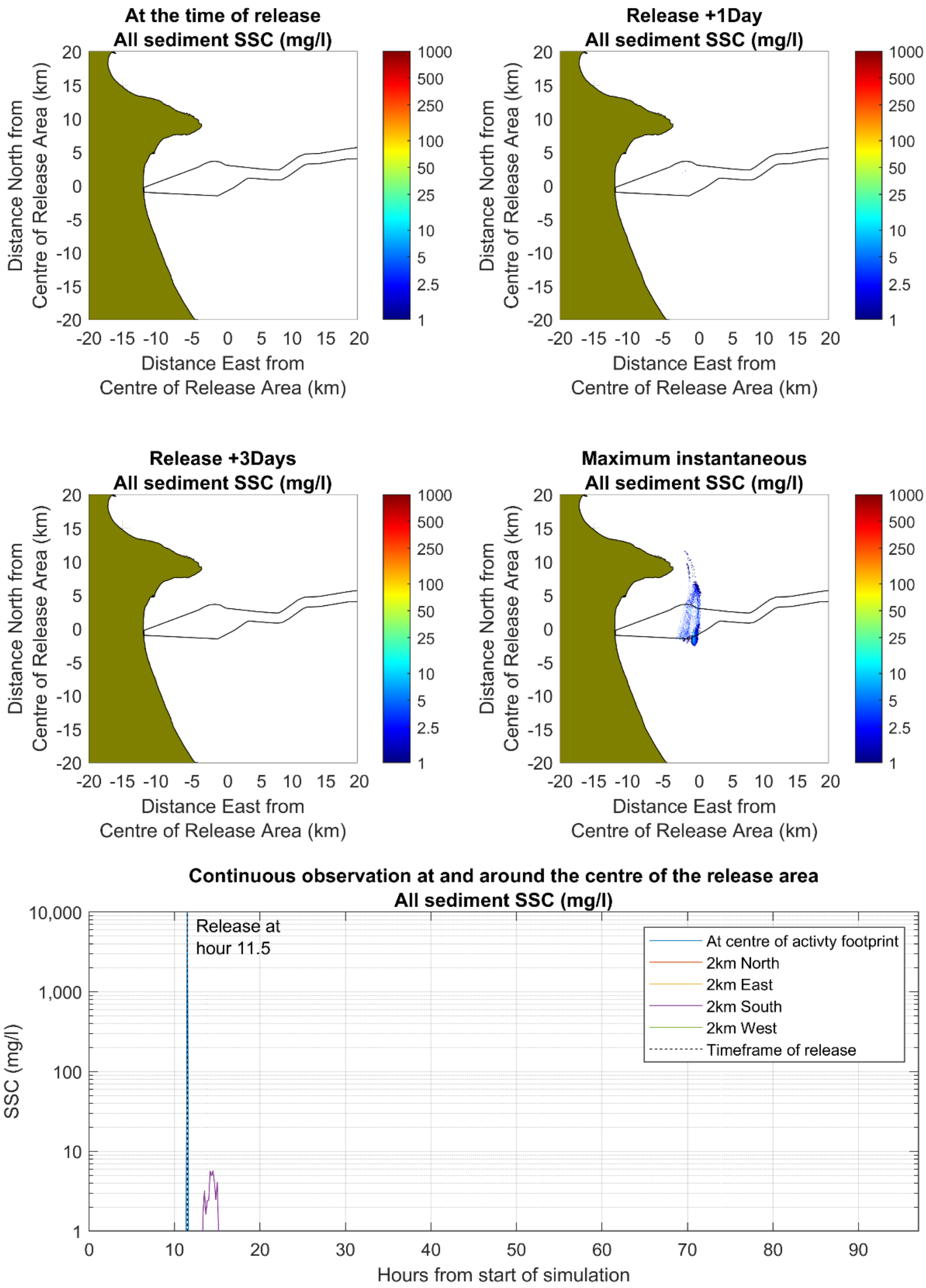


Figure C21. **Suspended sediment concentration (all sediment types) as a result of the passive phase plume from dredge spoil disposal in the nearshore cable crossing area offshore of Smithic Bank. Mean neap tide**

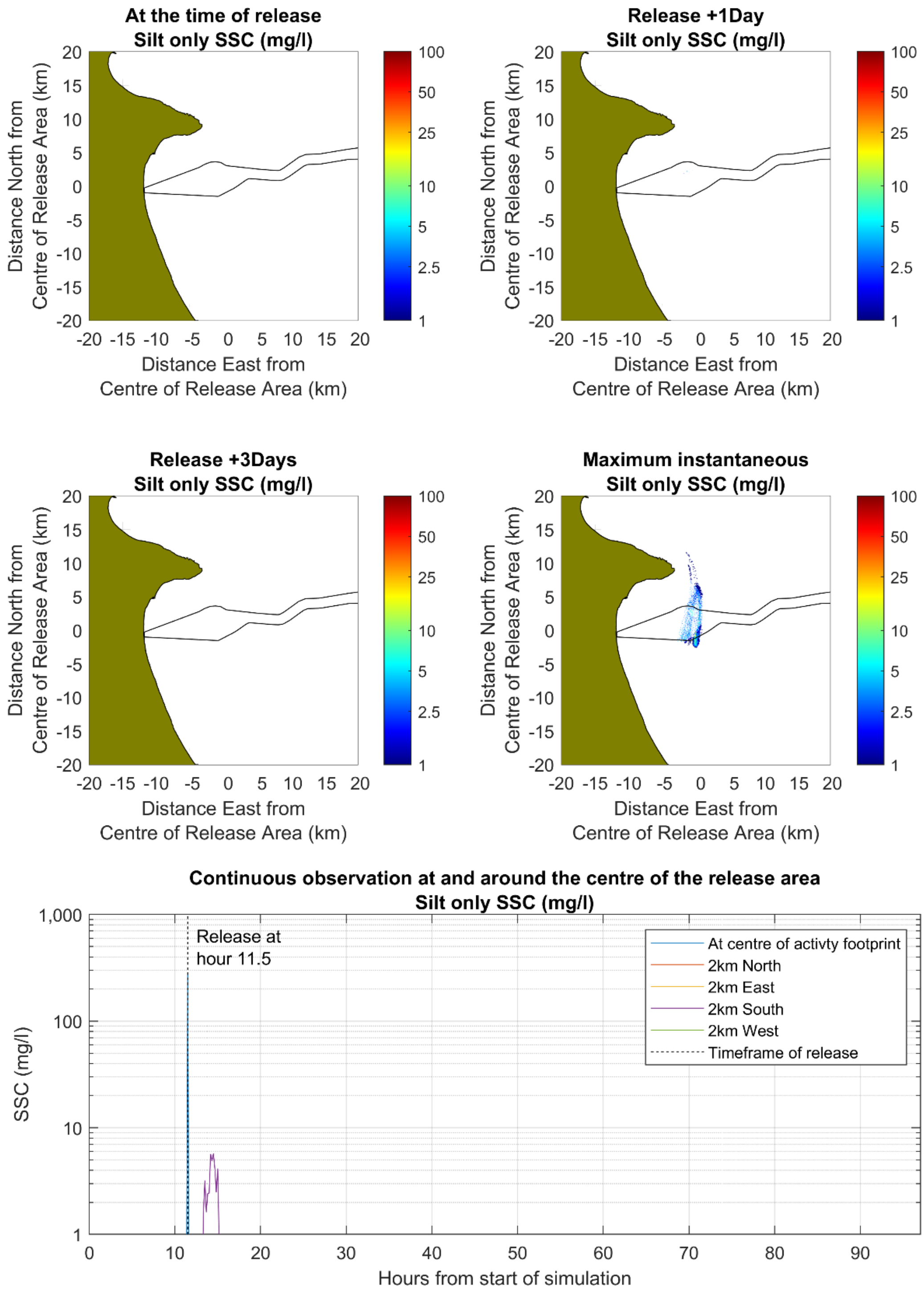


Figure C22. **Suspended sediment concentration (silt fraction only) as a result of the passive phase plume from dredge spoil disposal in the nearshore cable crossing area offshore of Smithic Bank. Mean neap tide**

