Awel y Môr Offshore Wind Farm

Category 6: Environmental Statement

Volume 4, Annex 2.1: Physical Processes Baseline Technical Report

Date: April 2022

Revision: B

Application Reference: 6.4.2.1

Pursuant to: APFP Regulation 5(2)(a)

REVISION	DATE	STATUS/ REASON FOR ISSUE	AUTHOR:	CHECKED BY:	APPROVED BY:
A	August 2021	PEIR	ABPmer	RWE	RWE
B	March 2022	ES	ABPmer	RWE	RWE

www.awelymor.cymru

RWE Renewables UK
Swindon Limited

Windmill Hill Business Park
Whitehill Way
Swindon
Wiltshire SN5 6PB
T +44 (0)8456 720 090
www.rwe.com

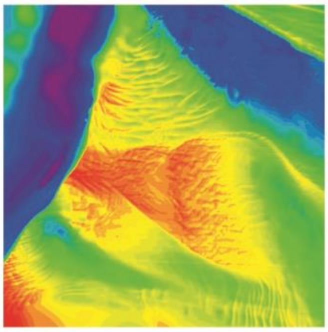
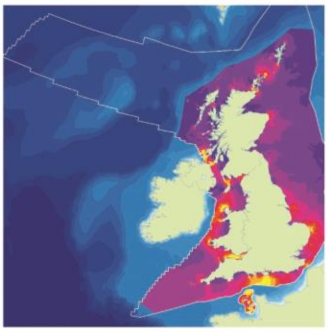
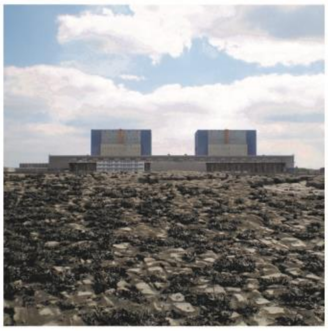
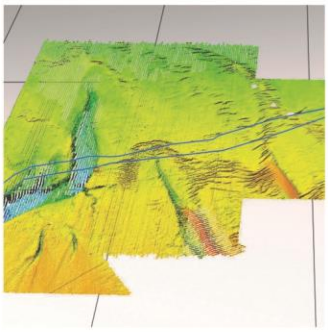
Registered office:
RWE Renewables UK
Swindon Limited Windmill
Hill Business Park Whitehill
Way
Swindon

GoBe

Awel y Môr Offshore Wind Farm Environmental Impact Assessment

Volume 4, Annex 2.1: Physical Processes Baseline Technical Report

March 2022

Innovative Thinking - Sustainable Solutions

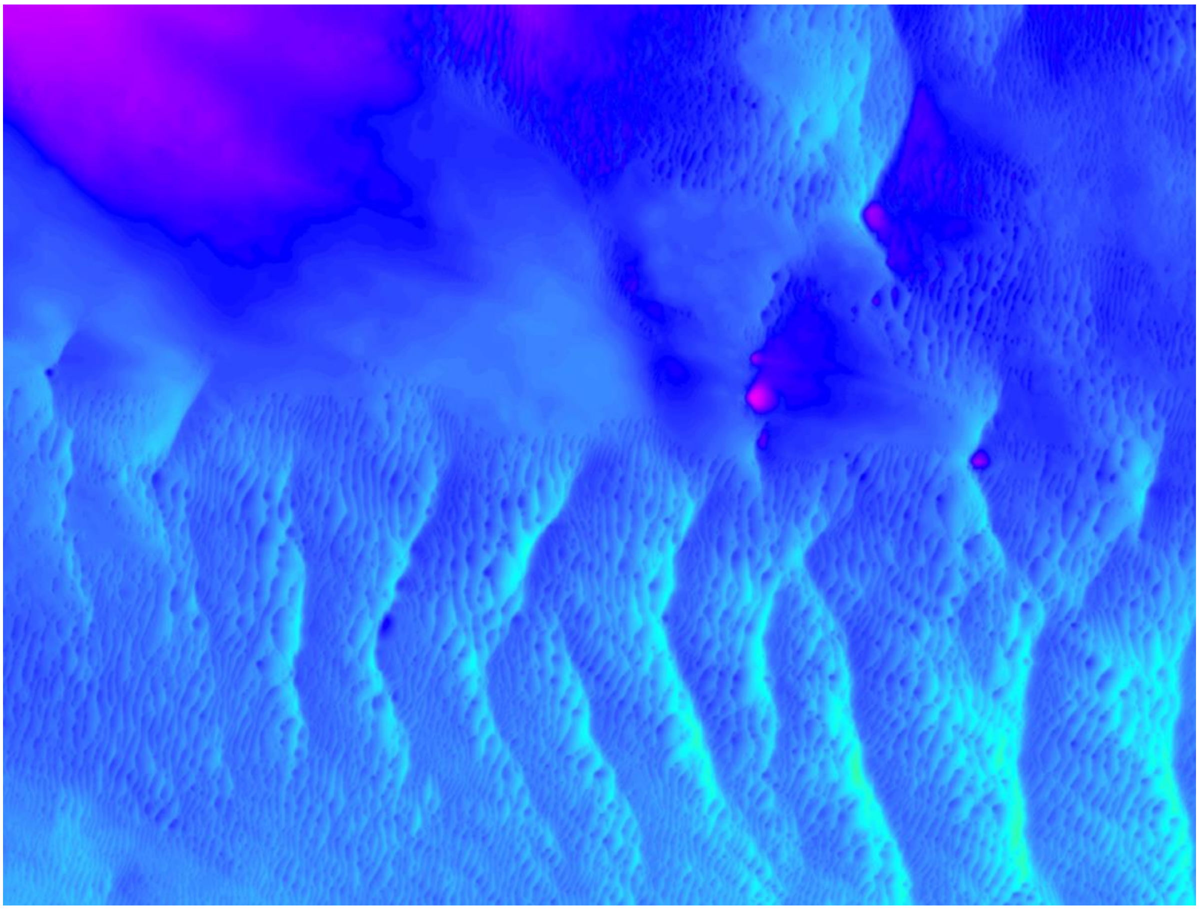
ABP mer

Page intentionally left blank

Awel y Môr Offshore Wind Farm
Environmental Impact Assessment

Volume 4, Annex 2.1: Physical Processes Baseline Technical Report

March 2022



Document Information

Document History and Authorisation		
Title	Awel y Môr Offshore Wind Farm Environmental Impact Assessment	
	Volume 4, Annex 2.1: Physical Processes Baseline Technical Report	
Commissioned by	GoBe	
Issue date	March 2022	
Document ref	R.3625	
Project no	R/4913/01	
Date	**Version**	**Revision Details**
26/03/2021	V0.1	Issued for Client review
09/04/2021	V0.3	Issued for Client review
15/04/2021	V0.5	Issued for Client review
09/06/2021	V2.1	Issued for Client review
09/07/2021	V3	Issued for Client use
02/11/2021	(ES) V0.1	Issued for Client review
29/11/2021	(ES) V0.2	Issued for Client review
16/11/2021	(ES) vFinal	Final
16/12/2021	(ES) vFinal	Issued for Client use
18/03/2022	(ES) vFinal1	Issued for Client Use (updated boundaries)

Prepared	Approved	Authorised
Anthony Brooks	David Lambkin	Heidi Roberts
[redacted]	[redacted]	[redacted]

Suggested Citation

ABPmer, (2022). Awel y Môr Offshore Wind Farm Environmental Impact Assessment, Volume 4, Annex 2.1: Physical Processes Baseline Technical ReportR.3625. A report produced by ABPmer for GoBe, March 2022.

ABPmer
Quayside Suite, Medina Chambers, Town Quay, Southampton, Hampshire SO14 2AQ
[redacted]

Contents

Appendix

Tables

Figures

1 Introduction

1.1 Overview

This study is undertaken by ABPmer on behalf of Awel y Môr offshore Wind Farm Limited, a subsidiary of RWE Renewables UK (RWE) (the Applicant), to provide a baseline description of physical processes in relation to the proposed Awel y Môr Offshore Wind Farm (AyM OWF). 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 2; Chapter 2 'Marine Geology, Oceanography and Physical Processes').

AyM is a proposed sister project to the west of the Gwynt y Môr offshore wind farm (GyM, operational since 2015), approximately 10 km north of Abergele and Rhyl on the North Wales coast. The offshore Export Cable Corridor (offshore ECC) runs approximately southeast, from the southern boundary of the array to a landfall at Ffrith (Figure 1). This figure also shows the wider study area for the physical processes assessment. It encompasses Liverpool Bay, as well as adjacent seabed areas up to mean high-water spring (MHWS) and includes the AyM array, offshore ECC and landfall.

The potential Zone of Influence defined by the study area boundary has primarily been determined using expert judgment, drawing upon knowledge developed from other operational Round 2 and Round 3 OWF projects. Direct changes to the seabed will be confined to the array and offshore ECC, with indirect changes (e.g. due to disruption of waves, tides or sediment pathways) experienced both inside and outside of the AyM project boundary. These indirect changes are expected to diminish with distance from the array and offshore ECC.

A summary of key findings is set out below and the conceptual understanding of the physical processes is shown in Figure 2.

- The study area can be characterised as a macro-tidal setting, with tidal elevations across Liverpool Bay increasing from west to east. The mean spring tidal range in the offshore array area and along the cable route options is approximately 6.5 m, increasing to approximately 7 m at the landfall.
- Currents speeds are approximately 0.75 to 1.0 m/s in the array, decreasing towards 0.5 m/s along the offshore ECC towards the landfall. In Liverpool Bay, the maximum flood currents (to the east) are greater than the maximum ebb currents (to the west) because the tidal rise time on the flood is shorter than the time of fall on the ebb. This asymmetry drives net sediment transport in an easterly direction.
- Mean sea level is expected to rise during the lifetime of the project. A rise in sea level may 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 and the equilibrium position of coastal features.
- The study area is open to northwesterly offshore waves that are generated within the Irish Sea. Locally generated waves related to the prevailing winds come from westerly, northwesterly and northern sectors.
- To the northeast of the AyM array is the permanent Liverpool Bay front which extends northwards from the River Dee. Stratification related to this front is predominantly associated with salinity gradients, although temperatures associated with outflows from the Dee, Mersey and Ribble estuaries can also have a seasonal effect.

- The seabed within Liverpool Bay largely consists of either sandy gravel or gravely sand. The seabed is relatively free of fines (defined as particles of less than 0.063 mm), with waves generally preventing the deposition of mud or silt, whilst tidal currents prevent the deposition of mud further offshore within Liverpool Bay.

- The Quaternary geology of the AyM array and offshore ECC has been shaped and influenced by a series of glacial events during the retreat of the British Isles ice sheet and Irish Sea Ice Stream. Overlying the bedrock is an extensive sequence of Quaternary glaciogenic and seabed sediments. These comprise a range of coarse and fine grained sediments.
- Net sediment transport along the north Wales coastline is predominantly by bedload in an easterly direction, at a moderate to high rate for sands, with some transport of finer material in suspension. In offshore areas, the direction is the result of the tidal current asymmetry; in shallower nearshore areas and on the beaches, the direction is the combined result of tidal current asymmetry and the relative angle of approach of waves.
- Both sand waves and megaripples are present in the array and offshore ECC and are over 4 m high in places. Within inshore areas of the offshore ECC, rates of migration are typically around 10 m/yr and may reach 25 m/yr locally.
- The offshore sandbanks of Constable Bank and Rhyl Flats are located immediately to the south of the array and are crossed by the offshore ECC. They are understood to have an important influence on the geomorphology of the adjacent coastline, through the possible exchange of sediments and potential impacts on hydrodynamics.
- The coastline within the study area extends from Carmel Head (in the west) to Southport (in the east). The coastal characteristics are highly varied, ranging from rocky cliffs (e.g. Great Orme's Head) to low lying settings characterised by accumulations of soft unconsolidated sediments (such as the Dee estuary).
- The shoreline policy at the landfall (as well as along much of the coastline in the study area) is Hold the Line, with a seawall and groynes in place. However, comparison of the topographic data available from the landfall shows vertical change in beach elevation occurring, in response to the migration of ridge and runnel features across the foreshore.

1.2 Approach

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

- Hydrodynamics:
  - Water levels;
  - Currents;
  - Wind and wave climate;
  - Stratification and frontal systems;
- 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.

Baseline understanding has been developed broadly in accordance with NRW Guidance Note 41 (*Guidance on Best Practice for Marine and Coastal Physical Processes Baseline Survey and Monitoring Requirements to Inform EIA of Major Development Projects;* Brooks *et al*., 2018) which requires that attention is 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 AyM array and offshore ECC are listed in Table 1.

Table 1. Marine nature conservation designations with relevance to physical processes and Awel y Môr OWF

Site	Closest distance to AyM array/offshore ECC	Features or description
International		
Liverpool Bay SPA	[Coincident with the offshore ECC]	Large areas of muddy sand and gravelly sand and a number of prominent sandbanks
Dee Estuary SAC	[Immediately adjacent to the offshore ECC]	Saltmarshes, intertidal mudflats, sandflats, sand dunes and sea cliffs
Dee Estuary SPA	[Immediately adjacent to the offshore ECC]	Saltmarshes, intertidal mudflats, sandflats, sand dunes and sea cliffs
Y Fenai a Bae Conwy / Menai Strait and Conwy Bay SAC	6 km	Large areas of sand and mud flats as well as subtidal sandbanks belonging to the Four Fathom Banks complex
Anglesey Terns / Morwenolaiid Ynys Môn SPA	14 km	Extends around most of the east, north and west coasts of Anglesey, generally from the mean high water mark out to between 10 and 20 km from the shore

Site	Closest distance to AyM array/offshore ECC	Features or description
Traeth Lafan / Lavan Sands, Conway Bay SPA	21 km	Large intertidal area of sand and mudflats lying at the eastern edge of the Menai Straits
North Anglesey Marine SAC	21 km	Encompasses a range of habitats including coarse and sandy sediments, rock and mud
National		
Traeth Pensarn SSSI	6 km	Large area of intertidal sand and mud flat
Gronant Dunes and Talacre Warren SSSI	3 km	Large area of sand dunes and foreshore located between Prestatyn and Gronant
Creigiau rhiwledyn/ Little Ormes Head SSSI	10 km	Limestone headland on the eastern side of Llandudno Bay
Pen Y Gogarth / Great Ormes Head SSSI	11 km	Site is significant for (among other things) its Carboniferous Limestone and associated sedimentary deposits
Arfordir Gogleddol Penmon SSSI	18 km	Steep Carboniferous limestone cliffs of geological interest
Traeth Lafan SSSI	21 km	Large intertidal area of sand and mud flats lying at the eastern edge of the Menai Straits
Puffin Island - Ynys Seiriol SSSI	17 km	Carboniferous limestone island approximately 1 km off the eastern tip of Anglesey
Glannau Penmon – Biwmares SSSI	19 km	Muddy and boulder strewn shore containing tide-swept sediments flanked by soft cliffs

