FIVE ESTUARIES OFFSHORE WIND FARM

ENVIRONMENTAL STATEMENT

VOLUME 6, PART 5, ANNEX 2.1: PHYSICAL PROCESSES BASELINE TECHNICAL REPORT

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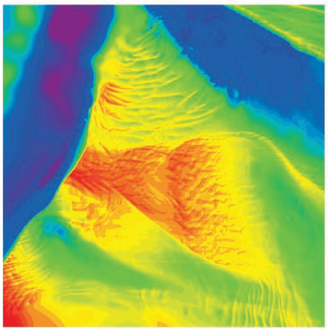
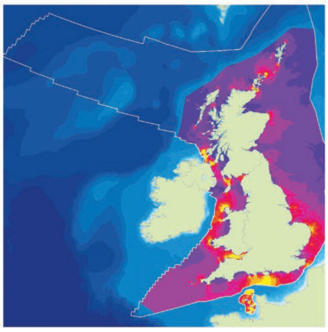
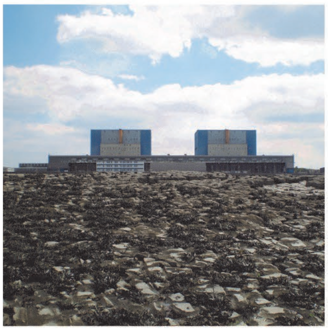
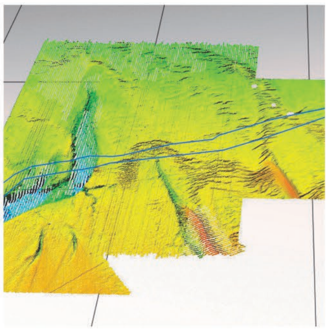
GoBe Consultants Ltd

Five Estuaries Offshore Wind Farm Environmental Impact Assessment

Volume 6, Part 5, Annex 2.1: Physical Processes Baseline Technical Report

January 2024

Innovative Thinking - Sustainable Solutions

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Five Estuaries Offshore Wind Farm Environmental Impact Assessment

Volume 6, Part 5, Annex 2.1: Physical Processes Baseline Technical Report

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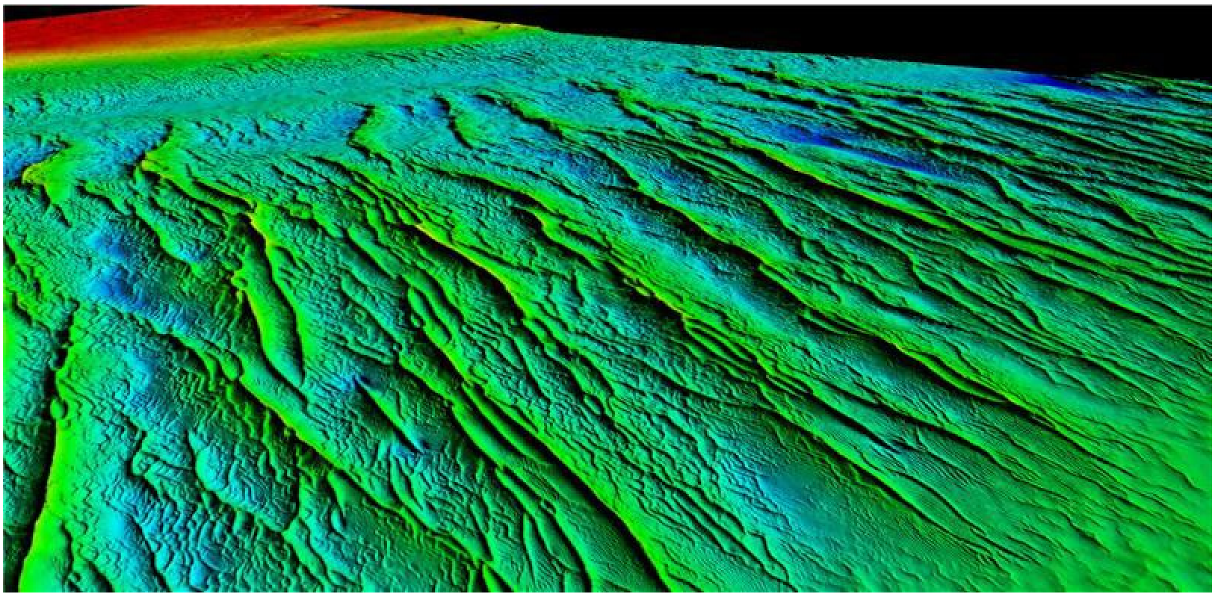

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Contents

Tables

Figures

Acronyms and abbreviations

ACM	Anglian Coastal Monitoring
BGS	British Geological Survey
BODC	British Oceanographic Data Centre
BP	Before Present
CD	Chart Datum
Cefas	Centre for Environment, Fisheries and Aquaculture Science
Defra	Department for Environment, Food and Rural Affairs
DTM	Digital Terrain Model
EA	Environment Agency
ECC	Export Cable Corridor
EIA	Environmental Impact Assessment
ES	Environmental Statement
GGOWF	Greater Gabbard Offshore Wind Farm

GGOWL	Greater Gabbard Offshore Wind Farm Ltd
GIS	Geographic Information System
GOWF	Galloper Offshore Windfarm
GWF	Galloper Wind Farm Ltd
HAT	Highest Astronomical Tide
Ka	Thousand years
LAT	Lowest Astronomical Tide
LiDAR	Light Detection and Ranging
Ma	Million years
MALSF	Marine Aggregate Levy Sustainability Fund
MAREA	Marine Aggregate Regional Environmental Assessment
MBES	Multibeam Echosounder
MCZ	Marine Conservation Zone
mg/l	Milligrams per litre
MHWN	Mean High Water Neap
MHWS	Mean High Water Spring
MLWN	Mean Low Water Neap
MLWS	Mean Low Water Spring
NTLSF	National Tide and Sea Level Facility
ODN	Ordnance Datum Newlyn
OWF	Offshore Windfarm
PDZ	Policy Development Zone
PEIR	Preliminary Environmental Information Report
RCP	Representative Concentration Pathway
REC	Regional Environmental Characterisation
RWE	RWE Renewables Ltd
SAC	Special Area of Conservation
SMP	Shoreline Management Plan
SMP2	Shoreline Management Plan 2
SNSSTS	Southern North Sea Sediment Transport Study
SPM	Suspended Particulate Matter
TEDA	Thames Estuary Dredging Association
Tp	Peak wave period
UK	United Kingdom
UKCP	United Kingdom Climate Projections
UKHO	United Kingdom Hydrographic Office
VE	Five Estuaries Offshore Wind Farm
VE OWFL	Five Estuaries Offshore Wind Farm Limited

Cardinal points/directions are used unless otherwise stated.

SI units are used unless otherwise stated.

1 Introduction

1.1 Overview

The proposed Five Estuaries Array Areas and Offshore Export Cable Corridor are located in the southern North Sea, within the Approaches to the Outer Thames Estuary, on the east coast of England.

This study is undertaken by ABPmer on behalf of Five Estuaries Offshore Wind Farm Limited (VE OWFL), to provide a baseline description of physical processes in relation to the proposed Five Estuaries Offshore Wind Farm (VE). This baseline description sets out the 'conceptual understanding' of the coastal system in which the project is located and describes how the processes operating within this system link together and evolve in response to applied forces. This understanding underpins the assessments of potential impacts resulting from the Project (Volume 6, Part 2, Chapter 2 'Marine Geology, Oceanography and Physical Processes').

VE is a proposed extension to the east of the Galloper offshore wind farm (GOWF, operational since 2018), approximately 30 km off the Suffolk coast. The Export Cable Corridor (ECC) runs approximately westward from the VE Array Areas to a landfall located between Holland-on-Sea and Frinton-on-Sea on the Essex coast (Figure 1).

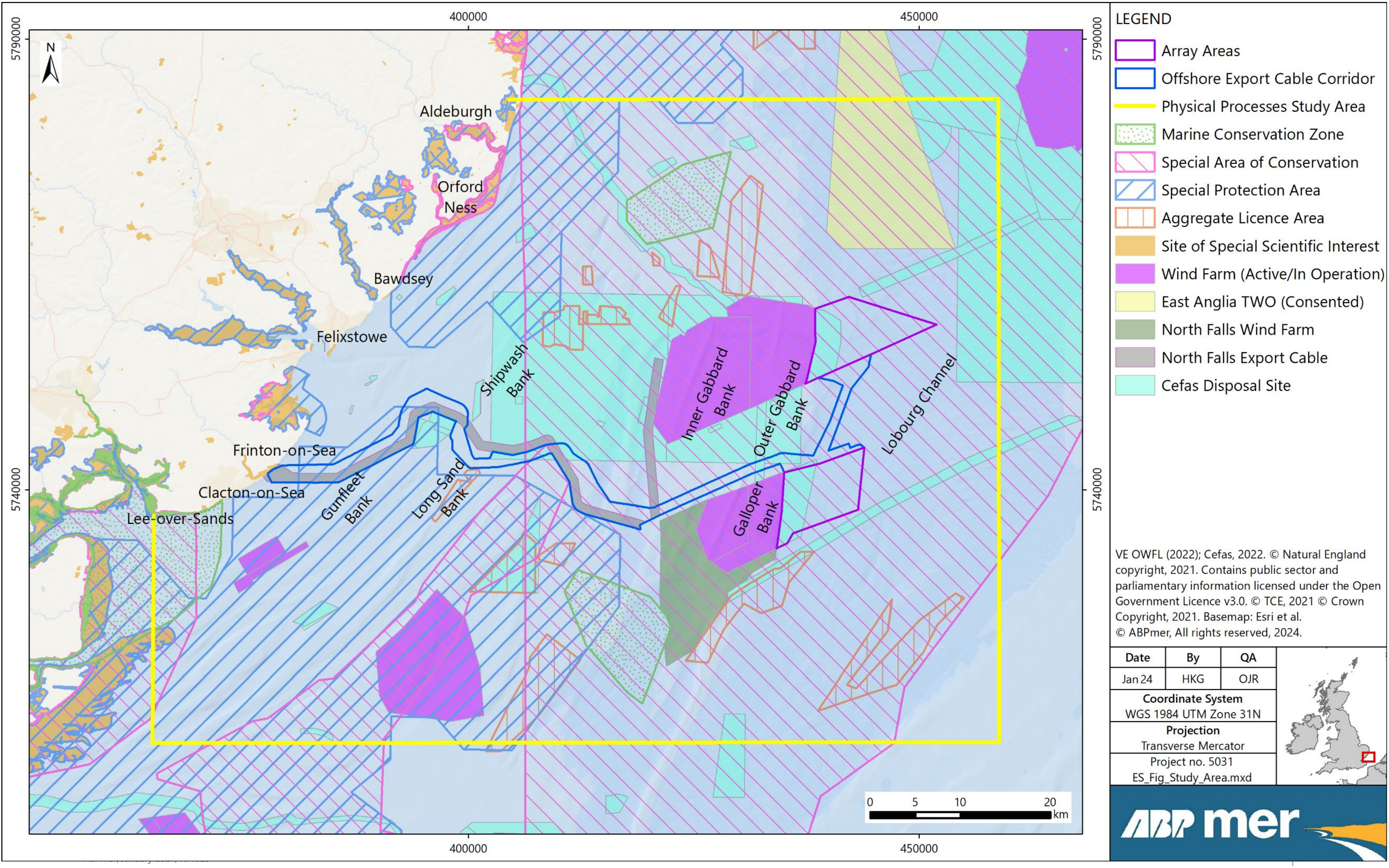
The study area shown in Figure 1 has been informed by expert judgement, based on (amongst other things) physical process understanding developed from work undertaken for the nearby (operational) Galloper and Greater Gabbard OWFs and analysis of prevailing wave direction and tidal excursion distance. Direct changes to the seabed will be confined to the array and ECC, with indirect changes (e.g., due to disruption of waves, tides or sediment pathways) experienced both inside and outside of the Project boundary. These indirect changes are expected to diminish with distance from the array and ECC.

1.2 Approach

Physical processes within the study area have been considered under the following categories:

- Metocean regimes:
    - Water levels;
    - Currents;
    - Wind and waves
- Sediments, sediment transport and morphology; and
- Coastlines, beaches and nearshore processes

The natural variability of the above is explored in the absence of any of the proposed structures for the development. Consequently, this provides the 'baseline' conditions within the study area upon which impacts from the project can be assessed.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Felixstowe
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Clacton-on-Sea
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Gunfleet Bank
Long Sand Bank
Shipwash Bank
Inner Gabbard Bank
Outer Gabbard Bank
Galloper Bank
Lobourg Channel
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LEGEND
Array Areas
Offshore Export Cable Corridor
Physical Processes Study Area
Marine Conservation Zone
Special Area of Conservation
Special Protection Area
Aggregate Licence Area
Site of Special Scientific Interest
Wind Farm (Active/In Operation)
East Anglia TWO (Consented)
North Falls Wind Farm
North Falls Export Cable
Cefas Disposal Site
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Baseline understanding has been developed in accordance with industry best practice, with attention given to:

- The identification of the processes maintaining the system, the reasons for any past changes, and sensitivity of the system to changes in the controlling processes.
- The identification and quantification of the relative importance of high-energy, low frequency ("episodic" events), versus low-energy, high frequency processes.
- The identification of the processes controlling temporal and spatial morphological change (e.g., longevity and stability of bedforms; cliff recession; loss of beach volume; or bank and channel migration; intertidal accretion/ erosion), which may require a review of bathymetric and topographic data.
- The identification of sediment sources, pathways and sinks, and quantification of transport fluxes.
- The identification of the inherited geological, geophysical and geotechnical properties of the sediments at the site, and the depth of any sediment strata.
- The interaction of waves and tides and the subsequent quantification of the extent to which seabed sediment is mobilised.
- The assessment of the scales and magnitudes of processes controlling sediment transport rates and pathways.

1.3 Nationally and internationally designated sites

The study area overlaps with several nationally and internationally designated nature conservation sites, which contain qualifying geological and geomorphological features. The locations of these sites are also included in Figure 1. The sites are primarily designated for the habitats they contain rather than for the presence of geological and geomorphological features. However, changes to the physical characteristics of these sites have the potential to impact the habitats they support and, therefore, consideration will be given in the physical processes assessment. The designated sites that are coincident with (or very close to) the Five Estuaries Array Areas and offshore ECC are listed in Table 1.

Table 1. Marine nature conservation designations with relevance to physical processes

Site	Closest Distance to VE	Features or description
UK'S NATIONAL SITE NETWORK		
Alde, Ore and Butley Estuaries Special Area of Conservation (SAC)	15.2 km	Network of three estuaries flanked by salt marsh and mudflats, with shingle bar at the mouth.
Essex Estuaries SAC	7.5 km	Large estuarine site typical of an undeveloped, coastal plain estuarine system with associated open coast mudflats and sandbanks
Hamford Water SAC/ Special Protection Area (SPA)	3.2 km	Large, shallow estuarine basin comprising tidal creeks, islands, intertidal mud, sand flats and saltmarshes
Margate and Long Sands SAC	[Coincident with ECC]	Contains a number of Annex I Sandbanks composed of well-sorted sandy sediments, with muddier and more gravelly sediments in the troughs between banks
Orfordness - Shingle Street SAC	12.3 km	Extensive shingle spit containing series of undisturbed ridges with vegetated shingle, accompanied by coastal lagoons

Site	Closest Distance to VE	Features or description
Southern North SAC	[Coincident with Array Areas and ECC]	Site covers a very large area (36,951 km^2) and includes a mix of habitats, such as sandbanks and gravel beds
Alde-Ore Estuary SPA	12.3 km	Wide variety of habitats including intertidal mud-flats, saltmarsh, vegetated shingle and saline lagoons
Deben Estuary SPA	11.4 km	Estuarine setting characterised by saltmarsh and intertidal mud flats in most areas, along with reedswamp, unimproved neutral grassland and scrub
Foulness (Mid-Essex Coast Phase 5) SPA	18.8 km	Site characterised by the presence of extensive saltmarsh habitats
Outer Thames Estuary SPA	[Coincident with ECC]	Comprises areas of sand banks and inter-tidal sand/ mud flats. It also includes shallow and deeper water, high tidal current streams and a range of mobile mud, sand, silt and gravely sediments
Stour and Orwell Estuaries SPA	12.8 km	The estuaries include extensive mud-flats, low cliffs, saltmarsh and small areas of vegetated shingle on the lower reaches.
Blackwater, Crouch, Roach and Colne Estuaries Marine Conservation Zone (MCZ)	4.2 km	Extensive areas of mudflats and saltmarsh, which support a wide range of species including internationally and nationally important numbers of waterfowl
Kentish Knock East MCZ	6.2 km	Sandbank setting, with the site characterized by predominantly mixed sediments with areas of sandy sediment and coarse gravel and pebbles
Orford Inshore MCZ	14.4 km	Habitats composed of subtidal mixed sediments which are important nursery and spawning grounds.
SITES OF SPECIAL SCIENTIFIC INTEREST		
Alde-Ore Estuary Site of Special Scientific Interest (SSSI)	12.3 km	Major shingle landforms with accompanying cliffs which are of scientific importance
Bawdsey Cliffs SSSI	11.1 km	The cliffs provide over 2km of section in the Butleyan division of the Early Pleistocene Red Crag
Clacton Cliffs & Foreshore SSSI	4.2 km	Site designated for its geological importance, with sediment filled channels containing rare fossils
Colne Estuary SSSI	9.4 km	A short branching estuary whose shingle spit is of geomorphological importance
Deben Estuary SSSI	11.4 km	Estuarine setting characterised by saltmarsh and intertidal mud flats in most areas, along with reedswamp, unimproved neutral grassland and scrub
Foulness SSSI	18.8 km	Site characterised by the presence of extensive saltmarsh and mudflat habitats

Site	Closest Distance to VE	Features or description
Hamford Water SSSI	3.7 km	Large, shallow estuarine basin comprising tidal creeks, islands, intertidal mud, sand flats and saltmarshes
Harwich Foreshore SSSI	11.9 km	Site contains designated exposures of Harwich Stone Bands
Holland on Sea Cliff SSSI	0.1 km	Site contains designated cliffs containing geologically important gravel sequences
Landguard Common SSSI	10.0 km	Sand and shingle spit consisting of a loose shingle foreshore backed by vegetated beach
Leiston-Aldeburgh SSSI	29.6 km	Contains a range of habitats including vegetated shingle
The Naze SSSI	4.0 km	Geologically important site containing designated Pleistocene cliff exposures
Orwell Estuary SSSI	13.7 km	Long and relatively narrow estuary with extensive mudflats and some saltmarsh.
Stour Estuary SSSI	12.8 km	Estuarine site containing mud and saltmarsh habitats, along with geologically important exposures of early Eocene sediments

2 Data Sources

The study has used Project specific, publicly available data, existing marine process studies and geophysical data and reports from the adjacent Galloper and Greater Gabbard OWFs. The process investigations and data considered are outlined in Table 2, Table 3 and Figure 2 , with the spatial extent of bathymetry data used to inform the analysis shown in Figure 3.

Table 2. Key existing process investigations and datasets from the VE study area

Source	Summary	Spatial Coverage of VE
Galloper Wind Farm Project, Environment Statement – Chapter 9: Physical Environmental Document Reference – 5.2.9 Source: RWE Npower Renewables et al (2011)	Characterisation and monitoring data for the existing operational Galloper OWF site (including geophysical, geotechnical, benthic and metocean data)	Partial coverage of the physical processes study area.
Greater Gabbard OWF Environmental Statement (Physical Processes) (GGOWL, 2005)	Characterisation and monitoring data for the existing operational Greater Gabbard OWF site (including geophysical, geotechnical, benthic and metocean data	Partial coverage of the physical processes study area.
Outer Thames Estuary Regional Environmental Characterisation Source: MALSF (2009)	Characterisation data (geophysical and benthic) from offshore and nearshore areas	Partial coverage of the physical processes study area.
Thames Marine Aggregate Regional Environmental Assessment (MAREA) Source: TEDA (2012)	Characterisation data (geophysical and benthic) from offshore and nearshore areas	Partial coverage of the physical processes study area.
Historical changes in the seabed of the Greater Thames Estuary (Burningham & French, 2008)	Processes understanding across the wider FEOWF study area, including analysis of historic bed level change	Partial coverage of the physical processes study area.
Seabed mobility in the Greater Thames Estuary (Burningham & French, 2009)	Processes understanding across the wider FEOWF study area	Partial coverage of the physical processes study area.
Seabed dynamics in a large coastal embayment: 180 years of morphological change in the outer Thames Estuary (Burningham & French, 2011)	Processes understanding across the wider FEOWF study area, including analysis of historic bed level change	Partial coverage of the physical processes study area.
National Tide and Sea Level Facility (NTSLF) Source: www.ntslf.org	Tidal water levels from point locations within the study area	Partial coverage of the physical processes study area.

Source	Summary	Spatial Coverage of VE
British Oceanographic Data Centre (BODC) Source: www.bodc.ac.uk/	Hydrodynamic data (inc. current speed & direction) from point locations within the study area	Partial coverage of the physical processes study area.
Cefas WaveNet data Source: www.cefas.co.uk/cefas-data-hub/wavenet/	Wave records from point locations within the study area	Partial coverage of the physical processes study area.
ABPmer SEASTATES Source: www.seastates.net/	Modelled hindcast wave and hydrodynamic data from across the study area	This is a national dataset providing full coverage of the physical processes study area.
Hydrodynamic and wave data from the Marine Renewables Atlas Source: ABPmer et al. (2008)	Modelled hindcast wave and hydrodynamic data from across the study area	This is a national dataset providing full coverage of the physical processes study area.
UKCP18 climate change projections Source: Palmer *et al.* (2018)	Sea level rise predictions for coastal locations within the study area	Partial coverage of the physical processes study area.
British Geological Survey (BGS) offshore geoindex [including seabed sediments and geology] Source: www.bgs.ac.uk/GeoIndex/offshore.htm	Seabed sediment maps (based on Folk classification) and borehole records from point locations within the study area	This is a national dataset providing full coverage of the physical processes study area.
United Kingdom Hydrographic Office (UKHO) Source: UKHO (2022)	Bathymetric data for the study area in the form of multibeam and single beam data, as well as Admiralty Charts	This is a national dataset providing full coverage of the physical processes study area.
Suspended Sediment Climatologies around the UK Source: Cefas (2016)	Monthly and seasonal Suspended Particulate Matter (SPM) maps for the study area	This is a national dataset providing full coverage of the physical processes study area.
Southern North Sea Sediment Transport Study (SNSSTS) Source: SNSSTS (2002)	Information on observed and modelled longshore and seabed sediment transport in the study area	Partial coverage of the physical processes study area.
Anglian Coastal Monitoring (ACM) programme Source: https://coastalmonitoring.org/anglian/	Monitoring data to inform coastal characteristics and change including topographic survey data, aerial imagery and oceanographic data.	Partial coverage of the physical processes study area.
Environment Agency Source: www.gov.uk/government/organisations/environment-agency	LiDAR and coastal monitoring reports from around the coastline in the study area	Partial coverage of the physical processes study area.

Source	Summary	Spatial Coverage of VE
Shoreline Management Plan (SMP) 7: Lowestoft to Felixstowe Source: Suffolk District Council (2009)	Information on coastal characteristics and behaviour, as well as proposed future management strategies	Partial coverage of the physical processes study area.
SMP 8: Essex and South Suffolk Source: Environment Agency (2010)	Information on coastal characteristics and behaviour, as well as proposed future management strategies	Partial coverage of the physical processes study area.
(Various)	Public and grey literature considering coastal morphology and behaviour at sensitive coastal locations within the study area (e.g., The Crown Estate (2016), Natural England (2017)).	Partial coverage of the physical processes study area.