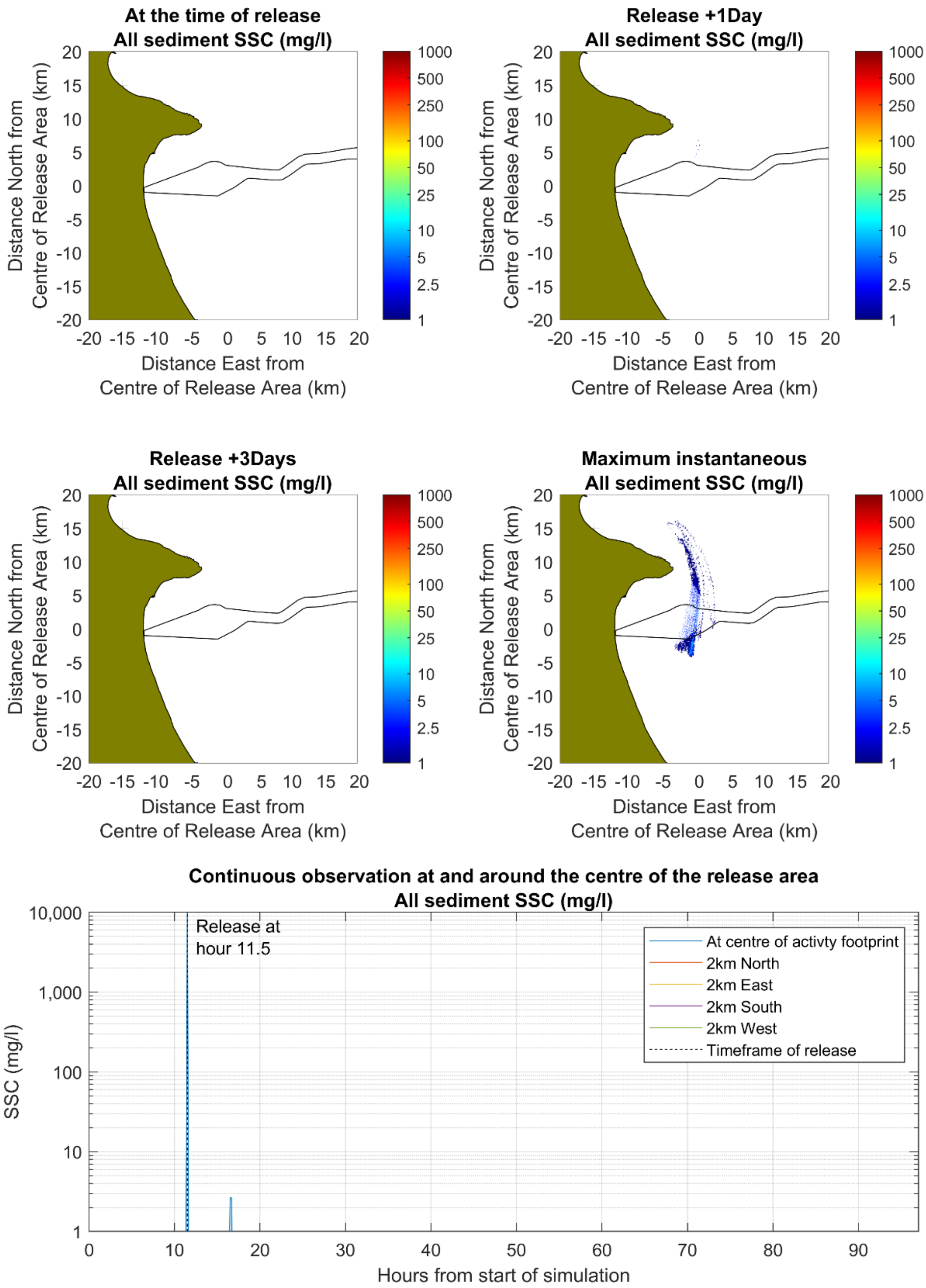


Figure C23. Suspended sediment concentration (all sediment types) as a result of the passive phase plume from dredge spoil disposal in the nearshore cable crossing area offshore of Smithic Bank. Mean spring tide