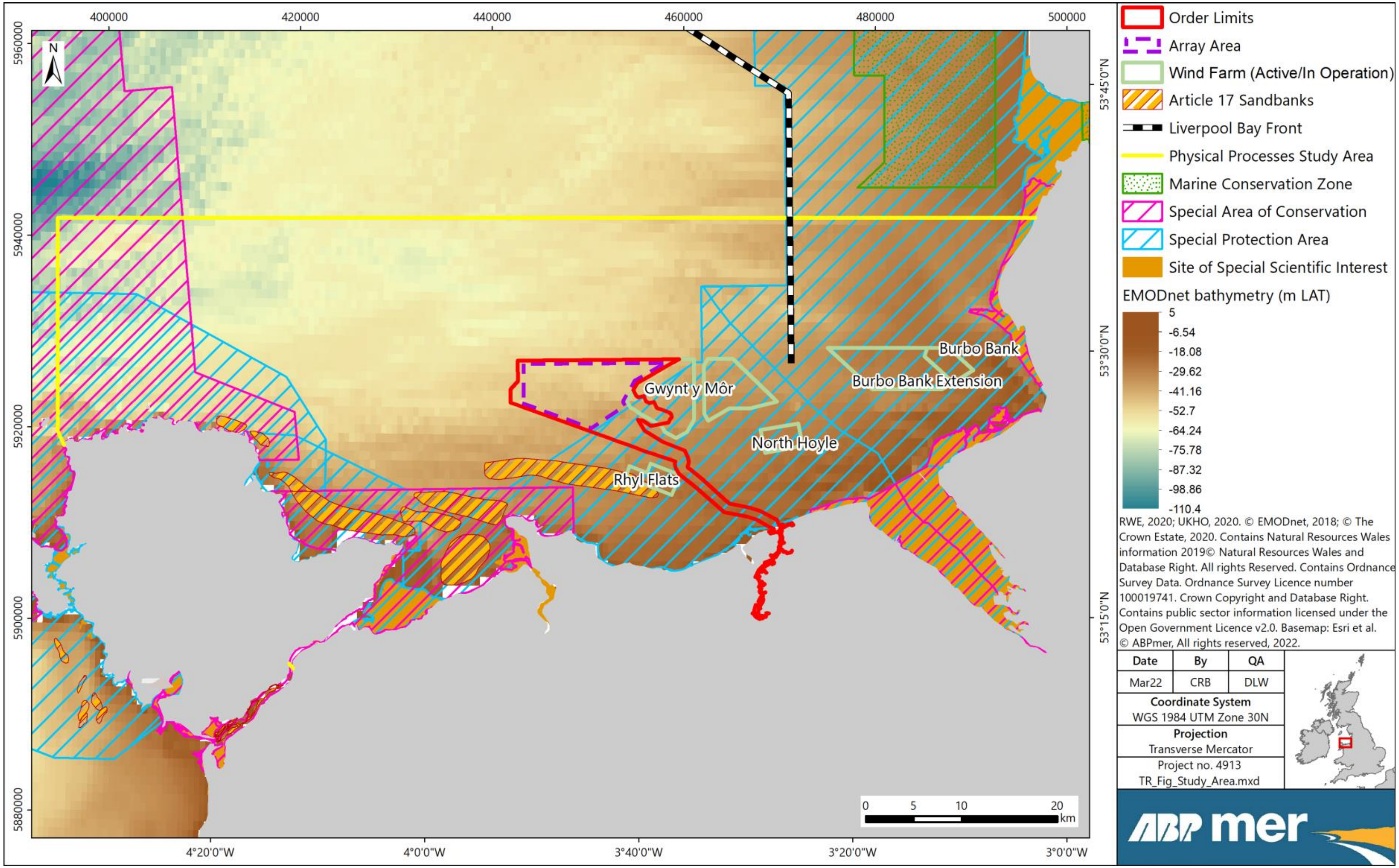
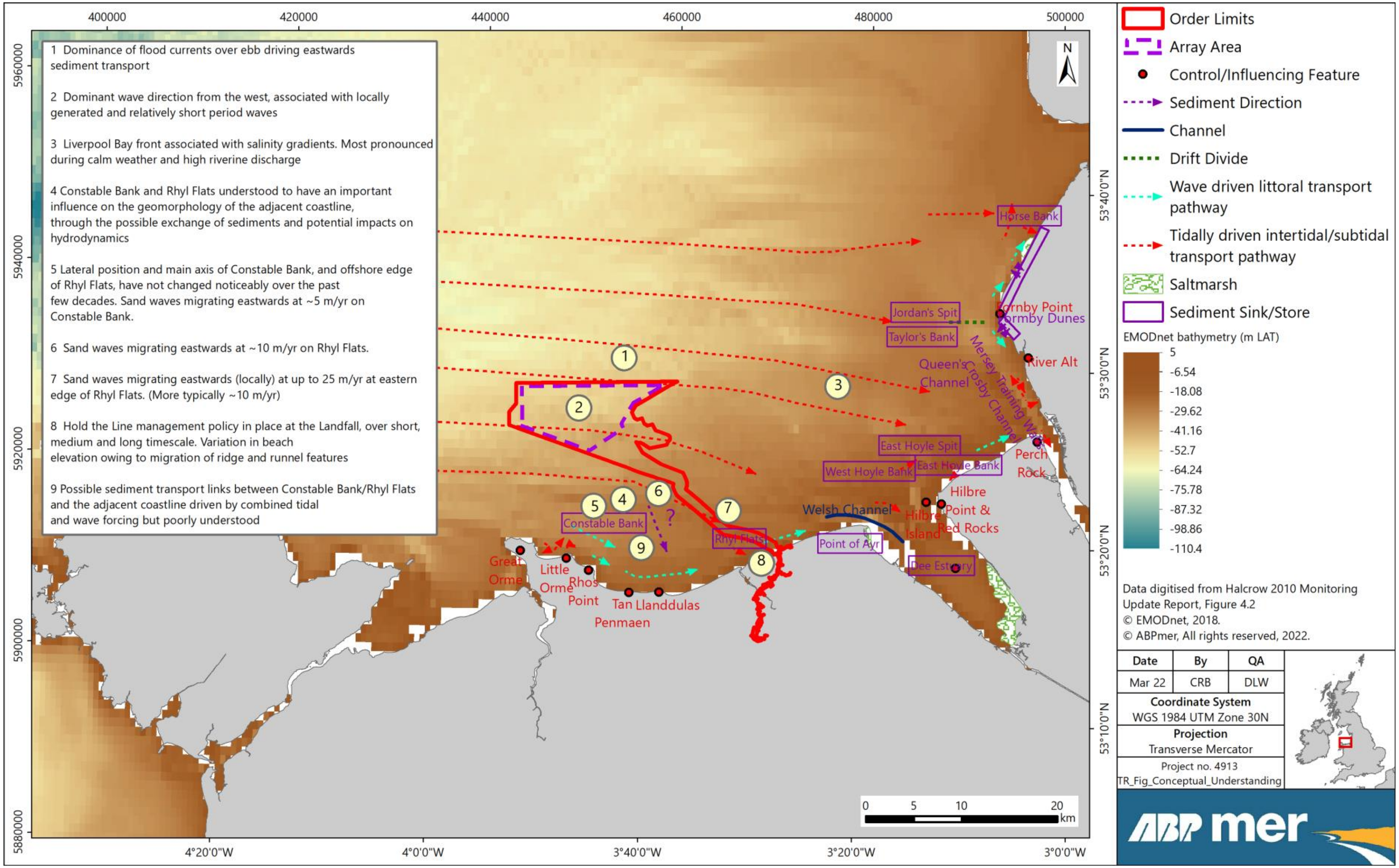


Figure 1. Study area



Adapted from Halcrow, 2010a

Figure 2. Conceptual understanding of regional scale marine physical processes

2 Data Sources

Baseline understanding has been developed through consideration of a range of data sources and existing process investigations from the study area. These are summarised in Table 2 and Figure 3, and include:

- AyM project specific offshore geophysical (Fugro, 2020a,b) and Unmanned Aerial Vehicle (UAV) Photogrammetry landfall survey data (Fugro, 2020c), both collected in 2020;
- Geophysical, geotechnical, benthic and oceanographic data collected to inform the Gwynt y Môr (GyM) OWF EIA;
- Data available from a number of marine data portals; and
- Existing physical process investigations from across the study area.

It is noted here that the AyM project specific geophysical survey (undertaken in 2020) did not cover the area of the interlink cable to GyM (Figure 3). However, geophysical survey data collected as part of the the GyM site characterisation works is available, along with recent high-resolution bathymetry data collected by UKHO (Table 2 and Table 3). Together, this data is sufficient to inform baseline understanding in this area.

To inform understanding of morphological change to the seabed within and nearby to the AyM array and offshore ECC, a number of recent and historic bathymetric datasets were sourced, processed and compared. These are listed in Table 3, with spatial extents summarised in Figure 4.

Table 2. Key data sources used to inform the investigation

Source	Summary	Coverage of Awel Y Môr OWF Array and offshore ECC
Data portals		
LLe Geoportal and Welsh Coastal Monitoring Centre and Colwyn Bay Coastal Observatory http://lle.gov.wales/home [redacted]	Welsh coastal survey data including LiDAR and beach topographic survey data	Array, offshore ECC and landfall
IMARDIS and SEACAMS [redacted]	Geophysical, bathymetric and hydrodynamic data available through the information component of the SEACAMS2 program	Array and offshore ECC
National Tide and Sea Level Facility (NTSLF) [redacted]	Tidal water levels from tide gauge stations	[Wider study area]
British Oceanographic Data Centre (BODC) [redacted]	Hydrodynamic data from point locations across the study area	Array and offshore ECC

Source	Summary	Coverage of Awel Y Môr OWF Array and offshore ECC
BGS Strategic Environmental Assessment data portal [redacted]	Geophysical, geotechnical and benthic data from the study area	Array and offshore ECC
Cefas WaveNet [redacted]	Wave buoy data	Wider study area
UKCP18 climate change projections https://ukclimateprojections-ui.metoffice.gov.uk/ui/home	Projections in change to mean sea level (Palmer *et al.* 2018)	Landfall
British Geological Survey (BGS) offshore geoindex [redacted]	Data on seabed sediments and geology	Array and offshore ECC
United Kingdom Hydrographic Office (UKHO) [redacted]	Multibeam and single beam bathymetry data	Array and offshore ECC
ABPmer SEASTATES [redacted]	Hindcast wave data, water level and current data	Array and offshore ECC
Marine Renewables Atlas ABPmer *et al.* (2008)	Synoptic wind, wave and hydrodynamic data	Array and offshore ECC
Data and Reports from GyM		
Npower Renewables (2004)	GyM Offshore Wind Farm, Final Environmental Assessment Scoping Report	Wider study area
Npower Renewables (2005)	GyM Offshore Wind Farm, Environmental Statement. Chapter 5 The physical environment	Wider study area
ABPmer (2009)	Assessment of Seabed Variability across the GyM Offshore Wind Farm	Wider study area
Other Relevant Reports and Data		
Cefas (2016)	Suspended Sediment Climatologies around the UK	Array and offshore ECC
Halcrow (2011) Royal Haskoning (2010)	North West England and North Wales Shoreline Management Plan (SMP)2	Landfall

Source	Summary	Coverage of Awel Y Môr OWF Array and offshore ECC
	West of Wales SMP2	
Dŵr Cymru Welsh Water (DCWW) (2016)	Water level, current and CTD data collected from multiple locations across the study during 2015 and 2016	Wider study area
Environment Agency (2019)	Coastal flood boundary conditions for the UK: update 2018	Landfall
Halcrow (2010a,b)	Summary of supporting information for conceptual understanding of processes across the wider study area	Array, offshore ECC and landfall
Holmes and Tappin (2005)	Seabed and surficial geology and processes within DTI Strategic Environmental Assessment Area 6: The Irish Sea.	Array and offshore ECC
Pye and Blott (2017)	Barkby Beach to Point of Ayr: Geomorphology Review	[Wider study area]
Vincent *et al.* (2004)	Overview of the marine environment in the Irish Sea including information on frontal systems and stratification	Array and offshore ECC
Howarth (2005)	Description of the hydrography of the Irish Sea	Array and offshore ECC
Van Landegehem (2012)	Prediction of sediment wave migration across the Irish Sea, R3 Wind Farm Development Zone.	Wider study area
Sutton (2008)	Morphodynamic modelling of long-term change from the study area	Wider study area

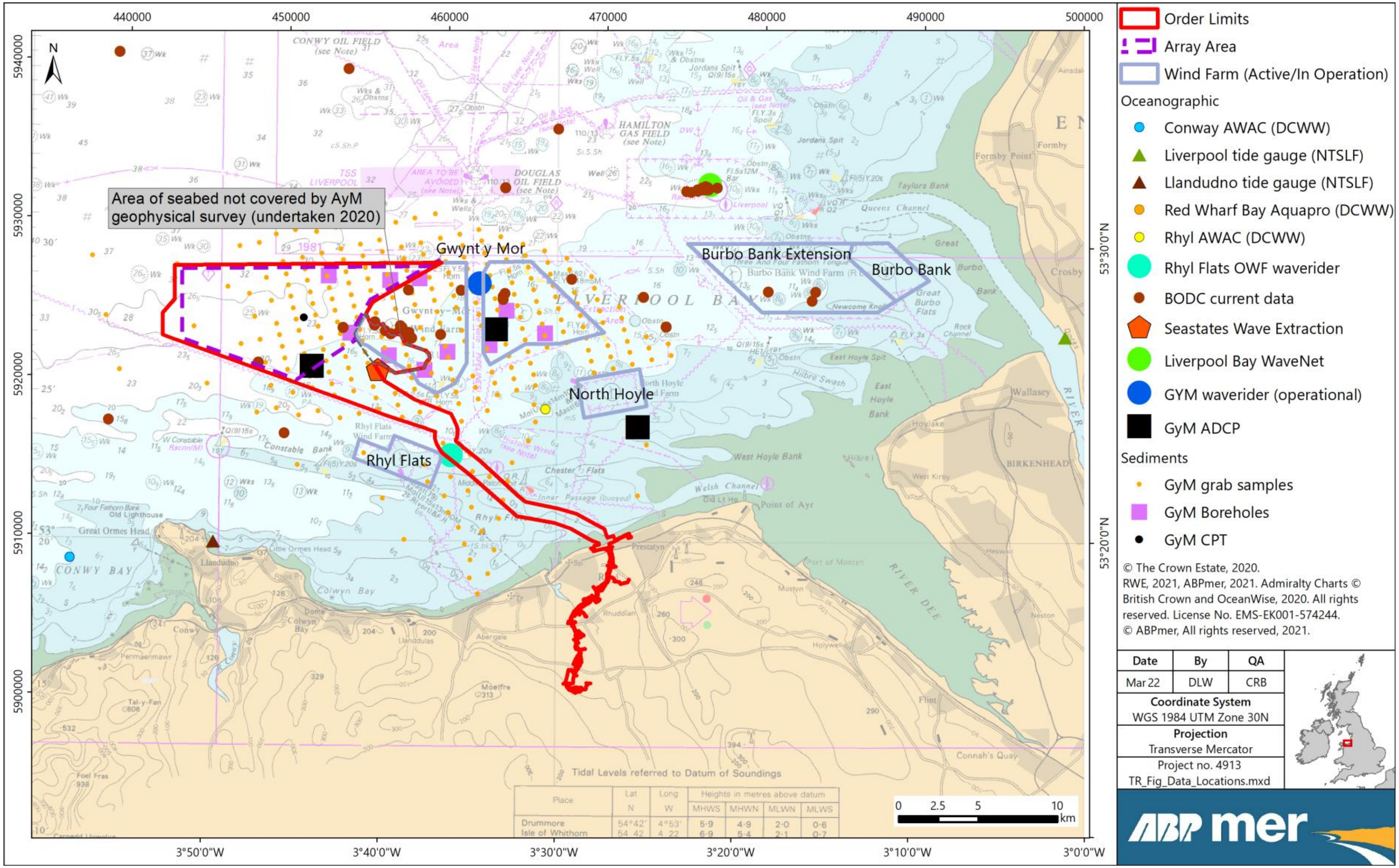


Figure 3. Data locations

Table 3. Key bathymetry datasets

Survey	Data Type	Year Collected	Description	Source
Awel Y Môr Wind Farm	Bathymetry, seabed sediments Bedforms Sed. thickness	2020	Multibeam, side-scan sonar and sub-bottom geophysical survey covering array and export cable corridor	Fugro (2020a,b)
Gwynt Y Môr Wind Farm	Bathymetry, seabed sediments Bedforms Sed. thickness	2002	'Phase 1' GyM array area [multi-beam, fine grid]	Osiris (2003a)
		2003	'Phase 2' West GyM array and East AyM array [multi-beam, coarse grid; line spacing 67.5 m]	Osiris (2003b)
		2004	'Phase 3' West GyM array and East AyM array [multi-beam, fine grid]	Osiris (2004)
Rhyl Flats Wind Farm	Bathymetry	2002	Multi-beam bathymetry	Fugro (2002)
		2005		Osiris (2005)
		2008		Osiris (2008)
		2012		Osiris (2012)
UKHO (latest)	Bathymetry	1969	'Approaches to the River Dee' [Single-beam]	UKHO
		1987	'Skerries to the River Dee Sheet 8' [Single-beam]	
		1987	'Skerries to the River Dee Sheet 12' [Single-beam]	
		2001	'Chester Flats Inner Passage to South Hoyle Channel' [Single-beam]	
		2018/2019	Little Ormes Head to Hilbre Point [multi-beam]	
		2019/2020	Red Wharf Bay to GyM [multi-beam]	
UKHO (historic)	Bathymetry	1920s	'Great Ormes Head to River Dee' [Lead line survey]	UKHO
		1960s	'Approaches to Liverpool and the River Dee' [Single-beam]	
SEACAMS/ SEACAMS2	Bathymetry	2014	'Colwyn Bay to Prestatyn' [Multi-beam]	[redacted]/
		2017	'LLandudno to Talacre' [Multi-beam]	[redacted]
		2018	'North Wales Coast' [Multi-beam]	[redacted]
SEA 6	Bathymetry	2004	'Constable Bank' [Multi-beam]	[redacted]
AmSedIS	Bathymetry Sed. thickness	2012	Research cruise CV12007 [Multi-beam; shallow seismic]	Van Landeghem (2012)
IMAGIN	Bathymetry Seabed sediments Bedforms Sed. thickness	2005	'Area 5' [Multi-beam; coarse grid. Boomer seismic profiling]	Sutton (2008)

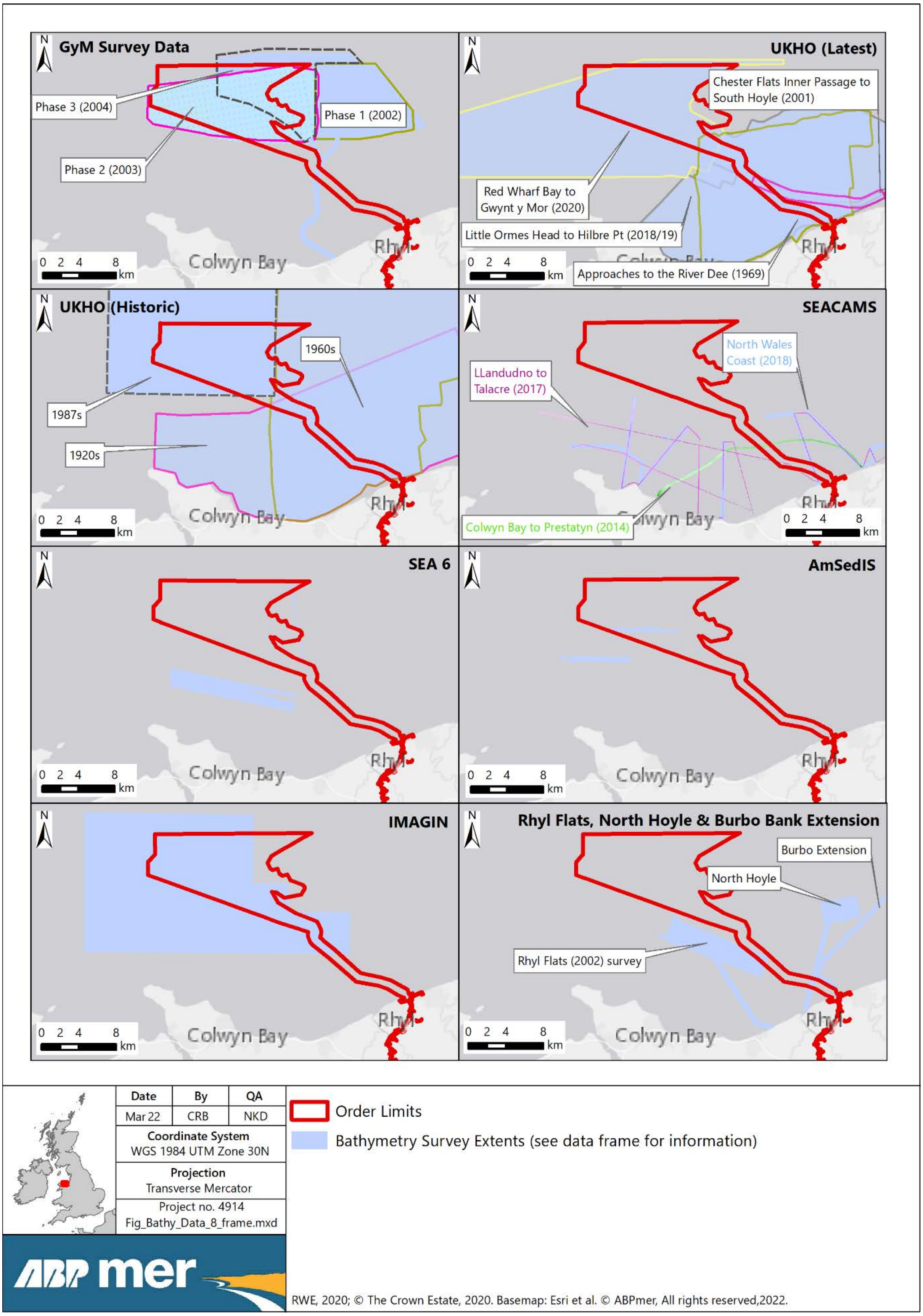


Figure 4. **Spatial extent of bathymetry datasets (used alongside the project-specific 2020 geophysical survey)**

3 Hydrodynamic Regime

3.1 Overview

The Irish Sea is open to tidal influences from the north, along the North Channel and south along St. George's Channel. The incoming tide arrives from both directions almost simultaneously and moves through the Irish Sea to meet around the Isle of Man to then flow east into Liverpool Bay, Morecambe Bay and Solway Firth. From high water, the tide retreats and reverses to flow west out of Liverpool Bay. This process repeats daily with a cycle of around 12.5 to 13 hours, which typically produces two high and low waters a day. The tidal regime is generally well understood, with this periodic form dominated by the semi-diurnal lunar tidal component (ABPmer, 2005).