Table 3. Geophysical data identified or used to inform baseline understanding of seabed morphological change

Survey	Data Type	Year Collected	Description	Comment	Source
VE Geophysical Survey	Multibeam bathymetry and sub bottom geophysics	2021	Full coverage of Array Areas; circa 90% coverage of ECC	Geophysical survey of the VE Array Areas and ECC	Fugro (2022a, b)
UKHO Marine data portal	Multibeam and singlebeam bathymetry	1984	HI193 HI194 Thames Estuary Areas 1 and 2 Sledway and Shipway	Combined survey coverage provides full coverage of the VE study area (incl. Array Areas and ECC). Data resolution dependent on survey data type (multibeam vs. singlebeam).	UKHO Marine Data Portal (2022)
		1985	HI197 Approaches to the Rivers Blackwater and Couch		
		1987	HI354 Smiths Knoll to South Falls		
		1988	HI421 Gunfleet Sand to the Naze		
		1995	HI667 Orfordness to North Foreland		
		1995	HI674 Smiths Knoll to Sandettie		
		1996	1996 HI690 Shipwash to Black Deep Blk 1		
		1997	1997 H693 Kentish Knock		
		1997	1997 HI743 Long Sand and Black Deep		
		1998	1998 2006-358334 Harwich Deep Water Channel Area Harwich Channel No 1 Buoy to South Shelf Buoy		
		1998	1998 2006-358335 Harwich Deep Water Channel		
		2000	2000 HI887 Kings Channel		
		2001	HI922 South West TSS		
		2002	2002 HI995 Knock Deep		
		2002	2002 HI996 Knock Deep		
		2003	2003 2006-360498 Thames Estuary Barrow Deep 50 m		
		2003	2003 2015-074071 Thames Estuary Sunk 50 m		
		2007	HI1159 Dover Strait Blk 10-15 2 m, Single beam at 2 m resolution		
		2009	2009 2009-158485 Thames Estuary East Swin to Barrow 50 m		
		2009	2009 2009-158510 Thames Estuary Kings Channel to East Swin 50 m		
		2010	HI1339 Thames Estuary and Dover Strait, Single beam at 2 m resolution		
		2011	HI1368 Sunk Inner, 1 m resolution		
		2012	2012-156759 Orford Ness Whiting Bay		
		2012	2012 - 2017-248601 Clacton on Sea to Pennyhole Bay		
		2012	HI1398 Sunk Inner Area TE3A, 1 m resolution		
		2012	2012 2013-131570 Thames Estuary Barrow Deep 50m		
		2012	2012 HI1398 Kings Channel TE7 1 m FMCUBE		
		2013	2013-208214 Whiting Bank, 2 m resolution Single Beam		
		2013	2013 2017-257179 East Coast Rivers		
		2013	2013 2017-257179 Harwich to The Naze		
		2013	2013 HI1417 Western Approaches to North Hinder, 1 m Resolution		
		2013	2013 HI1433 Thames Estuary Long Sand, 2 m resolution Single Beam		
		2013	2013 HI1433 Thames Estuary TE3A, 1 m Resolution		
		2013	2013 HI1433 Thames Estuary Long Sand 2 m SB		
		2014	2014 2015-019426 Kentish Knock, 2 m Resolution Single Beam		
		2014	2014 HI1424 DWR North Hinder to Brown Ridge, 2 m Resolution		
		2014	2014 HI1459 TE3A Sunk, 1 m Resolution		
		2014	2014 HI1459 TE6 Black Deep, 1 m Resolution SDTP		
		2014	2014 HI1459 Thames Estuary Long Sand, 2 m Resolution SDTP		
		2015	2015 2015-101038 Whiting Bank, 2 m Resolution SDTP		
		2015	2015 2017-198832 Walton Backwaters		
		2015	2015 HI1474 Sunk TSS 1 m Cube		
		2015	2015 HI1483 Thames Estuary TE3A Sunk, 1 m Resolution CUBE		
		2016	2016 HI1522 Thames Estuary TE3A, 1 m Resolution CUBE		
		2016	2016 HI1522 Thames Estuary TE8, 1 m Resolution CUBE		
		2016	2016 HI1522 Thames Estuary TE10 1 m Resolution CUBE		
		2017	2017 2017-159705 Whiting Bank 2 m SDTP		
		2017	2017 2017-257179 Wallet		
		2017	2017 HI1518 Southern Approach to Sunk TSS Block 1 1 m CUBE		
		2017	2017 HI1518 Southern Approach to Sunk TSS Block 2 0-40 m 1 m CUBE		
		2017	2017 HI1518 Southern Approach to Sunk TSS Block 2 40-51 m 2 m CUBE		
		2017	2017 HI1518 Southern Approach to Sunk TSS Block 3 10-40 m 1 m CUBE		
		2017	2017 HI1518 Southern Approach to Sunk TSS Block 3 40-61 m 2 m CUBE		
		2017	2017 HI1546 Thames Estuary RRS TE3A 1 m CUBE		
		2018	2018 2018-247796 Whiting Bank 2 m SDTP		
		2018	2018 HI1614 Thames Estuary TE3A Sunk		

Survey	Data Type	Year Collected	Description	Comment	Source
Greater Gabbard OWF studies	Multibeam bathymetry	2018	2018 2018-234735 Gabbard Wind Farm 0-40 m 2 m SDTP	Gridded bathymetry data, varying spatial coverage	UKHO Marine Data Portal (2022)
		2018	2018 2018-234735 Gabbard Wind Farm 38-80 m 4 m SDTP		
Galloper OWF studies	Multibeam bathymetry	2010	2010 Galloper Geophysical Survey – EIA studies	Multibeam bathymetry with varying coverage of the FEOWF study area	Osiris 2010
		2012	2012 Galloper Geophysical Survey - SI Phase 1		EMU 2012
		2013	2013 Galloper Geophysical Survey - SI Phase 2		Gardline 2013
		2016	2016 Galloper Geophysical Survey - SI Phase 3		Gardline 2016
		2018	2018 Galloper Geophysical Survey - Operational Baseline		
		2019	2019 Galloper Geophysical Survey - Scour Survey		A2SEA 2019
		2020	2020 Galloper Geophysical Survey - Scour Survey		A2SEA 2020
EA MBES data	Multibeam bathymetry	2012	Multibeam bathymetry	Bathymetric coverage of the shallow subtidal region along the study coastal frontage.	Environment Agency, 2020a
		2013	Multibeam bathymetry		
		2018	Multibeam bathymetry		
EA LiDAR data	LiDAR topography	1999	Airborne LiDAR DTM	Combination of 1 m and 2 m resolution gridded LiDAR of proposed land fall locations	Environment Agency, 2020b
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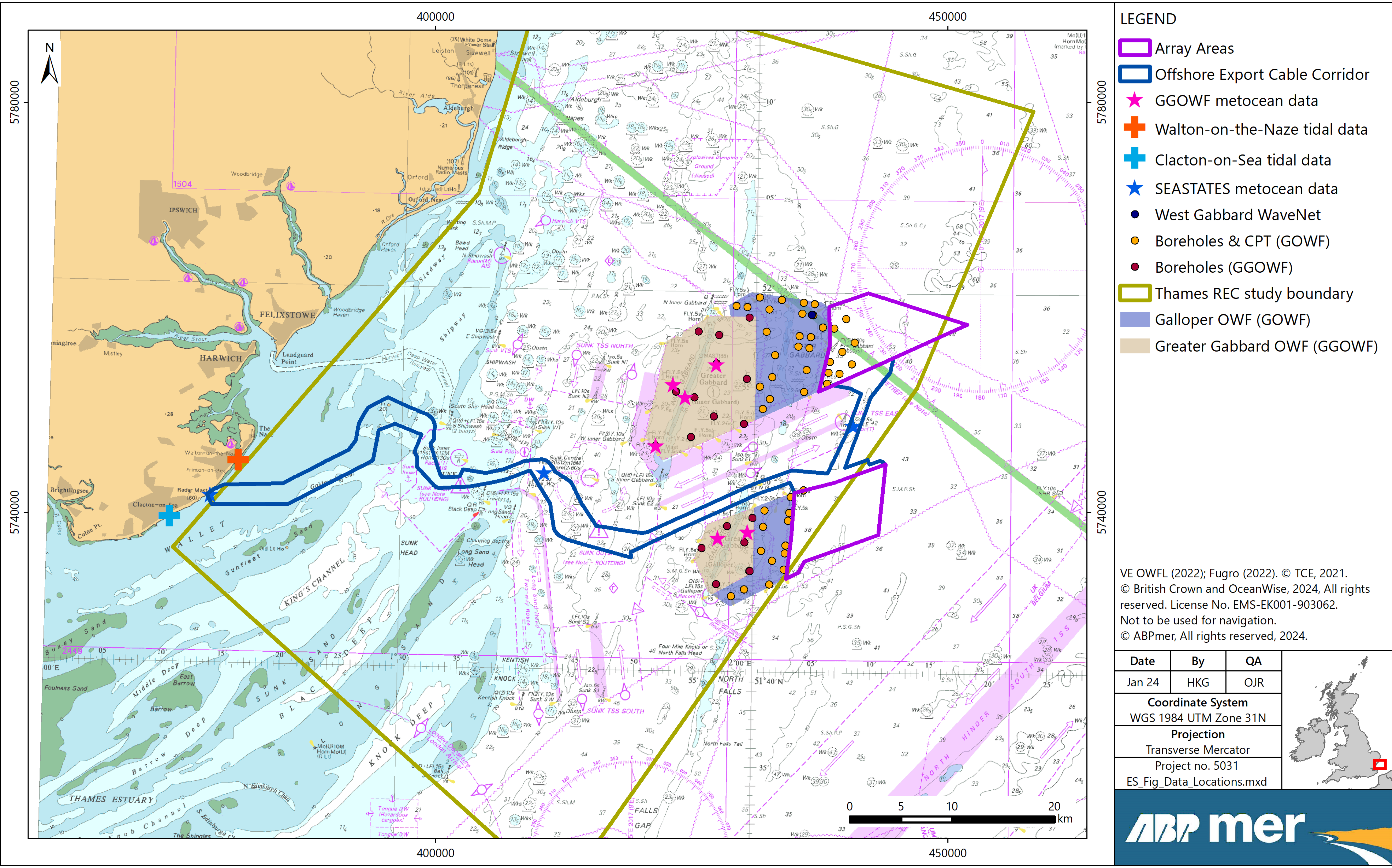
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NORTH FALLS
Greater Gabbard
LEGEND
Array Areas
Offshore Export Cable Corridor
GGOWF metocean data
Walton-on-the-Naze tidal data
Clacton-on-Sea tidal data
SEASTATES metocean data
West Gabbard WaveNet
Boreholes & CPT (GOWF)
Boreholes (GGOWF)
Thames REC study boundary
Galloper OWF (GOWF)
Greater Gabbard OWF (GGOWF)
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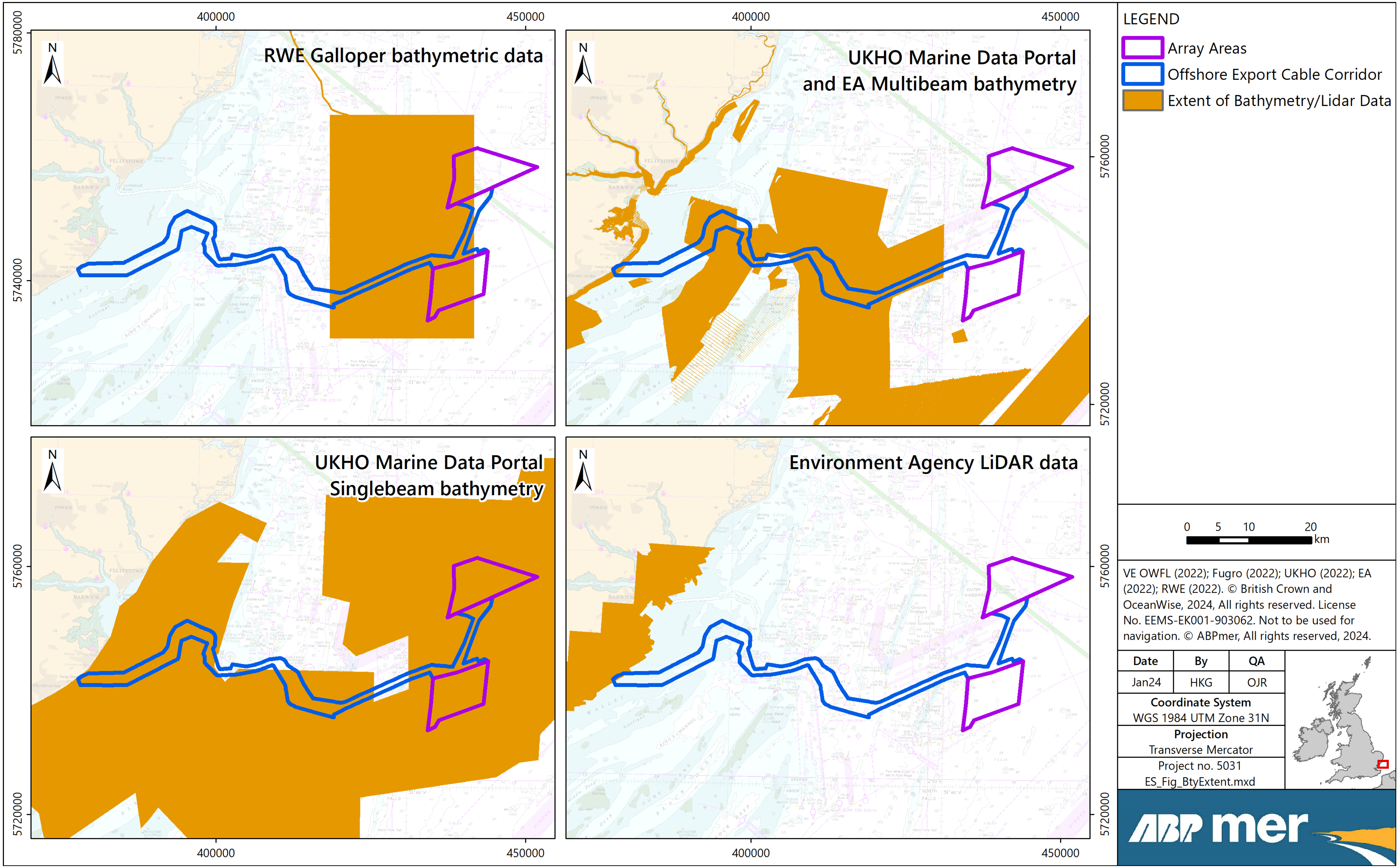
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Array Areas
Offshore Export Cable Corridor
Extent of Bathymetry/Lidar Data
0 5 10 20
km
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Date | By | QA
Jan24 | HKG | OJR
Coordinate System
WGS 1984 UTM Zone 31N
Projection
Transverse Mercator
Project no. 5031
ES_Fig_BtyExtent.mxd
ABP mer

3 Metocean Regime

3.1 Water levels

Tidal water levels across the study area increase from northeast to southwest, away from an amphidromic point to the north of the array areas. Within the array areas, the mean spring tidal range increases from *circa* 2.0 m in the north to 3.0 m in the south, whilst along the offshore export cable corridor, it varies from approximately 2.6 m offshore to 3.6 m at the landfall. Tidal ranges are approximately half of this on neap tides.

Summary tidal statistics for Clacton-on-Sea (to the south of the landfall) and Walton-on-the-Naze (to the north) are shown in Table 4.

Table 4. Summary tidal data for Clacton-on-Sea and Walton-on-the-Naze

Tide Level	Clacton-on-Sea (m Chart Datum (CD))	Clacton-on-Sea (m Ordnance Datum Newlyn (ODN))	Walton-on-the-Naze (mCD)	Walton-on-the-Naze (mODN)
Highest Astronomical Tide	5.20	2.91	4.80	2.94
Mean High Water Spring Tide	4.50	2.21	4.20	2.04
Mean High Water Neap Tide	3.50	1.21	3.40	1.24
Mean Sea Level	2.38	0.09	2.25	0.09
Mean Low Water Neap Tide	1.20	-1.09	1.10	-1.06
Mean Low Water Spring Tide	0.50	-1.79	0.40	-1.76
Lowest Astronomical Tide	0.00	-2.29	-0.10	-2.26
Mean Spring Range	4.00	1.71	3.80	1.64
CD to ODN	**-2.29**		**-2.16**	

Source: UKHO, 2022

Extreme water levels at the proposed development typically result from storm surge propagation within the North Sea. The processes associated with storm surge propagation in the North Sea are generally well understood, having been extensively studied. In brief, a storm surge is produced when high winds build up a wall of water, further exacerbated by the effects of atmospheric pressure (Prichard, 2013). Surge magnitude generally increases from north to south in the Southern North Sea, with the 50-year return period surge level (tide + surge) at the landfall predicted to be 3.59 mODN (Environment Agency, 2019). The impact of a surge will depend critically on the state of the tide with the biggest risk of flooding and erosion occurring if the surge peak coincides with high water on a spring tide.

3.2 Currents

Maps of surface current speeds (and directions) at various states of a representative mean spring tide are shown in Figure 4. Peak speeds are approximately 1.2 to 1.3 m/s across the Array Areas with little difference between the two. Along the offshore export cable corridor, flows generally reduce with proximity to the coast, from around 1.3 m/s offshore, to less than 1 m/s at the landfall. However, currents can become considerably faster and more complex locally around the major offshore sandbank features, and (to the south) in the approaches to the Thames and other smaller local estuaries.

Figure 5 shows modelled residual tidal flow across the study area. Finer sediment held in suspension will generally be transported in the direction of residual current flow and this is therefore an important consideration for the assessment of sediment plumes associated with construction related activities. On the basis of Figure 5, residual flow is found to be highly variable across the study area and ECC although is most pronounced around bank systems. Within the Array Areas, residual flow rates are very low.

Spring tidal excursion ellipses are shown in Figure 6. These ellipses show the approximate displacement path of water during a representative tidal cycle and so illustrate spatial variation in the orientation of the tidal axis, the degree of directional rotation and the magnitude of tidal current speed. In general, tidal streams across the study area are orientated broadly parallel to the adjacent coastline. Offshore flows are relatively rectilinear in nature (with minimal rotation of direction during the ebb and flood) (Figure 6). Closer to the coastline, tidal streams exhibit greater rotation during and between flood and ebb tidal phases.

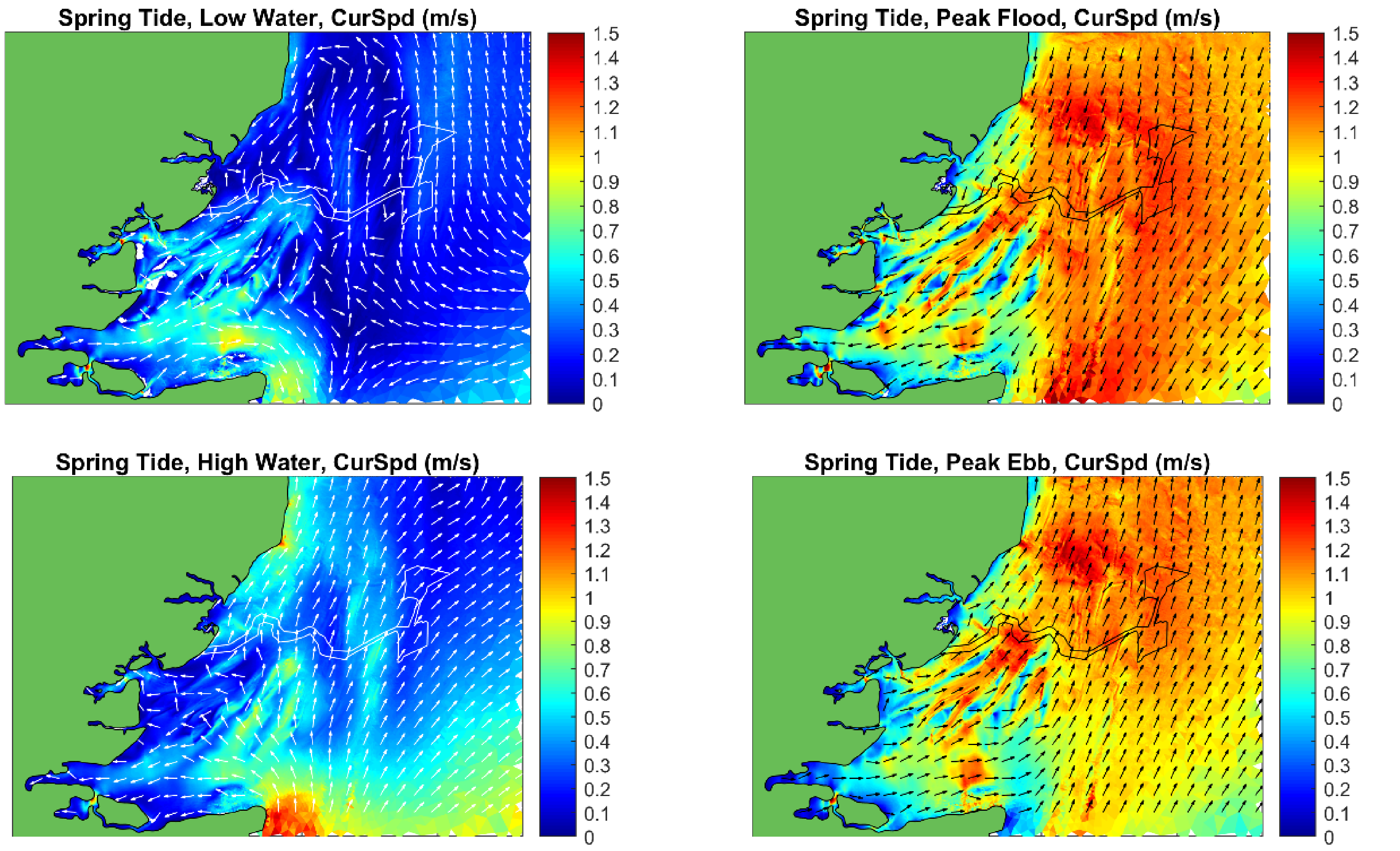


Figure 4. Baseline tidal current speed and direction during a representative spring tidal condition

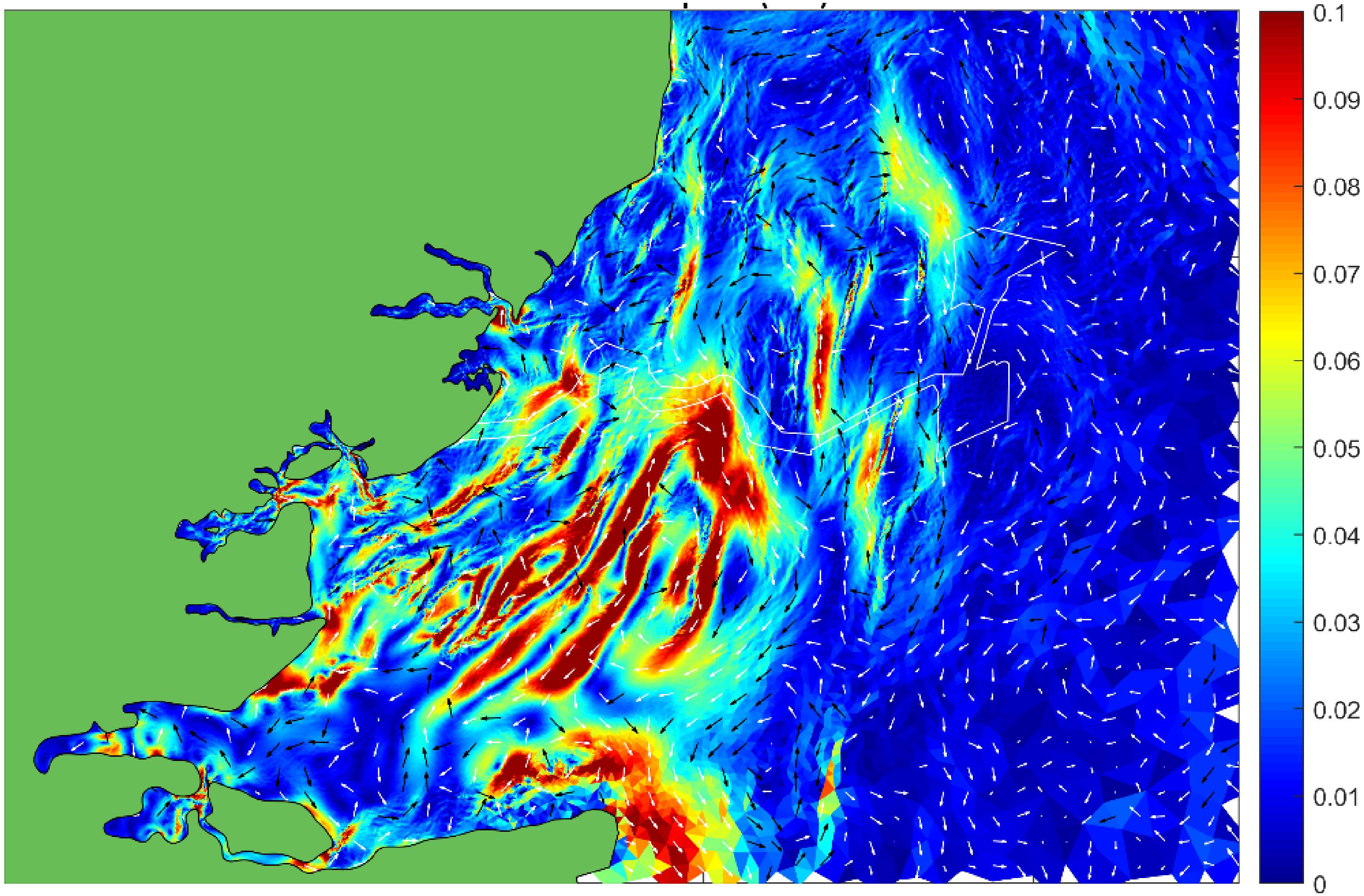
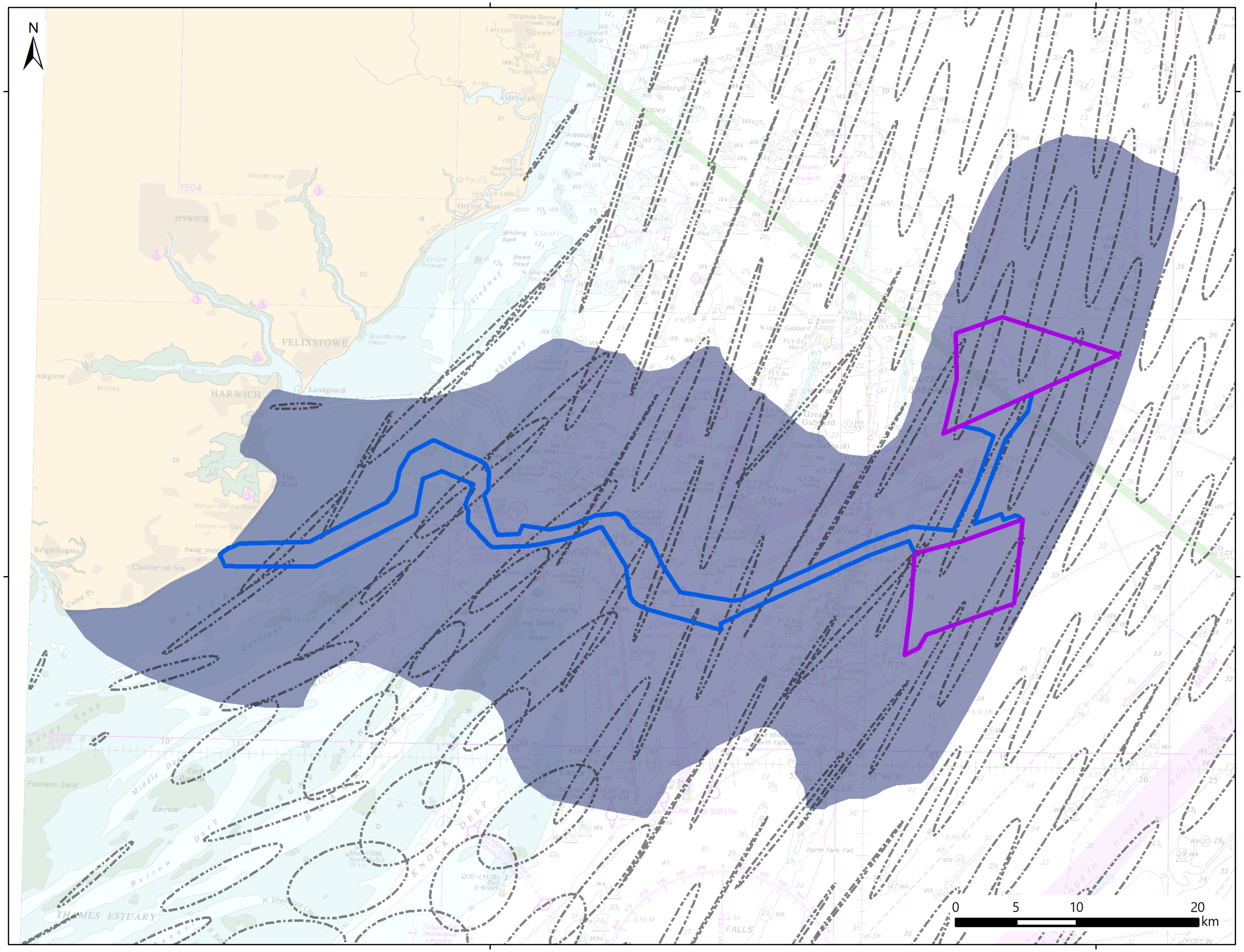


Figure 5. Baseline residual tidal current speed and direction (white & black arrows) measured over a representative spring-neap tidal period.