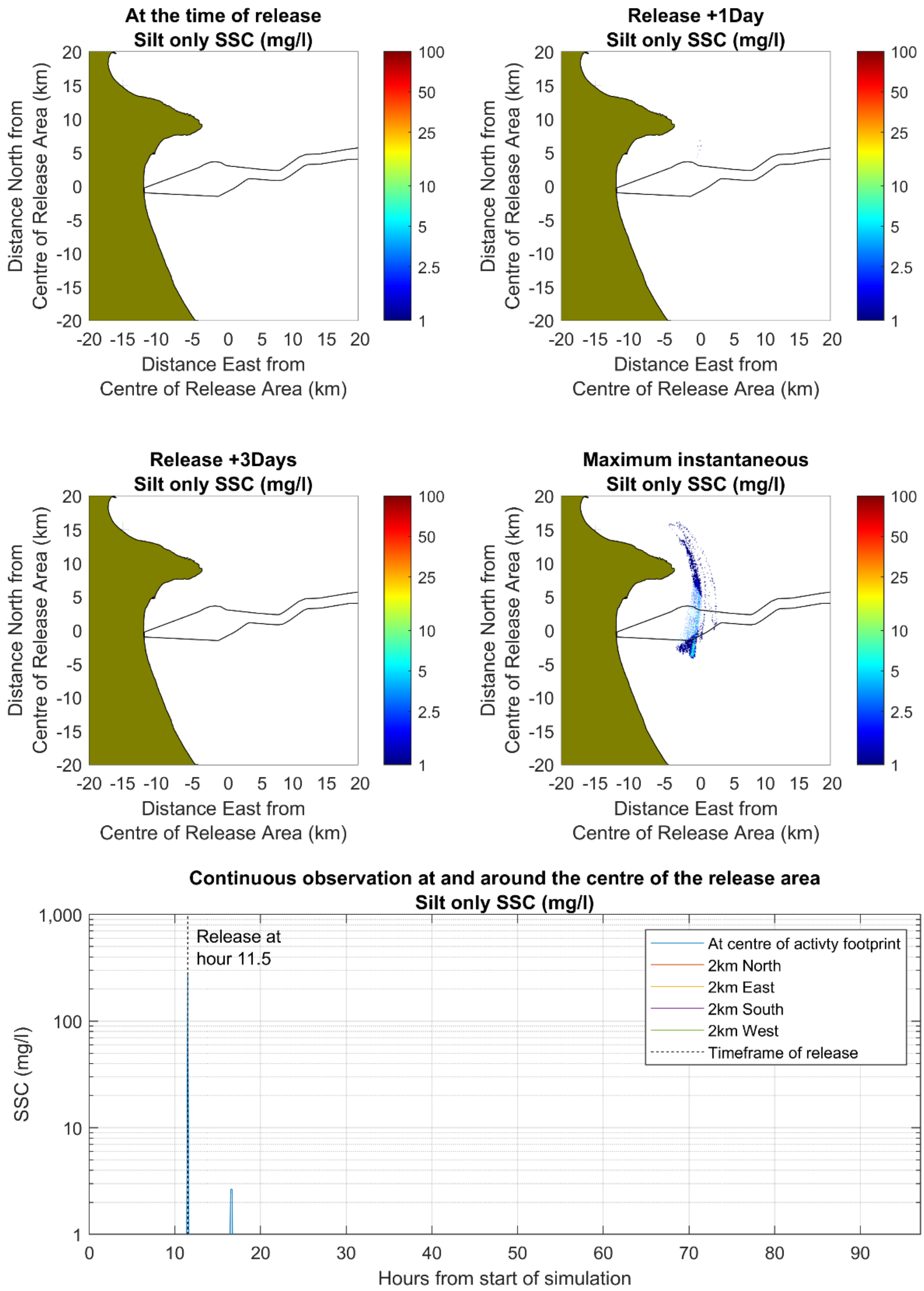


Figure C24. **Suspended sediment concentration (silt fraction only) as a result of the passive phase plume from dredge spoil disposal in the nearshore cable crossing area offshore of Smithic Bank. Mean spring tide**

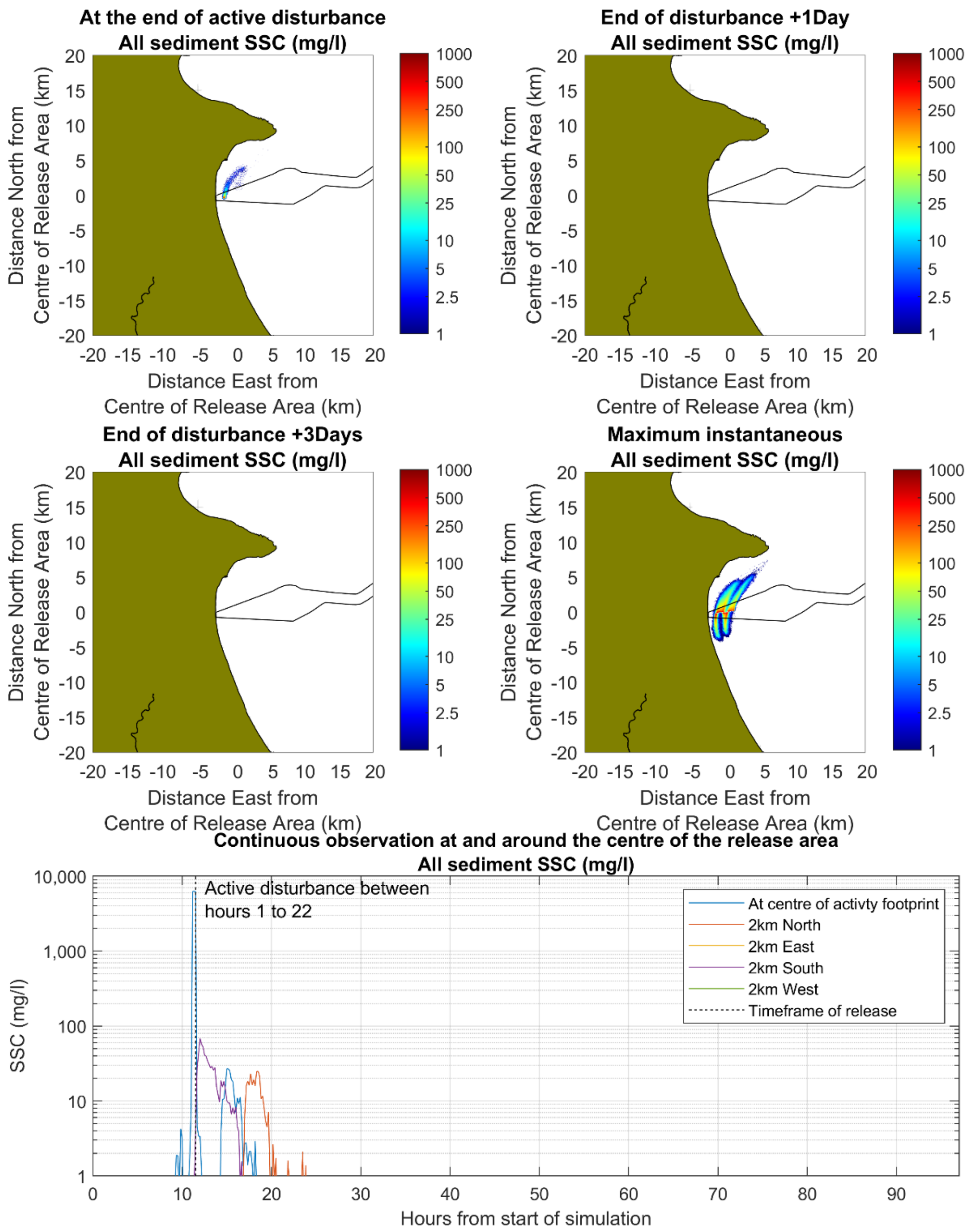


Figure C25. **Suspended sediment concentration (all sediment types) as a result of CFE dredging in the inshore area west of Smithic Bank. Mean neap tide**