Superimposed on these tidally driven circulations are various non-tidal effects which originate from meteorological influences. Persistent winds can generate wind-driven currents, set-up of water levels and develop sea states that lead to wind-wave generation and swell. Atmospheric pressure variations can also depress or raise the water surface to generate positive or negative surges, respectively. Within the main estuaries, further complex circulations arise through mixing of fresh water with seawater (ABPmer, 2005).

The general pattern of surface water movements through the Irish Sea and in Liverpool Bay is mostly influenced by the form of the seabed and the alignment of the coast. Where additional obstacles to flow are placed on the seabed then there is potential for modification to the local hydrodynamic regime.

3.2 Water levels

The study area can be characterised as a macro-tidal setting, with tidal elevations across Liverpool Bay increasing from west to east. The mean spring tidal range in the offshore array area and along the cable route options is approximately 6.5 m, increasing to approximately 7 m at the landfall. Maximum tidal range on a largest astronomical tide is in the order of 9 m and approximately half this on neap tides. Summary tidal statistics for Llandudno (to the west of the landfall) and Hilbre Island (to the east) are shown in Table 4.

Table 4. Summary tidal data for Hilbre Island and Llandudno

Tide level	Llandudno	Hilbre Island
Highest Astronomical Tide	4.75 m	5.27 m
Mean High Water Spring Tide	3.85 m	4.07 m
Mean High Water Neap Tide	2.05 m	2.27 m
Mean Sea Level	0.25 m	0.22 m
Mean Low Water Neap Tide	-1.55 m	-1.83 m
Mean Low Water Spring Tide	-3.35 m	-3.63 m
Lowest Astronomical Tide	-4.25 m	-4.83 m
Mean Spring Range	7.2 m	7.7 m
Predicted heights in m above Chart Datum ; Llandudno CD = -3.85 m ODN; Hilbre Island CD = -4.93 mODN		

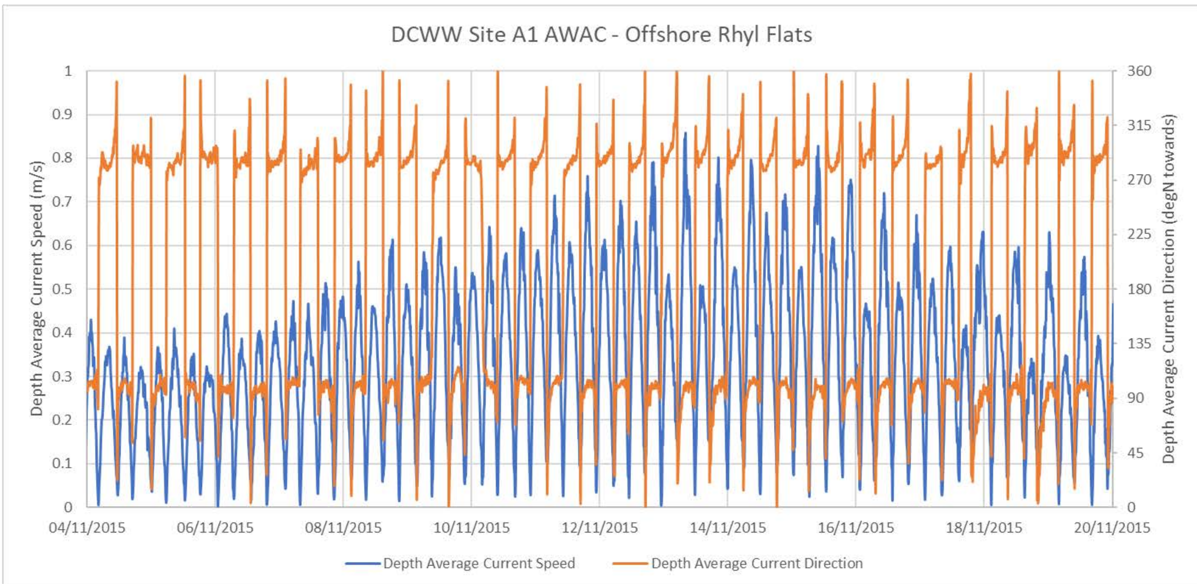
Source: UKHO, 2021

In the Irish Sea, the largest surges are generally associated with storms, secondary depressions, tracking eastward between Inverness and Shetlands. The largest surges occur in the eastern Irish Sea, with the 50-year return period surge level at the landfall predicted to be 5.38 m ODN (Howarth, 2005; 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.

3.3 Currents

Measured depth average current speed and direction at a location to the southeast of the array is shown in Figure 5, whilst a map of peak surface current speed on a mean spring tide is shown in Figure 6. Speeds are approximately 0.75 to 1.0 m/s in the array, decreasing towards 0.5 m/s along the offshore ECC towards the landfall. In the surrounding area, peak tidal current speeds are generally higher around Anglesey (to the west of AyM) and decrease gradually towards Liverpool (to the east). Currents can be considerably faster and more complex locally in the approaches to the Dee, Mersey and other smaller local estuaries. Mean neap tides are typically half the tidal range and peak current speed than mean spring tide values. Figure 6 also shows the relative size and orientation of mean spring tidal excursion ellipses throughout the region of interest from the UK Renewables Atlas (ABPmer *et al*. 2008). The ellipses illustrate the approximate distance and direction over which water is displaced during one mean spring tide (one flood and one ebb). The lengths of the ellipses are generally proportional to the associated peak current speed and are in the range 7-13 km across the array and offshore ECC, decreasing in a west to east direction and with proximity to the coast. The ellipses in this region are orientated broadly parallel to the adjacent coastline. They are relatively narrow, indicating that tidal currents are relatively rectilinear, i.e. with minimal variation in current direction from the main tidal axis over the tidal cycle.

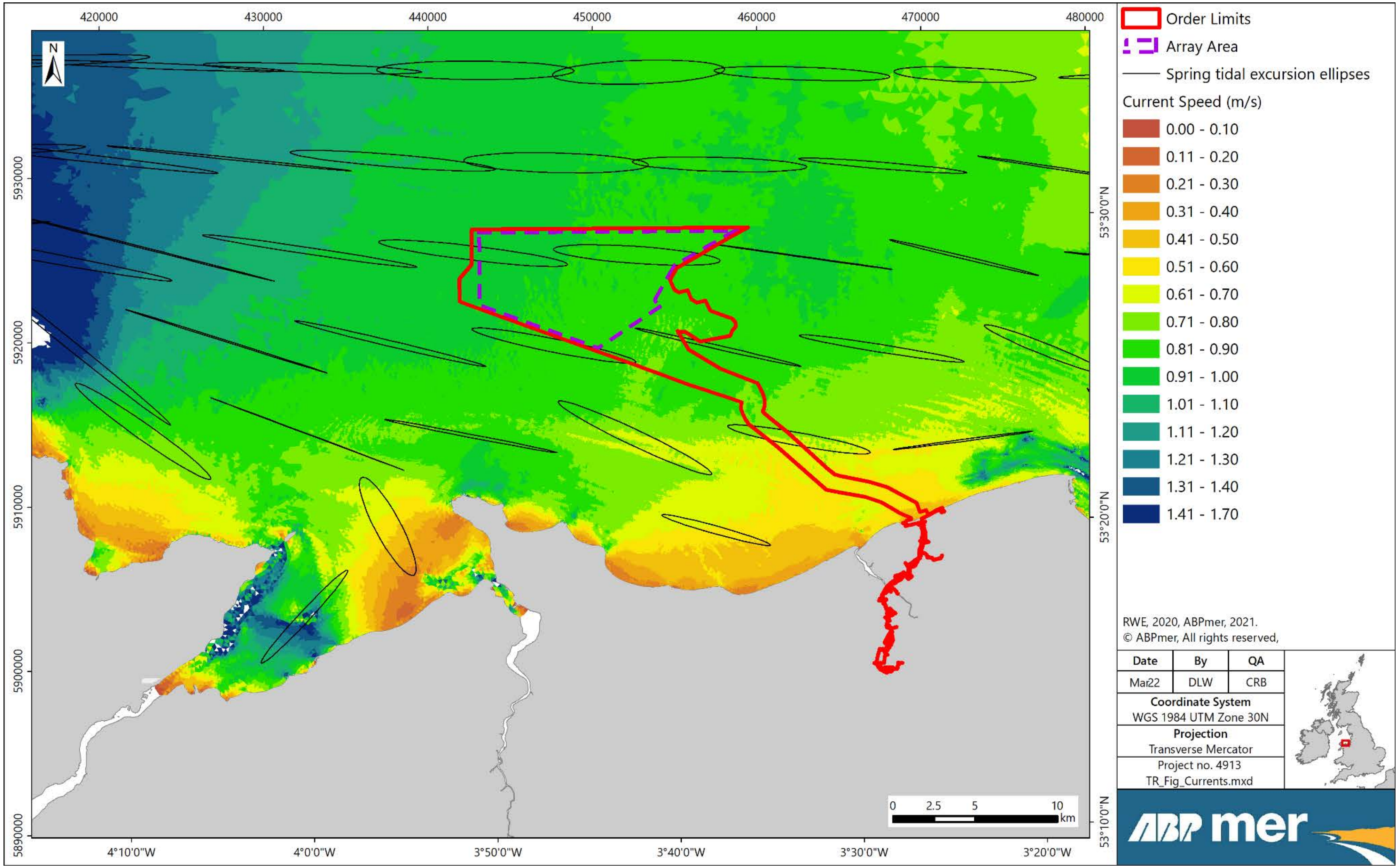
In Liverpool Bay, the maximum flood currents (to the east) are greater than the maximum ebb currents (to the west) because the tidal rise time on the flood is shorter than the time of fall on the ebb. This asymmetry drives sediment transport and is discussed in greater detail in Section 4.4.



Source: DCWW monitoring, Rhyl Flats)

Figure 5. Measured depth average current speed over a spring-neap cycle

Storm surges are typically associated with enhanced water levels and currents. However, the Irish Sea is semi-enclosed and the associated surge currents are weak, arising both directly from the wind drag at the sea-surface and to the sea surface gradients. The wind drag is limited to a surface layer of order 10 m thick, with a maximum speed at the surface of about 3% of the wind speed, decreasing rapidly with depth. The maximum 50-year return period depth-averaged current away from the coast is estimated to be ~0.5 m/s (Flather, 1987). Their direction is largely determined by topography not wind (Howarth, 2005).



Source: AyM hydrodynamic model (Volume 4; Annex 2.2) and UK Renewables Atlas (for tidal ellipses) (ABPmer *et al.* (2008)

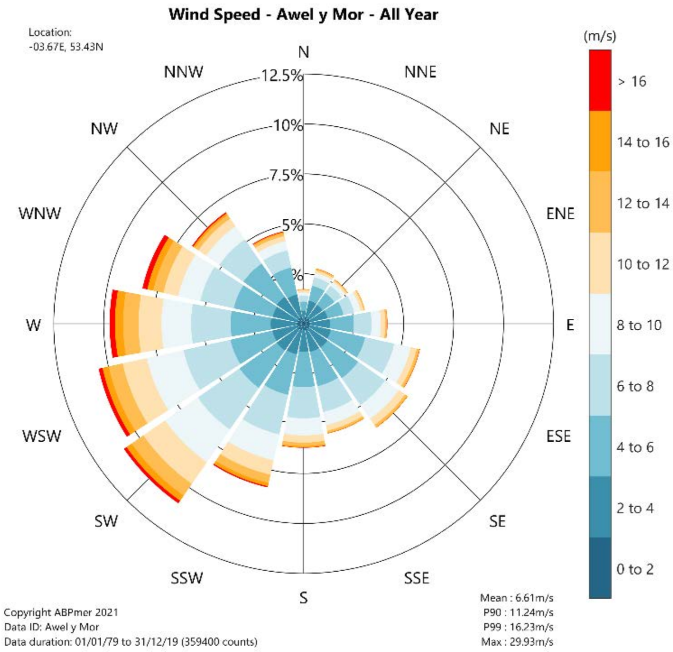
Figure 6. Peak surface current speed and tidal excursion ellipses for mean spring tide

3.4 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 and shows 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 are all originate from the west quadrant. The maximum observed wind speed in the record is 29.93 m/s.



Source: ABPmer, SEASTATES.net

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

3.5 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.

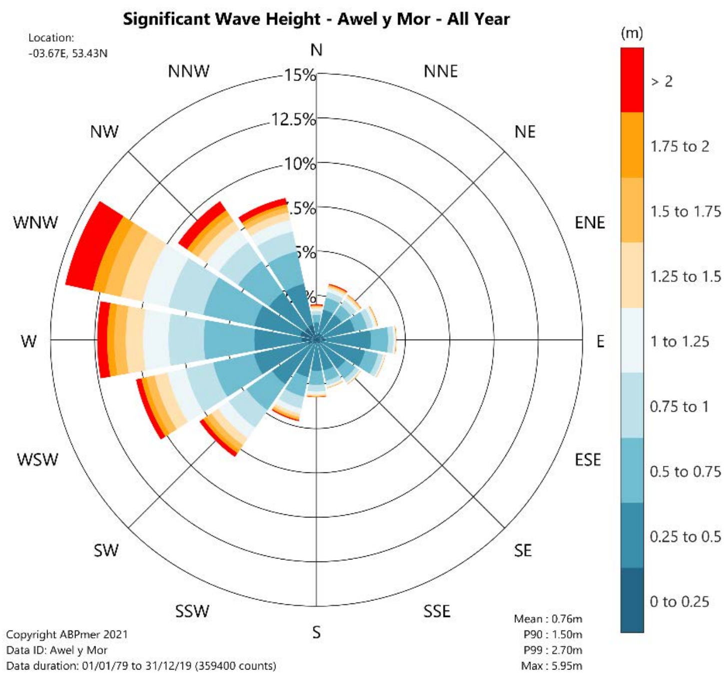
In shallower water, water depth is an additional limiting factor on the size of waves (ABPmer, 2005). Since the Irish Sea is sheltered with only two relatively narrow 'windows', along the axes of the St. George's and North Channels, the majority of waves are locally generated, of fairly short period and hence steep (Howarth, 2005).

The wave regime in Liverpool Bay can be regarded as the combination of swell waves moving into the area (having been generated remotely from the area) and locally generated wind-waves. The study area is open to northwesterly offshore waves that are generated within the Irish Sea. Locally generated waves related to the prevailing winds come from westerly, northwesterly and northern sectors.

A long-term hindcast record of wind data within study area is available from the ABPmer SEASTATES model. A frequency analysis of the data (which is presented as a wave rose in Figure 8) shows that:

- The most frequent wave direction is from the west, which accounts for approximately 30% of the record.
- The majority (90%) of the record comprises waves with period ≤ 4 seconds. These short wave-periods are indicative of wind waves and strongly suggest that the wave regime across the application site is dominated by waves of this type;
- Longer period waves (Tp ≥ 8 seconds) are observed although account for <1% of the record; and
- The largest wave height observed in the record was 5.9 m which approached from the west-northwest.

This long-term hindcast record is largely consistent with the metocean observations collected during the GyM oceanographic survey in 2005 (see RWE npower (2005)), despite the differing length of the records.



Source: ABPmer, SEASTATES.net

Figure 8. Rose plot of significant wave height and direction 1979 to 2019

3.6 Future change

Extremes analysis of the long-term wave hindcast record available from the ABPmer SEASTATES model is shown in Table 5. It is found that the largest waves come from the west-northwest with heights of approximately 4.4 m for a 1:1-year event, increasing to 7.26 m for a 1:50 year event.

Table 5. Extreme value analysis of significant wave height and wave period.