LEGEND

- Array Areas
- Offshore Export Cable Corridor
- Spring tidal excursion ellipse buffer
- Spring Tidal Excursion Ellipse

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Date	By	QA
Jan 24	HKG	OJR

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Projection
Transverse Mercator

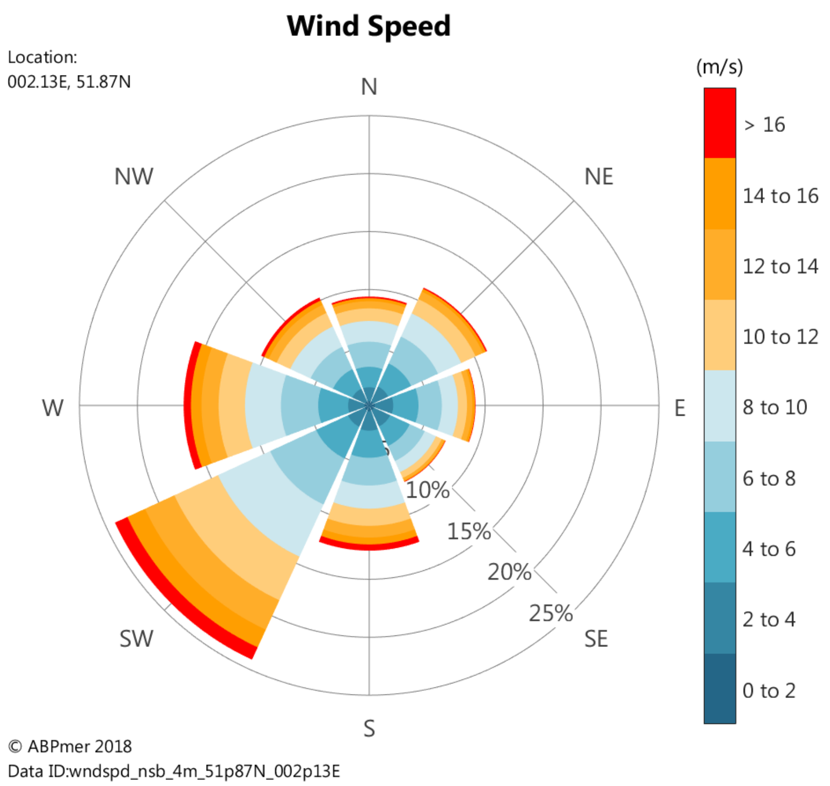
Project no. 5031
ES_Fig_Tidal_Ellipses_v2.mxd

3.3 Winds

An understanding of the wind climate is relevant to physical processes in so far as it is a controlling parameter in the prevailing wave regime and non-tidal water levels and currents. The relationship between wave generation and meteorological forcing means that the wind and wave regimes are similarly episodic and exhibit both seasonal and inter-annual variation in proportion with the frequency and magnitude of changes in wind strength and direction.

A long-term hindcast record of wind data within study area has been derived from ABPmer's SEASTATES models. A frequency analysis of the data is presented as a wind rose in Figure 7, along with frequency scatter tables of wind speed against direction in Table 5 to Table 7. These show that:

- The dominant wind direction is from the southwest and west, with winds occurring from this direction for around 40% of the time; and
- The strongest winds observed in the record all originate from the west quadrant. The maximum observed wind speeds in the records are 28.3 m/s in the array area, 28.1 m/s along the cable corridor and 23.3 m/s at the landfall location.



Source: ABPmer, SEASTATES.net

Figure 7. Rose plot of wind speed and direction, 1979 to 2019

Table 5. Frequency scatter table of wind speed vs wind direction - Landfall. (Source: ABPmer SEASTATES)

Landfall - Speed Wind Direction Scatter Table - All Data - Percentage (occurences as proportion of all data)

Wind Speed (m/s) Lower (>=)	Upper (<)	345–15	15–45	45–75	75–105	105–135	135–165	165–195	195–225	225–255	255–285	285–315	315–345	Sum	Cum. Sum	Exced.
24	25														100.00	0.00
23	24								0.00					0.00	100.00	0.00
22	23							0.00	0.00	0.00				0.00	100.00	0.00
21	22							0.00	0.00	0.00	0.00			0.00	100.00	0.00
20	21							0.00	0.00	0.00	0.00			0.01	99.99	0.01
19	20		0.00				0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.03	99.98	0.02
18	19	0.00	0.00				0.00	0.01	0.02	0.01	0.01	0.00	0.00	0.05	99.95	0.05
17	18	0.00	0.00	0.00		0.00	0.00	0.02	0.04	0.01	0.01	0.00	0.00	0.09	99.90	0.10
16	17	0.00	0.01	0.00	0.00	0.00	0.00	0.04	0.06	0.02	0.02	0.01	0.00	0.17	99.81	0.19
15	16	0.01	0.01	0.01	0.01	0.00	0.02	0.06	0.11	0.06	0.04	0.02	0.01	0.35	99.63	0.37
14	15	0.02	0.02	0.03	0.02	0.01	0.02	0.09	0.18	0.11	0.08	0.04	0.03	0.64	99.29	0.71
13	14	0.03	0.05	0.07	0.04	0.01	0.03	0.14	0.34	0.23	0.15	0.08	0.06	1.21	98.65	1.35
12	13	0.07	0.08	0.12	0.06	0.03	0.06	0.18	0.50	0.42	0.24	0.12	0.09	1.98	97.44	2.56
11	12	0.10	0.14	0.18	0.12	0.05	0.09	0.27	0.69	0.63	0.39	0.20	0.14	2.99	95.46	4.54
10	11	0.17	0.24	0.25	0.18	0.09	0.12	0.37	0.94	0.89	0.56	0.27	0.28	4.37	92.47	7.53
9	10	0.27	0.34	0.39	0.24	0.14	0.21	0.52	1.19	1.26	0.77	0.41	0.38	6.13	88.10	11.90
8	9	0.41	0.53	0.61	0.30	0.22	0.27	0.67	1.55	1.57	1.00	0.65	0.48	8.27	81.97	18.03
7	8	0.59	0.76	0.83	0.48	0.32	0.41	0.84	1.82	1.87	1.26	0.85	0.66	10.70	73.70	26.30
6	7	0.77	0.90	0.96	0.73	0.43	0.56	0.97	2.06	2.11	1.51	1.09	0.79	12.86	63.01	36.99
5	6	0.88	0.97	1.02	0.99	0.73	0.70	1.05	1.77	2.11	1.63	1.24	0.87	13.96	50.14	49.86
4	5	0.90	0.84	0.93	0.99	0.93	0.89	1.06	1.47	1.75	1.53	1.16	0.89	13.35	36.18	63.82
3	4	0.70	0.64	0.80	0.87	0.89	0.85	0.94	1.09	1.24	1.14	0.97	0.77	10.90	22.83	77.17
2	3	0.46	0.49	0.51	0.58	0.64	0.61	0.61	0.68	0.70	0.66	0.60	0.51	7.05	11.93	88.07
1	2	0.25	0.25	0.29	0.32	0.34	0.33	0.33	0.34	0.35	0.34	0.29	0.27	3.70	4.88	95.12
0	1	0.10	0.09	0.09	0.09	0.10	0.10	0.10	0.10	0.11	0.11	0.10	0.09	1.19	1.19	98.81
Sum		5.73	6.35	7.09	6.02	4.96	5.29	8.28	14.97	15.45	11.47	8.09	6.31	100.00		

Wind Direction (Deg) From

Table 6. Frequency scatter table of wind speed vs wind direction – ECC. (Source: ABPmer SEASTATES)

CableCorridor - Speed Wind Direction Scatter Table - All Data - Percentage (occurences as proportion of all data)

Wind Speed (m/s) Lower (>=)	Upper (<)	345–15	15–45	45–75	75–105	105–135	135–165	165–195	195–225	225–255	255–285	285–315	315–345	Sum	Cum. Sum	Exced.
29	30														100.00	0.00
28	29								0.00					0.00	100.00	0.00
27	28								0.00					0.00	100.00	0.00
26	27								0.00	0.00				0.00	100.00	0.00
25	26							0.00	0.00	0.00	0.00			0.01	100.00	0.00
24	25							0.00	0.00	0.00	0.00			0.01	99.99	0.01
23	24						0.00	0.00	0.01	0.00	0.00	0.00		0.02	99.99	0.01
22	23		0.00				0.00	0.01	0.02	0.01	0.01	0.00	0.00	0.04	99.97	0.03
21	22	0.00	0.00	0.00			0.00	0.01	0.03	0.01	0.01	0.00	0.00	0.07	99.93	0.07
20	21	0.00	0.00	0.00			0.00	0.02	0.04	0.02	0.02	0.01	0.00	0.12	99.86	0.14
19	20	0.01	0.01	0.00		0.00	0.01	0.03	0.07	0.04	0.03	0.01	0.01	0.21	99.74	0.26
18	19	0.01	0.01	0.01	0.00	0.00	0.01	0.06	0.11	0.06	0.05	0.02	0.02	0.36	99.53	0.47
17	18	0.02	0.02	0.01	0.01	0.00	0.01	0.08	0.19	0.10	0.08	0.05	0.03	0.62	99.16	0.84
16	17	0.03	0.04	0.04	0.02	0.01	0.02	0.10	0.28	0.19	0.13	0.08	0.05	1.00	98.55	1.45
15	16	0.06	0.06	0.07	0.05	0.02	0.03	0.15	0.42	0.34	0.20	0.11	0.09	1.61	97.55	2.45
14	15	0.09	0.10	0.11	0.07	0.03	0.06	0.21	0.54	0.49	0.29	0.17	0.13	2.30	95.94	4.06
13	14	0.15	0.16	0.17	0.14	0.06	0.08	0.28	0.71	0.66	0.40	0.22	0.20	3.24	93.64	6.36
12	13	0.22	0.23	0.26	0.17	0.09	0.12	0.36	0.91	0.91	0.54	0.27	0.26	4.34	90.40	9.60
11	12	0.29	0.34	0.35	0.23	0.14	0.19	0.45	1.08	1.12	0.68	0.40	0.35	5.62	86.06	13.94
10	11	0.37	0.51	0.53	0.27	0.20	0.23	0.54	1.39	1.36	0.82	0.52	0.47	7.22	80.44	19.56
9	10	0.52	0.68	0.65	0.39	0.27	0.32	0.62	1.59	1.56	0.93	0.65	0.53	8.69	73.22	26.78
8	9	0.58	0.77	0.77	0.53	0.37	0.43	0.69	1.67	1.65	1.11	0.80	0.61	9.98	64.52	35.48
7	8	0.71	0.84	0.84	0.64	0.44	0.50	0.75	1.62	1.67	1.19	0.86	0.61	10.67	54.54	45.46
6	7	0.72	0.84	0.91	0.76	0.55	0.53	0.82	1.40	1.53	1.16	0.89	0.66	10.79	43.87	56.13
5	6	0.65	0.70	0.86	0.76	0.66	0.64	0.86	1.14	1.25	1.05	0.80	0.66	10.05	33.08	66.92
4	5	0.55	0.55	0.72	0.76	0.70	0.66	0.81	0.89	0.90	0.81	0.70	0.54	8.59	23.03	76.97
3	4	0.42	0.45	0.57	0.62	0.58	0.59	0.62	0.66	0.62	0.58	0.52	0.41	6.64	14.44	85.56
2	3	0.28	0.32	0.36	0.43	0.44	0.43	0.41	0.41	0.38	0.35	0.32	0.30	4.44	7.80	92.20
1	2	0.17	0.18	0.20	0.24	0.24	0.24	0.23	0.23	0.23	0.22	0.18	0.18	2.54	3.36	96.64
0	1	0.07	0.06	0.06	0.06	0.07	0.08	0.07	0.07	0.07	0.07	0.06	0.07	0.82	0.82	99.18
Sum		5.92	6.90	7.49	6.17	4.88	5.20	8.19	15.49	15.19	10.75	7.65	6.19	100.00		

Wind Direction (Deg) From

Table 7. Frequency scatter table of wind speed vs wind direction – central Array Area. (Source: ABPmer SEASTATES)

CentralArray - Speed Wind Direction Scatter Table - All Data - Percentage (occurences as proportion of all data)

Wind Speed (m/s); Wind Direction (Deg) From

Lower (>=)	Upper (<)	345–15	15–45	45–75	75–105	105–135	135–165	165–195	195–225	225–255	255–285	285–315	315–345	Sum	Cum. Sum	Exced.
29	30														100.00	0.00
28	29								0.00	0.00				0.00	100.00	0.00
27	28								0.00	0.00	0.00			0.00	100.00	0.00
26	27								0.00	0.00	0.00			0.00	100.00	0.00
25	26							0.00	0.00	0.00	0.00	0.00		0.01	99.99	0.01
24	25							0.00	0.01	0.01	0.00		0.00	0.02	99.99	0.01
23	24	0.00	0.00				0.00	0.00	0.02	0.01	0.01	0.00	0.00	0.04	99.97	0.03
22	23	0.00	0.00				0.00	0.01	0.02	0.01	0.02	0.00	0.00	0.07	99.93	0.07
21	22	0.00	0.00	0.00			0.00	0.01	0.04	0.02	0.02	0.01	0.01	0.11	99.86	0.14
20	21	0.01	0.00	0.00			0.00	0.02	0.07	0.04	0.04	0.01	0.01	0.21	99.75	0.25
19	20	0.01	0.01	0.00		0.00	0.01	0.04	0.10	0.07	0.05	0.03	0.02	0.34	99.54	0.46
18	19	0.02	0.01	0.01	0.00	0.00	0.01	0.06	0.18	0.11	0.09	0.05	0.03	0.57	99.20	0.80
17	18	0.03	0.02	0.02	0.01	0.01	0.01	0.10	0.26	0.20	0.12	0.08	0.06	0.93	98.63	1.37
16	17	0.05	0.05	0.04	0.03	0.01	0.03	0.11	0.36	0.34	0.20	0.11	0.09	1.41	97.70	2.30
15	16	0.09	0.07	0.08	0.06	0.02	0.04	0.17	0.49	0.49	0.27	0.17	0.12	2.07	96.29	3.71
14	15	0.13	0.12	0.13	0.09	0.04	0.07	0.25	0.63	0.62	0.37	0.21	0.16	2.82	94.22	5.78
13	14	0.19	0.18	0.19	0.16	0.07	0.09	0.33	0.78	0.84	0.47	0.24	0.23	3.77	91.40	8.60
12	13	0.25	0.27	0.28	0.20	0.10	0.14	0.40	1.00	1.01	0.62	0.36	0.32	4.96	87.63	12.37
11	12	0.33	0.41	0.38	0.26	0.15	0.21	0.48	1.18	1.23	0.73	0.46	0.40	6.23	82.68	17.32
10	11	0.45	0.59	0.55	0.33	0.23	0.27	0.57	1.37	1.40	0.79	0.56	0.47	7.60	76.44	23.56
9	10	0.53	0.76	0.67	0.45	0.32	0.36	0.61	1.53	1.56	0.98	0.67	0.54	8.98	68.84	31.16
8	9	0.67	0.85	0.76	0.57	0.41	0.47	0.69	1.51	1.62	1.04	0.77	0.54	9.89	59.86	40.14
7	8	0.72	0.88	0.79	0.66	0.50	0.51	0.69	1.46	1.53	1.05	0.77	0.61	10.16	49.98	50.02
6	7	0.66	0.81	0.85	0.74	0.55	0.52	0.71	1.20	1.33	0.97	0.77	0.62	9.73	39.81	60.19
5	6	0.61	0.71	0.82	0.68	0.56	0.55	0.71	1.02	1.05	0.84	0.68	0.56	8.79	30.08	69.92
4	5	0.49	0.59	0.68	0.65	0.54	0.55	0.68	0.84	0.78	0.70	0.57	0.47	7.53	21.29	78.71
3	4	0.39	0.49	0.58	0.57	0.50	0.49	0.59	0.61	0.54	0.47	0.42	0.36	6.02	13.76	86.24
2	3	0.27	0.34	0.40	0.42	0.41	0.40	0.41	0.39	0.36	0.32	0.30	0.27	4.28	7.74	92.26
1	2	0.18	0.19	0.22	0.26	0.25	0.24	0.24	0.23	0.23	0.21	0.19	0.18	2.61	3.46	96.54
0	1	0.06	0.06	0.07	0.07	0.08	0.08	0.08	0.08	0.07	0.07	0.06	0.06	0.84	0.84	99.16
Sum		6.14	7.42	7.51	6.20	4.76	5.04	7.98	15.39	15.47	10.44	7.52	6.15	100.00		

3.4 Waves

The wave climate is the result of the transfer of wind energy to the sea, creating sea-states and the propagation of that energy across the water surface by wave motion. The amount of wind energy transfer and wind-wave development is a function of the available fetch distance across which the wind blows, wind speed, wind duration and the original state of the sea. The longer the fetch distance, the greater the potential there is for the wind to interact with the water surface and generate waves. In shallower water, water depth is an additional limiting factor on the size of waves.

The wave regime in the Southern North Sea is dominated by locally generated wind-waves across the wider North Sea region. The Array Areas are exposed to longer wave fetches (distances of open water over which waves can develop) from the north to northeast. Smaller but more frequently occurring wave conditions generated by local winds predominantly come from southerly and south-westerly directions.

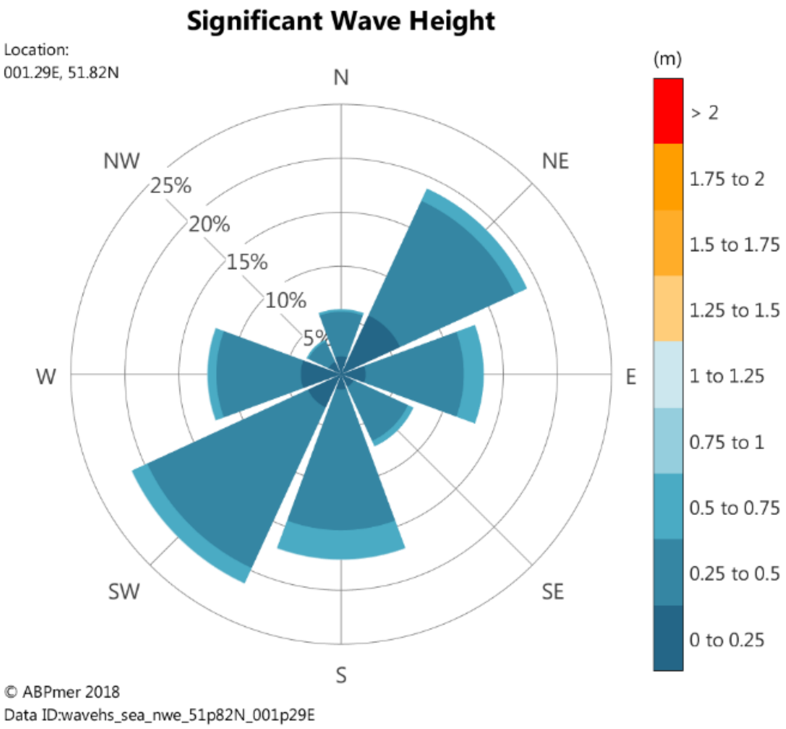
Further inshore, waves are progressively refracted to approach the adjacent coastline from a more southerly direction. A long-term hindcast record of wave data within the Array Areas is available from the ABPmer SEASTATES model. A frequency analysis of the data has been carried out at three locations: the landfall, cable corridor and cable array area.

This has been summarised in a series of wave roses (Figure 8 and Figure 9), as well as frequency scatter tables of wave height, period and direction (Table 8 to Table 13).

This analysis shows that:

- The most frequent wave direction at the landfall site is from the southwest, which accounts for approximately 23% of the record. The largest wave height observed in the record was 1.17 m.
- The most frequent wave direction along the cable corridor was from the north, accounting for 19% of the record, as well as the south/southwest, accounting for 17% and 22% of the record respectively. The largest wave height observed in the record at this location was 5.82 m.
- The largest wave height observed in the record at the central array area was 7.72 m. The most frequent wave direction at this location is from the southwest (27% of the record), and north/northeast (32% of the record).
- The majority (76%) of the record at the landfall comprises waves with period ≤ 4 seconds.
- The majority (86%) of the record at the cable corridor comprises waves with period ≤ 6 seconds, whilst 50% of waves have a period of between 4 and 6 seconds at the array area.
- Longer period waves (Peak wave period (Tp) ≥ 8 seconds) are observed although account for <1% of the record at all three locations.

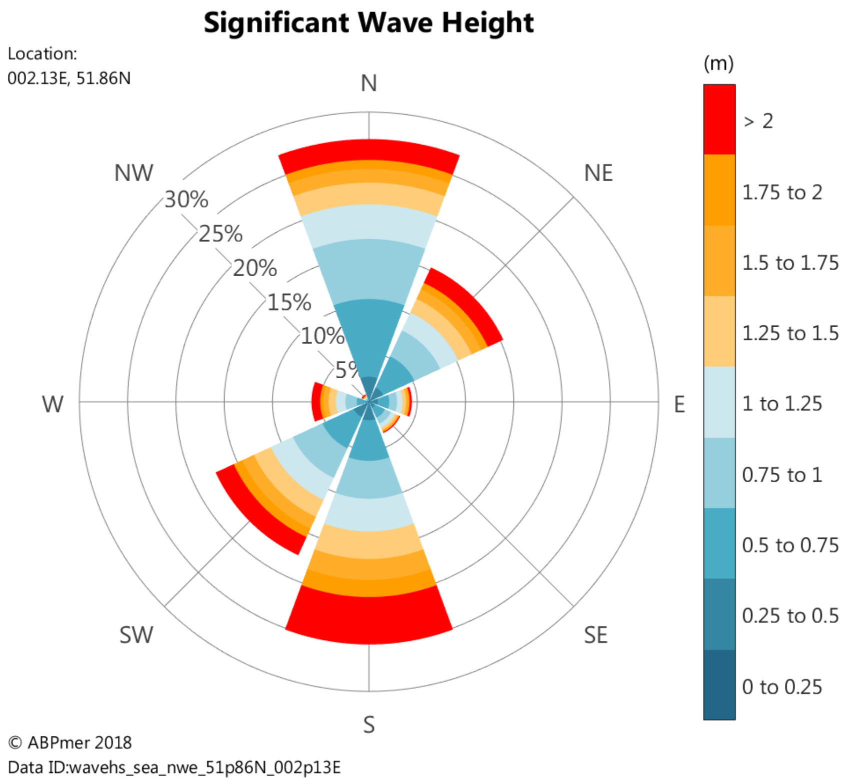
This long-term hindcast record is largely consistent with the metocean observations collected during the Greater Gabbard oceanographic survey in 2004 and 2005 (see GGOWL 2005 and 2011), despite the differing length of the records.