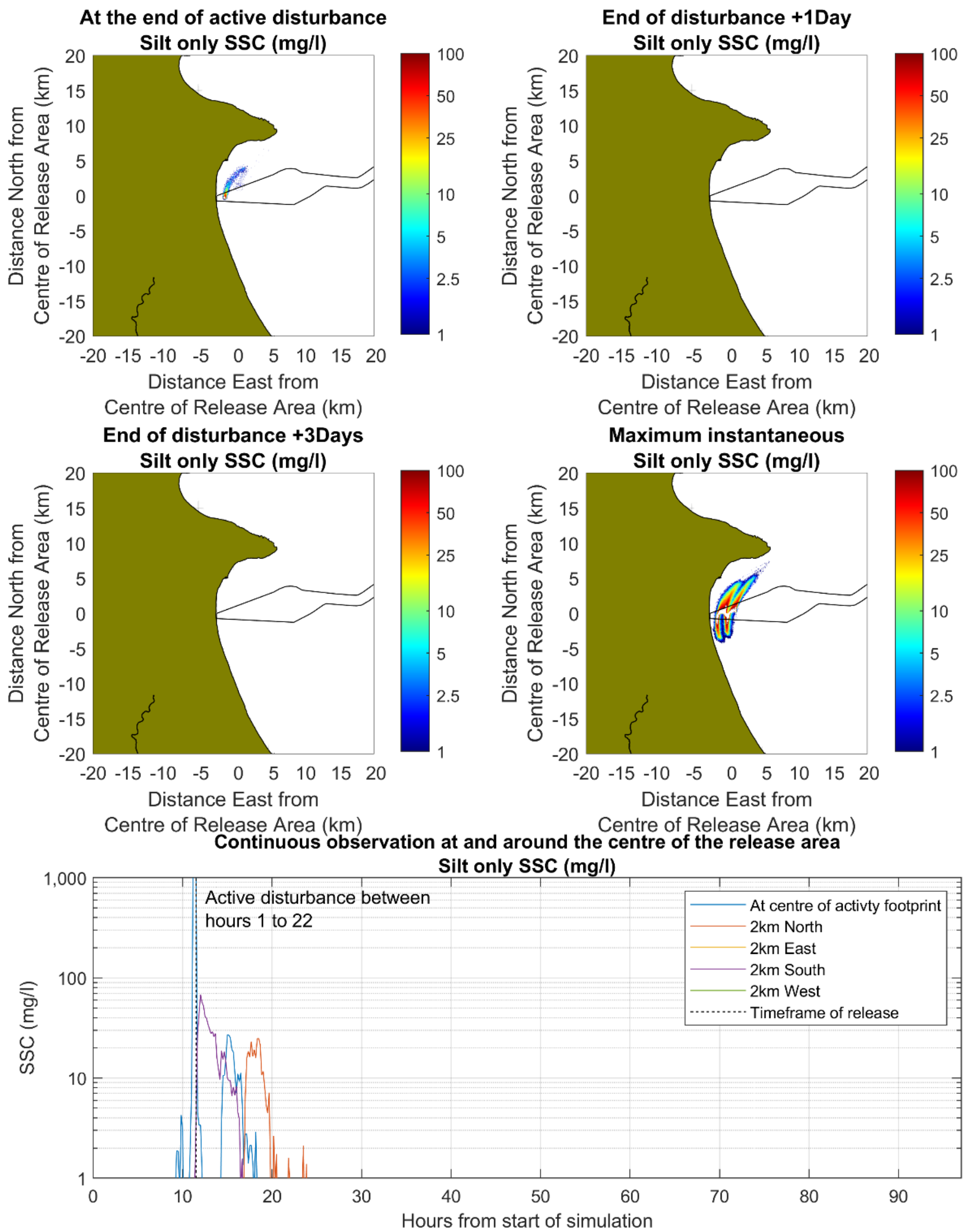


Figure C26. **Suspended sediment concentration (silt fraction only) as a result of CFE dredging in the inshore area west of Smithic Bank. Mean neap tide**

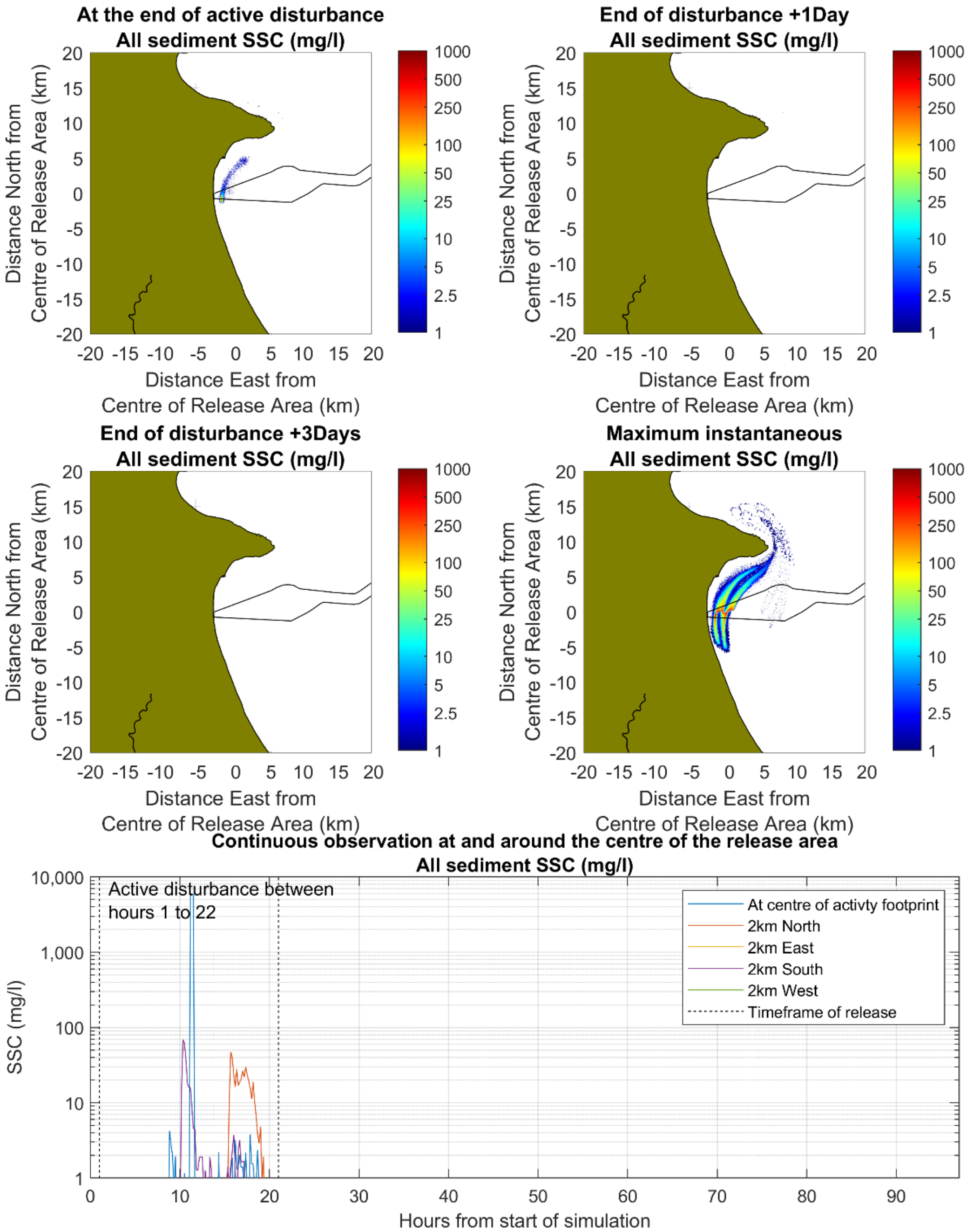


Figure C27. Suspended sediment concentration (all sediment types) as a result of CFE dredging in the inshore area west of Smithic Bank. Mean spring tide