Directional Sector	Case (Return Period)	Significant Wave Height (m)	Peak Wave Period (Tp, s)	Mean Wave Direction (°N)	Wind Speed @10 m (m/s)	Wind Direction (°N)
W	50% no exc	0.80	4.66	270	5.9	270
	0.1 yr RP	2.09	6.04	270	11	270
	1 yr RP	3.52	7.84	270	15	270
	10 yr RP	4.84	9.20	270	17	270
	50 yr RP	5.72	10.00	270	21.4	270
	100 yr RP	6.16	10.38	270	21.4	270
WNW	50% no exc	0.91	5.14	292.5	6.5	292.5
	0.1 yr RP	2.64	7.03	292.5	12.7	292.5
	1 yr RP	4.40	9.07	292.5	17.3	292.5
	10 yr RP	6.16	10.73	292.5	21.4	292.5
	50 yr RP	7.26	11.65	292.5	22.3	292.5
	100 yr RP	7.81	12.08	292.5	26	292.5
NW	50% no exc	0.73	4.65	315	4.9	315
	0.1 yr RP	2.42	6.74	315	12	315
	1 yr RP	3.96	8.62	315	16.3	315
	10 yr RP	5.50	10.16	315	21	315
	50 yr RP	6.60	11.13	315	22.3	315
	100 yr RP	7.04	11.50	315	22.3	315
NNW	50% no exc	0.66	4.37	337.5	5.3	337.5
	0.1 yr RP	2.20	6.40	337.5	11	337.5
	1 yr RP	3.63	8.22	337.5	15.5	337.5
	10 yr RP	5.06	9.71	337.5	19.8	337.5
	50 yr RP	6.05	10.62	337.5	24	337.5
	100 yr RP	6.49	10.99	337.5	21.3	337.5
N	50% no exc	0.57	4.02	0	4.37	0
	0.1 yr RP	2.09	6.25	0	11	0
	1 yr RP	3.52	8.11	0	15	0
	10 yr RP	4.84	9.51	0	17	0
	50 yr RP	5.72	10.34	0	21.4	0
	100 yr RP	6.16	10.73	0	21.4	0

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 0.35 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).

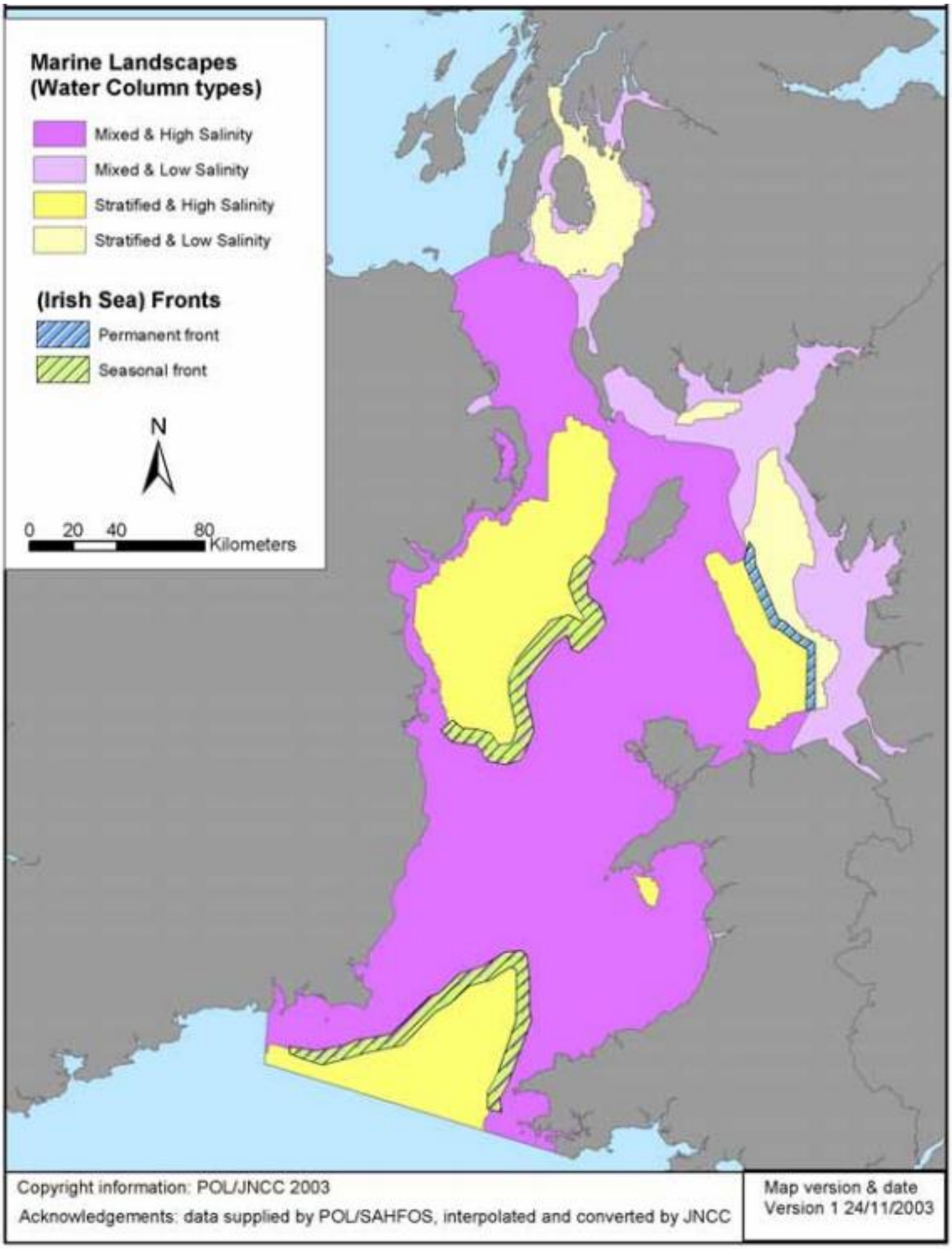
UKCP18 also includes projections of changes to storm surge magnitude in the future as a result of climate change. However, it is found that UKCP18 projections of change in extreme coastal water levels are dominated by the increases in mean sea level with only a minor (<10%) additional contribution due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

3.7 Stratification and frontal systems

A 'front' is an area separating two distinct water masses, with different densities as a result of varying salinity or temperature properties. Within the Irish Sea, a number of seasonal and permanent fronts exist due to the freshwater influence from the surrounding land, compared with the water properties of the sea area. To the northeast of the AyM array is the permanent Liverpool Bay front (Figure 1 and Figure 9), which extends northwards from the River Dee. Stratification related to this permanent front is predominantly associated with salinity gradients, although temperatures associated with outflows from the Dee, Mersey and Ribble estuaries can also have a seasonal effect (Norman, *et al*., 2014).

Conditions are most suitable for stratification at neap tides when the weather is calm and when river discharges are large. Once the water column has stratified surface to bed temperature differences can also occur in summer (Howarth, 2005)

Minimum stratification in Liverpool Bay is observed at the time of local high water, where the tides are dominated by a standing wave. The standing wave allows the fresh surface water to move faster than the underlying more-saline water on the ebb tide, creating a stratified water column. In the absence of mixing this reaches a maximum stability at, or soon after, low water. Then, on the flood tide, the shear acts to produce a reverse differential advection, which tends to reduce stratification reaching a minimum at, or near high water (ABPmer, 2005).



Source. JNCC Irish Sea Pilot (Vincent *et al.* 2004)

Figure 9. Water column marine landscapes and Irish Sea fronts

4 Sediments, Sediment Transport and Morphology

4.1 Seabed sediments

4.1.1 Overview

The seabed within Liverpool Bay largely consists of either sandy gravel or gravely sand (BGS, 1984). The seabed is relatively free of fines (defined as particles of less than 0.063 mm), with waves generally preventing the deposition of mud or silt, whilst tidal currents prevent the deposition of mud further offshore within Liverpool Bay (ABPmer, 2005).

The mean particle size of sand in the outer parts of Liverpool Bay is as large as 0.42 mm, equivalent to medium to coarse sand. In general, the median sand size decreases further inshore, this being indicative of a net shoreward transport of the finer fractions with the residual coarser fractions remaining offshore. Closer inshore there is a significant reduction in particle size with the material on the near-shore banks being about 0.20 mm in diameter. However, within the intertidal zone in areas where sandy sediment dominates, there is an increase in grain size, the median diameter of 0.25 mm being fairly constant along the coastline.

To the south of the array is the Constable Bank sandbank which is described in more detail in Section 4.5.4. Larger accumulations of sand are also evident in nearshore areas, characterised by relatively wide shallow gradient sandy beaches and offshore sand flats. On the section of coast where the export cable makes landfall (just to the east of Rhyl), the relatively shallow gradient beach extends sub-tidally approximately 10 km or more offshore. Here, the beach merges with the Rhyl Flats offshore sand flats complex, including the eastern end of Constable Bank and various sandbank features in the approaches to the Dee estuary. These are described in more detail in Section 5.

The Dee and Clwyd Estuaries are located within Liverpool Bay, to the southeast of the array. Much of the seabed sediments in the Dee are characterised by silty sand sediments, which overlie partly eroded boulder clay (glacial till). The seabed sediments in the upper reaches of the Clwyd Estuary are largely composed of well-sorted sand and mud. The seabed in the lower reaches of the estuary is largely composed of mud and gravel (Parsons & Pugh-Thomas, 1979).

4.1.2 Array

Seabed sediment characterisation within the array has primarily been delineated from variations in the reflectivity of the side scan sonar (SSS) data collected during the AyM geophysical survey, with sediment descriptions defined using the results of the environmental investigation (Fugro, 2020a), and BGS mapping (BGS, 1984). The east of the array is characterised by sandy sediments (inferred from lower SSS reflectivity) and numerous sand waves and megaripples, whilst the west of the array is characterised by sandy gravel (a more homogenous, medium reflectivity) (Figure 10). Seafloor sediments identified from environmental camera transects and grab samples, were found to comprise mostly of sand with varying proportions of gravel content, similar to the BGS mapping (Fugro, 2020a).

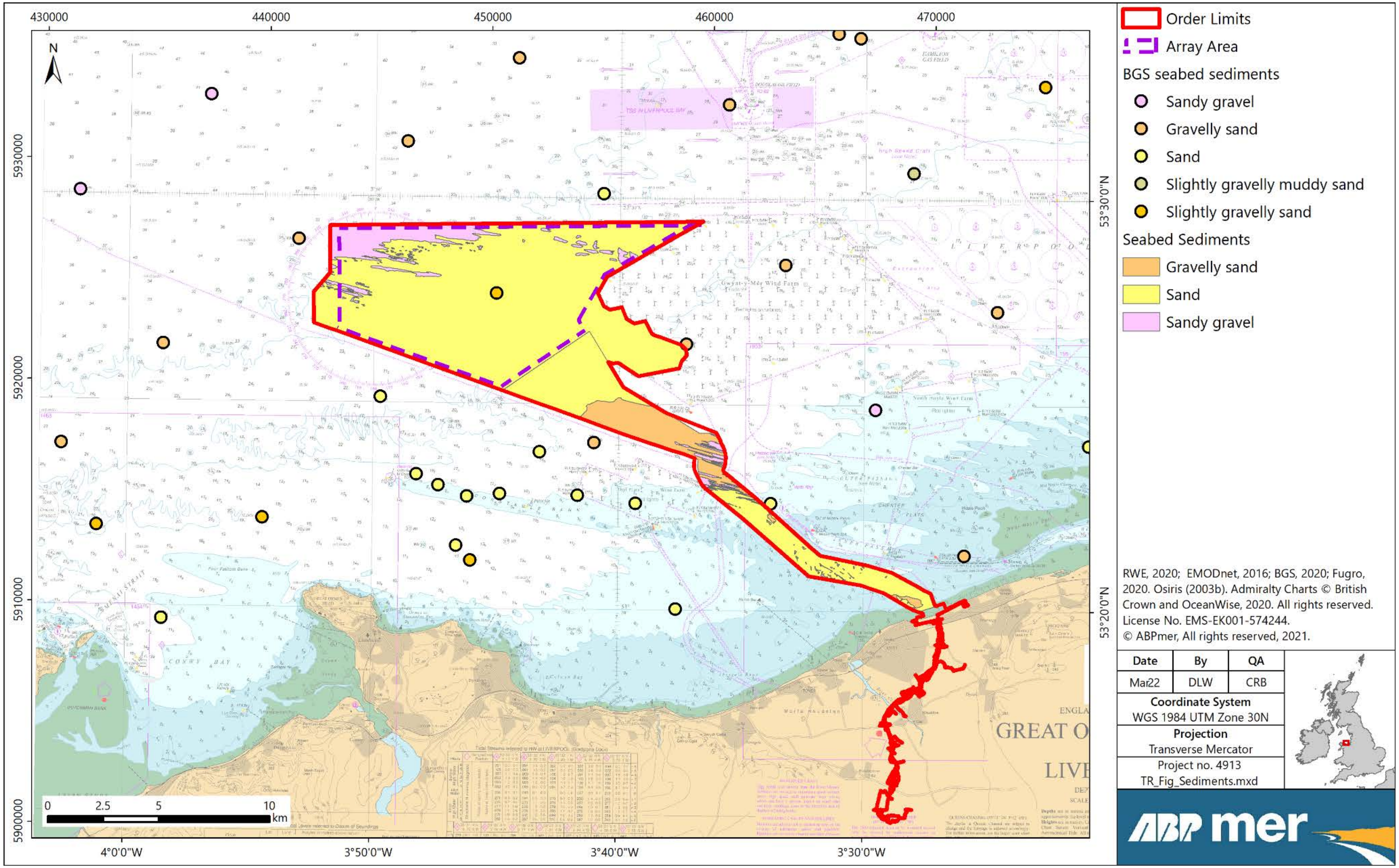


Figure 10. **Seabed sediments**

4.1.3 Offshore ECC

As for the array, seabed sediment characterisation has primarily been delineated from variations in the reflectivity of the AyM SSS data. The seabed within the offshore ECC comprises mostly sand with varying proportions of gravel (Figure 10). However, isolated patches of sandy gravel have been identified approximately midway between the landfall and array (Fugro, 2020b). These classifications generally match well with the less detailed BGS seabed sediment descriptions (BGS, 1984)

4.2 Geology and sub-strata

4.2.1 Overview

The solid geology of the Irish Sea broadly divides along a line from the Mull of Galloway through the Isle of Man to Anglesey. To the east a number of basins are present, the largest of which is the eastern Irish Sea Basin. At least three major Permo-Triassic and younger sedimentary basins have developed in this area. The first developed during the early Palaeozoic, the second during the Carboniferous and the last during the Permian and Mesozoic. All three main phases of sedimentation are represented in the Liverpool Bay area, capped by a thin cover of Quaternary material.

The Quaternary geology of the AyM array and offshore ECC has been shaped and influenced by a series of glacial events during the retreat of the British Isles ice sheet and Irish Sea Ice Stream (ISIS). Overlying the bedrock is an extensive sequence of Quaternary (150,000 years ago to present) glaciogenic and seabed sediments. Three major phases of Mid-Late Quaternary glaciations are identified in the Irish Sea, called the Elsterian, Saalian, and Weischelian. The lattermost of these glaciations is believed to be the most significant influence on the Quaternary sediments of AyM, due to ice cover in excess of 2 km thickness, lasting from *circa* 30,000 to 22,000 years ago (Hubbard *et al*, 2009).

4.2.2 Array and offshore ECC

On the basis of the sub-bottom profile data collected during the AyM geophysical survey, four main units have been interpreted in the array and offshore ECC, all originating from the past 30,000 years. The distribution, thickness and sedimentary characteristics of these units are summarised in Table 6 and Figure 11 (Fugro, 2020a,b).

The seabed sediments across the AyM and offshore ECC are the Holocene Surface Sands Formation (SSF). They are interglacial superficial sediments, typically composed of sands, silts and clays (Mellet *et al*, 2015) that are unconsolidated in nature and mobilised in the form of small bedforms and larger sand waves. The thickness of the Holocene SSF across the wider study area is typically <5 m (Bide *et al*., 2013). A coarse grained 'lag' deposit deriving from winnowing currents may be exposed at the seabed where the overlying mobile sediment has been removed (Mellet *et al*, 2015).

The pre-Holocene sediments at the site include the glacial Western Irish Sea Formation (WIS A and B Upper and Lower) and the older Cardigan Bay Formation (CBF). The WIS A formation is considered to represent the transition to late glacial in the Weischelian. The underlying WIS B Upper is a stratified unit which bears boulders, cobbles and shallow gas.

The depositional history of the CBF records Saalian into Weischelian, with the former draining the ice sheet margin due to deglaciation at around 115,000 years ago when the region was subject to marine transgression.

Table 6. Main stratigraphic units

Unit	Summary
R01 Holocene sediments;	Predominately unconsolidated, loose, medium sands with occasional shells and shells fragments and fine, rounded gravel. Up to 9.4 m thick in the southeast of the array and 7.2 m within the offshore ECC.
R02 Channel infills;	[No lithological description available] Channels tentatively interpreted as being formed from Welsh Ice Cap meltwater early in the marine transgression into the Holocene Up to 6.7 m thick in the east and centre of the array
R03 Western Irish Sea Upper;	Comprises fine to medium sand, progressing to fine to coarse sand and gravel with depth. Sandy boulder clay also potentially present. Up to 11.1 m thick in the south of the array and (locally) in the offshore ECC. Generally increasing in thickness from north to south.
R04 Western Irish Sea Lower.	Medium dense to dense, fine to coarse sand with occasional gravel and shell fragments, progressing into stiff, gravelly clay with cobbles. Up to 10 m thick in the west and east of the array and (locally) in the offshore ECC

.