Source: ABPmer, SEASTATES.net

Figure 8. Rose plot of significant wave height and direction at the landfall, over the period 1979 to 2009 (31 years) (directions indicate 'coming from')

The Essex and Suffolk coastlines have a spatially variable wave climate. The local orientation of the coastline relative to the predominant wave direction will then influence local conditions of sheltering, resulting sediment transport rates and directions. The wave climate will also be locally influenced by the effect of the offshore banks which are prevalent along this section of coast (see Section 4). Just offshore from the landfall, waves predominantly approach from the northeast and southwest although these waves will be refracted as they approach the coast (Figure 9).



Source: ABPmer, SEASTATES.net

Figure 9. **Rose plot of significant wave height and direction (right) at a location representative of the Array Areas, over the period 1979 to 2009 (31 years) (directions indicate 'coming from')**

Table 8. **Frequency scatter table of significant wave height vs peak wave period – Landfall. (Source: ABPmer SEASTATES)**

Significant Wave Height (m)		Peak Wave Period: Total Sea, (seconds)														
Lower (>=)		0	2	4	6	8	10	12	14	16	18	20	22		Cum.	
	Upper (<)	2	4	6	8	10	12	14	16	18	20	22	24	Sum	Sum	Exced.
1.25	1.50														100.00	0.00
1.00	1.25		0.01											0.01	100.00	0.00
0.75	1.00		0.33	0.04	0.00									0.37	99.99	0.01
0.50	0.75	0.00	6.09	1.83	1.68	0.12								9.72	99.61	0.39
0.25	0.50	2.25	60.65	5.95	1.03	0.10	0.00							69.98	89.89	10.11
0.00	0.25	7.28	9.02	1.43	1.28	0.53	0.20	0.08	0.04	0.03	0.01	0.00		19.92	19.92	80.08
Sum		9.53	76.11	9.25	3.99	0.75	0.20	0.08	0.04	0.03	0.01	0.00		100.00		
Cumulative Sum		9.53	85.64	94.89	98.88	99.63	99.83	99.91	99.95	99.99	100.00	100.00	100.00			
Exceedence		90.47	14.36	5.11	1.12	0.37	0.17	0.09	0.05	0.01	0.00	0.00	0.00			

Table 9. Frequency scatter table of significant wave height vs mean wave direction – Landfall. (Source: ABPmer SEASTATES)

Significant Wave Height (m)		Wave Direction (Deg) From										
Lower (>=)		337.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5		Cum.	
	Upper (<)	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5	Sum	Sum	Exced.
1.25	1.50										100.00	0.00
1.00	1.25					0.00	0.01	0.00	0.00	0.01	100.00	0.00
0.75	1.00	0.00	0.00	0.00	0.00	0.12	0.15	0.07	0.02	0.37	99.99	0.01
0.50	0.75	0.23	1.24	1.61	0.64	2.38	2.51	0.77	0.33	9.72	99.61	0.39
0.25	0.50	3.82	10.63	8.99	6.11	11.43	17.78	7.62	3.59	69.98	89.89	10.11
0.00	0.25	1.92	3.30	3.19	1.86	1.82	2.63	3.21	1.98	19.92	19.92	80.08
Sum		5.97	15.18	13.79	8.62	15.75	23.08	11.69	5.93	100.00		

Table 10. Frequency scatter table of significant wave height vs peak wave period – ECC. (Source: ABPmer SEASTATES)

Significant Wave Height (m)		Peak Wave Period: Total Sea, (seconds)													
Lower (>=)		0	2	4	6	8	10	12	14	16	18	20		Cum.	
	Upper (<)	2	4	6	8	10	12	14	16	18	20	22	Sum	Sum	Exced.
6.00	6.25													100.00	0.00
5.75	6.00					0.00							0.00	100.00	0.00
5.50	5.75													100.00	0.00
5.25	5.50				0.00	0.00							0.00	100.00	0.00
5.00	5.25					0.00							0.00	100.00	0.00
4.75	5.00				0.00	0.00							0.00	100.00	0.00
4.50	4.75				0.01	0.00							0.01	99.99	0.01
4.25	4.50				0.01	0.00							0.01	99.99	0.01
4.00	4.25				0.01	0.01							0.03	99.97	0.03
3.75	4.00				0.03	0.01							0.05	99.95	0.05
3.50	3.75				0.07	0.01							0.08	99.90	0.10
3.25	3.50			0.00	0.12	0.02							0.14	99.83	0.17
3.00	3.25			0.01	0.26	0.03							0.30	99.68	0.32
2.75	3.00			0.04	0.42	0.02							0.48	99.39	0.61
2.50	2.75			0.14	0.64	0.01							0.78	98.91	1.09
2.25	2.50			0.47	0.85	0.01							1.33	98.13	1.87
2.00	2.25			1.34	0.89	0.01							2.24	96.80	3.20
1.75	2.00			2.55	0.89	0.01							3.44	94.56	5.44
1.50	1.75		0.00	4.51	0.76	0.01							5.27	91.12	8.88
1.25	1.50		0.02	7.48	0.67	0.01							8.18	85.85	14.15
1.00	1.25		0.58	10.99	0.91	0.01							12.49	77.67	22.33
0.75	1.00		5.75	11.60	1.82	0.02							19.19	65.18	34.82
0.50	0.75	0.00	19.07	5.98	3.11	0.03							28.19	46.00	54.00
0.25	0.50	0.07	14.15	1.50	0.86	0.07	0.01	0.01	0.00		0.00		16.67	17.80	82.20
0.00	0.25	0.04	0.74	0.08	0.13	0.07	0.04	0.01	0.01	0.01	0.00		1.14	1.14	98.86
Sum		0.11	40.31	46.67	12.46	0.35	0.05	0.02	0.01	0.01	0.00		100.00		
Cumulative Sum		0.11	40.42	87.09	99.56	99.91	99.96	99.98	99.99	100.00	100.00	100.00			
Exceedence		99.89	59.58	12.91	0.44	0.09	0.04	0.02	0.01	0.00	0.00	0.00			

Table 11. **Frequency scatter table of significant wave height vs mean wave direction – ECC. (Source: ABPmer SEASTATES)**

Significant Wave Height (m)		Wave Direction (Deg) From										
Lower (>=)		337.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5		Cum.	
	Upper (<)	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5	Sum	Sum	Exced.
6.00	6.25										100.00	0.00
5.75	6.00					0.00				0.00	100.00	0.00
5.50	5.75										100.00	0.00
5.25	5.50					0.00				0.00	100.00	0.00
5.00	5.25					0.00				0.00	100.00	0.00
4.75	5.00		0.00			0.00	0.00			0.00	100.00	0.00
4.50	4.75		0.00			0.01	0.00			0.01	99.99	0.01
4.25	4.50		0.00		0.00	0.01	0.00	0.00		0.01	99.99	0.01
4.00	4.25		0.01		0.00	0.01	0.00	0.00		0.03	99.97	0.03
3.75	4.00	0.00	0.01		0.00	0.02	0.01	0.00	0.00	0.05	99.95	0.05
3.50	3.75	0.00	0.01	0.00	0.00	0.04	0.01	0.00	0.00	0.08	99.90	0.10
3.25	3.50	0.01	0.04	0.01	0.01	0.07	0.02	0.00	0.00	0.14	99.83	0.17
3.00	3.25	0.02	0.08	0.03	0.01	0.11	0.03	0.01	0.00	0.30	99.68	0.32
2.75	3.00	0.02	0.11	0.06	0.02	0.18	0.05	0.02	0.01	0.48	99.39	0.61
2.50	2.75	0.05	0.17	0.08	0.02	0.29	0.12	0.04	0.02	0.78	98.91	1.09
2.25	2.50	0.10	0.27	0.15	0.06	0.43	0.23	0.06	0.03	1.33	98.13	1.87
2.00	2.25	0.19	0.45	0.21	0.09	0.63	0.49	0.12	0.06	2.24	96.80	3.20
1.75	2.00	0.31	0.68	0.25	0.13	0.90	0.83	0.23	0.10	3.44	94.56	5.44
1.50	1.75	0.44	1.00	0.43	0.21	1.32	1.27	0.40	0.20	5.27	91.12	8.88
1.25	1.50	0.76	1.63	0.67	0.36	1.74	2.08	0.65	0.30	8.18	85.85	14.15
1.00	1.25	1.32	2.38	0.98	0.64	2.32	3.18	1.14	0.54	12.49	77.67	22.33
0.75	1.00	2.20	3.82	1.64	1.00	3.07	4.54	1.79	1.11	19.19	65.18	34.82
0.50	0.75	3.21	5.69	3.03	2.09	3.57	5.59	2.93	2.09	28.19	46.00	54.00
0.25	0.50	1.50	2.47	1.92	1.61	2.34	3.33	2.25	1.26	16.67	17.80	82.20
0.00	0.25	0.24	0.16	0.10	0.10	0.18	0.19	0.08	0.09	1.14	1.14	98.86
Sum		10.37	18.97	9.57	6.36	17.25	21.96	9.72	5.80	100.00		

Table 12. **Frequency scatter table of significant wave height vs peak wave period – Central Array Area. (Source: ABPmer SEASTATES)**

Significant Wave Height (m)		Peak Wave Period: Total Sea, (seconds)													
Lower (>=)		0	2	4	6	8	10	12	14	16	18	20		Cum.	
	Upper (<)	2	4	6	8	10	12	14	16	18	20	22	Sum	Sum	Exced.
7.75	8.00													100.00	0.00
7.50	7.75					0.00							0.00	100.00	0.00
7.25	7.50													100.00	0.00
7.00	7.25					0.00							0.00	100.00	0.00
6.75	7.00					0.00							0.00	100.00	0.00
6.50	6.75					0.00							0.00	100.00	0.00
6.25	6.50					0.00							0.00	100.00	0.00
6.00	6.25					0.00							0.00	99.99	0.01
5.75	6.00					0.01							0.01	99.99	0.01
5.50	5.75				0.00	0.01							0.01	99.98	0.02
5.25	5.50				0.00	0.02							0.02	99.97	0.03
5.00	5.25				0.01	0.02							0.03	99.95	0.05
4.75	5.00				0.01	0.03							0.04	99.93	0.07
4.50	4.75				0.03	0.03							0.06	99.89	0.11
4.25	4.50				0.07	0.03							0.10	99.82	0.18
4.00	4.25				0.12	0.03							0.15	99.72	0.28
3.75	4.00				0.19	0.04							0.23	99.58	0.42
3.50	3.75				0.33	0.05							0.38	99.35	0.65
3.25	3.50				0.56	0.03							0.59	98.97	1.03
3.00	3.25				0.85	0.01							0.86	98.38	1.62
2.75	3.00			0.00	1.31	0.01							1.32	97.52	2.48
2.50	2.75			0.08	1.81	0.01							1.89	96.20	3.80
2.25	2.50			0.46	2.21	0.00							2.67	94.31	5.69
2.00	2.25			1.57	2.19	0.00							3.76	91.63	8.37
1.75	2.00			3.41	1.61	0.00							5.02	87.87	12.13
1.50	1.75		0.00	5.86	1.26	0.00							7.12	82.85	17.15
1.25	1.50		0.01	8.79	1.24	0.00							10.04	75.73	24.27
1.00	1.25		0.31	11.82	1.65	0.00							13.79	65.69	34.31
0.75	1.00		4.17	11.81	3.71	0.00							19.70	51.90	48.10
0.50	0.75	0.00	13.47	5.71	3.55	0.01							22.75	32.20	67.80
0.25	0.50	0.03	7.06	1.27	0.66	0.03	0.00	0.00	0.00		0.00		9.05	9.45	90.55
0.00	0.25	0.01	0.29	0.04	0.03	0.01	0.01	0.00	0.00				0.40	0.40	99.60
Sum		0.04	25.31	50.84	23.39	0.39	0.01	0.00	0.00		0.00		100.00		
Cumulative Sum		0.04	25.36	76.19	99.59	99.98	100.00	100.00	100.00	100.00	100.00	100.00			
Exceedence		99.96	74.64	23.81	0.41	0.02	0.00	0.00	0.00	0.00	0.00	0.00			

Table 13. Frequency scatter table of significant wave height vs mean wave direction – Central Array Area. (Source: ABPmer SEASTATES)

Significant Wave Height (m) / Wave Direction (Deg) From

Lower (>=)	Upper (<)	337.5–22.5	22.5–67.5	67.5–112.5	112.5–157.5	157.5–202.5	202.5–247.5	247.5–292.5	292.5–337.5	Sum	Cum. Sum	Exced.
7.75	8.00										100.00	0.00
7.50	7.75					0.00				0.00	100.00	0.00
7.25	7.50										100.00	0.00
7.00	7.25						0.00			0.00	100.00	0.00
6.75	7.00					0.00	0.00			0.00	100.00	0.00
6.50	6.75					0.00	0.00			0.00	100.00	0.00
6.25	6.50					0.00	0.00			0.00	100.00	0.00
6.00	6.25					0.00	0.00	0.00		0.00	99.99	0.01
5.75	6.00					0.00	0.00	0.00		0.01	99.99	0.01
5.50	5.75	0.00	0.00			0.01	0.00	0.00		0.01	99.98	0.02
5.25	5.50	0.00	0.00			0.01	0.01		0.00	0.02	99.97	0.03
5.00	5.25	0.00	0.00			0.01	0.01		0.00	0.03	99.95	0.05
4.75	5.00	0.00	0.00			0.01	0.02	0.00	0.00	0.04	99.93	0.07
4.50	4.75	0.00	0.01		0.00	0.02	0.02	0.00	0.00	0.06	99.89	0.11
4.25	4.50	0.01	0.01		0.00	0.03	0.04	0.01	0.00	0.10	99.82	0.18
4.00	4.25	0.02	0.01		0.00	0.05	0.06	0.01	0.00	0.15	99.72	0.28
3.75	4.00	0.03	0.02	0.00	0.00	0.06	0.09	0.02	0.01	0.23	99.58	0.42
3.50	3.75	0.04	0.05	0.01	0.00	0.08	0.15	0.03	0.01	0.38	99.35	0.65
3.25	3.50	0.06	0.07	0.01	0.01	0.14	0.23	0.04	0.02	0.59	98.97	1.03
3.00	3.25	0.11	0.11	0.02	0.01	0.17	0.34	0.06	0.04	0.86	98.38	1.62
2.75	3.00	0.17	0.15	0.05	0.01	0.22	0.56	0.10	0.05	1.32	97.52	2.48
2.50	2.75	0.26	0.23	0.08	0.03	0.28	0.77	0.16	0.08	1.89	96.20	3.80
2.25	2.50	0.34	0.36	0.13	0.05	0.40	1.02	0.24	0.14	2.67	94.31	5.69
2.00	2.25	0.48	0.50	0.18	0.07	0.54	1.44	0.36	0.19	3.76	91.63	8.37
1.75	2.00	0.69	0.70	0.23	0.11	0.71	1.88	0.47	0.24	5.02	87.87	12.13
1.50	1.75	1.01	1.07	0.39	0.18	0.86	2.48	0.75	0.37	7.12	82.85	17.15
1.25	1.50	1.53	1.61	0.58	0.33	1.10	3.26	1.00	0.63	10.04	75.73	24.27
1.00	1.25	2.28	2.24	0.88	0.57	1.35	4.03	1.37	1.07	13.79	65.69	34.31
0.75	1.00	3.66	3.56	1.42	0.90	1.72	4.82	1.99	1.62	19.70	51.90	48.10
0.50	0.75	3.74	4.09	2.09	1.57	2.22	4.49	2.46	2.09	22.75	32.20	67.80
0.25	0.50	1.28	1.31	1.18	0.93	1.23	1.66	0.81	0.65	9.05	9.45	90.55
0.00	0.25	0.05	0.04	0.05	0.04	0.04	0.09	0.04	0.04	0.40	0.40	99.60
Sum		15.76	16.15	7.32	4.82	11.30	27.48	9.92	7.25	100.00		

3.5 Future change

Extremes analysis of the long-term wave hindcast record available from the ABPmer SEASTATES model is shown in Table 14. It is found that the largest waves are observed at the central array area, with heights of approximately 5.2 m for a 1:1-year event, increasing to 7.7 m for a 1:50 year event.

Table 14. Extreme value analysis of significant wave height and wave period

Location	Return Period (years)	Significant Wave Height Hs (m)	Mean Wave Period Tz (s)
Landfall	1	0.9	2.1
	5	1.0	2.3
	10	1.1	2.3
	25	1.2	2.4
	50	1.2	2.5
Cable Corridor	1	4.0	5.4
	5	4.8	5.9
	10	5.1	6.0
	25	5.5	6.3
	50	5.8	6.4
Central Array Area	1	5.2	6.2
	5	6.3	6.8
	10	6.7	7.0
	25	7.3	7.3
	50	7.7	7.5

Information on the rate and magnitude of anticipated relative sea level change during the 21st Century is available from UKCP18 (Palmer *et al*. 2018). It is predicted that by 2060, relative sea level may have risen by approximately 0.4 m above present day (2021) levels (Representative Concentration pathway (RCP) 8.5, 95%ile)) at the landfall with rates of change increasing over time.

Sea level rise may result in a loss of intertidal habitat through the process of ‘coastal squeeze’ caused by the presence of coastal defences preventing natural roll back and future equilibrium position of coastal features. A rise in sea level may also allow larger waves, and therefore more wave energy, to reach the coast in certain conditions and, consequently, result in an increase in local rates or patterns of erosion.

UKCP18 provides projections of changes in wave climate over the 21st Century. The findings indicate that within the study area, mean annual maxima significant wave heights may decrease but by less than 0.2 m by 2100 (Palmer *et al*., 2018). However, natural variability is noted to be high in this area and there is substantial uncertainty in projecting future change (e.g., Palmer et al. 2018; Bonaduce et al. 2019; Wolf et al. 2020).

UKCP18 also includes projections of changes to storm surge magnitude in the future as a result of climate change. However, it is found that UKCP18 projections of change in extreme coastal water levels are dominated by the increases in mean sea level with only a minor (<10%) additional contribution due to atmospheric storminess changes over the 21st century (Palmer *et al*. 2018).

4 Surficial Sediments, Sediment Transport Regime and Morphology

4.1 Seabed sediments

4.1.1 Overview

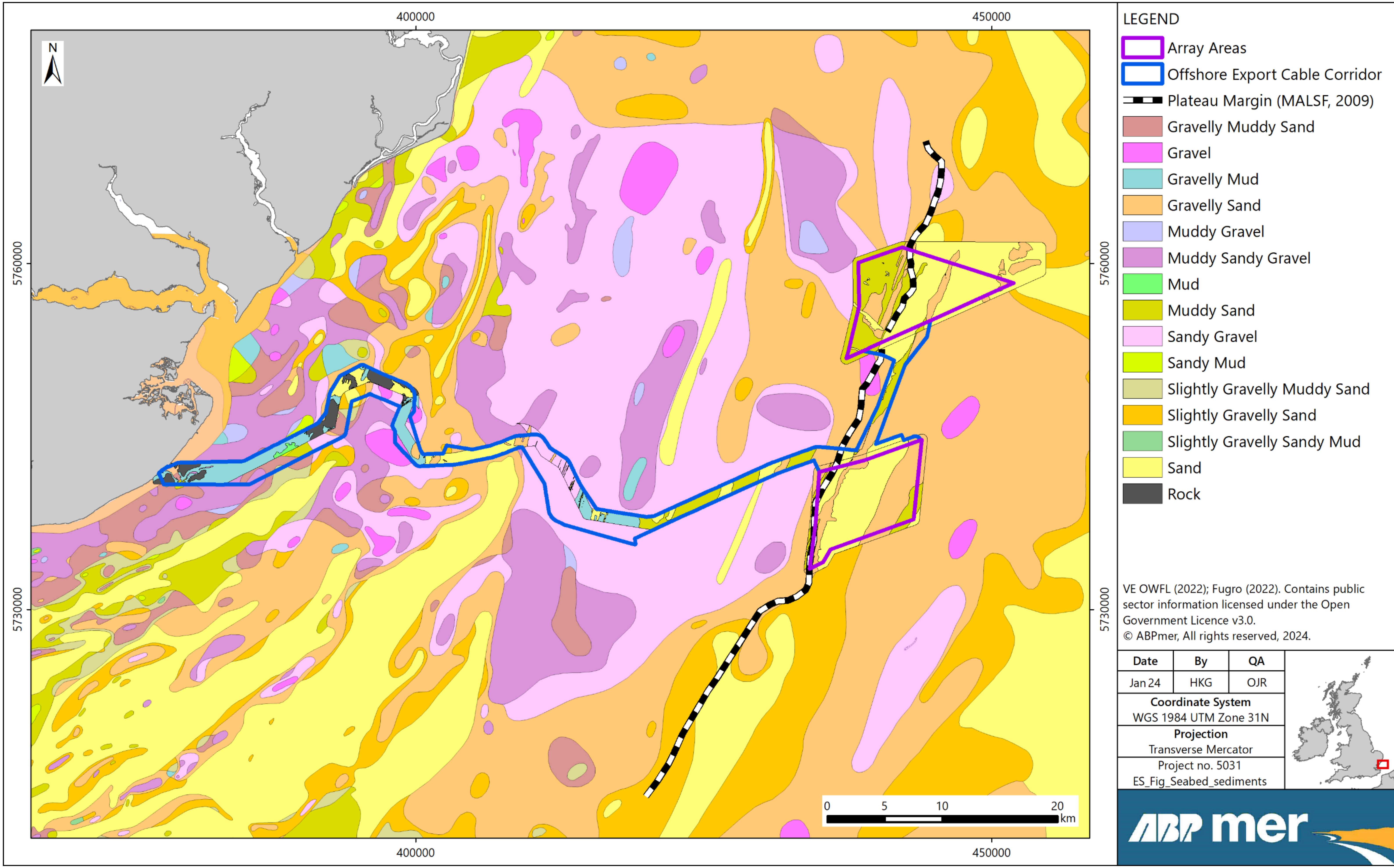
The seabed within the study area primarily consists of sands and gravels (which are occasionally muddy) and some exposed bedrock. Whilst some areas of the seabed are relict, recent erosional and depositional processes have influenced many areas of the seabed in this region. In particular these processes include the marine inundation following the last glacial period when sea levels rose >100 m and the action of waves, tides and currents over the last 5,000 years. The combination of the relict seafloor components and recent marine processes has resulted in the morphological and compositional characteristics of the modern seabed in this region (MALSF, 2009).

4.1.2 Array Areas

Seafloor sediments in the Array Areas (and ECC) have been determined by Fugro (2022a,b) from acoustic variations in the low frequency side scan sonar acoustic reflectivity and changes in morphology derived from the bathymetry. The seabed is found to be dominated by coarse grained sediments, with sands and gravelly sands accounting for *circa* 75% of the footprint of the Array Areas (Figure 10). The remaining areas are characterised by the presence of muddy sand, which is found in the west of the northern Array Area and in localised northeast- to southwest-trending bands in the southern Array Area. Two small, isolated patches of outcrop or sub-crop were also identified in the northern Array Area (Fugro, 2022a).