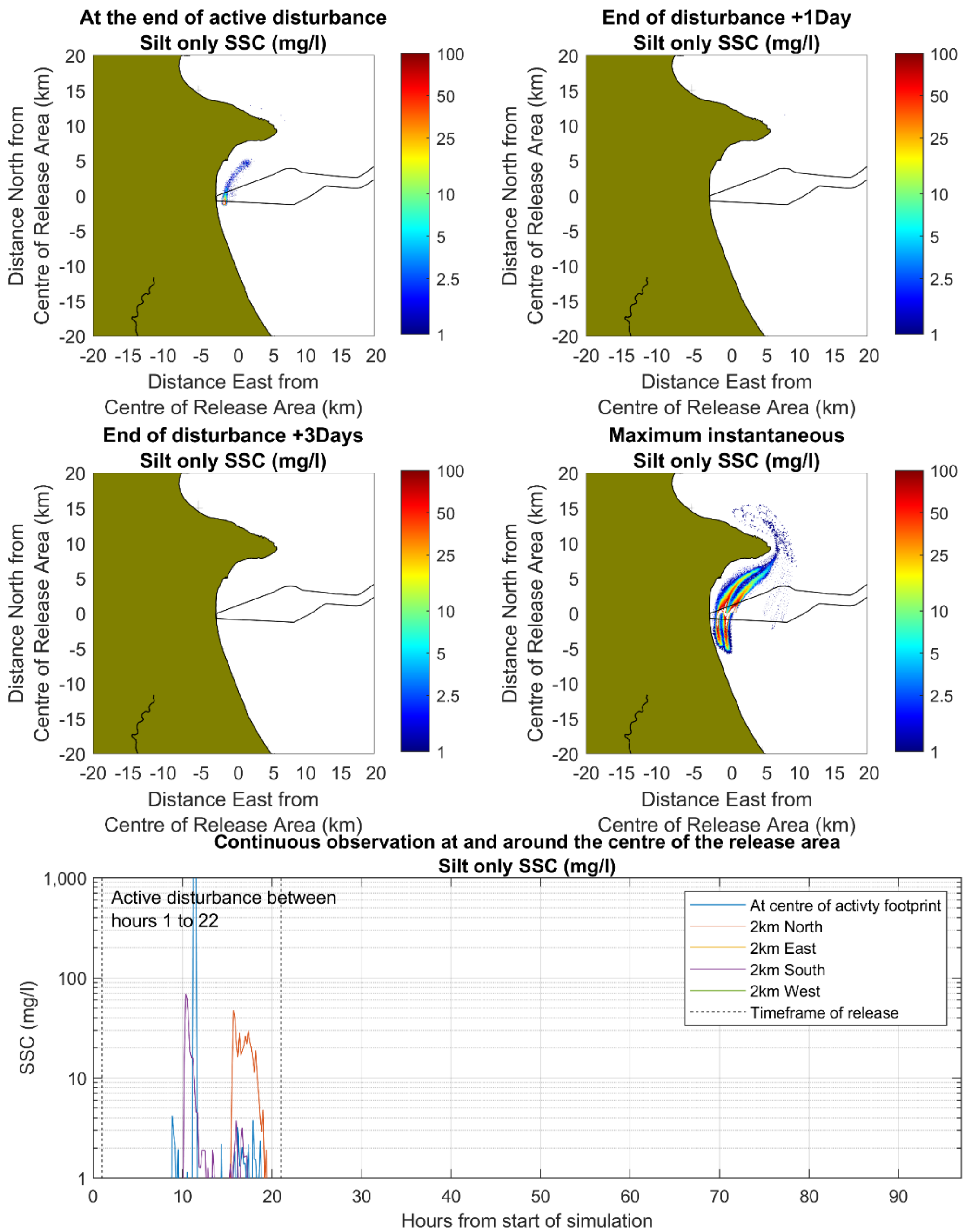


Figure C28. **Suspended sediment concentration (silt fraction only) as a result of CFE dredging in the inshore area west of Smithic Bank. Mean spring tide**

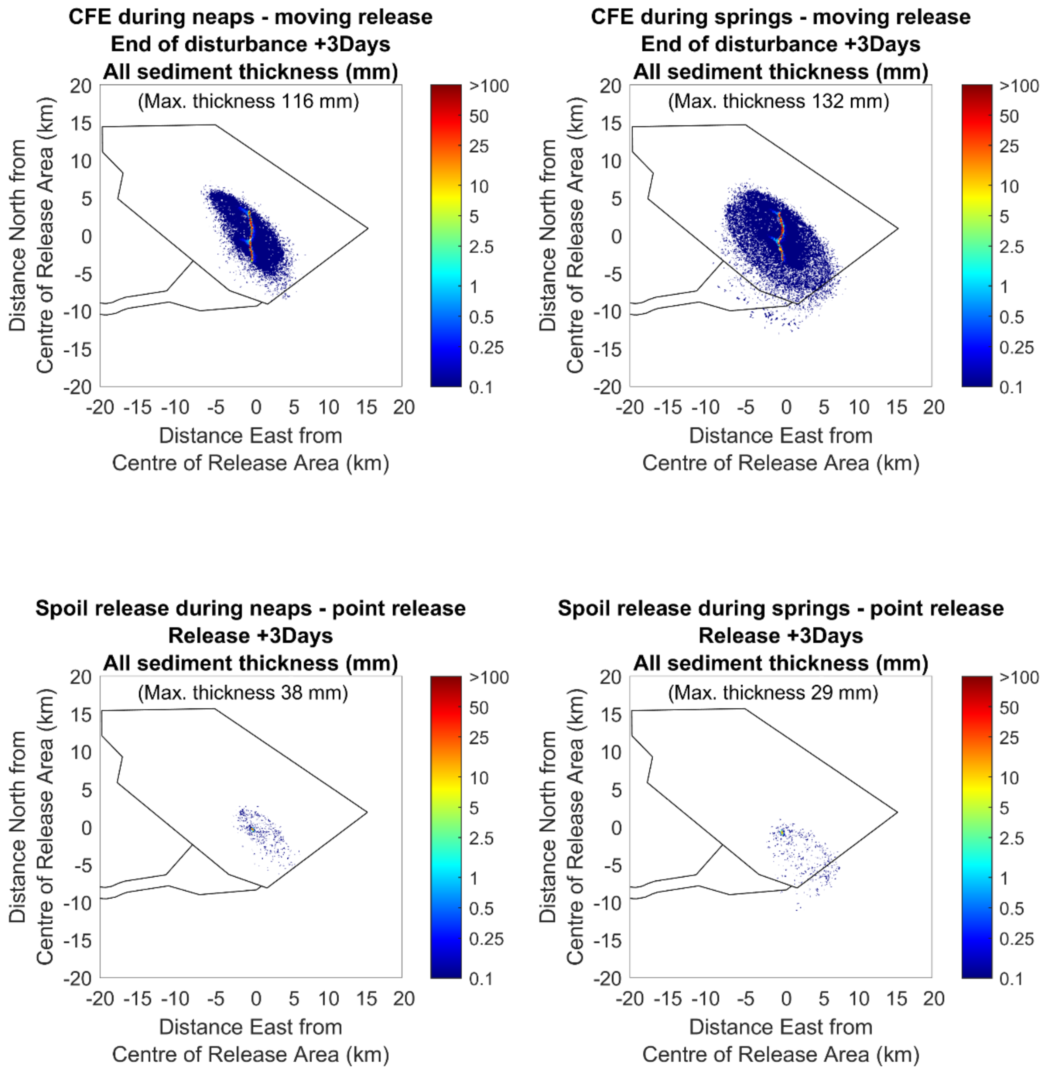


Figure C29. Sediment settlement thickness (all sediment types) as a result of CFE dredging and the passive phase plume from dredge spoil disposal in the Hornsea Four array area. Mean spring and neap tides