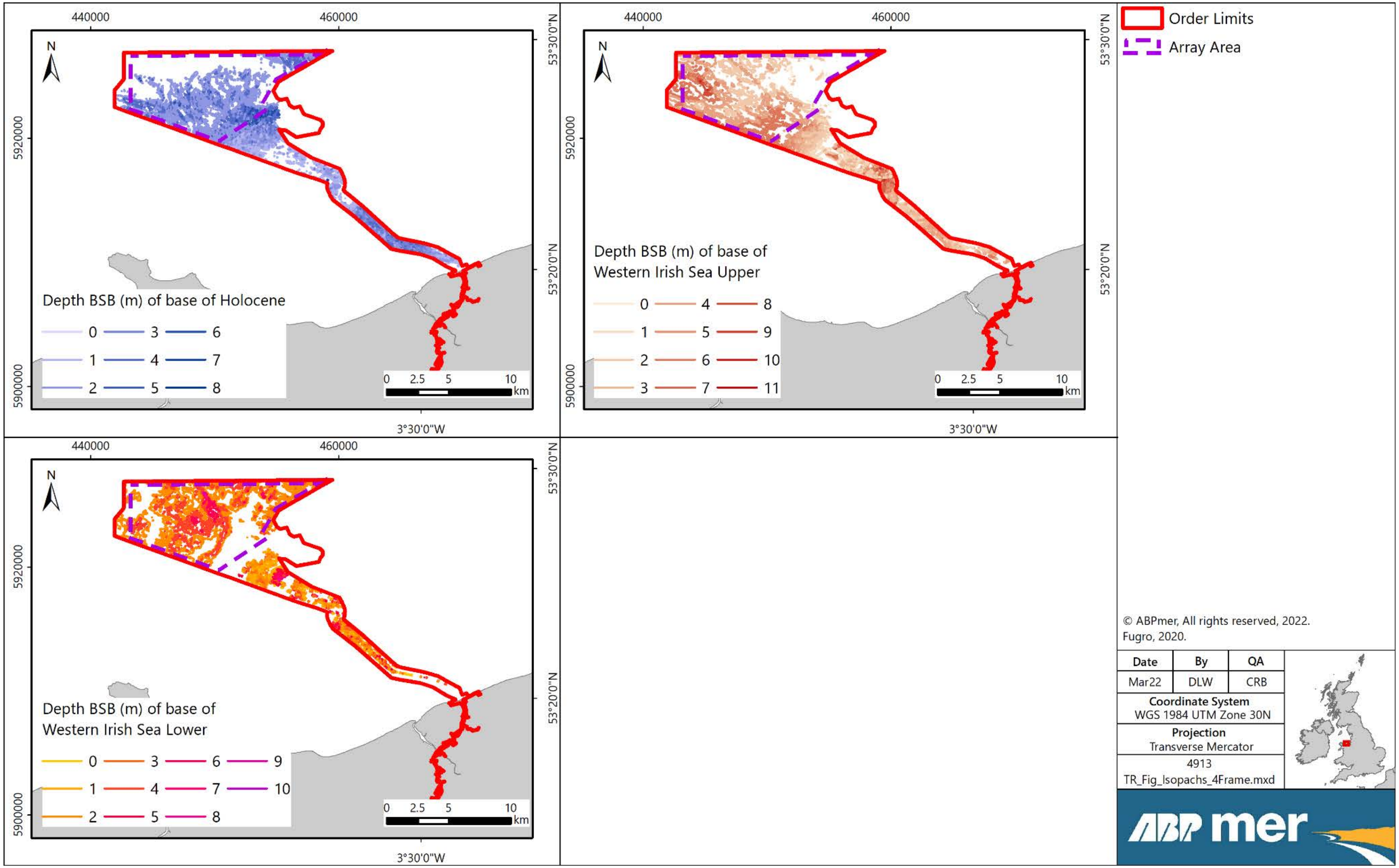
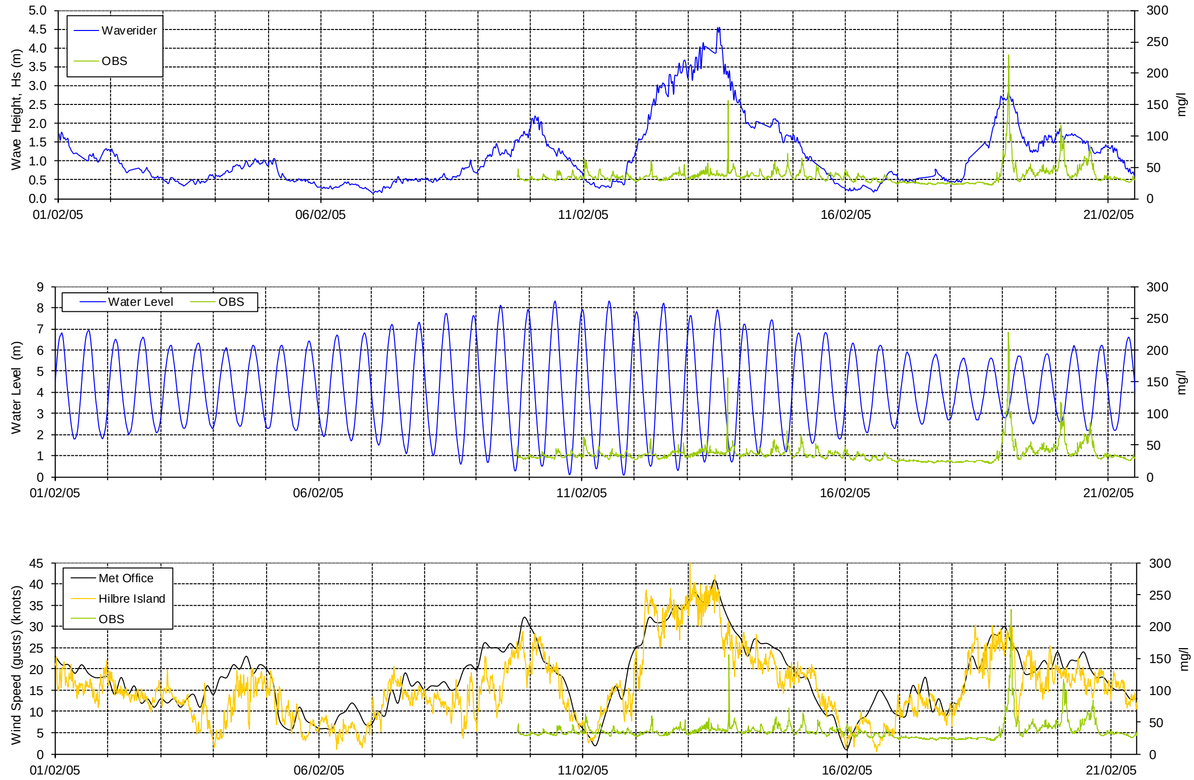


Figure 11. Distribution and thickness of sedimentary units.

4.3 Suspended sediments

Optical Backscatter data (OBS) was previously collected from a location on the southern margin of the AyM array as part of the GyM oceanographic survey (Figure 3). The data approximately covers a spring-neap cycle (in February 2005), during which time short periods of stormier conditions were observed. The available data suggest that close (0.1 m) to the seabed, SSC at times exceeded 200 mg/l although was more typically in the range 25-50 mg/l (Figure 12). The comparatively weak correlation between SSC and stormier conditions can be explained at least in part by the relatively deep water at the monitoring location (~ 22 m below LAT) moderating the strength of the wave orbital currents at the bed.

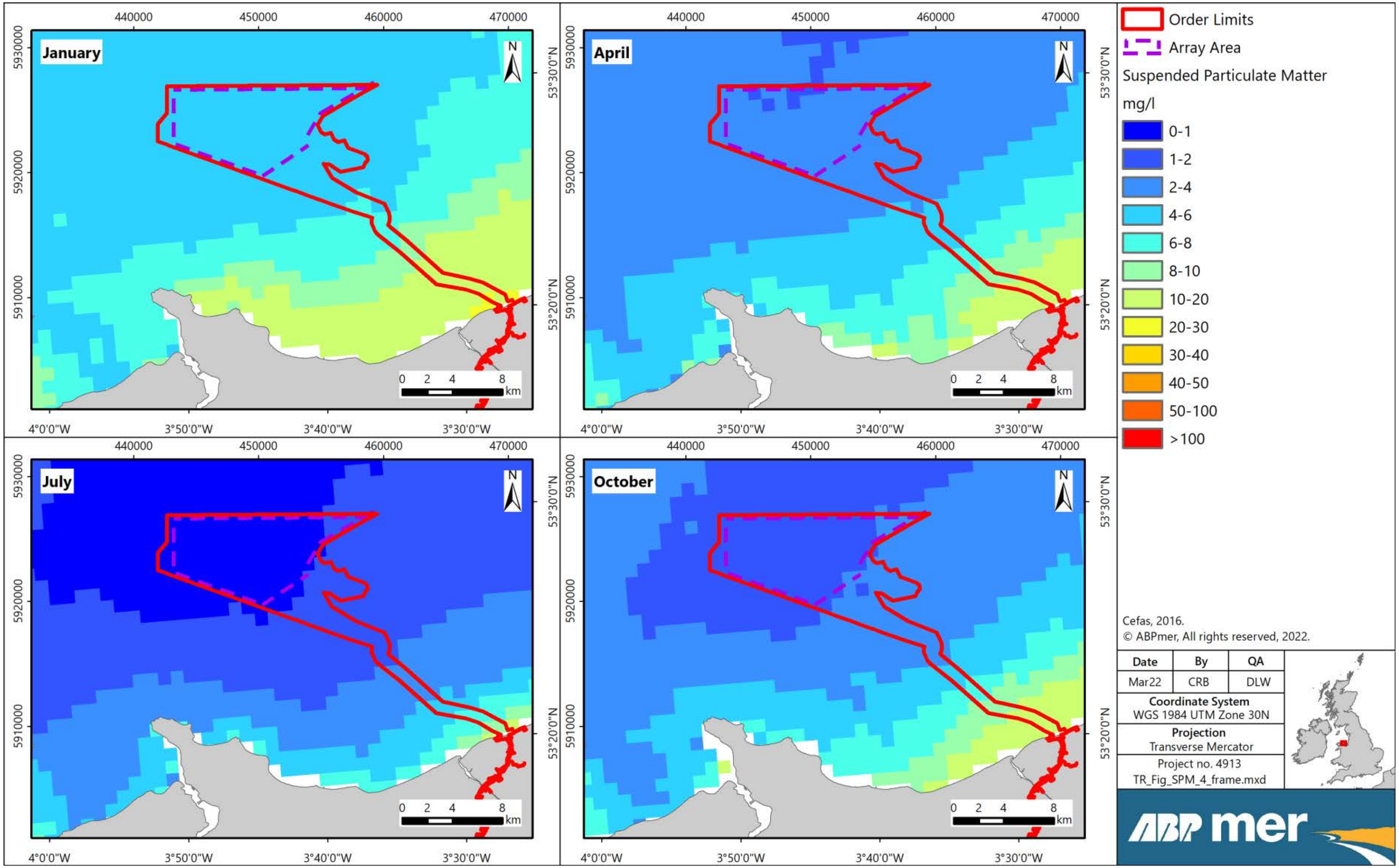


Source: RWE Npower, 2005

Figure 12. Relationship between SSC, waves, water levels and wind

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 for the array area.

Within the AyM array, average (surface) SPM is approximately 2 to 3 mg/l, increasing during winter months to values of approximately 5 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 generally slightly higher, reaching a peak close to the coast at the landfall. During winter months, mean values are between 5 to 25 mg/l although, as for the array, higher values are anticipated during spring tides and storm conditions, with the greatest concentrations encountered close to the seabed.



Source: Cefas, 2016

Figure 13. Average suspended particulate matter concentration for the period 1998-2015

Within the wider study area, a permanent turbidity maximum is observed north of Anglesey - the 'Anglesey Turbidity Maximum' – which is generated by strong tidal dissipation (Robins et al. 2014). In it, surface SPM concentrations in excess of 10 mg/l compare to background levels in the surrounding water of 3-4 mg/l (Bowers et al., 1998) although these levels may be modulated by natural variability in the North Atlantic Oscillation, which correlates to the wind climate (White et al. 2003).

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 decrease to the east, away from the narrows between the southern side of the Isle of Man and the coast of Anglesey (Figure 6).

Coughlin et al. (2021) recently used numerical modelling to assess the role of currents and waves in driving seabed mobility throughout the Irish Sea region. Exceedance frequency values were used to calculate a number of sediment disturbance and mobility indexes with spatial variability illustrated through a series of mapped layers. On the basis of this research, the AyM array is found to be located within an area of seabed in which disturbance is dominated by tidal forcing rather than waves. Along the offshore ECC, waves become more important.

Glacial deposits to the south of the Isle of Man and in St George's Channel are subjected to high tidal currents. Erosion of these deposits causes sand-sized material to be transported northwards and eastwards in the direction of the strongest tidal flow. The Irish Sea is thus a major source of sand deposited within Liverpool Bay.

The general regional scale patterns of sediment transport in Liverpool Bay are shown in Figure 2 (which is derived from a similar figure presented in Halcrow, 2010a). Net sediment transport along the north Wales coastline is predominantly by bedload in an easterly direction, at a moderate to high rate for sands, with some transport of finer material in suspension. In offshore areas, the direction is the result of the tidal current asymmetry; in shallower nearshore areas and on the beaches, the direction is the combined result of tidal current asymmetry and the relative angle of approach of waves. There are predicted to be (southerly) sediment transport links between Constable Bank and Rhyl Flats and the adjacent coastline, driven by combined tidal and wave forcing but this is poorly understood (Halcrow, 2010c).

The transport rate is moderate to high for sand, but lower for shingle as a consequence of the hydrodynamic energy climate (Motyka and Brampton, 1993). The transport of sand between Liverpool Bay, the Dee and the Mersey follows the residual currents within the Bay. There are few natural barriers to the net eastward drift in this region, although down drift problems are prominent due to coastal protection schemes (Motyka and Brampton, 1993).

4.4.2 Array and offshore ECC

An analysis of potential sediment mobility within the AyM array and offshore ECC in response to tidal currents is presented in Figure 14, Figure 15 and Table 7. This is based on a 30-day record of current data extracted from the hydrodynamic model developed to inform the assessment (Volume 2, Annex 2.2; Awel y Môr Offshore Wind Farm: hydrodynamic and wave modelling calibration report). Table 7 sets out the proportion of the time series during which each sediment fraction is potentially mobilised whilst Figure 14 shows the direction of residual flow.

It is apparent from Table 7 that tidal currents have the potential to regularly mobilise fine and medium sand sized material within the AyM array and offshore ECC. Very coarse sand is only mobile during springs whilst granule sized gravel is not mobile.

Potential mobility of sediment in response to tidal currents is expected to diminish along the offshore ECC with increasing proximity to the coast, in response to slower current speeds (Figure 6). However, close inshore, mobilisation of material by wave induced currents will gradually increase, especially landward of the depth of closure (which is calculated to be ~5.1 m LAT; see Section 5.3).

Both the numerical sediment transport modelling and available morphological evidence (Section 4.5) suggests that bedload transport of sand sized material occurs in a broad net easterly direction across the study area. However, closer inshore some transport occurs to the southwest, associated with flows into/out of the Dee estuary, whilst in very shallow waters (such as across Rhyl Flats), modelled tidally driven transport pathways are less consistent with the observed direction where wave driven sediment transport becomes increasingly influential (Figure 15, Figure 16). More complex patterns of tidally driven sediment transport are also predicted around Constable Bank, with net transport in a clockwise direction, with predominantly easterly transport on the northern flank and westerly transport on some parts of the southern flank (Figure 17).

The suggestion of bedload transport in an easterly direction in offshore areas is consistent with published information on the direction of net sediment transport in this region (e.g. Kenyon & Cooper, 2005; Halcrow, 2010a)): this pattern can be readily explained as a result of the relatively higher peak flood current speeds, which lead to a longer net duration of eastward flowing currents (Section 3.3). The finding of more westerly transport close to the coast is consistent with the modelling work undertaken by Halcrow (2010b).

Finer material 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 the modelled data shown in Figure 14, residual flow is found to be highly variable across the AyM array and much of the offshore ECC although is generally towards the west in inshore areas.

Table 7. Estimated potential sediment mobility (tidal currents)

Location		Sediment Fraction			
		Fine Sand (215 µm)	Medium Sand (425 µm)	Very Coarse Sand (1,200 µm)	Granule Gravel (2,000 µm)
1 (array)	Mobility Summary	Not mobile during lowest neaps	Not mobile during lowest neaps	Only mobile during springs	Not mobile
	Mobility % time	51%	41%	7%	0%
2 (array)	Mobility Summary	Not mobile during lowest neaps	Not mobile during lowest neaps	Only mobile during springs	Not mobile
	Mobility % time	43%	33%	2%	0%

Location		Sediment Fraction			
		Fine Sand (215 µm)	Medium Sand (425 µm)	Very Coarse Sand (1,200 µm)	Granule Gravel (2,000 µm)
3 (offshore ECC)	Mobility Summary	Not mobile during lowest neaps	Not mobile during lowest neaps	Only mobile during springs	Not mobile
	Mobility % time	51%	42%	7%	0%
4 (offshore ECC)	Mobility Summary	Not mobile during lowest neaps	Not mobile during lowest neaps	Not mobile	Not mobile
	Mobility % time	45%	34%	0%	0%

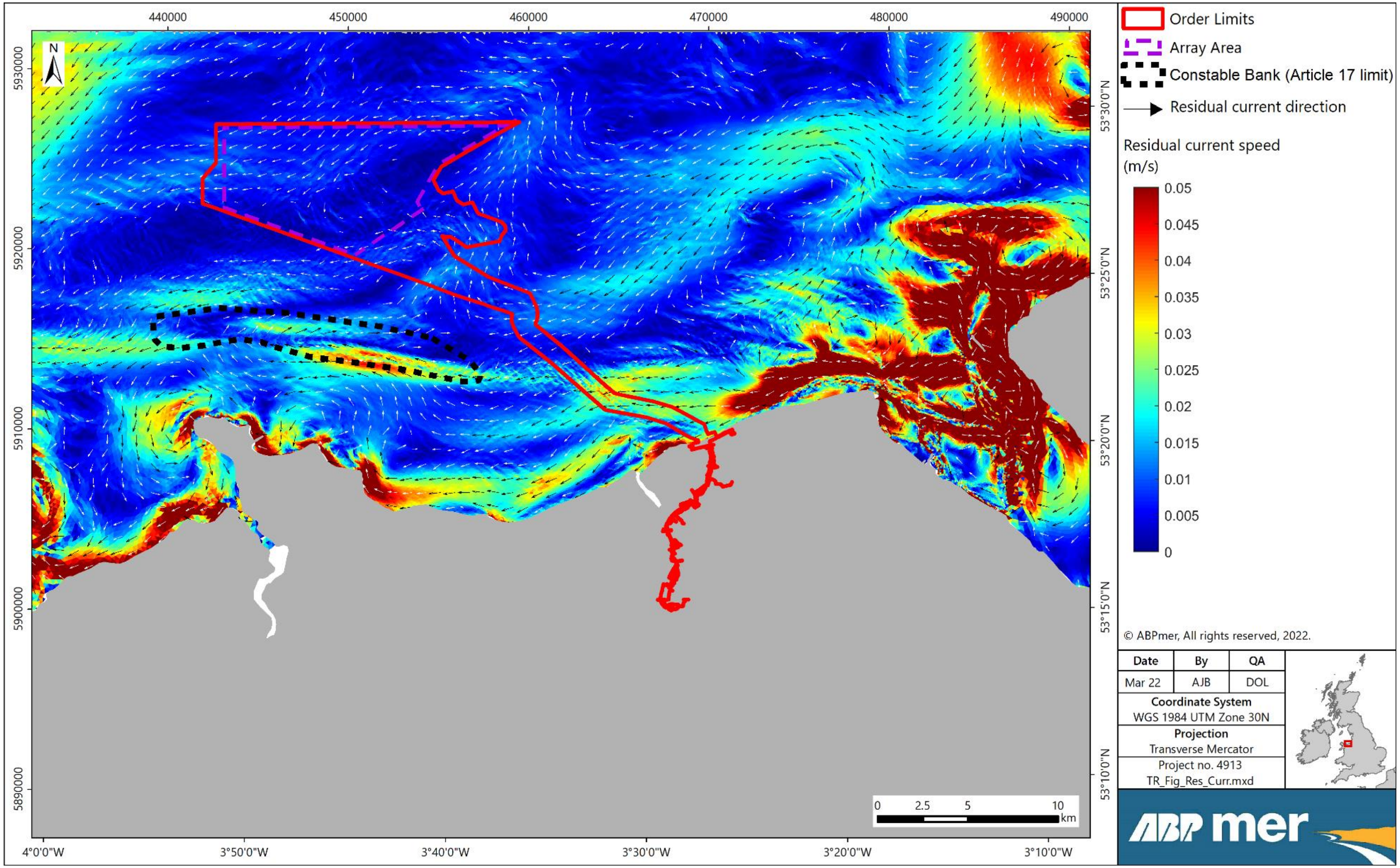


Figure 14. **Baseline residual tidal current speed and direction measured over a representative spring-neap tidal period.**