4.1.3 ECC

The distribution of seabed sediments along the ECC is highly complex, with coarse grained (sands and gravels) and fine grained (muddy) sediments widespread (Fugro, 2022b) (Figure 10). In many nearshore areas (<20 km from the coast), rock is found at or very near to the surface, alongside extensive areas of gravelly mud. This unit likely reflects winnowing of the underlying London Clay formation. The seabed sediment classifications from the project-specific survey show a relatively poor degree of correlation with the regional-scale BGS mapping also shown in Figure 10. However, this most likely reflects differences in the resolution of the two datasets,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450000
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5730000
N
0
5
10
20
km
LEGEND
Array Areas
Offshore Export Cable Corridor
Plateau Margin (MALSF, 2009)
Gravelly Muddy Sand
Gravel
Gravelly Mud
Gravelly Sand
Muddy Gravel
Muddy Sandy Gravel
Mud
Muddy Sand
Sandy Gravel
Sandy Mud
Slightly Gravelly Muddy Sand
Slightly Gravelly Sand
Slightly Gravelly Sandy Mud
Sand
Rock
VE OWFL (2022); Fugro (2022). Contains public sector information licensed under the Open Government Licence v3.0.
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WGS 1984 UTM Zone 31N
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4.2 Geology and sub-strata

4.2.1 Overview

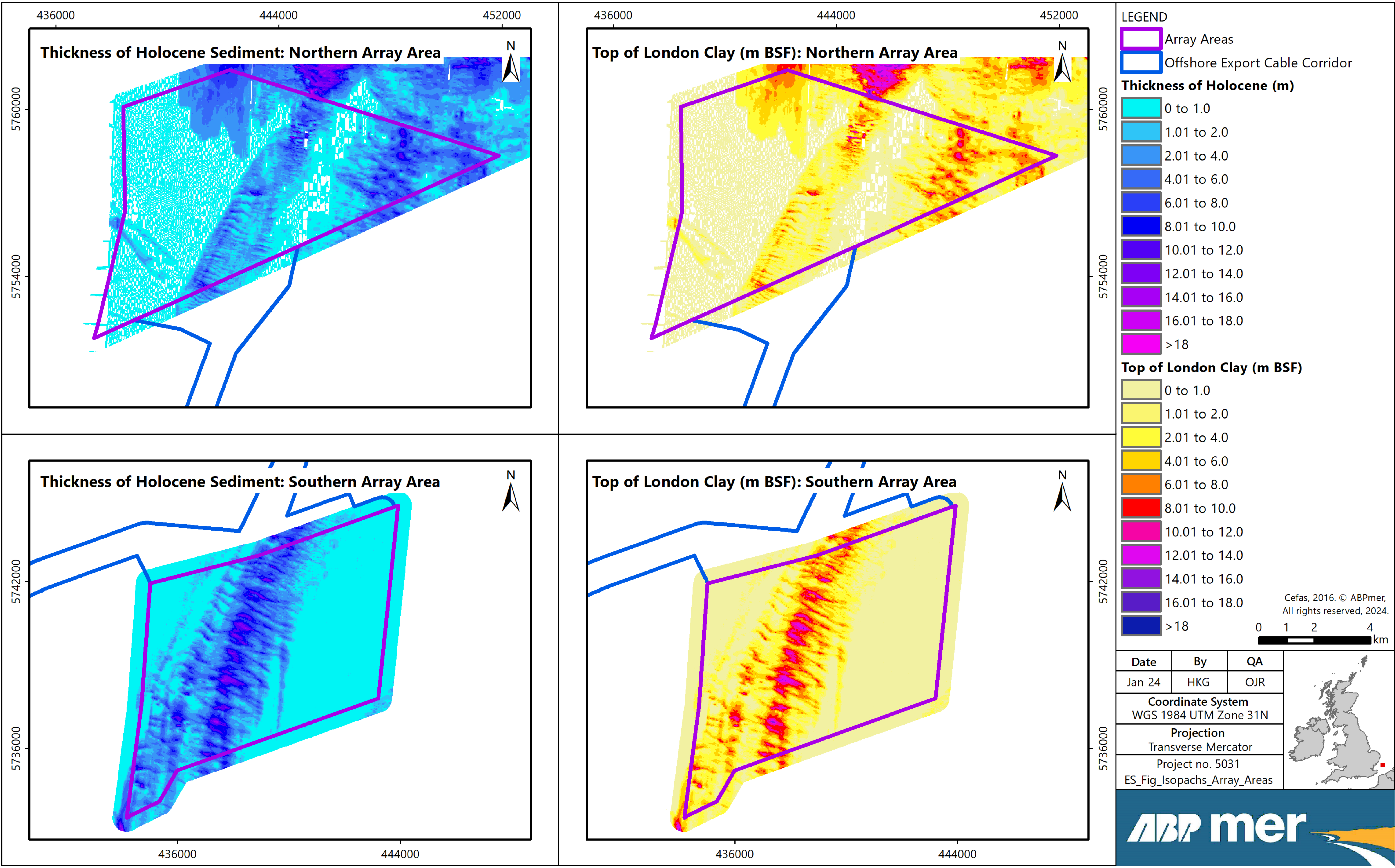
The Outer Thames Estuary lies within the Cenozoic London Basin and is underlain by Upper Cretaceous chalk. The Cretaceous (145-65 Ma), Paleogene (65-23 Ma) and Neogene (23-2.5 Ma) sequences which are present have been either eroded and exposed at seabed or covered by sediments deposited during the Quaternary period (last 2.6 million years). These Quaternary deposits and eroded, relict land surfaces have formed in response to the growth and decay of Pleistocene ice sheets and associated changes in relative sea level (MALSF, 2009). In particular, the Outer Thames Estuary has been greatly influenced by the migration of the Thames-Medway drainage system southwards, in response to changing sea levels and hydrological regimes (Bridgland, 1994).

4.2.2 Array Areas and ECC

On the basis of the sub-bottom profile data collected during the VE geophysical survey, four main units have been interpreted in the Array Areas and ECC, all deposited within the past 56 Ma. The distribution, thickness and sedimentary characteristics of these units are summarised in Table 15 and in Figure 11 and Figure 12 (Fugro, 2022a,b).

Table 15. Main stratigraphic units

Unit	Summary
Holocene	The Holocene sediments corresponded to present-day surficial sediments, commonly existing as a veneer of sediment overlying the London Clay Formation but also associated with seafloor bedforms (Fugro, 2022b). Reach a maximum thickness of 19 m below the seafloor in the northern Array Area and 16 m below the seafloor along the ECC.
Pleistocene	Pleistocene deposits have been interpreted as a variety of channel complexes of varying sizes, incising through London Clay Formation and Harwich Formation. These deposits often exist where channels and depressions within the London Clay Formation have been infilled. Pleistocene deposits of up to 7 m below the seafloor were identified in the Array Areas and >12 m below the sea floor in the ECC (Fugro, 2022a, b)
London Clay Formation	Dominated by fine-grained deep-water marine clayey silts, silty clays and clays, which produced the thick (commonly >100 m) sequences of the London Clay Formation (MALSF, 2009). Found at or close to the surface in much of the Array Areas and within 2 m of the seafloor along most of the ECC, deepening in areas where it has been incised by the Pleistocene channels or absent where eroded, exposing the Harwich formation (Fugro, 2022a,b).
Harwich Formation	Consists of sands and silts deposited in the shallow sub-littoral environment on the southern margin of the North Sea Basin (MALSF, 2009). The Harwich Member was only observed within nearshore areas (<20 km from the coast) of the ECC. The top of the unit was identified between 0 and 19.8 m below the sea floor, with sub-crop or outcrop also interpreted (Fugro, 2022b).


Thickness of Holocene Sediment: Northern Array Area
Top of London Clay (m BSF): Northern Array Area
Thickness of Holocene Sediment: Southern Array Area
Top of London Clay (m BSF): Southern Array Area
436000
444000
452000
5760000
5754000
5742000
5736000
N
LEGEND
Array Areas
Offshore Export Cable Corridor
Thickness of Holocene (m)
0 to 1.0
1.01 to 2.0
2.01 to 4.0
4.01 to 6.0
6.01 to 8.0
8.01 to 10.0
10.01 to 12.0
12.01 to 14.0
14.01 to 16.0
16.01 to 18.0
>18
Top of London Clay (m BSF)
0 to 1.0
1.01 to 2.0
2.01 to 4.0
4.01 to 6.0
6.01 to 8.0
8.01 to 10.0
10.01 to 12.0
12.01 to 14.0
14.01 to 16.0
16.01 to 18.0
>18
Cefas, 2016. © ABPmer, All rights reserved, 2024.
0 1 2 4 km
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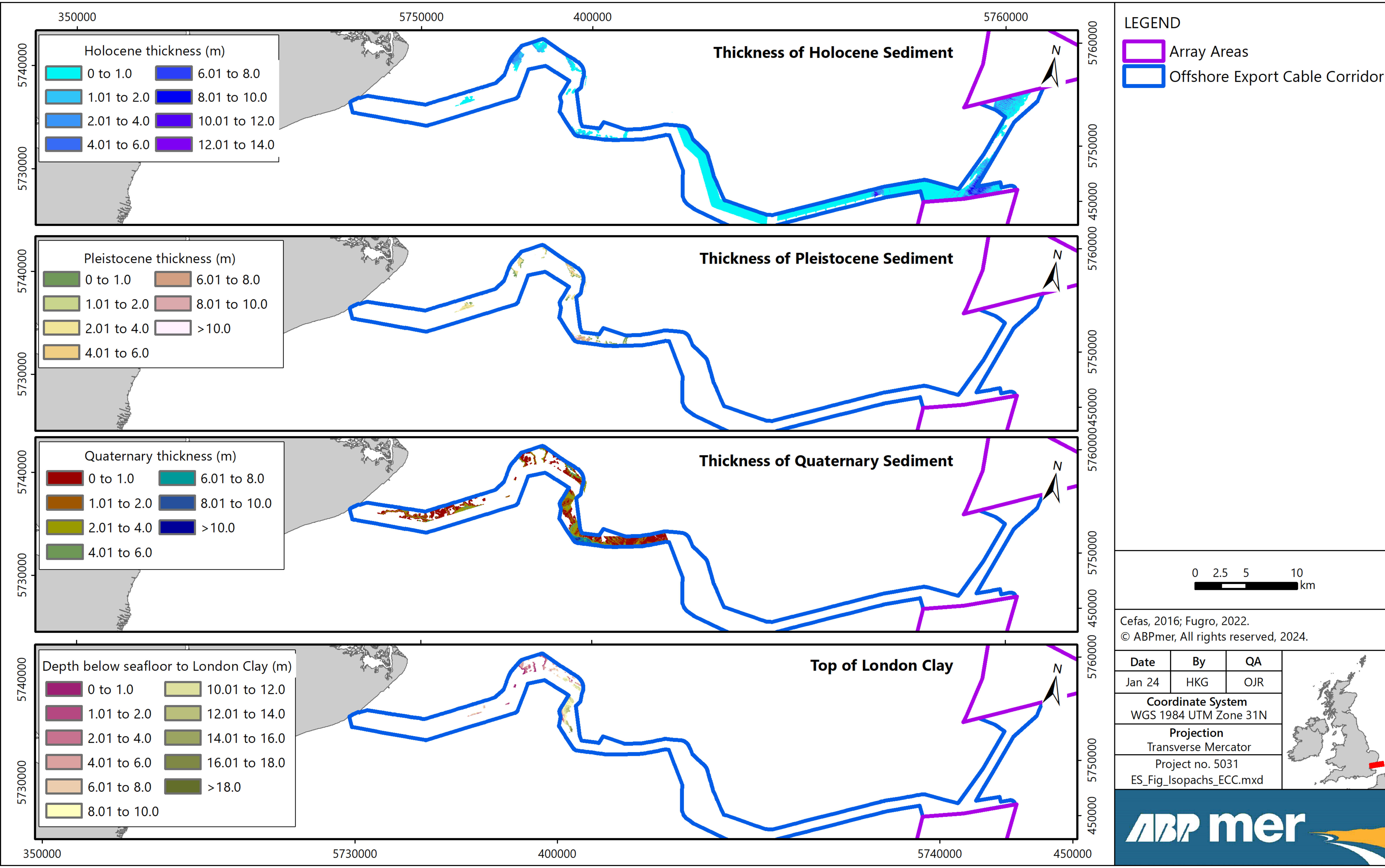

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Coordinate System
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Projection
Transverse Mercator

Project no. 5031
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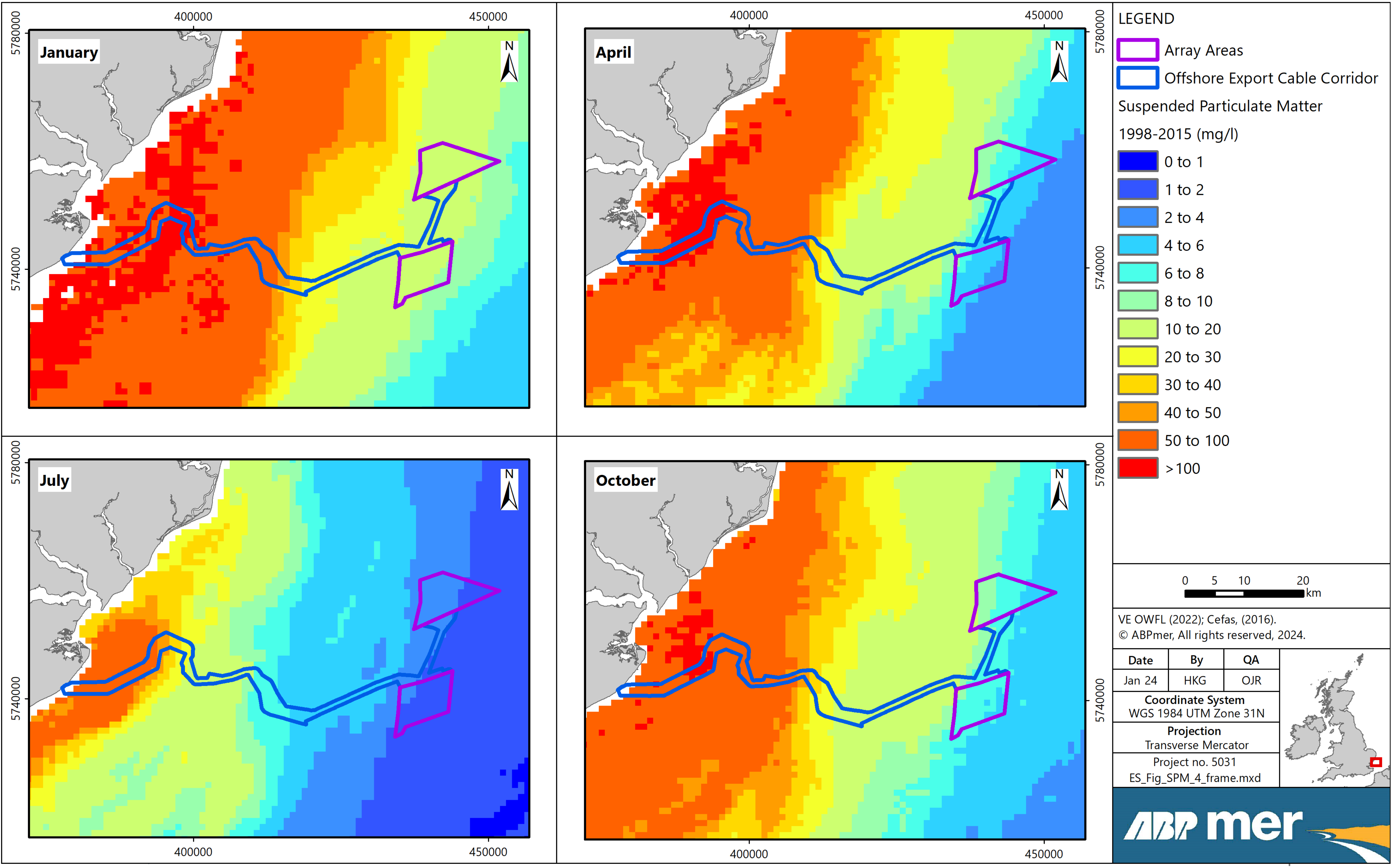
4.3 Suspended sediments

Satellite derived information on seasonal suspended particulate matter (SPM) concentrations in surface waters across the study area is also available from Cefas (2016) and shown in Figure 13.

Within the array areas, summer (surface) SPM is approximately 1 to 3 mg/l in the array areas, increasing during winter months to values of approximately 10-20 mg/l. Higher values are anticipated during spring tides and storm conditions, with the greatest concentrations encountered close to the seabed. Within the offshore ECC, values are much higher, reaching a peak close to the coast at the landfall. During winter months, mean values exceed 100 mg/l although, as for the array areas, higher values are anticipated during spring tides and storm conditions, with the greatest concentrations encountered close to the seabed.

An important component of the suspended sediment regime in this region is the 'English River' (or East Anglia Plume), an advective current along the interface between the seasonally stratified water to the north and the well-mixed water to the south that flows intermittently north-eastwards from the outer Thames area towards the island of Texel in the Netherlands. This current is fed by suspended sediments largely derived from eroding areas of cliff line along the English east coast (Dyer & Moffatt, 1998; SNSSTS, 2002). Less is known about the main sink areas for this fine sediment, although high concentrations of mud are found in the surface sediments along the 40 m depth contour in Dutch waters and in the German Bight. In these locations it is thought that the bed shear stresses fall below a critical threshold during part of the tidal cycle, enabling the deposition of mud (Pietrzak et al., 2011). The 'English River' therefore represents a key regional sediment transport pathway delivering fine grained material to the east.

The plume varies in intensity and length and depends strongly on the local current and wave fields (Pleskatchevski et al., 2002). Indeed, both observational data and numerical modelling suggest that this cycle of deposition and erosion is strongly seasonal with the majority of the supply of fine particles occurring in the winter and with deposition mainly during summer months (Odd & Murphy, 1992). Numerical modelling of suspended matter transport in this region also suggests that vertical mixing due to waves is the dominant process to erode the resuspended particulate matter bottom deposits and to bring the material to the sea surface (Pleskatchevski et al., 2002).


January
April
July
October
400000
450000
5780000
5740000
N
LEGEND
Array Areas
Offshore Export Cable Corridor
Suspended Particulate Matter
1998-2015 (mg/l)
0 to 1
1 to 2
2 to 4
4 to 6
6 to 8
8 to 10
10 to 20
20 to 30
30 to 40
40 to 50
50 to 100
>100
0 5 10 20
km
VE OWFL (2022); Cefas, (2016).
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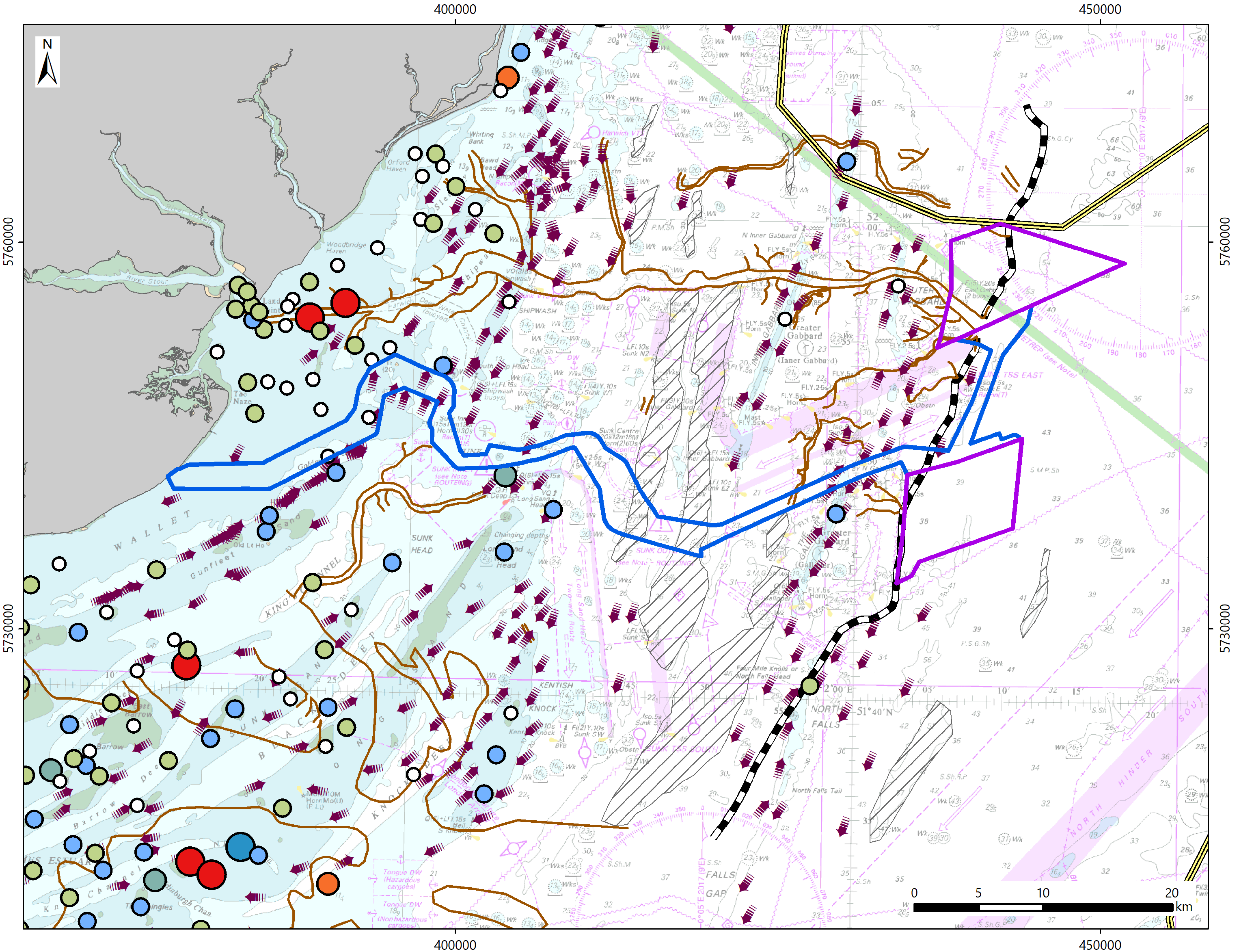
4.4 Sediment transport

4.4.1 Overview

Across the study area, tidal currents, together with the agitation of the seabed by wave action, are sufficiently high to induce shear stresses, which exceed the critical shear stress for initiating the movement of sand on the seabed. Bedload transport is controlled by peak currents, which are described by Sager and Sammler (1975) and Kenyon and Cooper (2005) and are shown to be relatively high across the Array Areas and most of the ECC, albeit decreasing within inshore areas close to the coast (Figure 4).

The regional-scale patterns of sediment transport are illustrated in Figure 14, collated from a number of regional studies (Defra, 2009; SNSSTS, 2002; TEDA, 2012; MALSF, 2009). In general, the transport of sand-sized sediment across the Southern North Sea is mainly in the form of bedload (sediment sliding or rolling along the seabed due to the action of currents and waves). Finer material is mainly transported in suspension, with relatively higher loads entrained in the outflow from coastal rivers and estuaries.

Offshore, the direction of net sediment transport is predominantly from north to south, mainly as the result of tidal asymmetry (currents are relatively stronger and/or more prolonged on the southerly flowing tide). More locally, as a result of flow-obstacle interaction, the net transport of sediment around the major offshore sandbanks is in a clockwise direction, i.e. with south to north movement of material and migration of bedforms along the western margin of the bank and north to south along the eastern edge. In shallower water nearshore, net sediment transport rates and directions are more locally variable, driven by a combination of tidal currents and the relative angle of wave approach. In many areas of the lag deposits, no bedforms are visible, implying insignificant transport of sandy sediment occurs under the current-scouring hydrodynamic regime (MALSF, 2009).



LEGEND

- Array Areas
- Offshore Export Cable Corridor
- Bedload Parting Zone

SNSSTS, 2002

- Net Bedload Transport

MALSF, 2009:

- Interpreted Channel Systems
- Plateau Margin
- Enclosed Deeps

Historic Trend in Seabed Elevation (m/yr) (Burningham & French, 2009)

- -0.005 to 0.005
- -0.05 to -0.005
- -0.1 to -0.05
- -0.3 to -0.1
- 0.005 to 0.05
- 0.05 to 0.1
- 0.1 to 0.3

VE OWFL (2022); Fugro (2022).

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Coordinate System
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Projection
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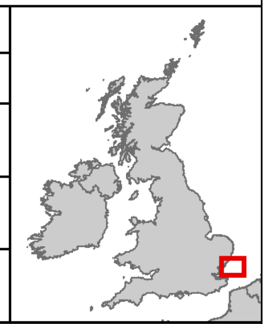


4.4.2 Array Areas and ECC

An analysis of potential sediment mobility within the Array Areas and ECC in response to tidal currents is presented in Figure 15, Figure 16 and Figure 17.

This is based on a spring-neap cycle (~16 days) of current data extracted from the hydrodynamic model developed to inform the assessment (Volume 6, Part 5, Annex 2.2: Physical Processes Model Design and Validation). Key findings are summarised below:

- Where present, sand is expected to be highly mobile in both the Array Areas and along the ECC. This is particularly the case on and around the active bank systems and throughout much of the nearshore area;
- Rates of sediment transport are expected to generally be higher in the Southern Array Area in comparison to the Northern Array Area, consistent with increased distance from the bedload parting zone to the north of the Array Areas;
- At the regional scale, sediment transport is broadly in a southerly direction although superimposed on this are highly complex localised patterns of sediment circulation around banks and other topographic features;
- The modelled directions of sand transport show good overall correlation with the morphological evidence of sediment transport, based on the asymmetry of sandwaves (Figure 17). The model also captures the clockwise circulation of sediment transport which is known to occur around the major bank systems in the study area (Kenyon & Cooper, 2005));
- The only notable difference between the modelled and observed patterns of sediment transport is found within the inshore area, close to the coast (*circa* < 5km). Here, the model suggests sand is being transported from southwest to northeast whereas the (sparse) morphological evidence suggests transport is occurring in the opposite direction (e.g. SNSSTS, 2002; Kenyon & Cooper, 2005). However, it is noted that in this area, bedrock is generally found close to the surface and the morphological evidence for sediment transport is limited. Accordingly, the observational evidence underpinning the inferred direction of net sediment transport isn't as robust as for locations slightly further offshore in the study area.