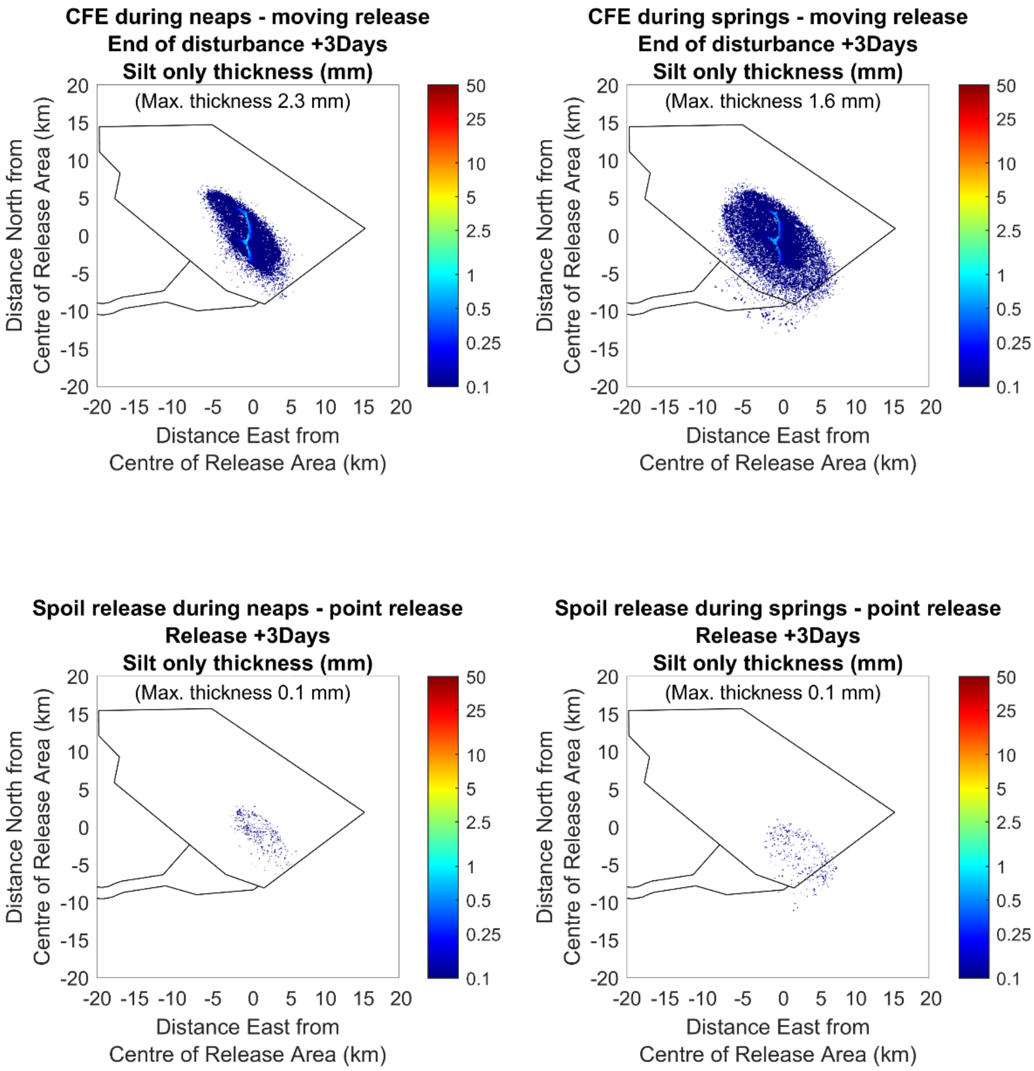


Figure C30. Sediment settlement thickness (silt fraction only) as a result of CFE dredging and the passive phase plume from dredge spoil disposal in the Hornsea Four array area. Mean spring and neap tides

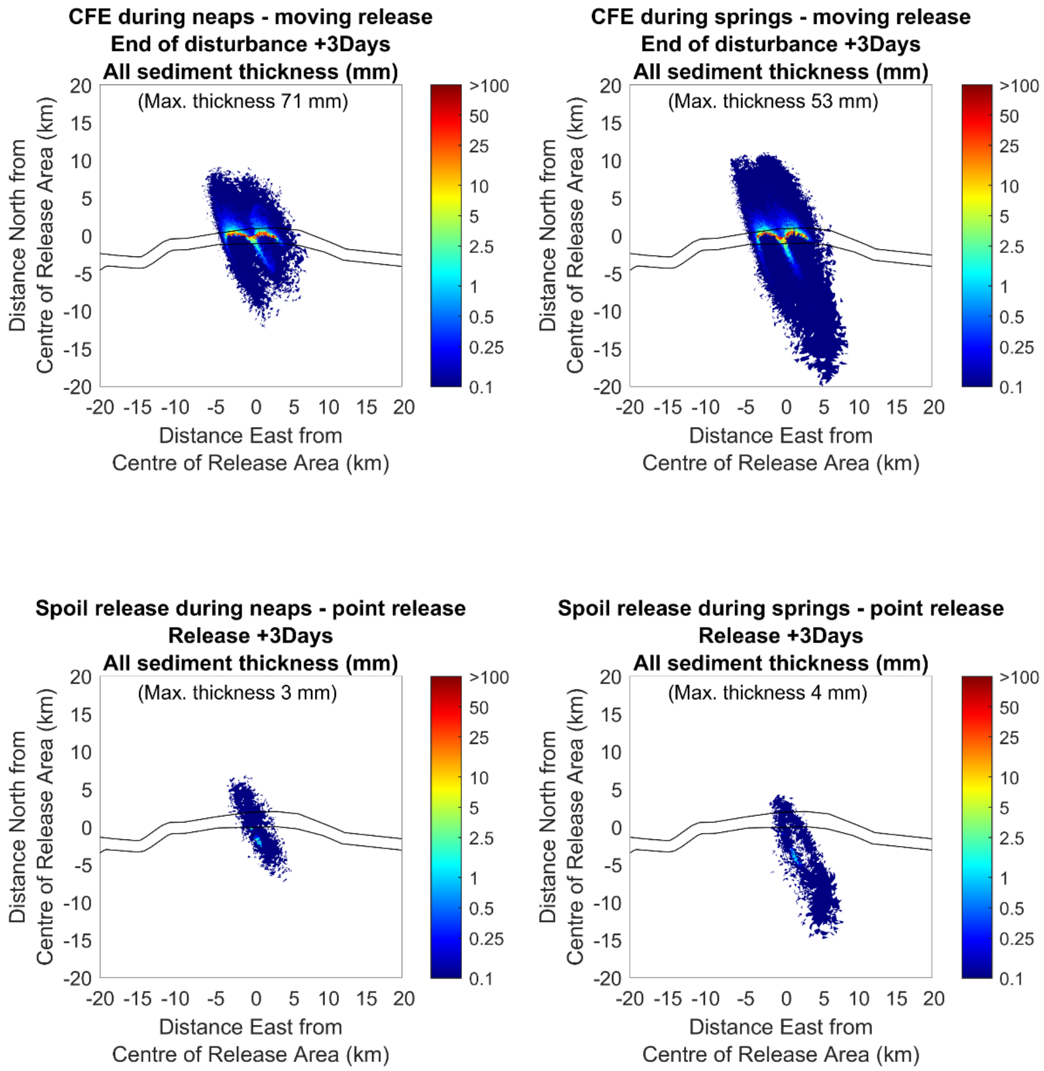


Figure C31. Sediment settlement thickness (all sediment types) as a result of CFE dredging and the passive phase plume from dredge spoil disposal in the HVAC booster station search area. Mean spring and neap tides