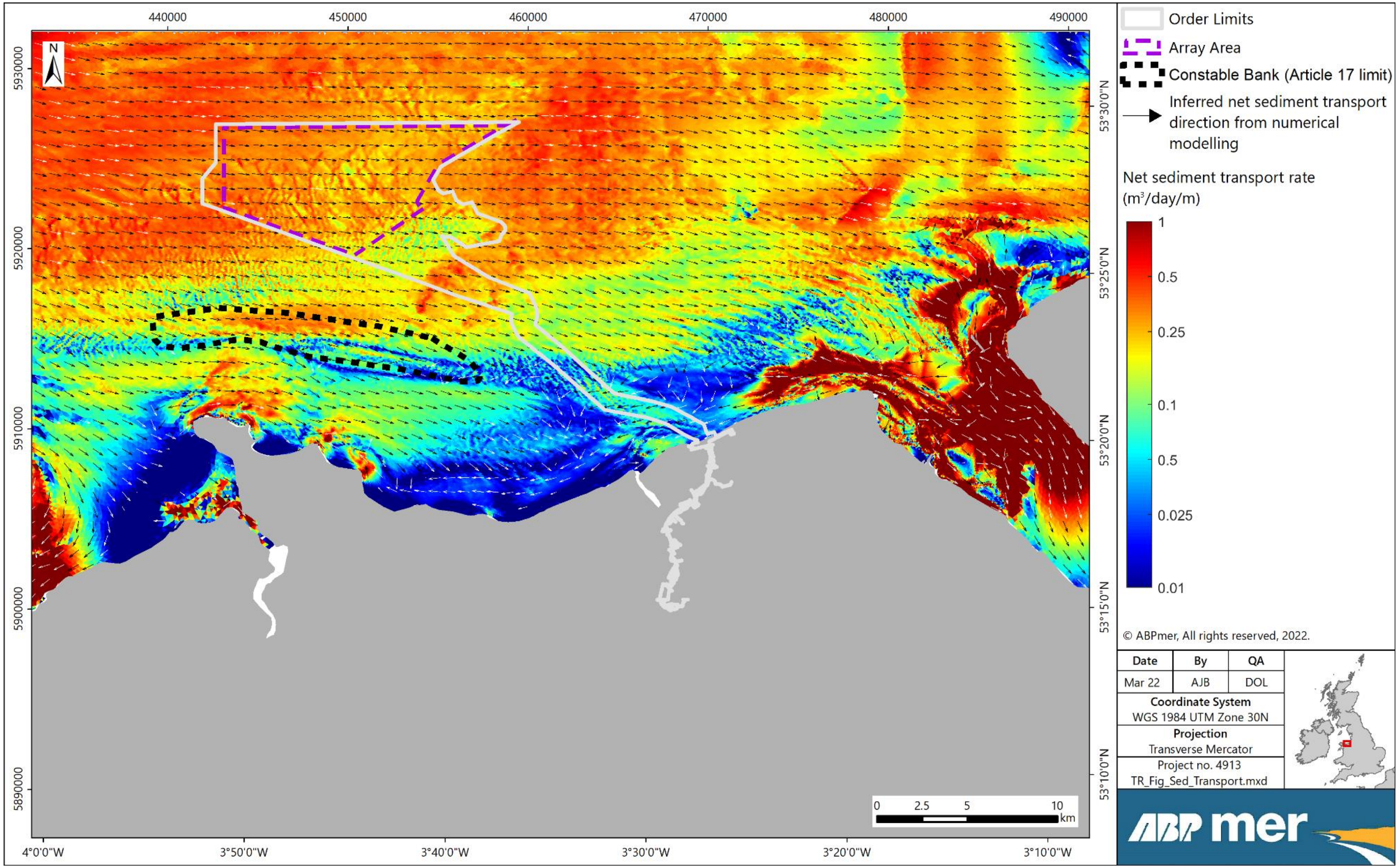


Figure 15. **Baseline residual sediment transport rate and direction across the study area, measured over a representative spring-neap tidal period.**

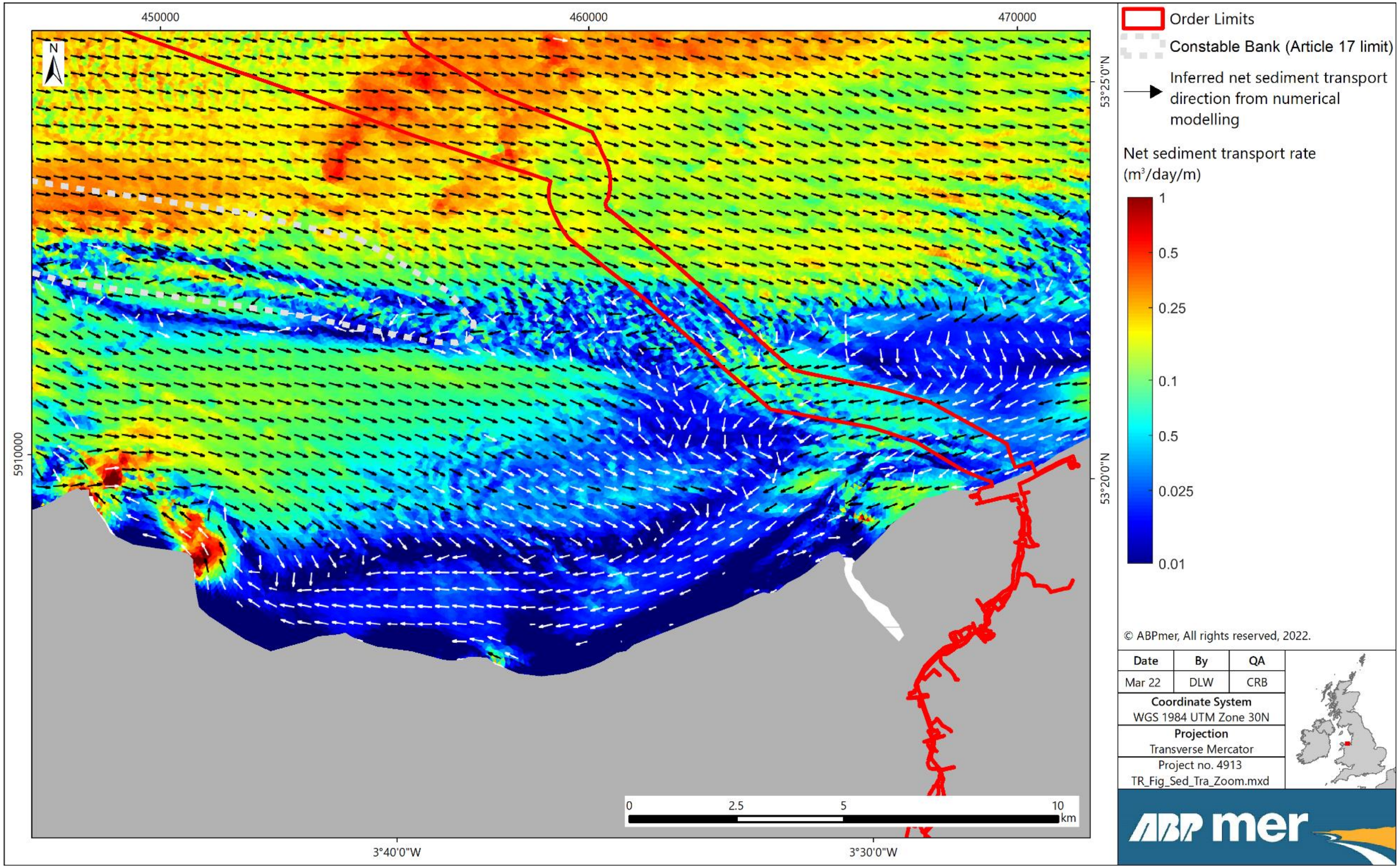


Figure 16. **Baseline residual sediment transport rate and direction in the vicinity of Constable Bank and Rhyl Flats, measured over a representative spring-neap tidal period.**

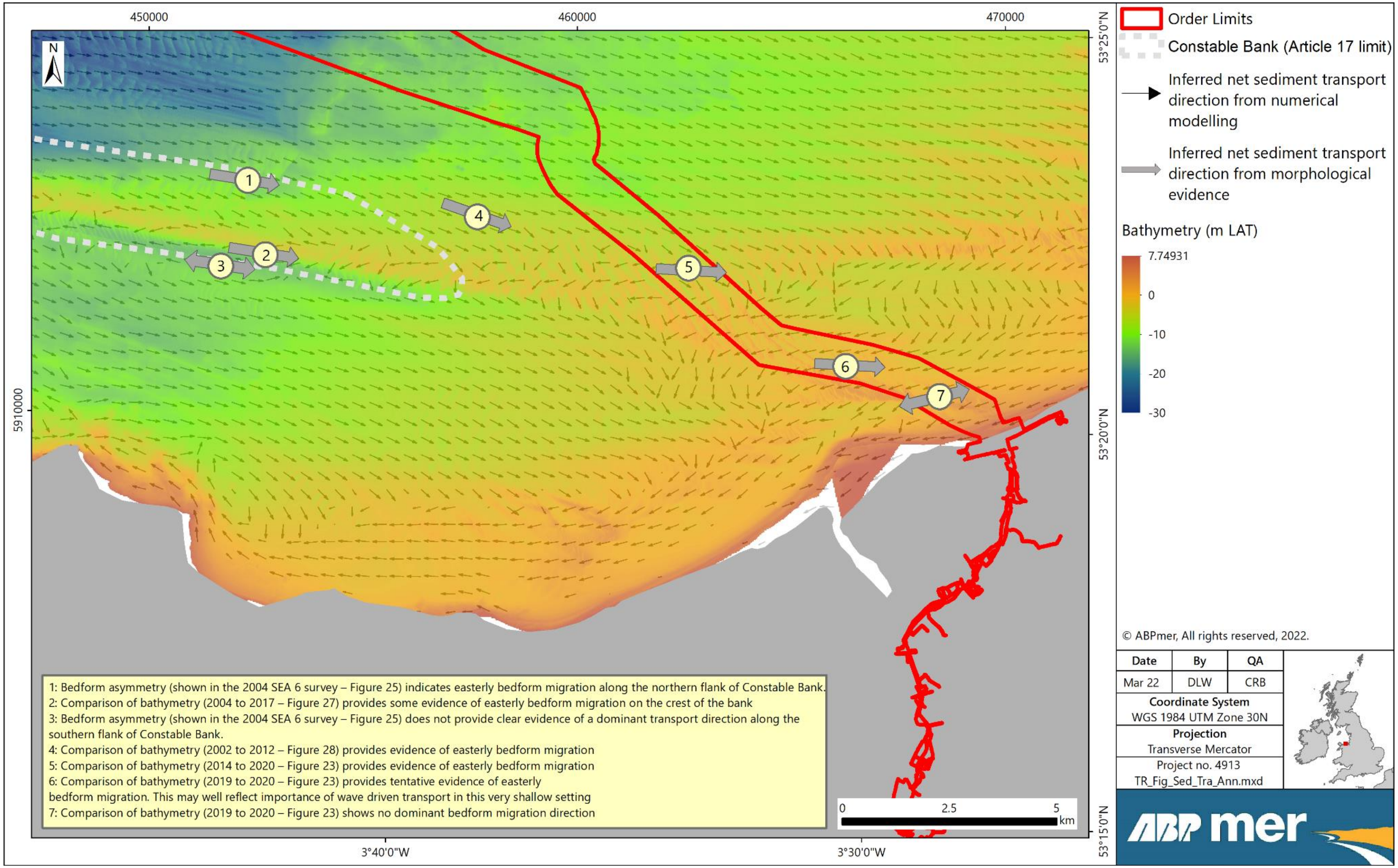


Figure 17. **Consideration of modelled baseline residual sediment transport in the vicinity of Constable Bank and Rhyl Flats alongside morphological evidence for sediment transport**

4.5 Morphology

4.5.1 Overview

The seabed across the study area is covered by a wide range of mobile sediments, the grade of which is controlled largely by the speed of the local tidal streams and the effects of the rise in sea level during the early Holocene. Much of Liverpool Bay is covered with sand and gravel, and some of the seabed areas off the north Wales coast are the focus of aggregate extraction activities; muddier sediment is found in the estuaries entering the bay (Barne *et al*. 1996).

As described in ABPmer (2005), Liverpool Bay is generally characterised by three main seabed formations:

- Sand ribbons and patches with mega-ripple relief of <0.3 m;
- Sand wave fields with an amplitude of approximately 2 m and wavelength of between 10 and 20 m; and
- Individual sand waves with an amplitude of approximately 12 m which often carry minor transverse waves.

The distribution and behaviour of these bedforms is described in this section, firstly for the array and offshore ECC and then for the wider study area.

4.5.2 Array

Water depths within the AyM array generally increase towards the northwest, between approximately 15 and 42 m below LAT (Figure 18). The seafloor in the southeast is characterised by undulating sand waves and megaripples, whereas the seafloor in the northwest is mostly featureless (Figure 19). The local absence of larger bedforms despite a plentiful supply of sediment is likely due to a locally lower mean peak current speed (as shown at a coarse scale in Figure 6).

Megaripples were typically found to be around 0.3 to 2 m in height, with wavelengths varying between 5 and 25 m. Sand waves were typically found to be around 3 to 8 m in height, with wavelengths varying between 25 and 750 m. Crests are typically orientated north to south. Maximum seabed gradients are ~1.4° over the relatively featureless seabed, 30° over the megaripples, and 18.5° over the sand waves (Fugro, 2020a).

During survey operations it was observed that the sand waves were actively mobile and migrating significantly in the time between adjacent survey lines (Fugro, 2020a). This observation is consistent with known empirical relationships between current speed and sediment availability (Appendix A) and known asymmetry in the tidal regime (Section 3.3). It is also confirmed by a comparison of the 2020 multibeam data collected from the array with (i) older (single beam) UKHO data collected in 1987 (Figure 20); (ii) data collected in 2003, as part of the GyM geophysical survey (Figure 21); and (iii) recent multibeam data collected from the AyM array area in 2019-2020 by UKHO (Figure 22).

The comparison of the 2003 (GyM) and 2020 (AyM) multibeam datasets provides tentative evidence for reversed sediment wave migration, with the translation of crests from east to west seemingly at odds with (i) the asymmetry of the bedforms (which would indicate movement from west to east); (ii) the wider understanding of bedload sediment transport in this region (e.g. Kenyon & Cooper, 2005; Halcrow, 2010b); and (iii) patterns of residual sediment transport based on outputs from the project-specific AyM model (Figure 15). Van Landeghem (2012) and Van Landeghem *et al*. (2012) make similar observations about apparent reversed sediment wave migration from a comparison of bathymetric data from this region. However, the apparent east to west translation of bedform crest form does not necessarily imply sediment transport in this direction and could instead reflect 'anti-dune' behaviour. An attempt has been made to explore this further through comparison of the 2020 AyM data with (i) the UKHO 2019/2020 multibeam data and (ii) the UKHO 1987 single beam data. However, too little time had elapsed between the project specific multibeam survey (collected summer 2020) and the latest UKHO multibeam data (collected in 2019-2020) for robust conclusions to be drawn. The relatively coarse nature of the older (1987) UKHO single beam data also makes a detailed comparison of bedform movement problematic.