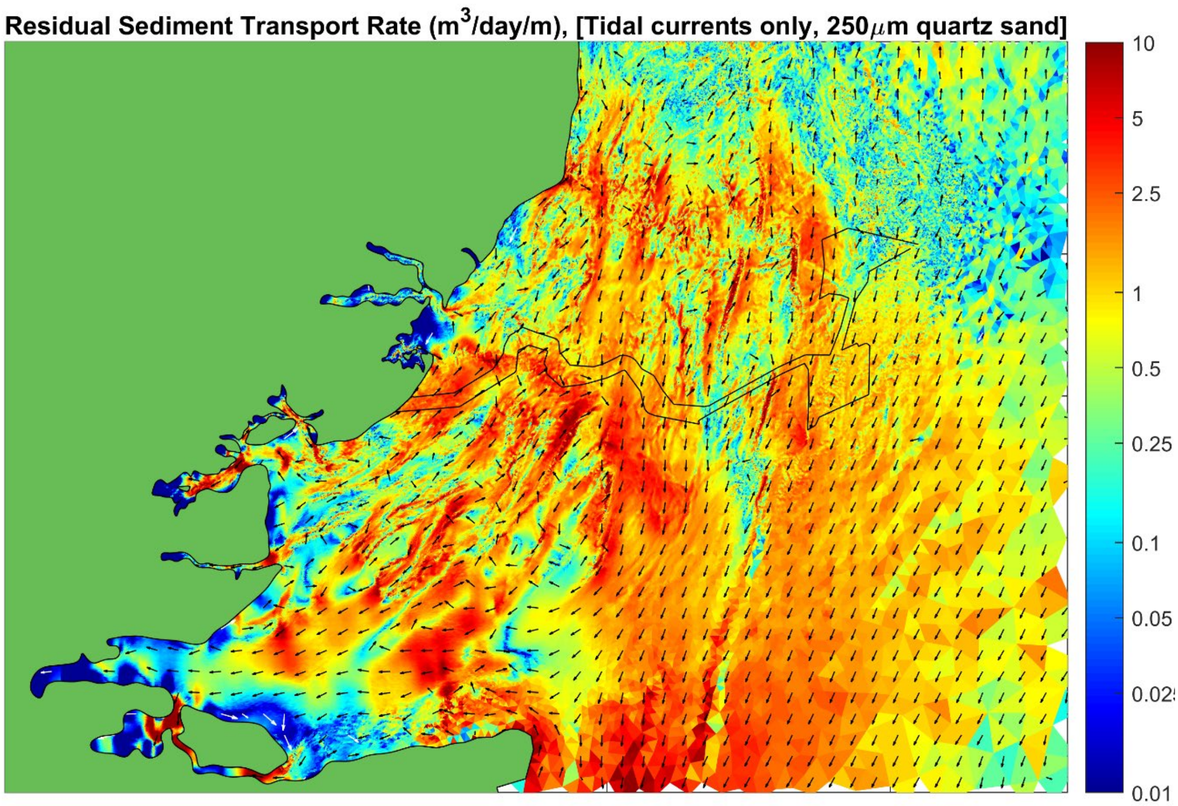


Figure 15. **Baseline residual sediment transport rate and direction across the wider study area, measured over a representative spring-neap tidal period**

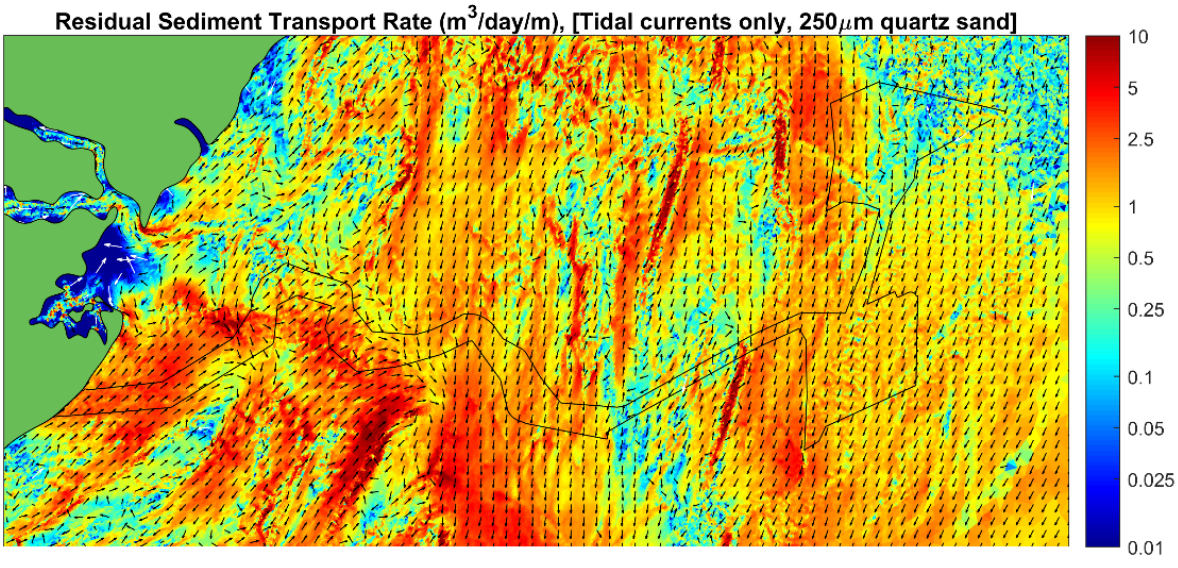
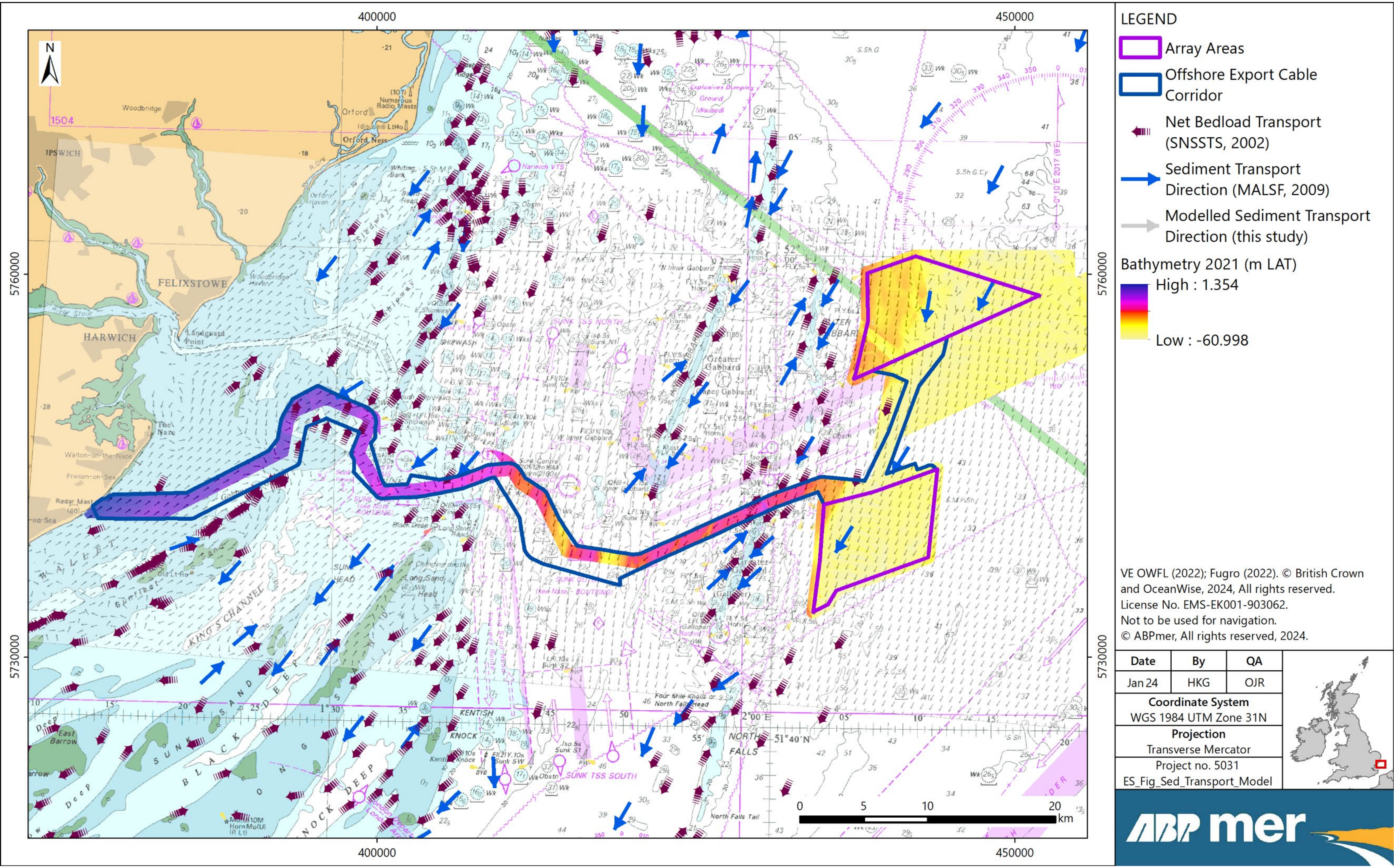


Figure 16. **Baseline residual sediment transport rate and direction within the Array Areas and along the ECC, measured over a representative spring-neap tidal period**


LEGEND
Array Areas
Offshore Export Cable Corridor
Net Bedload Transport (SNSSTS, 2002)
Sediment Transport Direction (MALSF, 2009)
Modelled Sediment Transport Direction (this study)
Bathymetry 2021 (m LAT)
High : 1.354
Low : -60.998
VE OWFL (2022); Fugro (2022). © British Crown and OceanWise, 2024, All rights reserved. License No. EMS-EK001-903062.
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ES_Fig_Sed_Transport_Model
400000
450000
5760000
5730000
0 5 10 20 km
N
FELIXSTOWE
HARWICH
IPSWICH
Woodbridge
Orford
Orford Ness
The Naze
Walton-on-the-Naze
Frinton-on-Sea
KING'S CHANNEL
SUNK HEAD
KENTISH KNOCK
NORTH FALLS
Greater Gabbard
SUNK TSS SOUTH
SUNK TSS NORTH
SHIPWASH
BLACK DEEP
SUNK SAND
KNOCK DEEP

4.5 Morphology

4.5.1 Overview

The regional-scale morphology of the study area has previously been described in detail within MALSF (2009). Three broad areas can be identified (Figure 18):

- Western Zone;
- Central Zone; and
- Eastern Zone.

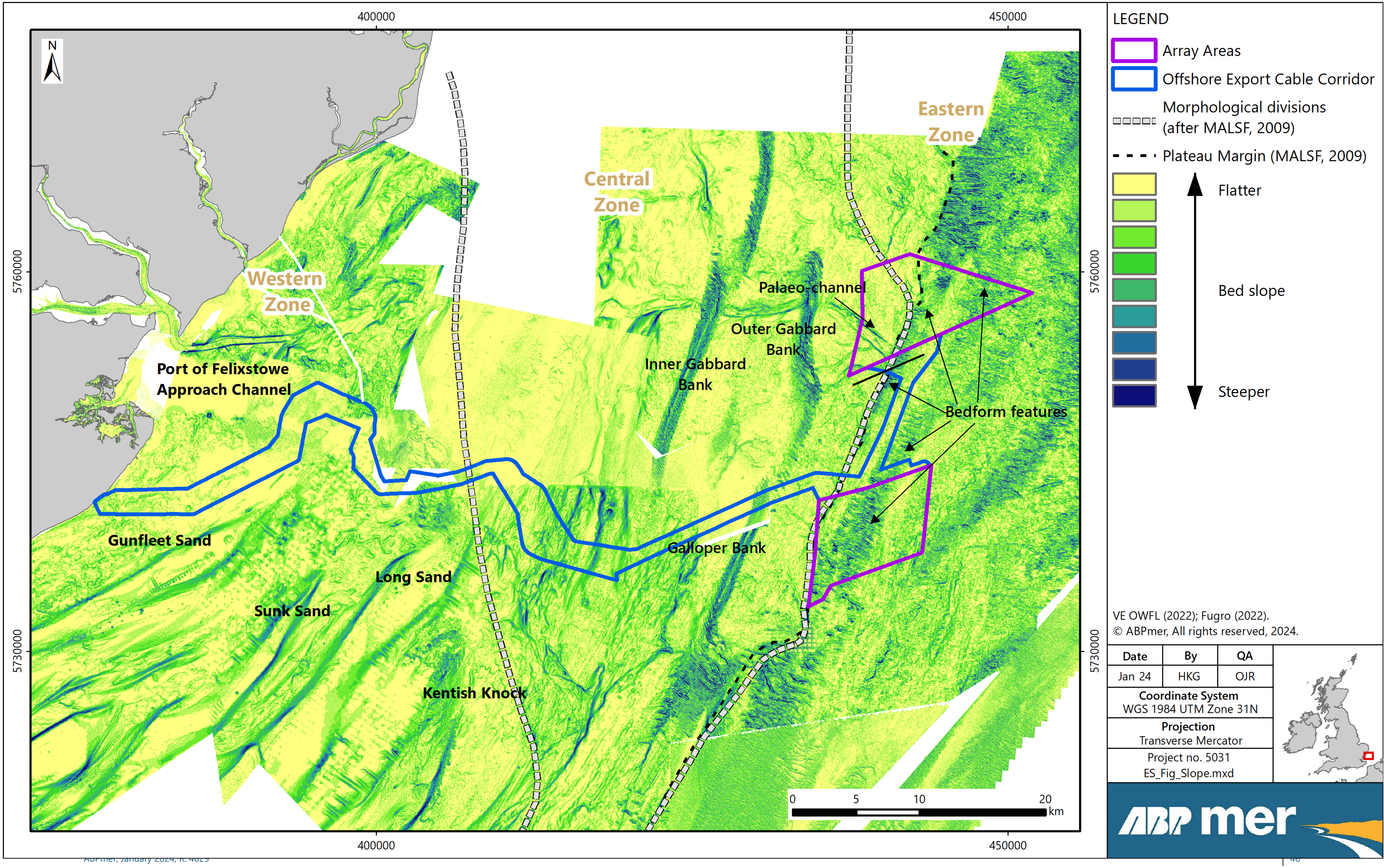
The **Western Zone** is dominated by a series of coast-parallel, regularly spaced, NE-SW trending sandbanks and associated channels and troughs. The sandbanks, for example, Long Sand and Sunk Sand located just to the south of the ECC - are 1 to 5 km across, 10 to 30 km long and the crests are typically exposed at low water. The crests of the large sandbanks do not show evidence of superimposed bedforms, however, bedforms of various sizes are commonly present on the flanks. On the flanks of the sandbanks the crests of the dunes are typically oriented NW-SE, indicative of south-westerly (on the east flank) and north-easterly (on the west flank) sediment transport directions. Bedforms are often absent in the troughs and interbank areas, although megaripples and occasional sand streaks are present in the vicinity of the sandbanks, orientated parallel to the bank margins (MALSF, 2009).

The **Central Zone** is characterised by a flat, relatively rough seabed platform with isolated troughs and sandbanks. The bedforms are commonly small-scale and generally consist of megaripples, sand streaks, sand ribbons, and sand patches. At the offshore limit of the central zone, water depths reach around 40 mLAT, but across the majority of the zone, depths lie around 20 to 30 mLAT. The sandbanks in the Central Zone include the Inner Gabbard, Greater Gabbard and The Galloper – located just to the west of the Array Areas. The sandbanks trend NNE to SSW, are approximately 10 km long, 1 to 2 km wide and their crests lie at depths of 5 to 10 mLAT. These banks are typically asymmetrical (steeper slopes facing west) and subparallel to the dominant tidal flow direction, offset in an anticlockwise orientation (Kenyon *et al*., 1981). There is no evidence for any (underlying) geological control in the location of the banks.

The banks in this zone are classified as open-shelf ridges (Dyer and Huntley, 1999). Bathymetric comparisons over 400 years by Burningham and French (2008) suggest that the ridges have experienced no significant erosional or depositional change over the last 200 to 300 years since they were first charted.

The flat seabed is disrupted by two 2 km wide, 20 km long, parallel troughs trending north to south immediately west of the Inner Gabbard and just to the north of the ECC. They are separated by a 1 km wide ridge which is level with the adjacent seafloor. These troughs are named the Inner Gabbard Deeps, with the bases of the troughs eroded into bedrock and lying 20 to 30 m below the adjacent seabed, reaching depths of ~60 m LAT. Enclosed deeps (or over-deepened valleys) such as these are found throughout the North Sea Basin and adjacent glaciated land masses and have been the subject of much discussion in the literature. The favoured theories for development of the Inner Gabbard Deeps are either formation under steady-state sub-glacial drainage of meltwater and groundwater driven by hydrostatic pressure gradients within a few kilometres of the ice front, or catastrophic ice proximal meltwater discharge (termed jökulhlaups).

At least two east-west trending unfilled channels around 1 km wide extend across the zone, including channels emanating from the mouth of the Rivers Stour and Orwell which are traceable across the zone and into the Northern Array Area.


400000
450000
5760000
5730000
N
Western Zone
Central Zone
Eastern Zone
Port of Felixstowe Approach Channel
Palaeo-channel
Outer Gabbard Bank
Inner Gabbard Bank
Bedform features
Gunfleet Sand
Galloper Bank
Long Sand
Sunk Sand
Kentish Knock
0 5 10 20 km
LEGEND
Array Areas
Offshore Export Cable Corridor
Morphological divisions (after MALSF, 2009)
Plateau Margin (MALSF, 2009)
Flatter
Bed slope
Steeper
VE OWFL (2022); Fugro (2022).
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The bases of the unfilled channels lie up to 10 m below the adjacent seabed and are palaeo river valleys which are thought to have formed *circa* 720 ka BP (MALSF, 2009). Where the River Stour palaeo-channel meets the Northern Array Area, it is around 7 m deeper than the adjacent seabed and approximately 1.2 km in width (Fugro, 2022a).

The **Eastern Zone** (in which the majority of the Array Areas are located) is flat and generally lies at depths of approximately 40 m to 55 mLAT. The zone is devoid of sandbanks and is dominated by a series of NW to SE trending sandwaves with wavelengths >100 m and amplitudes of up to 15 m. The sandwaves decline in size to the south. All of the sandwaves in the zone are interpreted as being mobile, particularly due to their sharp and distinct crests. (This is investigated further in Section 4.5.2.) The Eastern Zone is sediment rich when compared to the adjacent Central Zone, a result of significant sediment supply from the north and from localised erosion of the underlying Plio-Pleistocene Crag deposits (BGS, 1988).

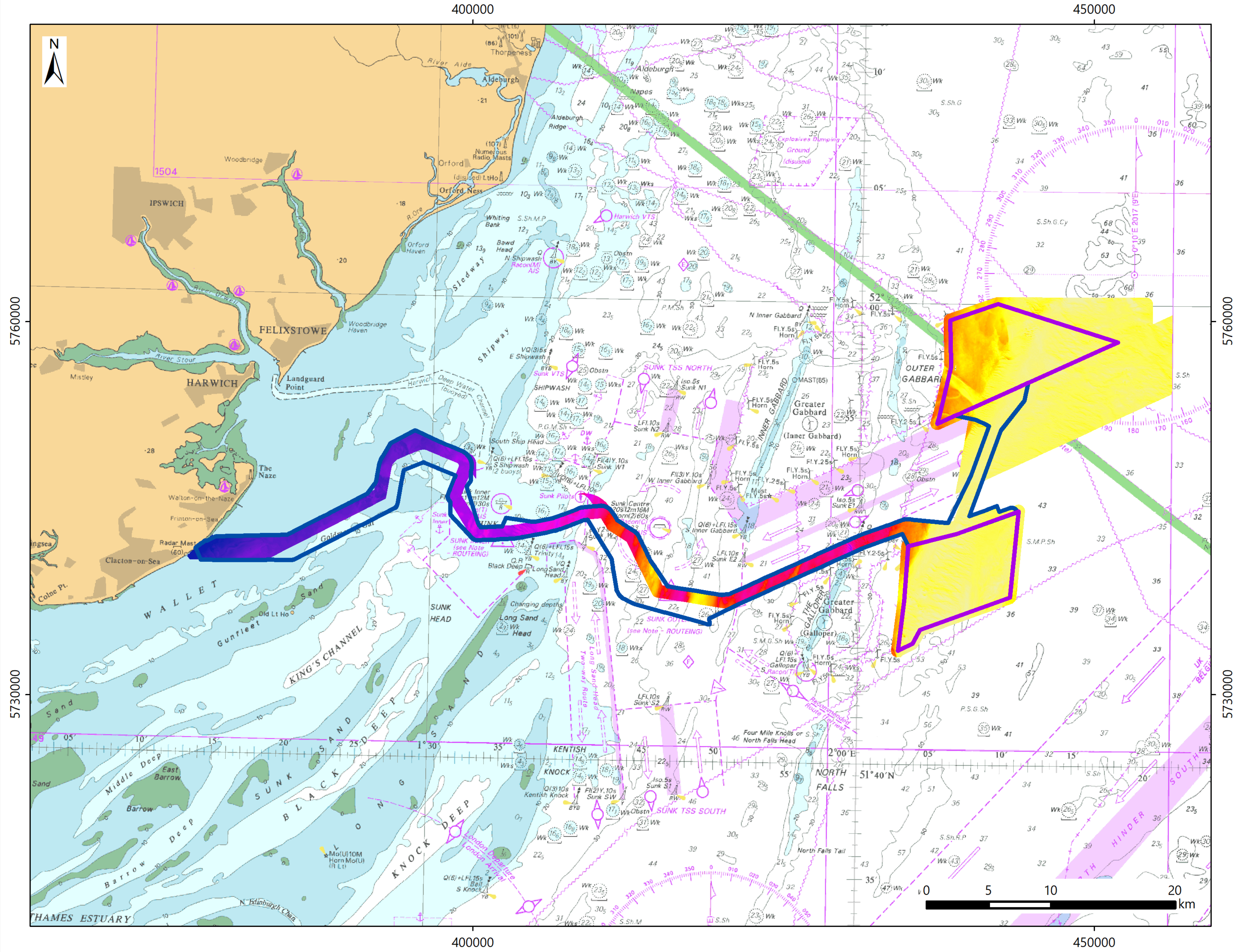
The zone is bounded to the west by an abrupt step-margin adjacent to the central zone platform, which is orientated approximately NNE to SSW, bisecting the Northern Array Area. The trough in which the Array Areas are situated is the Lobourg Channel, a relict channel feature which is thought to have drained into the southern North Sea at times of lower sea level during Pleistocene glacial episodes. However, an alternative interpretation is that the abrupt step-margin could represent a remnant lake margin associated with the ice-damming that is believed to have occurred at each glacial maximum, the catastrophic breaching of which could have been the process by which the English Channel River system developed.

4.5.2 Array Areas

Consideration of the project specific geophysical survey data shows that water depths within the Northern Array Area range between 25 m and 55 m below LAT (Fugro 2022a) (Figure 19). Depths are greatest in the north and north-east of the site and are associated with the troughs of bedforms. Depths shallow abruptly in the west, in relation to the plateau margin discussed in Section 4.5.1, with the seafloor being relatively flat and featureless on the plateau, with limited sediment cover. Sandwaves with superimposed megaripples are visible in the centre of the Northern Array Area (Figure 20). The largest sand waves measured approximately 12 m in height with wavelengths of approximately 300 m (Figure 21) (Fugro, 2022a).

Water depths within the Southern Array Area range between 22 m and 60 m below LAT (Fugro 2022a) (Figure 19). Depths are greatest in the south, within a trough of a bedform. As in the Northern Array area, depths shallow abruptly in the west. Sandwaves with superimposed megaripples, are visible in the east and centre of the Southern Array Area (Figure 20 and Figure 22). The largest sand waves measured approximately 12 m in height and exhibited wavelengths of approximately 250 m (Fugro, 2022a).

During survey operations it was observed that the megaripples and sand waves were actively mobile and were migrating in the time between adjacent survey lines (Fugro, 2022a). This assertion is supported by a comparison between the 2021 project specific bathymetric data and the earlier (2009) multibeam bathymetric survey data collected for Galloper OWF, where the two surveys overlap in the Southern Array Area (Figure 22 and Figure 23). This analysis suggests that these sandwaves are migrating in a southerly direction but at a rate of only around 1 m/yr. This observation is consistent with the findings of regional scale sediment transport studies in this region (e.g. SNSSTS, 2002; Kenyon & Cooper, 2005). Overlapping multibeam survey data is not available for the region of large sandwaves mapped in the Northern Array Area. However, single beam data is available from the UKHO (1987 and 1995). A comparison between this data and the recent project specific (2021) survey data does suggest these sandwaves are mobile although the overall modest amount of vertical change between the surveys would suggest that rates of bedform migration are indeed low (Figure 24).