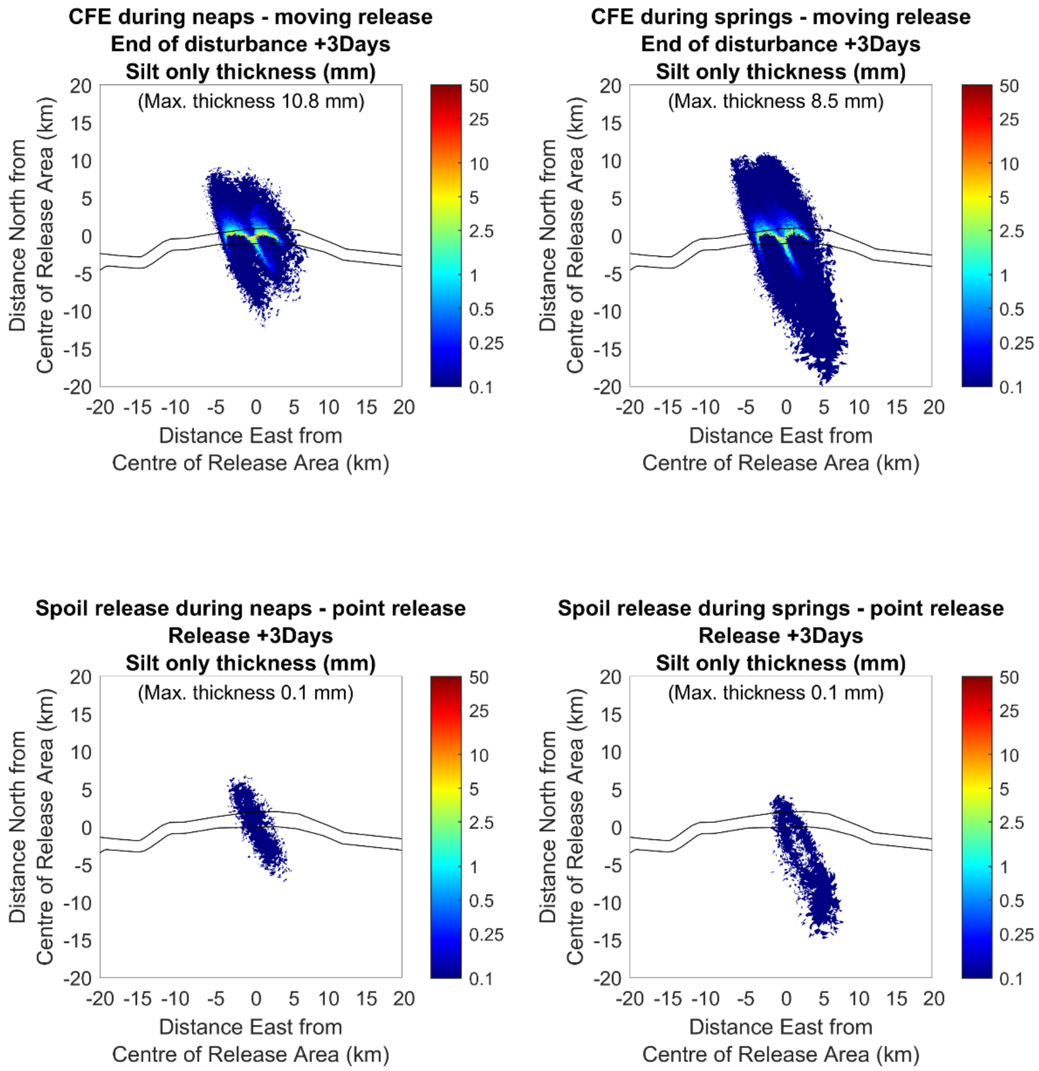


Figure C32. Sediment settlement thickness (silt fraction only) as a result of CFE dredging and the passive phase plume from dredge spoil disposal in the HVAC booster station search area. Mean spring and neap tides

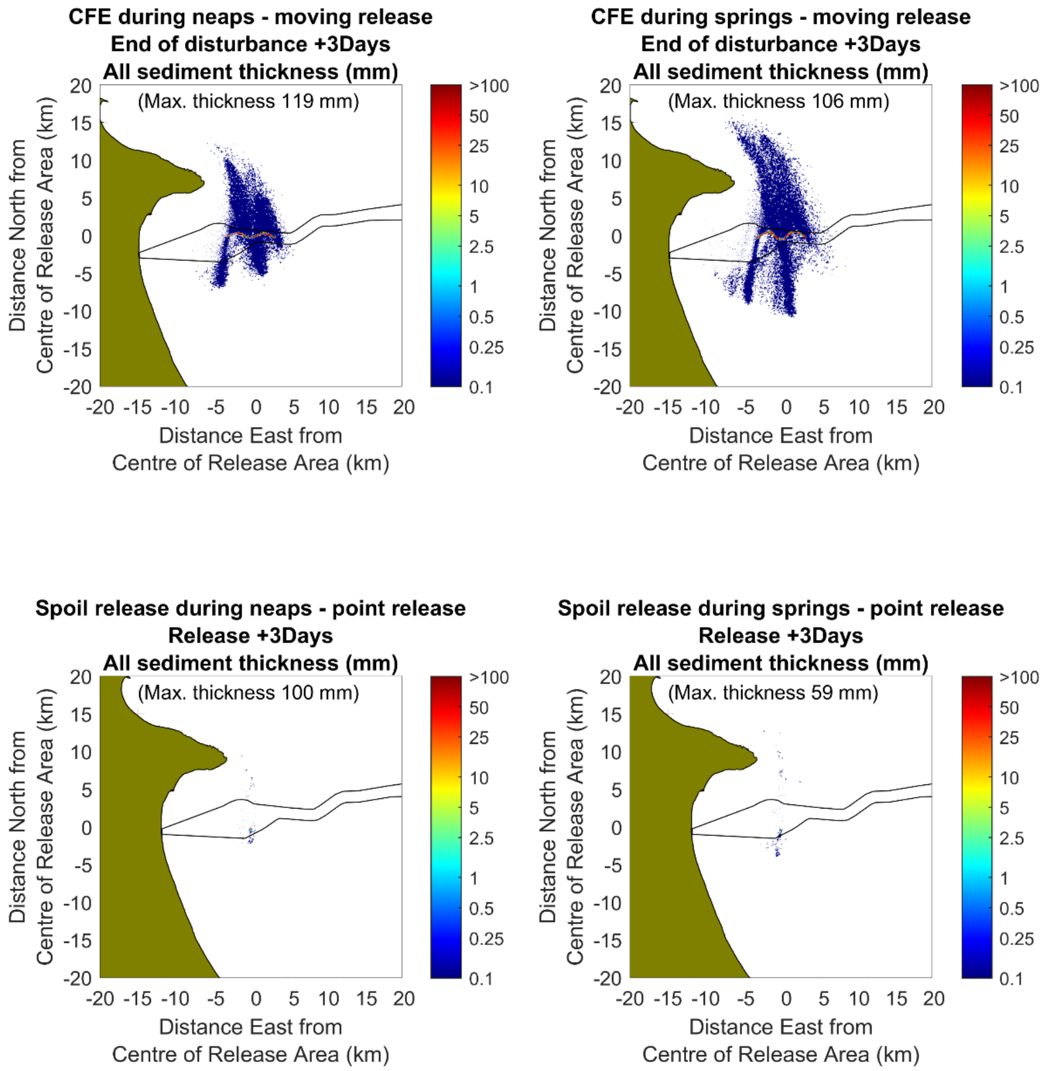


Figure C33. Sediment settlement thickness (all sediment types) as a result of CFE dredging and the passive phase plume from dredge spoil disposal in the nearshore cable crossing area offshore of Smithic Bank. Mean spring and neap tides