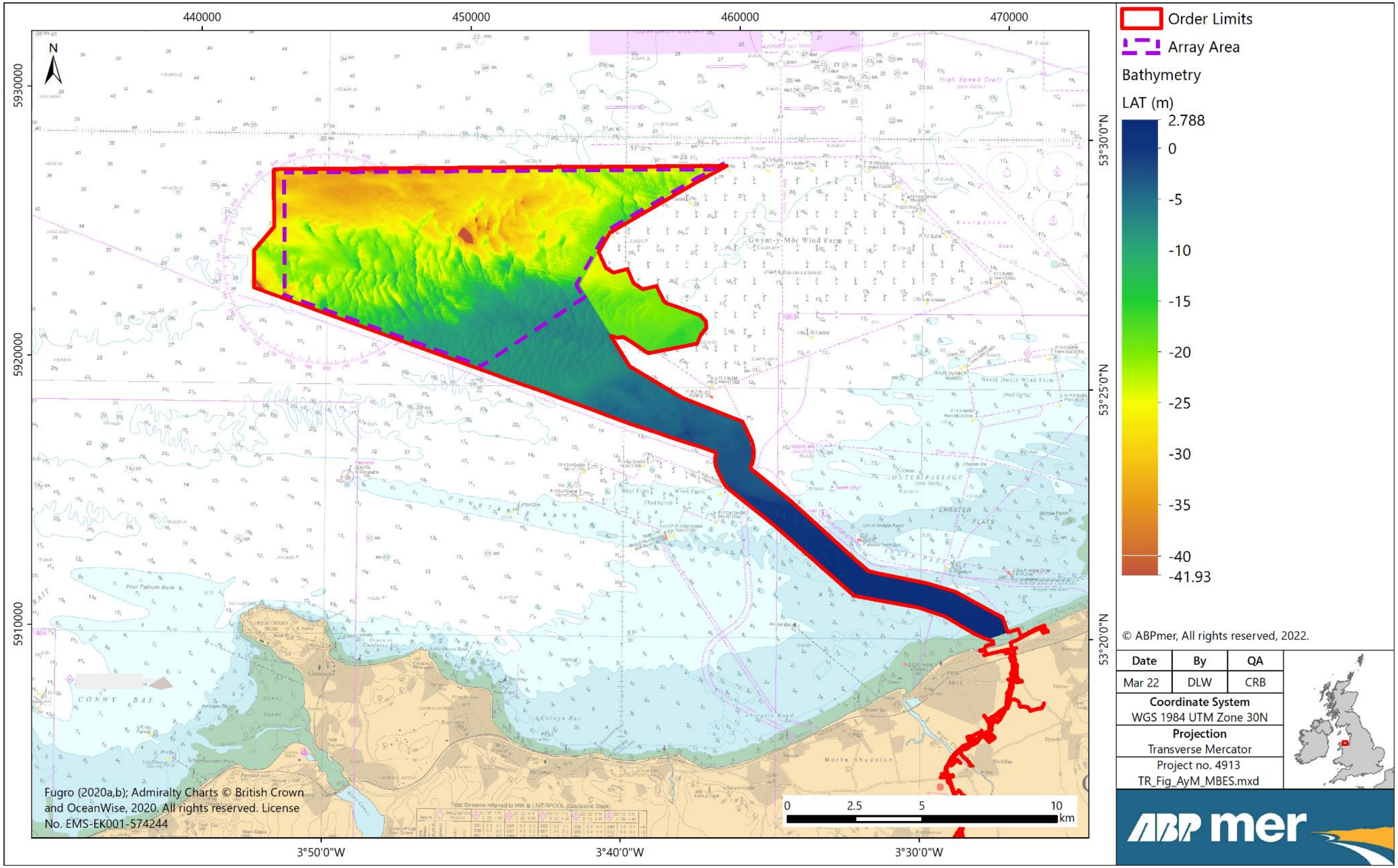


Figure 18. **Bathymetry across the AyM array and offshore ECC**

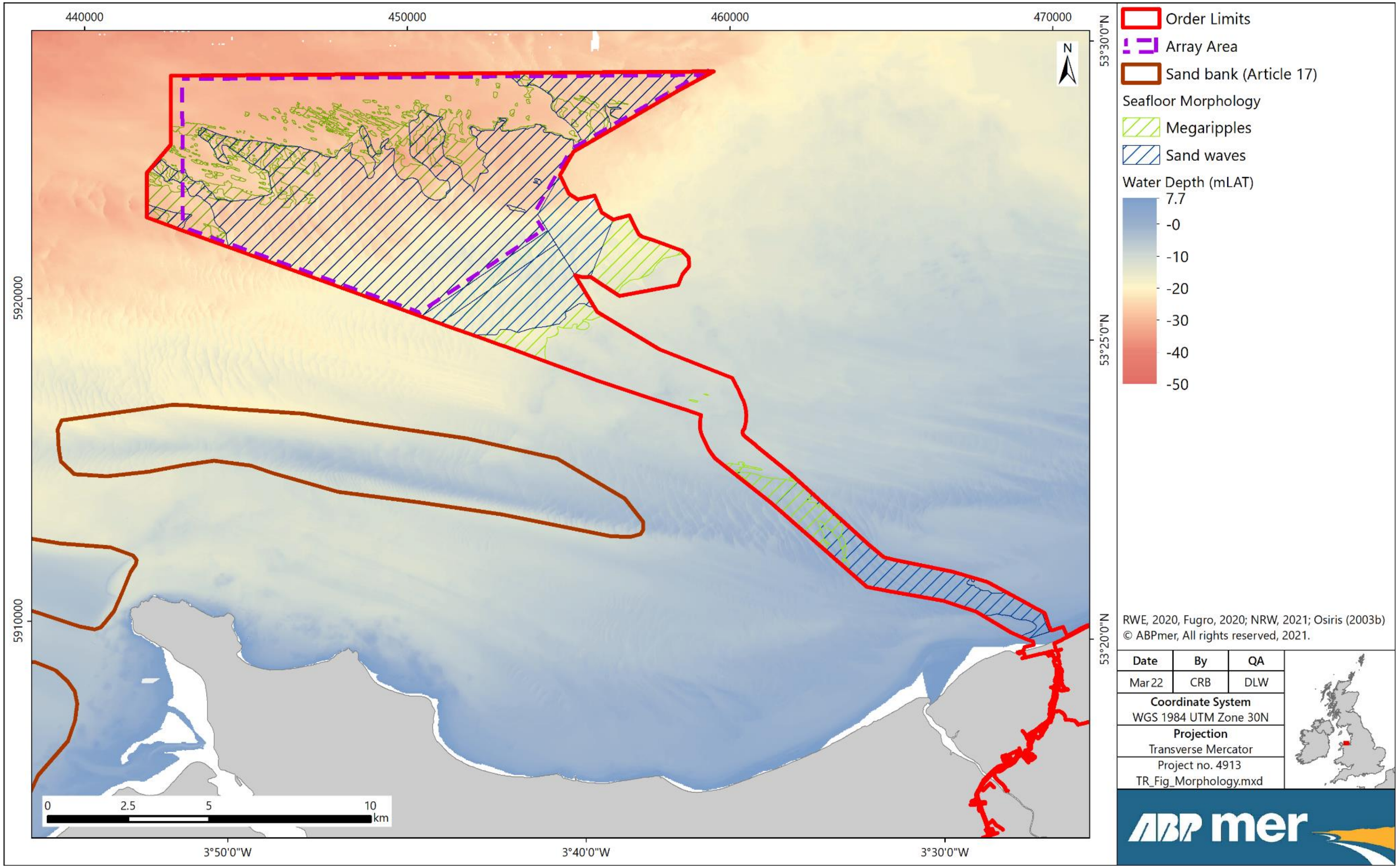


Figure 19. Bedforms mapped within and nearby to the AyM array area and offshore ECC

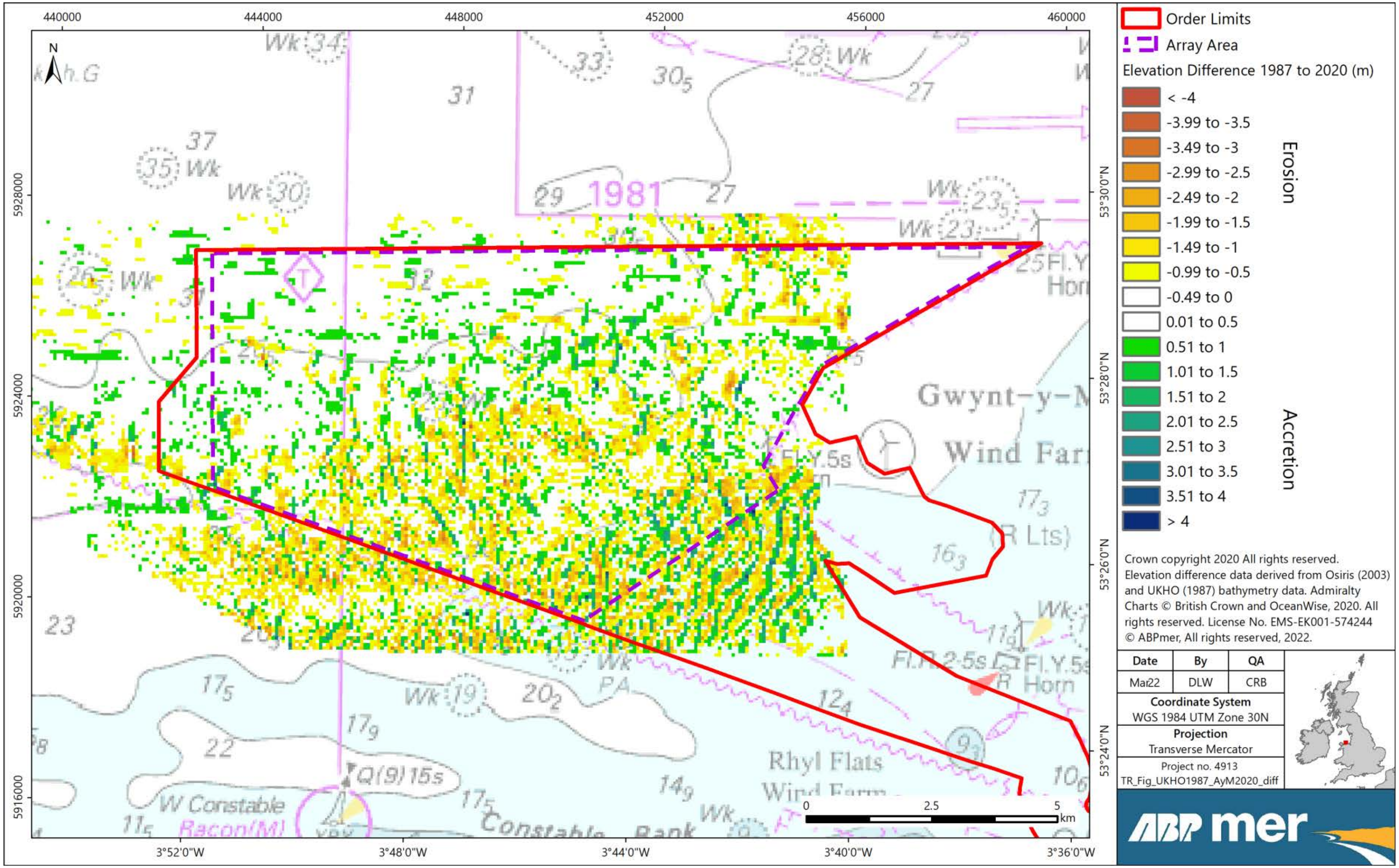


Figure 20. **Bathymetric change over the period 1987 (UKHO) to 2020 (AyM survey data)**

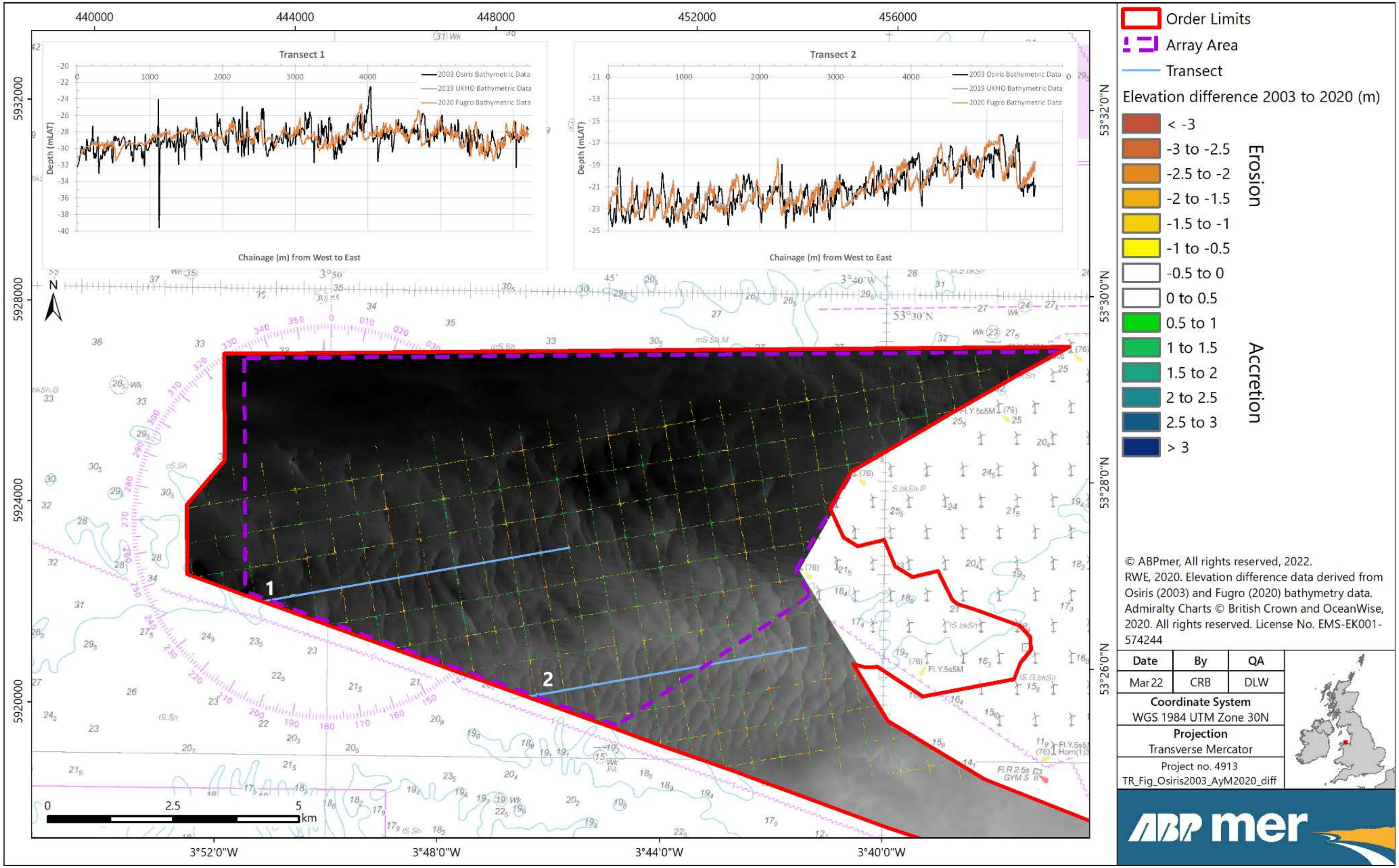


Figure 21. **Bathymetric change over the period 2003 (GyM survey data) to 2020 (AyM survey data)**

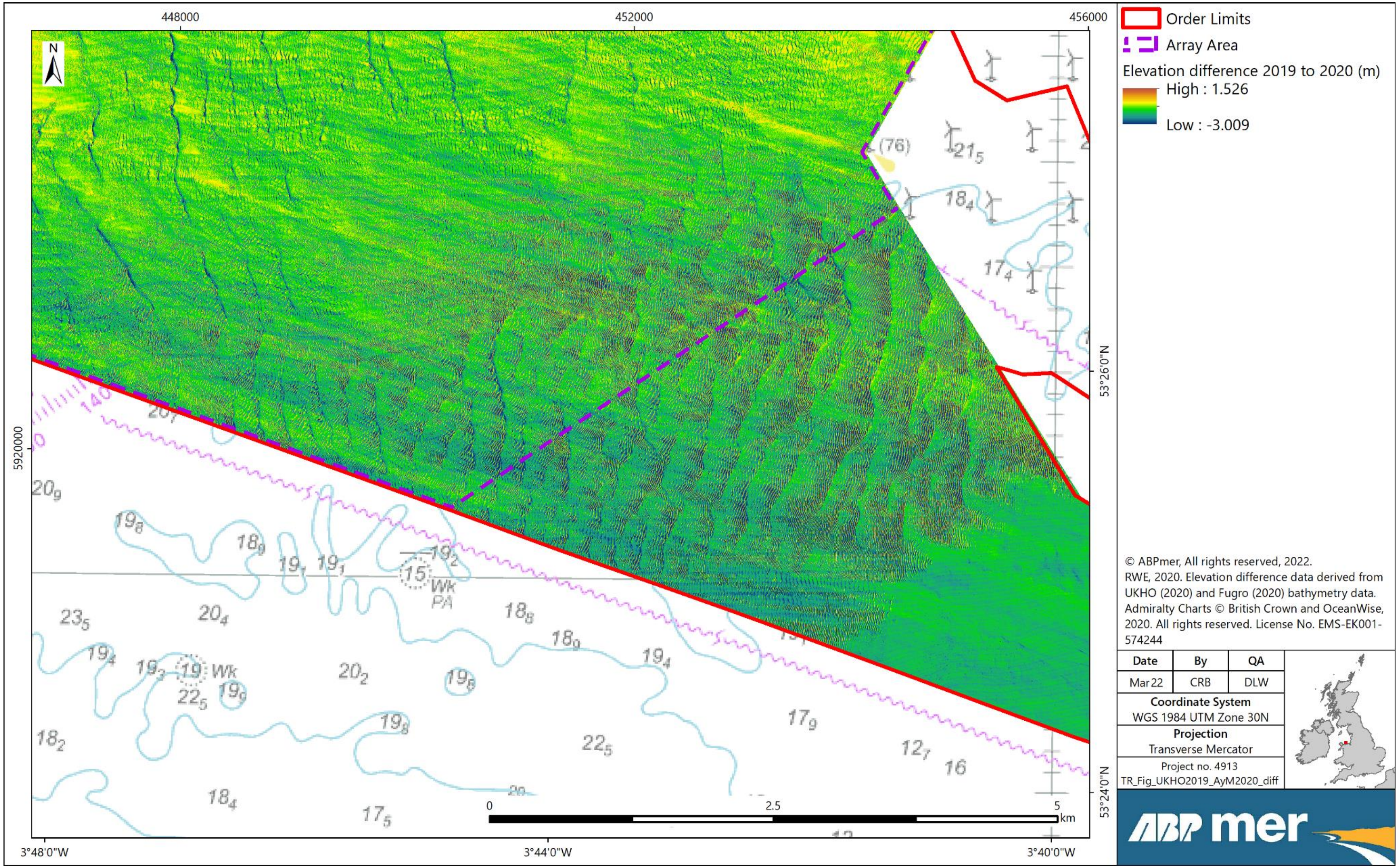


Figure 22. **Bathymetric change over the period 2019 to 2020, based on a comparison of UKHO (2019-2020) and AyM (2020) survey data**

4.5.3 Offshore ECC

Water depths within the offshore ECC generally increased towards the northwest, between 2.8 m above LAT to 23.8 m below LAT (Fugro, 2020b) (Figure 18). Three relatively distinct seabed areas can be identified, as shown in Figure 19:

- Undulating sandwave/ megaripple bedforms from the landfall out to a distance of approximately 10 km offshore;
- Relatively flatter seabed, with more localised gradients over erosional features where the surface sands were coarser and thinner between *circa* 10 km and 17 km from the landfall;
- Undulating sand waves and overlying megaripples from ~17 km from the landfall to the array boundary.