LEGEND

Array Areas

Offshore Export Cable Corridor

Bathymetry 2021 (m LAT)

High : 1.354

Low : -60.998

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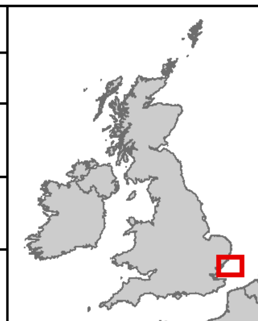

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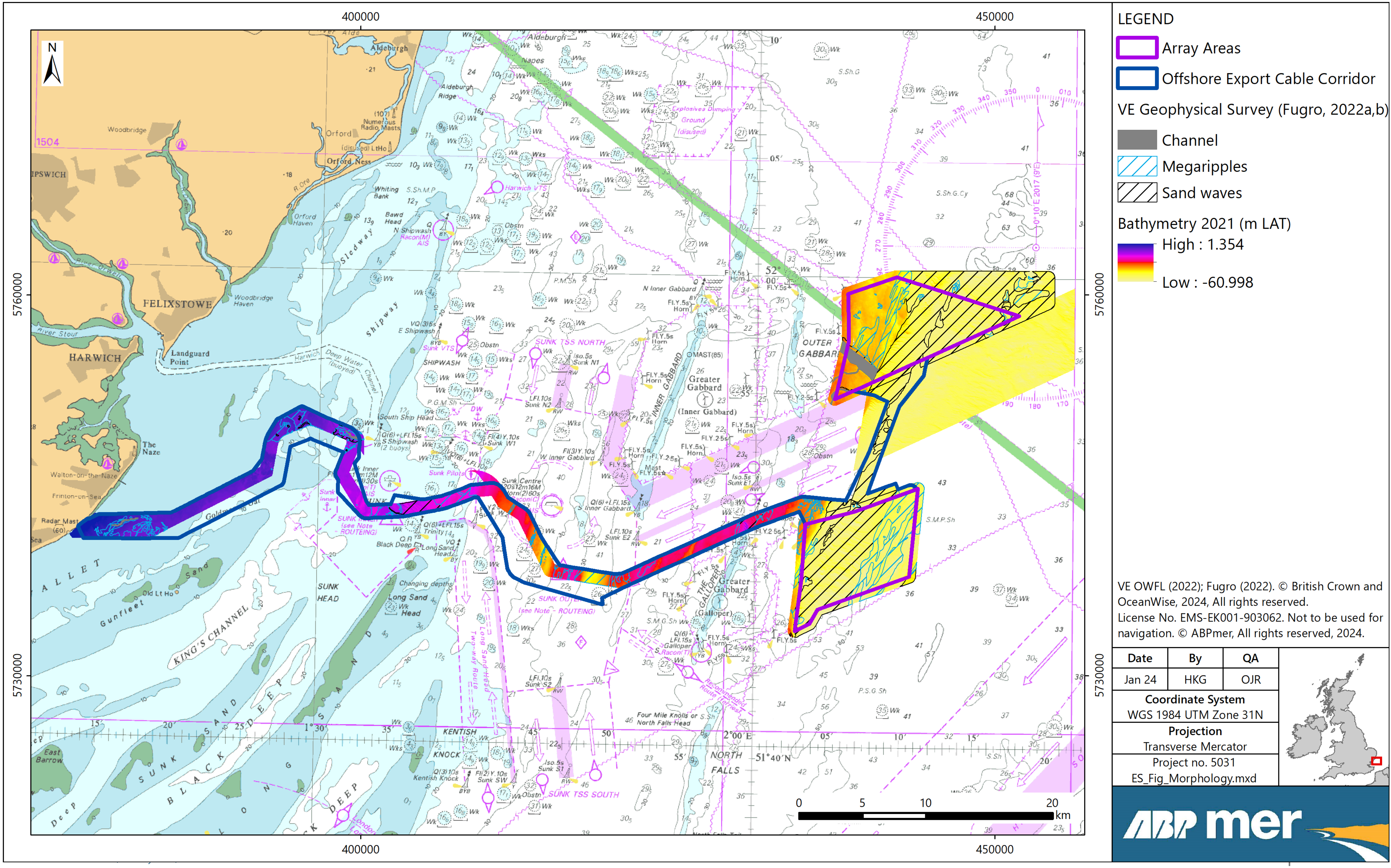
400000
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LEGEND
Array Areas
Offshore Export Cable Corridor
VE Geophysical Survey (Fugro, 2022a,b)
Channel
Megaripples
Sand waves
Bathymetry 2021 (m LAT)
High : 1.354
Low : -60.998
0
5
10
20
km
FELIXSTOWE
HARWICH
IPSWICH
The Naze
Walton-on-the-Naze
Frinton-on-Sea
Aldeburgh
Orford Ness
OUTER GABBARD
Greater Gabbard
(Inner Gabbard)
SUNK TSS NORTH
SUNK TSS SOUTH
SUNK HEAD
KING'S CHANNEL
KENTISH KNOCK
NORTH FALLS
THE GALLOPER
Long Sand Head
SHIPWASH
Harwich VTS
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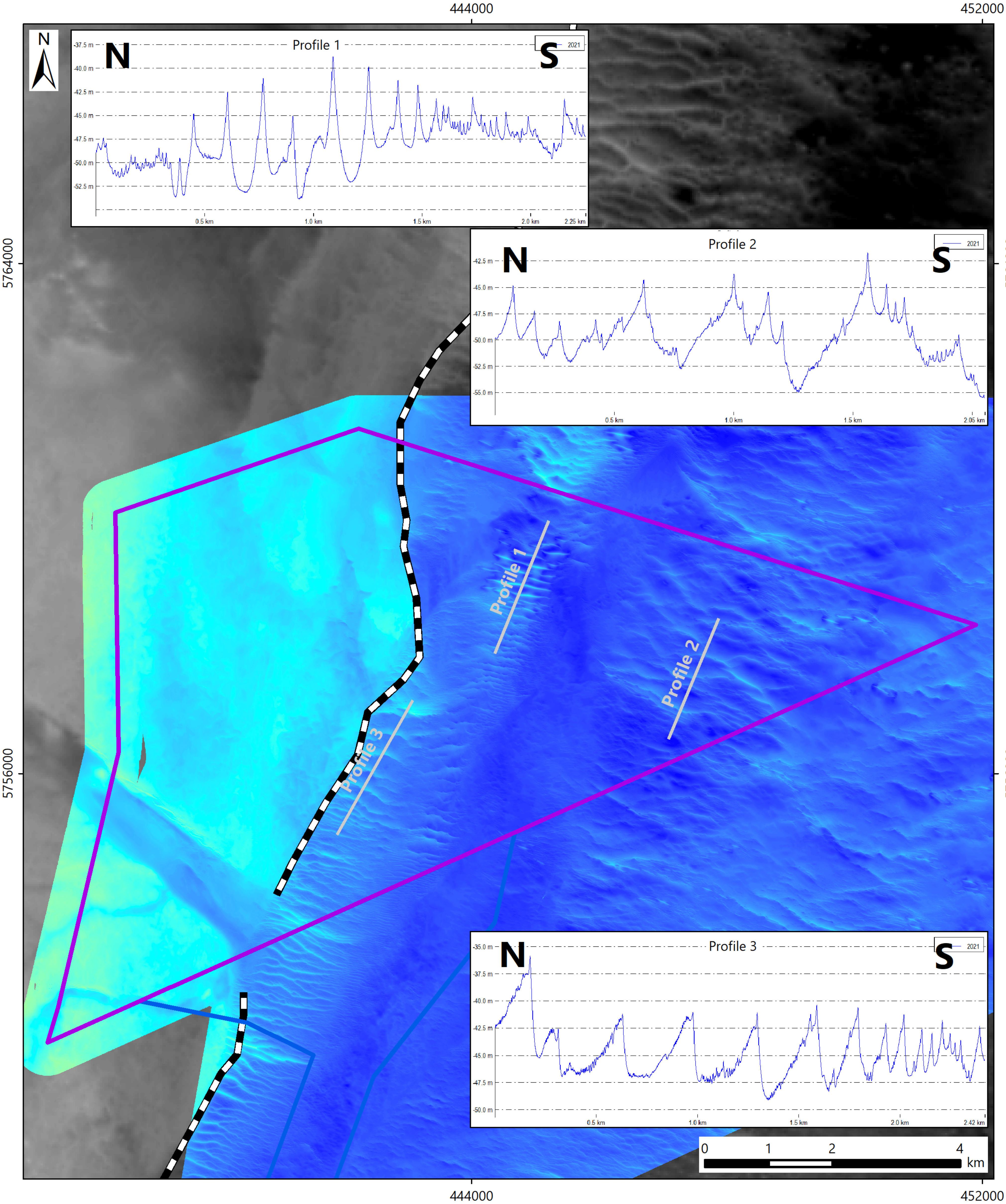

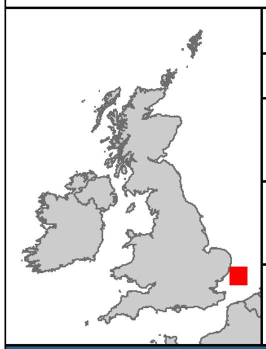

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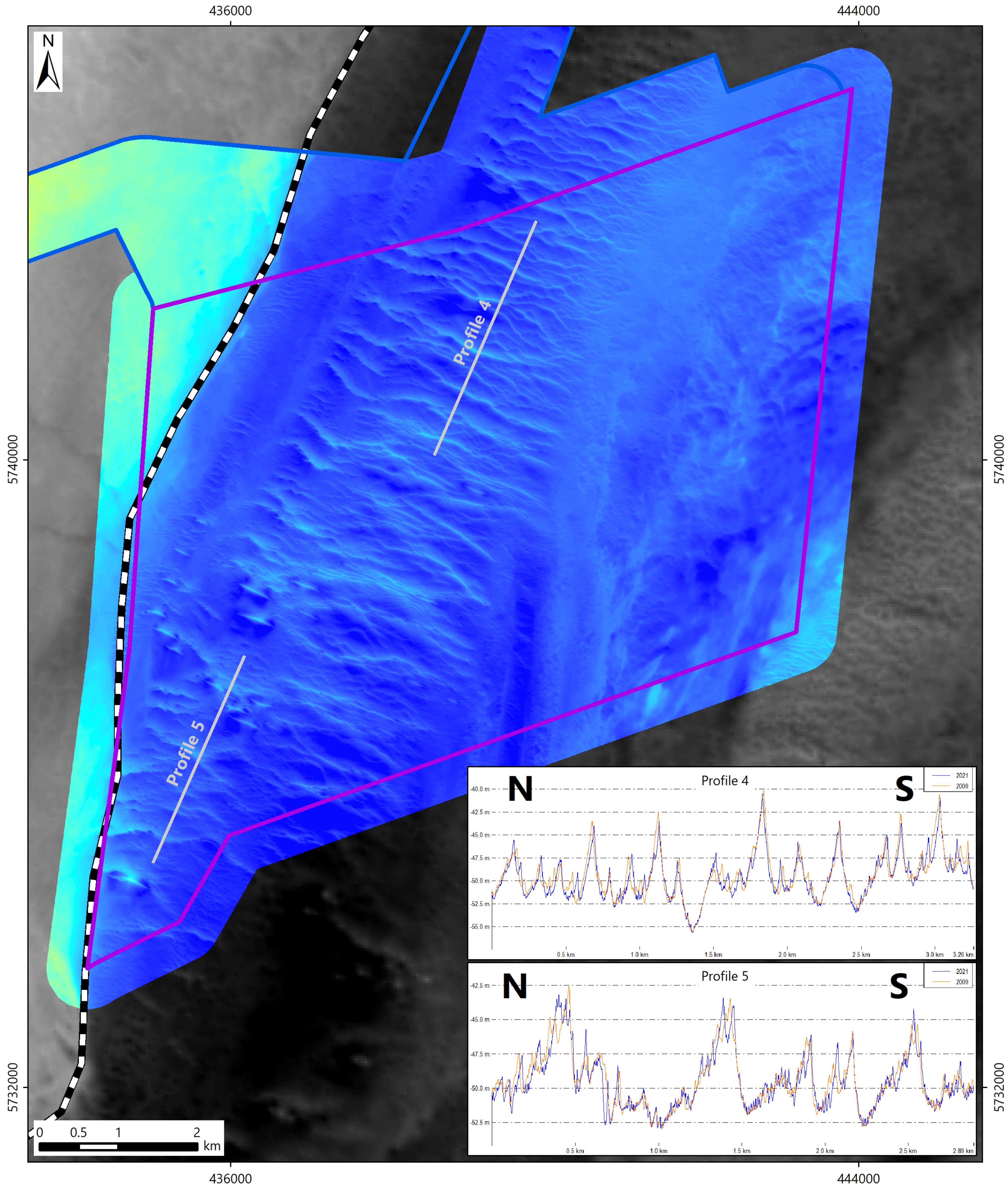
LEGEND

- Array Areas
- Offshore Export Cable Corridor
- Sandwave Transect
- Plateau Margin (MALSF, 2009)

Bathymetry 2021 (m LAT)
High : 1.354
Low : -60.998



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Coordinate System
WGS 1984 UTM Zone 31N

Projection
Transverse Mercator

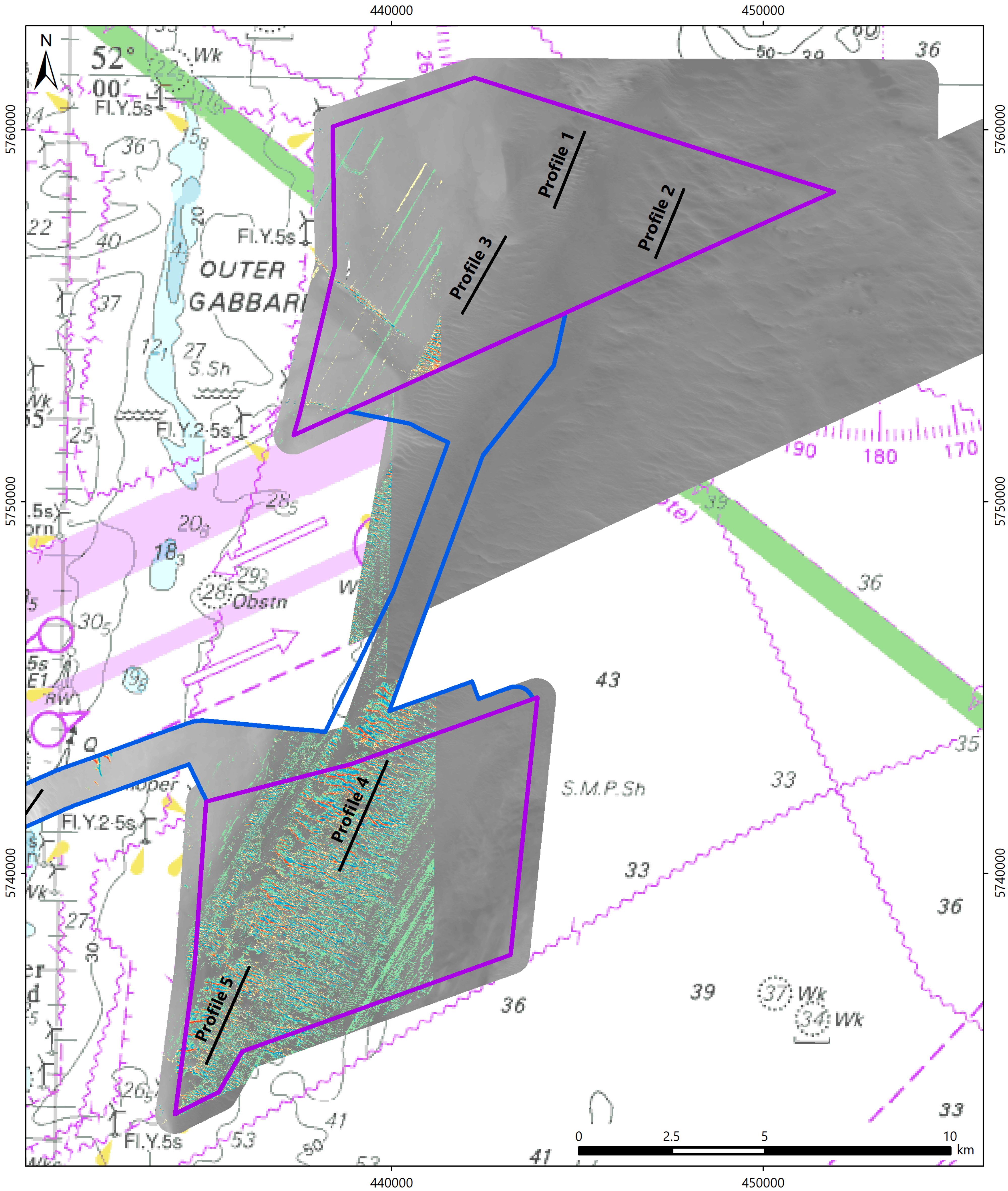
Project no. 5031
ES_Fig_Southern_Array_Area_Profile

LEGEND

- Array Areas
- Offshore Export Cable Corridor
- Sandwave Transect
- Plateau Margin (MALSF, 2009)

Bathymetry 2021 (m LAT)
High : 1.354
Low : -60.998

ABP mer



Date	By	QA
Jan 24	HKG	OJR

Coordinate System
WGS 1984 UTM Zone 31N

Projection
Transverse Mercator

Project no. 5031
ES_Fig_Array_Areas_Difference

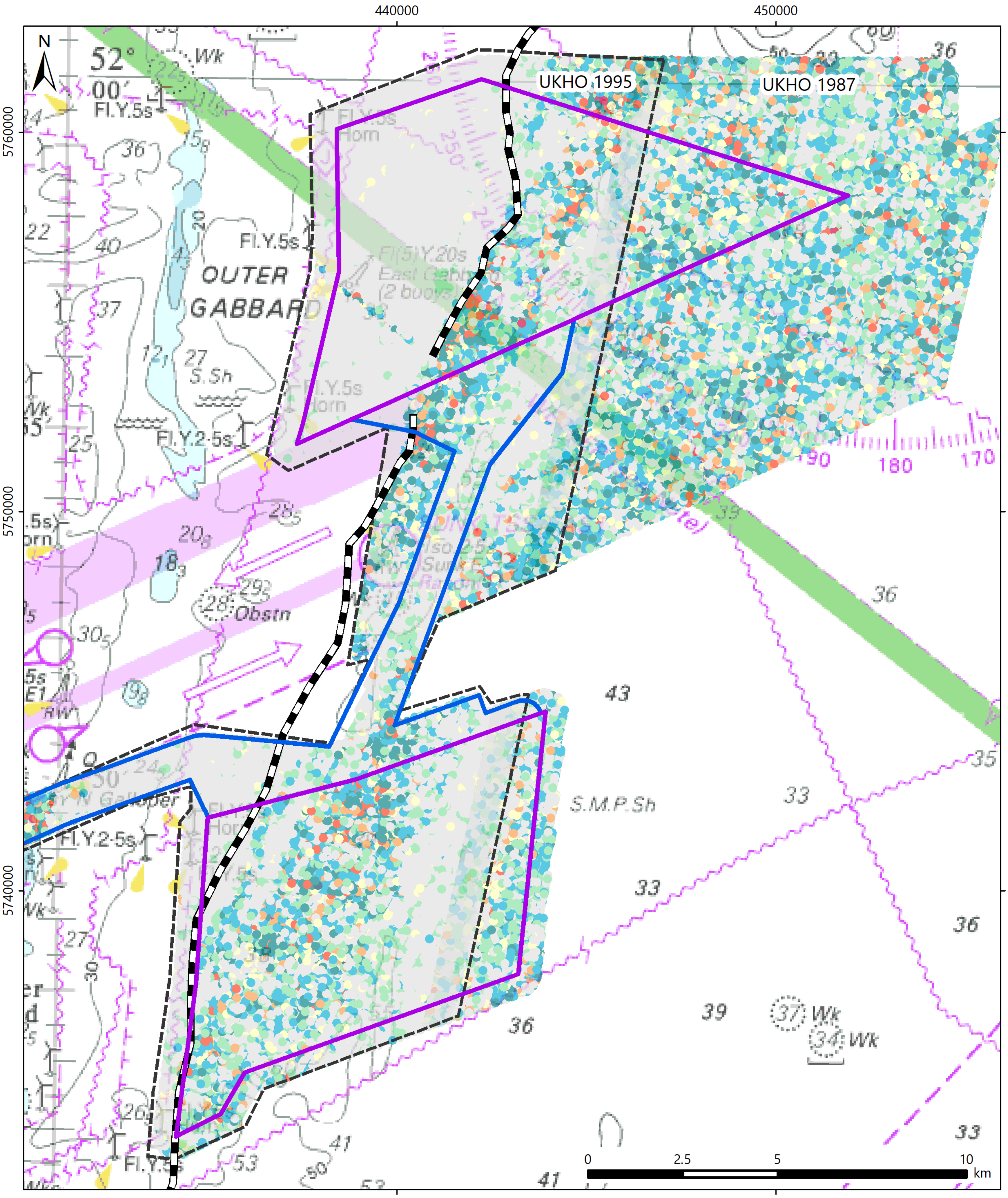
LEGEND

- Array Areas
- Offshore Export Cable Corridor
- Sandwave Transect

Bathymetry 2021 (m LAT)
1.354
-60.998

Difference (m) 2021-2009

- < - 6.00
- -5.99 to -2.00
- -1.99 to -1.00
- -0.99 to -0.50
- -0.49 to 0.50
- 0.51 to 1.00
- 1.01 to 2.00
- 2.01 to 6.00
- > 6.00



Date	By	QA
Jan 24	HKG	OJR

Coordinate System
WGS 1984 UTM Zone 31N

Projection
Transverse Mercator

Project no. 5031
ES_Fig_Array_Areas_UKHO

ABP mer

LEGEND

- Array Areas
- Offshore Export Cable Corridor
- Plateau Margin (MALSF, 2009)
- UKHO 1995 Bathymetry Data

Difference (m)

- < - 6.00
- -5.99 to -2.00
- -1.99 to -1.00
- -0.99 to -0.50
- -0.49 to 0.50
- 0.51 to 1.00
- 1.01 to 2.00
- 2.01 to 6.00
- > 6.00

Bathymetry difference data shown for 2021-1995 and 2021-1987.

4.5.3 ECC

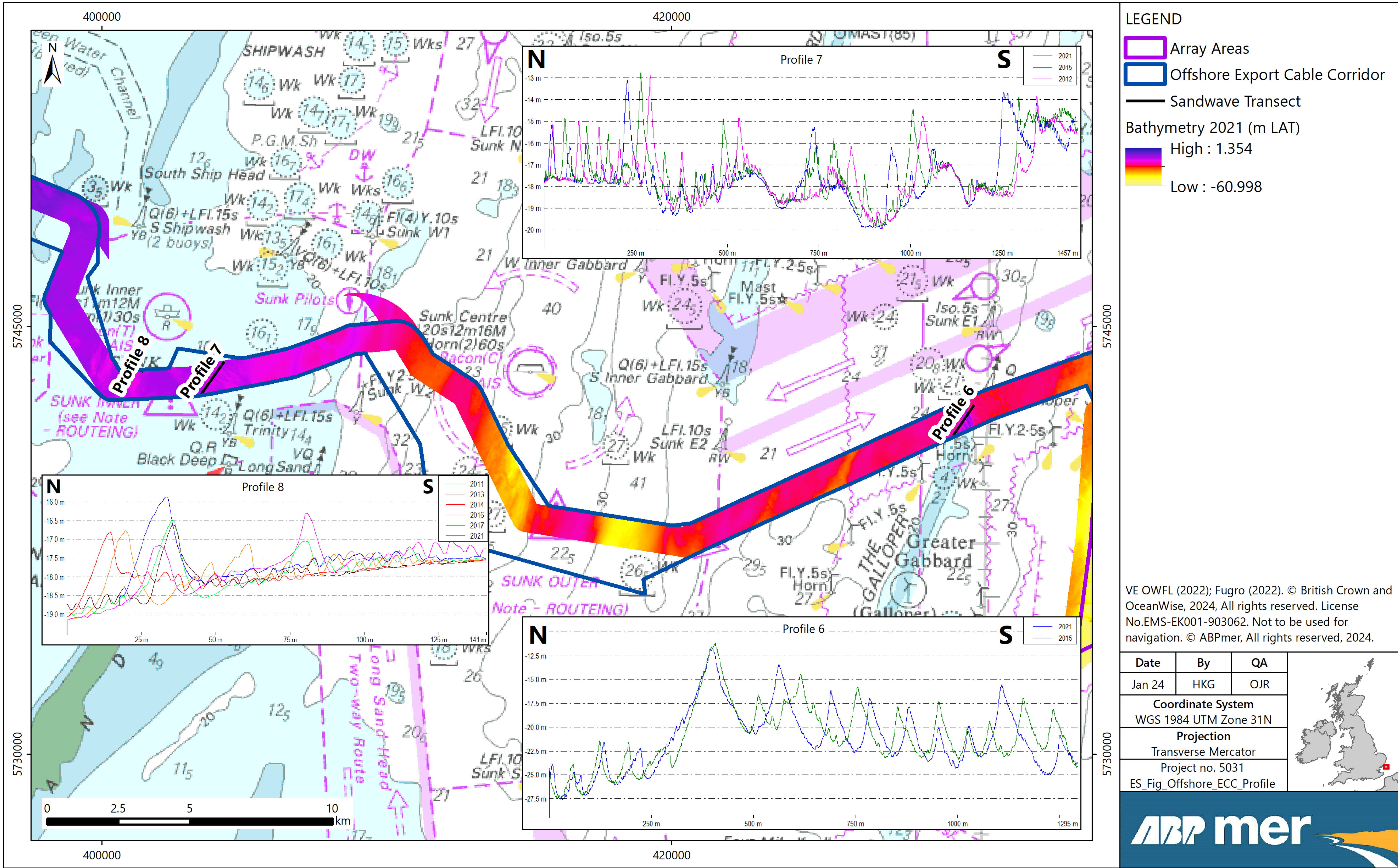
Along the ECC, water depths ranged from 0.3 m below LAT to *circa* 57 m below LAT (Figure 19). Towards the west, the seafloor is relatively flat with some rocky outcrop (Figure 10 and Figure 12) and sections of flat, featureless seafloor between these (Figure 20). Progressing further east, toward the middle and eastern part of the ECC, there are large sand waves and megaripples visible (Figure 25). Bedforms are predominantly located in areas where sand was interpreted as the primary sediment type (Fugro, 2022b).