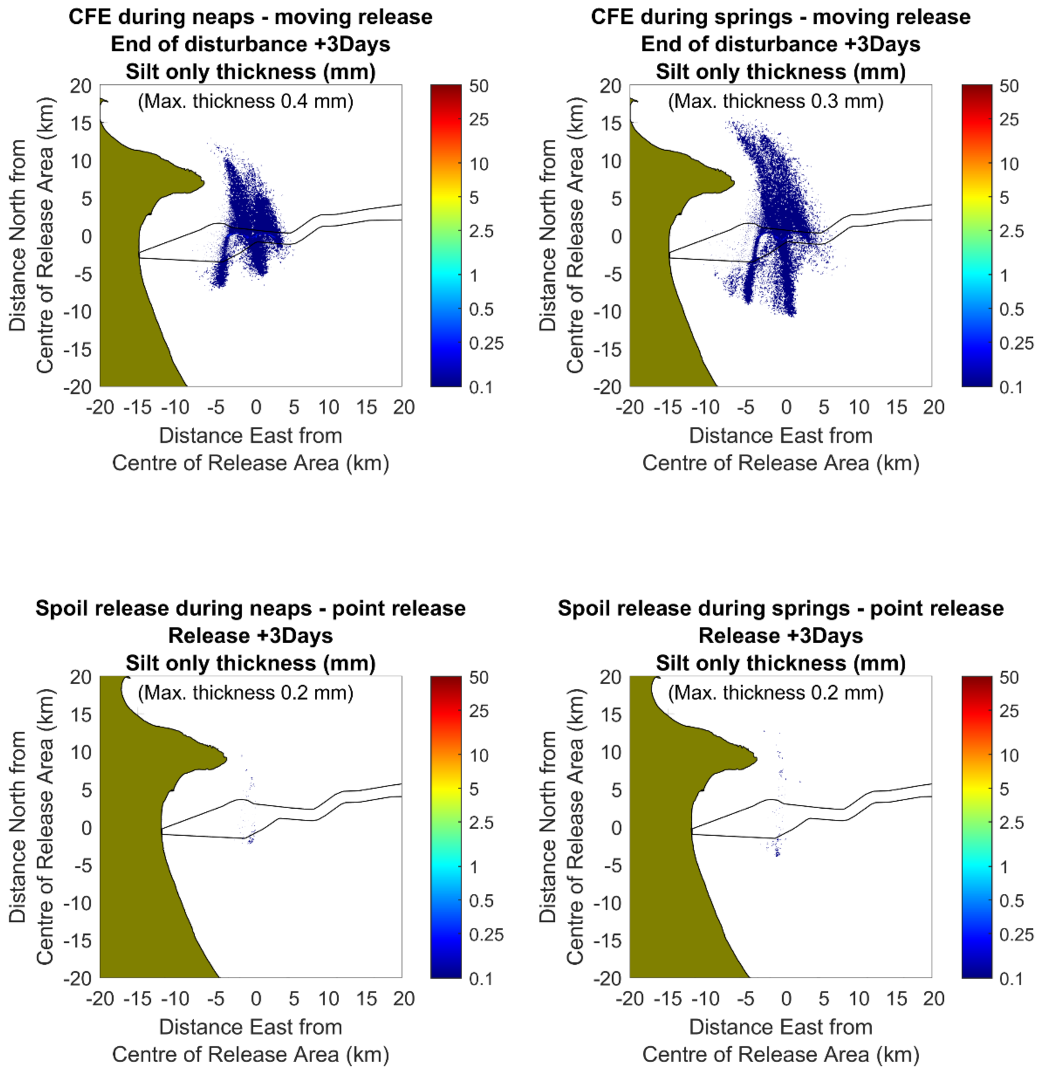


Figure C34. **Sediment settlement thickness (silt fraction only) as a result of CFE dredging and the passive phase plume from dredge spoil disposal in the nearshore cable crossing area offshore of Smithic Bank. Mean spring and neap tides**

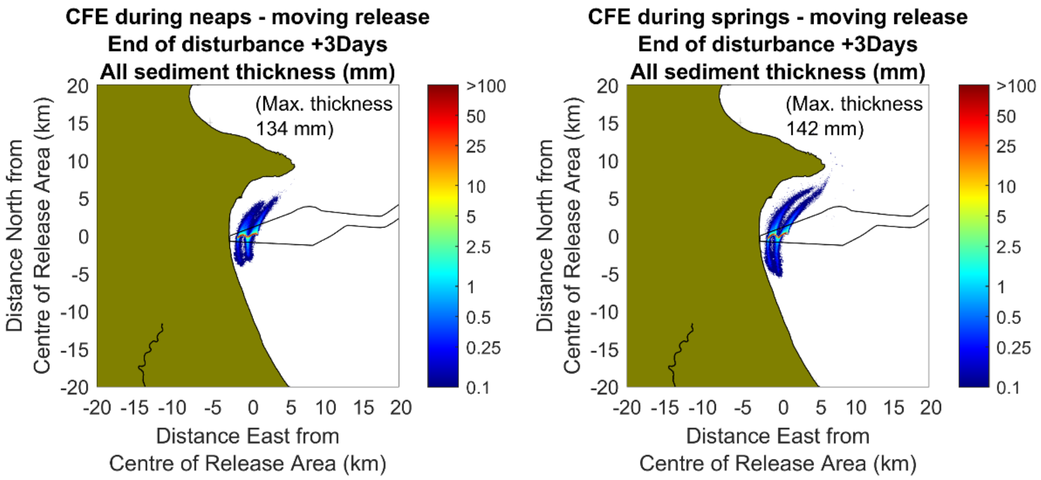


Figure C35. **Sediment settlement thickness (all sediment types) as a result of CFE dredging in the inshore area west of Smithic Bank. Mean spring and neap tides**

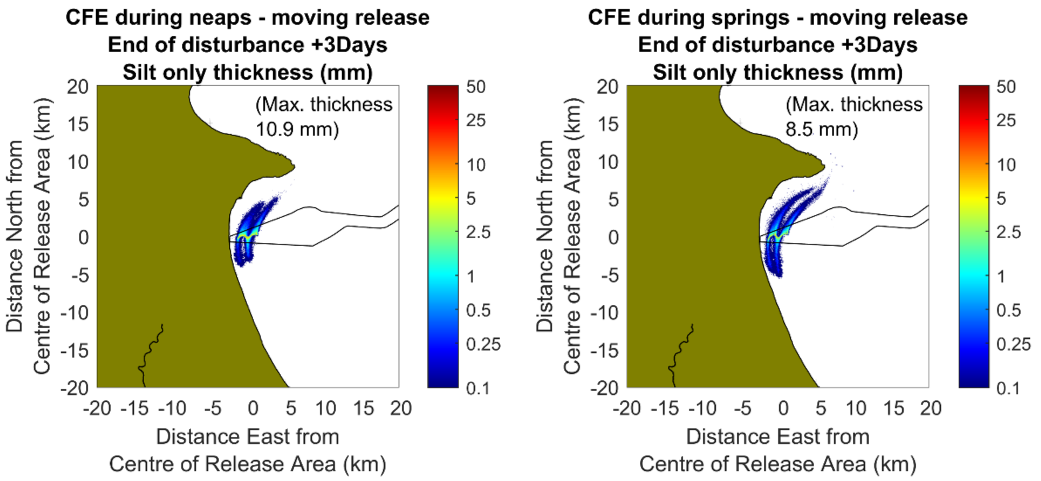


Figure C36. **Sediment settlement thickness (silt fraction only) as a result of CFE dredging in the inshore area west of Smithic Bank. Mean spring and neap tides**

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