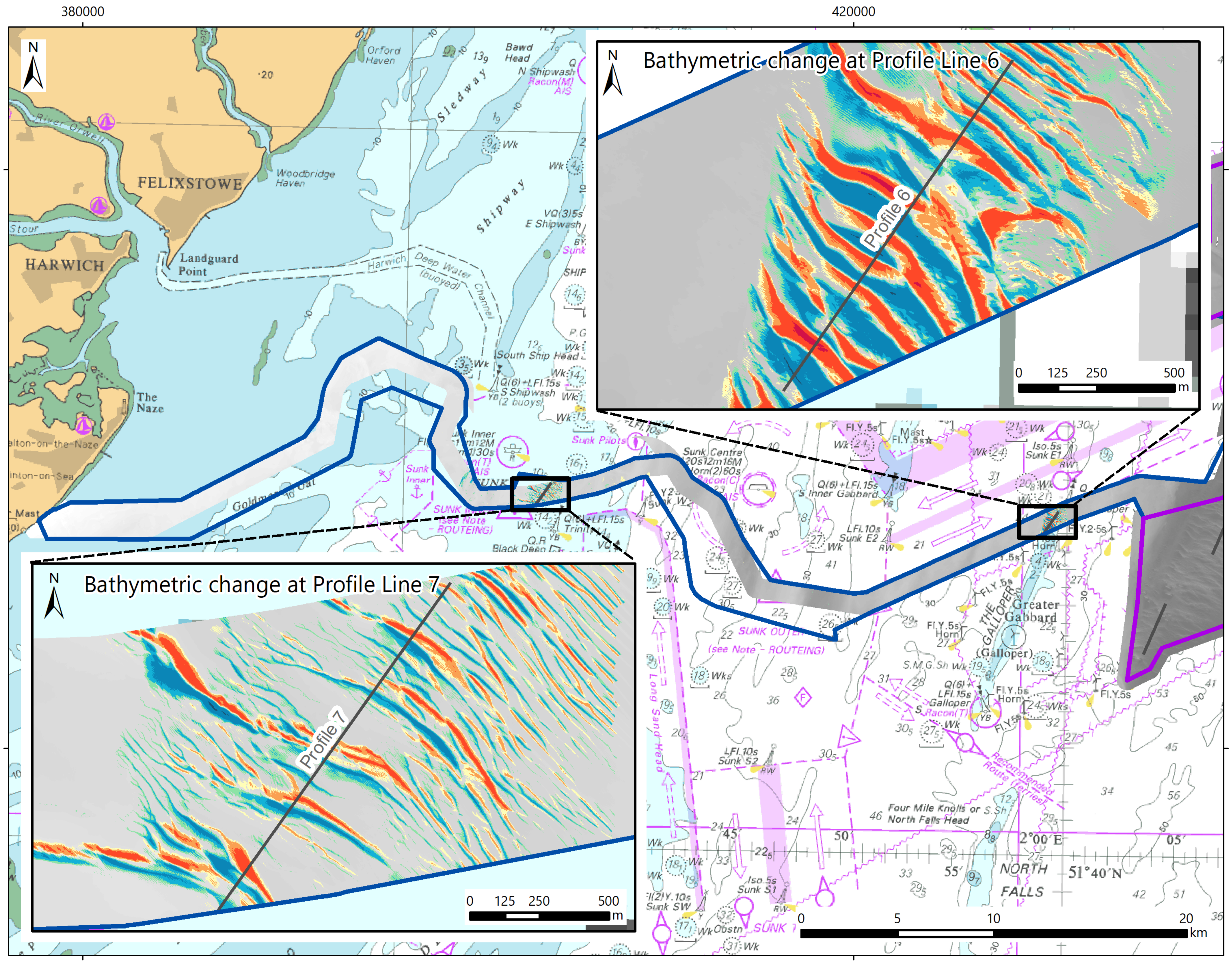
Within the ECC, megaripples are typically found to be between 0.1 and 0.8 m in height, with average wavelengths between 2 and 20 m. Most of the megaripples are present within the areas of interpreted sand, although some isolated patches were present in areas of interpreted gravelly mud, gravelly sand, and even as thin veneers within the outcrop/subcrop areas. Sand waves are defined as medium to large structures of sinuous shape. Sand waves are typically found to be between 0.7 and 7.5 m in height along the ECC, with average wavelengths between 25 and 50 m, up to a maximum of approximately 260 m for the largest sand waves (Fugro, 2022b).

During survey operations it was observed that the megaripples and sand waves were actively mobile and were migrating in the time between adjacent survey lines. This was investigated further through consideration of the differences in seabed elevation observed between the project specific (2021) bathymetric survey and earlier seabed surveys by the UKHO (since 2012) (Figure 25 and Figure 26). It is found that:

- The northern tip of the Galloper bank shows evidence of a number of associated sandwave features migrating over (and possible around) the underlying bank. The orientation of the associated bedforms (Profile Line 6), and the asymmetry of the crests, indicates migration of features from south to north along the western edge of the Galloper Bank, consistent with the regional conceptual understanding (illustrated in Figure 14). At the northern tip of the bank, the bedform migration direction becomes less clearly defined. This is likely associated with the clockwise circulation of sediment around the bank.
- Further inshore at Sunk Sand (Profile 7), there is clear evidence of sand wave migration to the north. Rates vary both spatially and temporally but appear to reach ~7 m/yr.
- UKHO regularly survey the waters approaching Harwich Deep Water Channel, likely in response to the potential navigational hazards posed by migrating sandwaves. Profile Line 8 clearly shows that the bed is mobile in this region although it is difficult to discern the rate and/or direction of bedform displacement.

Long-term morphological evolution of the seabed and larger sandbank features has been assessed in a number of previous studies, over varying temporal and spatial scales. Relevant to nearshore areas of the ECC, Burningham & French (2009) analysed the variation of sandbanks in the Outer Thames between 1824 and 2003. Over the approximately 180-year span of the study data, the assessment identified broad-scale changes to bed elevation as the major bank features migrated laterally, mostly in a general west to east direction. A summary of the study results is provided in Figure 27, which indicates average lateral migration rates of the nearshore banks of around 7 to 10 m/year.


LEGEND
Array Areas
Offshore Export Cable Corridor
Sandwave Transect
Bathymetry 2021 (m LAT)
High : 1.354
Low : -60.998
Profile 7
Profile 8
Profile 6
Profile 6
N
S
400000
420000
5745000
5730000
0
2.5
5
10
km
VE OWFL (2022); Fugro (2022). © British Crown and OceanWise, 2024, All rights reserved. License No.EMS-EK001-903062. Not to be used for navigation. © ABPmer, All rights reserved, 2024.
Date
By
QA
Jan 24
HKG
OJR
Coordinate System
WGS 1984 UTM Zone 31N
Projection
Transverse Mercator
Project no. 5031
ES_Fig_Offshore_ECC_Profile



LEGEND

- Array Areas
- Offshore Export Cable Corridor
- Sandwave Transect

Difference (m) 2021-2015

- < - 6.00
- -5.99 to -2.00
- -1.99 to -1.00
- -0.99 to -0.50
- -0.49 to 0.50
- 0.51 to 1.00
- 1.01 to 2.00
- 2.01 to 6.00
- > 6.00

Bathymetry 2021 (m LAT)

- 1.354
- -60.998

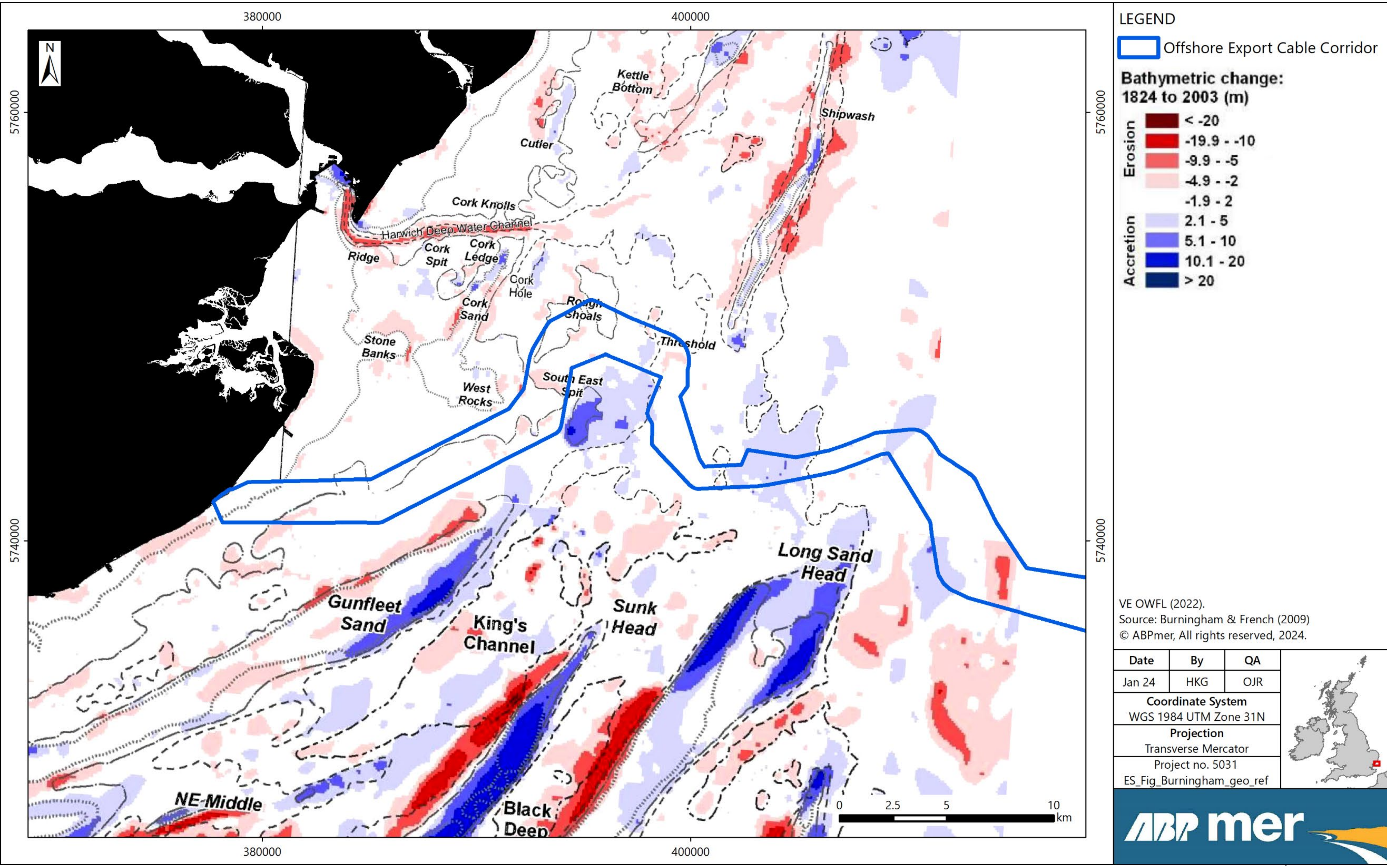
Date	By	QA
Jan 24	HKG	OJR

Coordinate System
WGS 1984 UTM Zone 31N

Projection
Transverse Mercator

Project no. 5031

ES_Fig_ECC_Difference.mxd


380000
400000
5760000
5740000
N
Kettle Bottom
Shipwash
Cutler
Cork Knolls
Harwich Deep Water Channel
Ridge
Cork Spit
Cork Ledge
Cork Hole
Cork Sand
Rough Shoals
Threshold
Stone Banks
South East Spit
West Rocks
Long Sand Head
Gunfleet Sand
King's Channel
Sunk Head
NE Middle
Black Deep
0 2.5 5 10 km
LEGEND
Offshore Export Cable Corridor
Bathymetric change: 1824 to 2003 (m)
Erosion
< -20
-19.9 - -10
-9.9 - -5
-4.9 - -2
-1.9 - 2
Accretion
2.1 - 5
5.1 - 10
10.1 - 20
> 20
VE OWFL (2022).
Source: Burningham & French (2009)
© ABPmer, All rights reserved, 2024.
Date
By
QA
Jan 24
HKG
OJR
Coordinate System
WGS 1984 UTM Zone 31N
Projection
Transverse Mercator
Project no. 5031
ES_Fig_Burningham_geo_ref
ABPmer

5 Coastline and Nearshore Processes

5.1 Overview

The coastline within the study area extends from Lee-over-Sands (in the south) to Thorpeness (in the north). It largely consists of soft cliffs, shingle or sand beaches and coastal lagoons, along with a series of estuary systems (including the Blackwater, Stour, Orwell, Deben, Ore and Alde). This stretch of coast has a long history of change with many erosion and flooding events recorded over the centuries. Longshore drift of beach material dominates although rates and directions of sediment transport are highly variable, both spatially and temporally (SNSSTS, 2002; Environment Agency, 2010). The Shoreline Management Plan for much of the coastline is 'no active intervention' but with preferred policies of 'hold the line' or 'managed realignment' in place for parts of the coastline. In places, coastal erosion is a major challenge and despite a long history of coastal defence works, accelerated erosion of the soft cliffs and denudation of beach material regularly occurs during high-tide and/or storm conditions (Environment Agency, 2015). This is expected to accelerate with rising sea levels and (possible) increases in storm intensity.

Sediment transport along this section of coastline is generally from northeast to southwest (SNSSTS, 2002), with low to moderate net drift rates. The movement of material along different sections of coastline is highly dependent on the angle of wave attack and the relative orientation of the coastline. The SMP2 (Environment Agency, 2010) describes the alongshore transport between Jaywick and Walton as 'variable, but generally towards the south-southwest'. The supply of material from the north is limited by the presence of erosion protection coastal defences, with groynes constructed along large sections of the frontage designed to accumulate sediment, widening and realigning the foreshore locally, and so providing some protection to the foreshore and coastal hinterland from wave action. Transport continues to the west of Jaywick to Colne Point, which acts as a sediment sink.

The historical wave climate has been extracted for a location near the landfall from the ABPmer SEASTATES wave hindcast database (ABPmer, 2013), comprising a 40-year hourly timeseries of significant wave height, and associated wave period and direction. These data were used to estimate the 'depth of closure'. The depth of closure defines the offshore extent of normal beach processes and is the depth contour beyond which wave action causes little or no net sediment transport between intertidal and nearshore regions. The method of Nicholls *et al.* (1996) was used, in conjunction with an estimated non-breaking significant wave height not exceeded more than 12 hours per 40 years. The resulting estimated depth of closure is found to be ~ -1.5 mLAT. This is shallow in comparison to other locations along this coast and reflects (amongst other things) the orientation of the coastline compared to the predominant local wind direction, resulting in comparatively smaller waves at the coast.

5.2 Local setting

The proposed Landfall (Essex coastline at Holland Haven, between Frinton-on-Sea and Holland-on-Sea) is located within the SMP2 Management Unit C (Tendring Peninsula), in SMP2 Policy Development Zone C2 (Holland Haven) (see Figure 1 for locations). The future management policy is listed as 'Hold the Line' for the next 50-years (Environment Agency, 2010). For epoch 3 (out to 2105) there is a dual policy of either Managed Realignment or Hold the Line. In either case, flood defence to the dwellings, roads and sewerage treatment works will be continued. The standard of protection will be maintained or upgraded.

The location, construction and access/ egress to any Project infrastructure considered within the area will need to take account of the longer-term management intent of the area, which could become a managed realignment site. As such, any proposed infrastructure will need to ensure it is adequately protected against flood risk as part of the planning stage.

The coastline within the landfall area is heavily managed with an almost continuous concrete sea wall at the back of the beach, fronted by a mixture of sloped smooth and/or rock revetment. Wooden groynes between Clacton and Holland on Sea to the southwest (downdrift) of the landfall area were replaced with numerous fishtail rock breakwaters in approximately 2014 to 2015, which has increased the volume of sediment on the beach foreshore, and so the foreshore width. The new groynes extend both physically and in terms of influence into the western edge of the landfall area. Wooden groynes have been historically present on the coastline to the northeast (updrift) of the landfall area, as far as The Naze headland. The character of the beach and coastline in the landfall area is therefore presently stable due to the coastal defences present; however, the future stability of the coastline will remain dependent on the future management policies and activities for both the local area and for coastal regions up drift (to the northeast).

The available historic Google Earth images (covering the period 2000 to 2022) help show the relatively consistent character of the Landfall coastline in Figure 28 to Figure 32. Associated cross-shore profiles from the available Light Detection and Ranging (LiDAR) data are described in further detail below.

Figure 28. Aerial imagery at the landfall (December 2000). Source: Google Earth

Figure 29. Aerial imagery at the landfall (December 2005). Source: Google Earth

Figure 30. Aerial imagery at the landfall (April 2011). Source: Google Earth

Figure 31. Aerial imagery at the landfall (September 2017). Source: Google Earth

Figure 32. Aerial imagery at the landfall (March 2022). Source: Google Earth

In addition to the aerial imagery provided in Figure 28 to Figure 32, historic LiDAR data (collected and made available by the Environment Agency) has also been analysed, with a series of cross-shore profiles provided in Figure 33 (see Figure 34 for profile location, which also shows the observed range of vertical change between LiDAR surveys undertaken between 1999 and 2019). Comparison of the historic LiDAR and profiles shows a relatively stable foreshore over the 20-year period covered by the available data (1999 to 2019), with vertical change in beach elevation typically in the range 0 to 2 m.

However, the influence of the fish tail groynes can be clearly seen in Profile 1 with significant (~3 m) accretion occurring across the beach in response to their construction between the 2010 and 2016 LiDAR surveys. Some lowering of the beach at Profile 2 (500 m to the north of Profile 1) following construction of the groynes is also apparent although further analysis is required to establish a causal link. The new coastal defences (including raised elevation) are clearly shown in Profile 3.

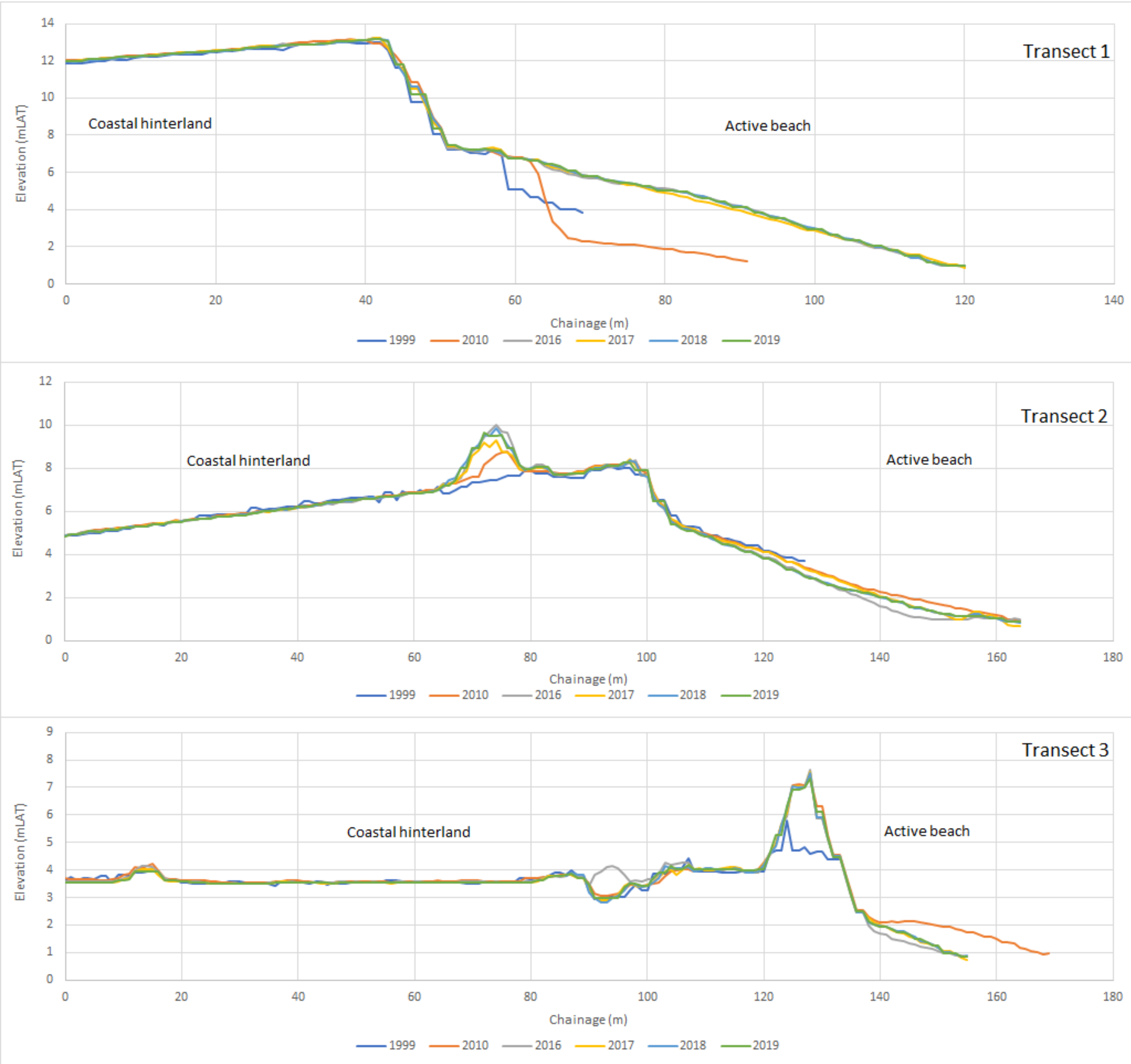
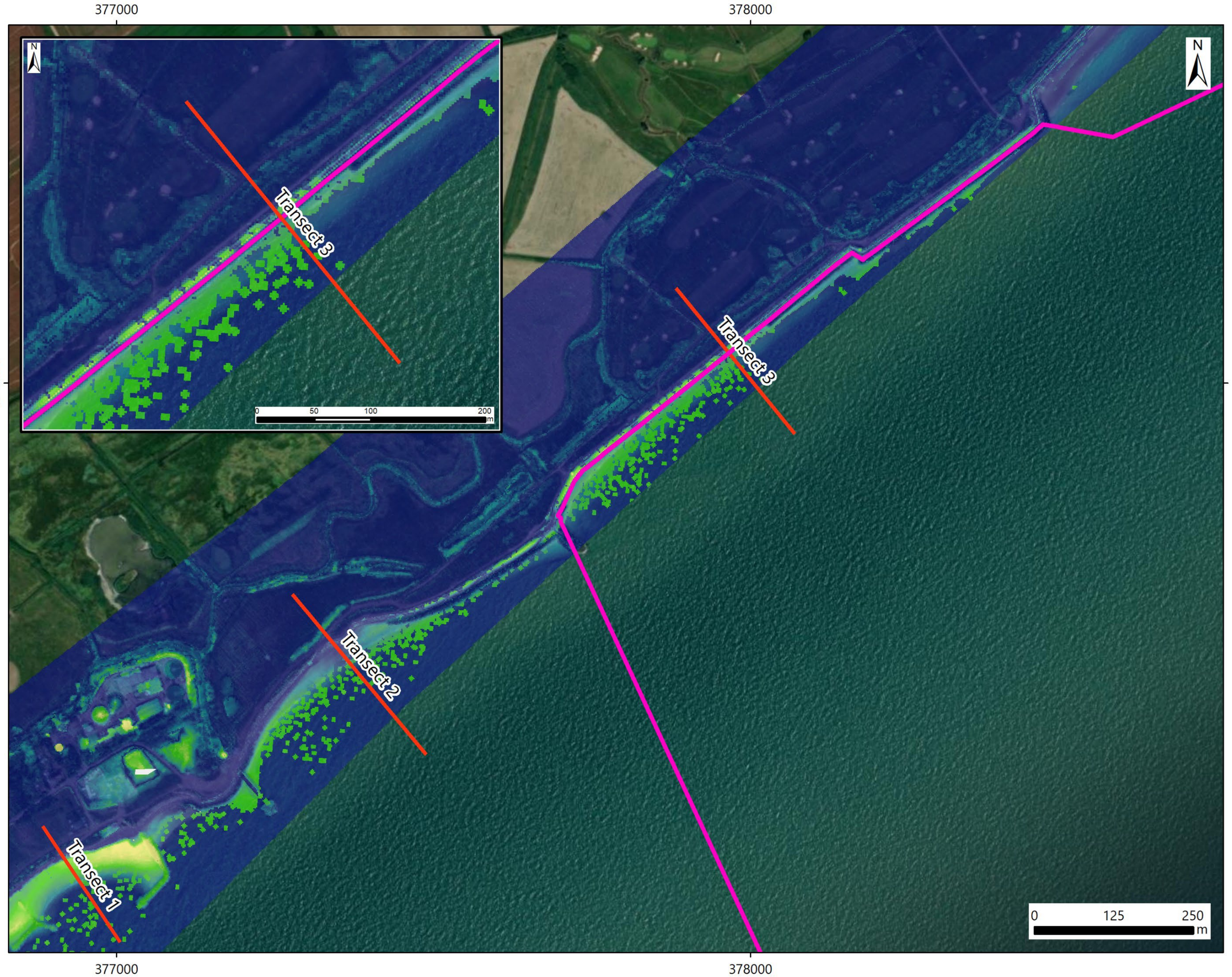


Figure 33. Comparison of recent and historic LiDAR profiles at the landfall between 1999 and 2019



LEGEND

Offshore Export Cable Corridor

LiDAR transect

Max difference in LiDAR elevation (1999 to 2019) (m)

13

0

VE OWFL (2022). EA, 2022.
RWE, 2020, ABPmer, 2020. Basemap: Esri et al.

Date	By	QA
Jan 24	HKG	OJR

Coordinate System
WGS 1984 UTM Zone 31N

Projection
Transverse Mercator

Project no. 5031
ES_Fig_Landfall_LiDAR_v2

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