Maximum seabed gradients were measured over the megaripples at 24.9°, over sand waves at 28.8°, and over the relatively flatter seabed at 7° (Fugro, 2020b).

Analysis of available bathymetry from the offshore ECC demonstrates that where sedimentary bedforms are present, they are expected to be mobile resulting in seabed variability. This is illustrated in Figure 23 which shows a comparison of project-specific and older bathymetric data from a region of overlapping data on and around the outer Welsh Passage Channel, on the eastern edge of Rhyl Flats:

- Transects through the overlapping SEACAMS (2014), UKHO (2019) and Fugro (2020b) survey data, also shown in Figure 23, reveal that the sandwaves within the offshore ECC have similar dimensions to those in the Rhyl Flats wind farm, wavelength approximately 120 to 250 m and a height of approximately 2 m. These are seen to be rapidly migrating in an easterly direction at rates of around 10 m/yr, but locally up to 25 m/yr.
- Very close inshore (where water depths are ~1 to 3 m below LAT), the evidence for easterly transport is less clear. Although bedforms are present, their form is variable over time, most probably in response to regular re-working by wave action. This makes the determination of migration direction more difficult.

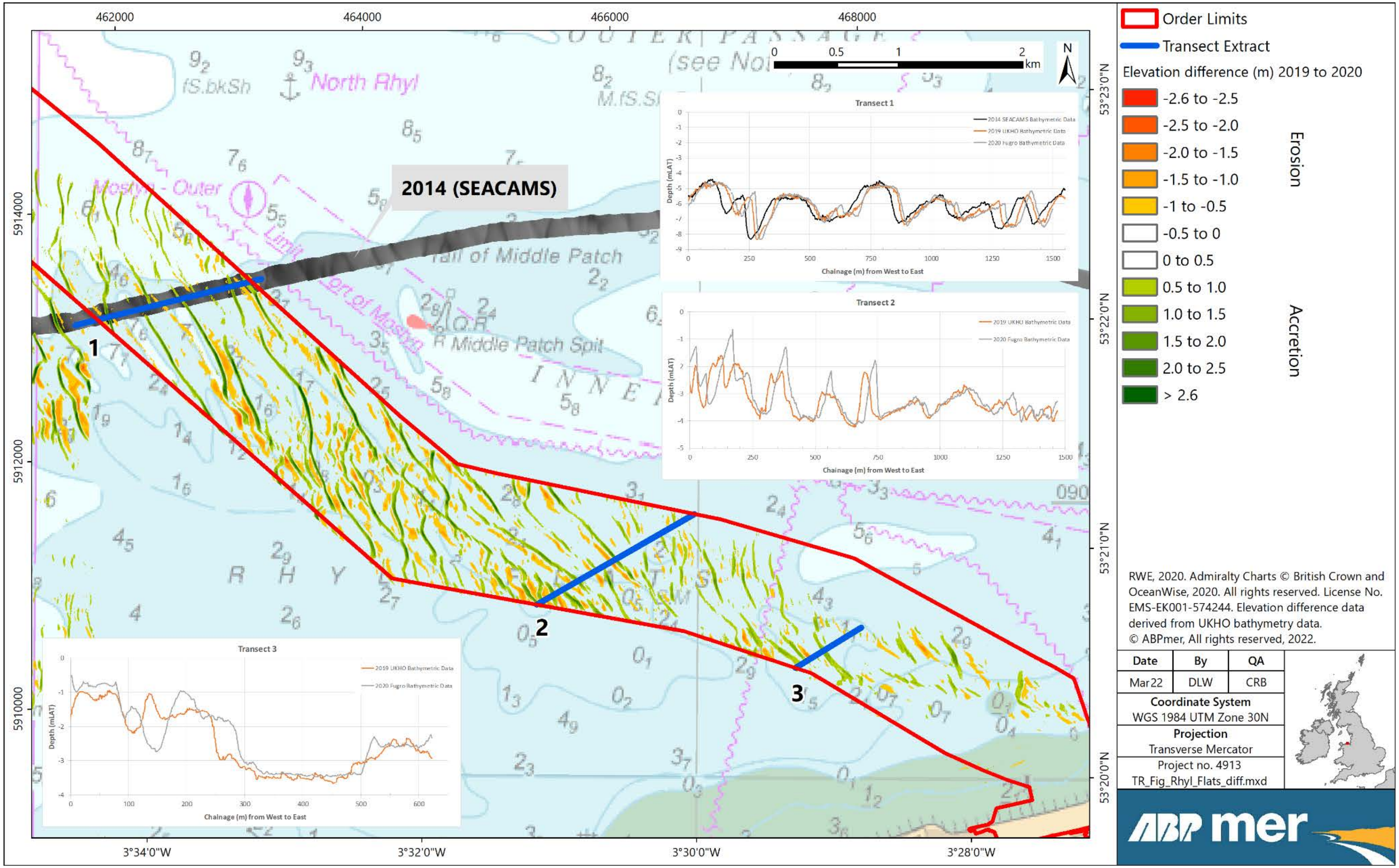


Figure 23. Bathymetric change across Inner Rhyl Flats and Inner Passage

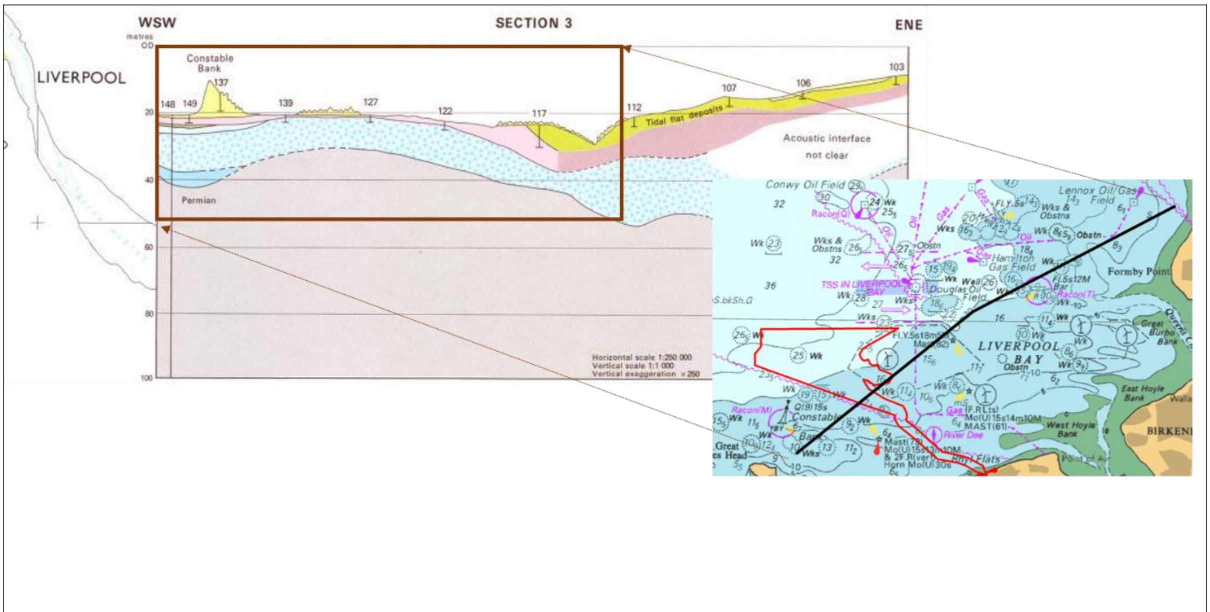
4.5.4 Features of interest in the wider study area

The offshore ECC crosses the far eastern end of Constable Bank, an offshore sandbank feature orientated more or less parallel to the adjacent coastline. Around the point at which the offshore ECC crosses Constable Bank, it merges with Rhyl Flats, an extensive subtidal sandbank attached to the adjacent coastline. The offshore sandbanks of Constable Bank and Rhyl Flats are understood to have an important influence on the geomorphology of the adjacent coastline, through the possible exchange of sediments and potential impacts on hydrodynamics (Halcrow, 2010a). They are key areas of focus within the impact assessment and as such, the morphology and behaviour of these two features are described further in this section.

Constable Bank

The following description is compiled from a variety of information sources, including Kenyon and Cooper (2005), Van Landeghem *et al*. (2009), Van Landeghem (2012), UKHO Admiralty Charts and comparative analysis of the various bathymetry data sets available to the study.

The offshore western part of Constable Bank is approximately 20 km long. The bank is located in surrounding water depths of approximately -12 to -16 mLAT with water depth over the crest approximately -5 to -6 mLAT along most of its length. The crest elevation is approximately 10 m above the surrounding seabed (Figure 24).



Source: BGS, 1984

Figure 24. Cross sectional profile across Constable Bank and seabed

The main body and crest of the (western part) of Constable Bank is approximately 500 to 750 m wide. The additional width of the flanks and associated large sandwaves is approximately 1 km to the north and 250 m to the south, resulting in an overall width of approximately 2 km. The width of the bank gradually increases to the east as it merges with Rhyl Flats. Water depths where the bank has merged with Rhyl Flats are slightly less, approximately -4 to -5 mLAT.

The southern flank of the bank is consistently steeper (gross gradient ~1:25, ~2.3°) than the northern flank (gross gradient ~1:50 to 1:100, ~0.6-1.2°). Local seabed gradients may be greater than the gross estimate locally, due to the additional slope of superimposed sandwave features.

The accumulation of sediment in and around Constable Bank supports active sand waves, which are transported eastwards over a floor of underlying basal conglomerate (poorly sorted glacial till) (Figure 25). Sediment mobility is largely driven by relatively high peak current speeds of approximately 1.2 m/s in the vicinity of the bank (ABPmer SEASTATES and Admiralty Chart tidal observations), in conjunction with the regional pattern of tidal current asymmetry (consistently faster flow on flood tides to the east) (Section 3.3).

Sediments on the north flank and shallow crest of the bank also interact occasionally with larger waves coming from offshore. In a dynamic equilibrium process, this interaction limits the overall height to which the bank can grow (relative to LAT), and affects the shape of larger sandwave crests.

Interaction of waves with Constable Bank is understood to play an important role in controlling wave climate at the adjacent coastline, affecting patterns of beach morphology, coastal evolution and flood risk (Halcrow, 2010a). However, the actual extent to which Constable Bank provides direct sheltering of the coast is debatable. Modelling undertaken to support the development of the North West and North Wales Shoreline Management Plan (SMP) 2 shows that whilst substantial lowering of the bank locally reduces wave heights quite significantly, these changes reduce towards the shore with minimal change observed at the shoreline (Halcrow, 2010c).

Larger sandwaves are present along the length of Constable Bank, on both flanks and over the crest, often with coherent connecting crest lines. Larger sandwave crest lines on the top of the bank appear displaced to the east, indicating a locally higher rate of sediment transport and faster rate of sandwave migration in the shallower water. Individual sandwave crests on both flanks are typically asymmetric in profile, with the east facing side steeper than the west, also indicating eastward net migration (Figure 25). Larger sandwaves on the northern flank of the bank have relatively longer wavelengths than on the southern flank. Sandwaves on the northern flank and on the crest have more rounded crest profiles, whilst those on the southern side are sharper crested; this is thought to be because the northern side of the bank is more exposed to wave action.

The indicators of bedload transport are in the same direction (eastward) on both sides of the bank, which is consistent with the regional transport pattern, but is relatively unusual for offshore linear sandbanks more generally. If this pattern is maintained, and in the absence of an opposing transport path to maintain it, the bank could eventually shorten (from the east) and eventually disappear on timescales in the order of a few hundred years (Kenyon and Cooper, 2005).

Based on a visual comparison of historical navigation charts from 1873 and 1933, the GyM EIA baseline (RWE npower, 2005) suggests 'a loss of material and a change of general morphology' on and around Constable Bank. Whilst erosion is generally consistent with the expected long-term trend, no specific discussion or appraisal was provided about the accuracy of the original data collection (likely sparse lead line soundings with unknown adjustment for vertical datums offshore) or chart presentation affecting the comparison.

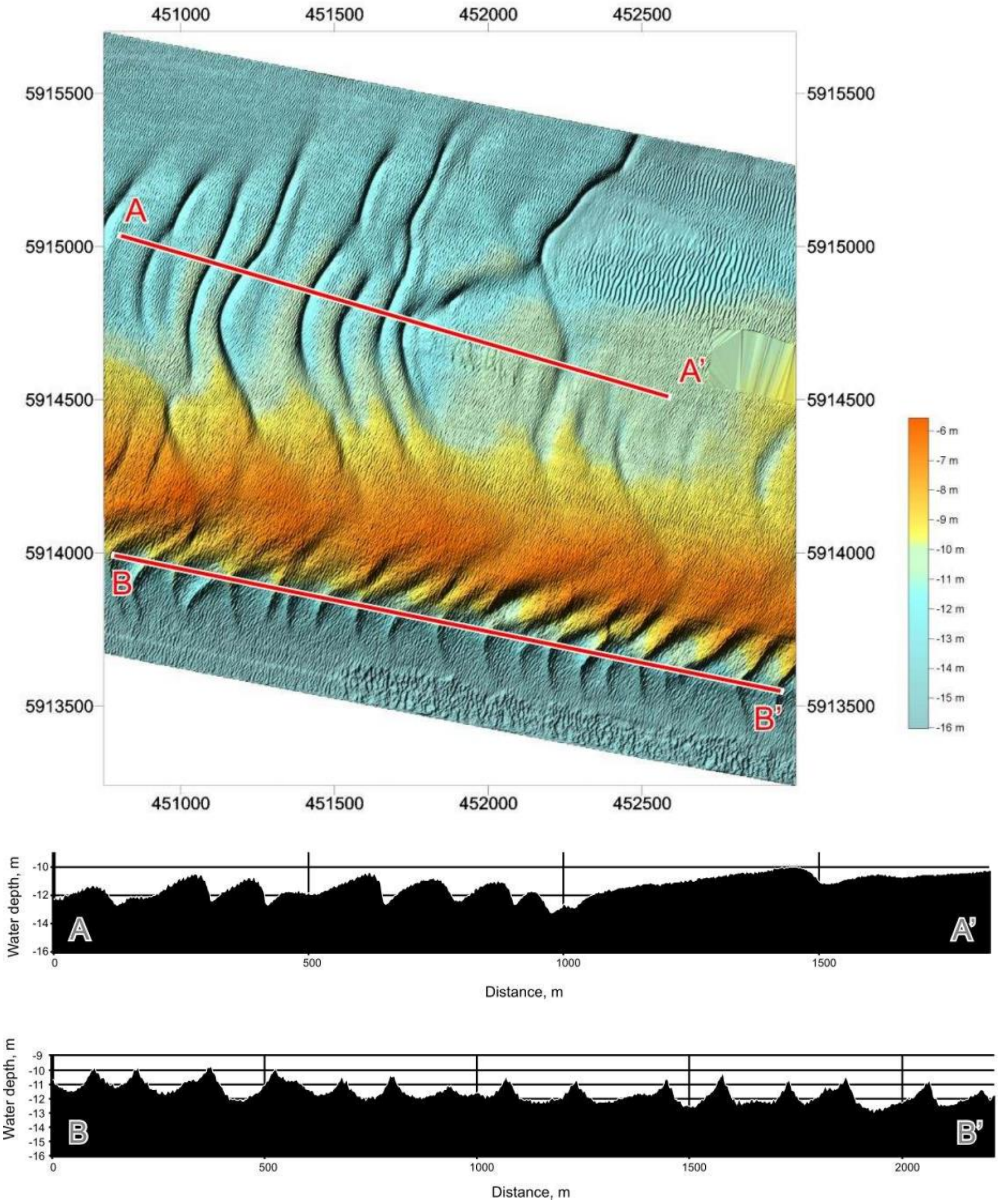


Image Source: Kenyon and Cooper (2005)
Data Source: SEA6 survey for DTI – collected 2004 (Holmes & Tappin, 2005)

Figure 25. Swath bathymetry of a portion of the outer part of Constable Bank. Profiles show rounded sandwaves north of the bank and sharp crested sandwaves south of the bank

Figure 26 provides an assessment of changes to the lateral position of Constable Bank between the 1920's (UKHO) and 2004 (SEACAMS) data. Similar comparisons where the bank meets the edge of Rhyl Flats are also shown, including intermediate 1960's (UKHO) data. This assessment does not rely on the overall vertical accuracy of older data. The comparison indicates that the present lateral position and main axis of Constable Bank, and offshore edge of Rhyl Flats, have not changed noticeably in this time.

As described in Van Landeghem *et al*. (2009), and illustrated in Figure 25, sandwave features in the vicinity of Constable Bank are frequently compound in nature, with smaller sandwaves superimposed on larger bedforms. Larger sandwaves on the flanks and crest of Constable Bank have a typical wave length of 120 m, up to 600 m in places on the northern flank, and a height of approximately 2 m.

Sandwave crest migration rates of approximately 5 m/yr are reported by Van Landeghem *et al*. (2012), based on comparison of the overlapping sections of the SEA6 (2004) and Sutton (2008) IMAGIN swath bathymetry data sets. A similar rate was determined in this study by comparison of the overlapping SEA6 (2004) and SEACAMS (2017) bathymetry data (shown in Figure 27). At this rate, sandwave features are likely to migrate one full wavelength approximately every 24 years, and so will likely migrate more than one wavelength during the proposed 30-year AyM operational period, subjecting any given location to a full range of crest and trough elevations. Smaller megaripples superimposed on the larger sandwaves are also widely present (wavelength typically 7 to 10 m and height in the order of tens of centimetres) and are mobile on even shorter timescales.

.

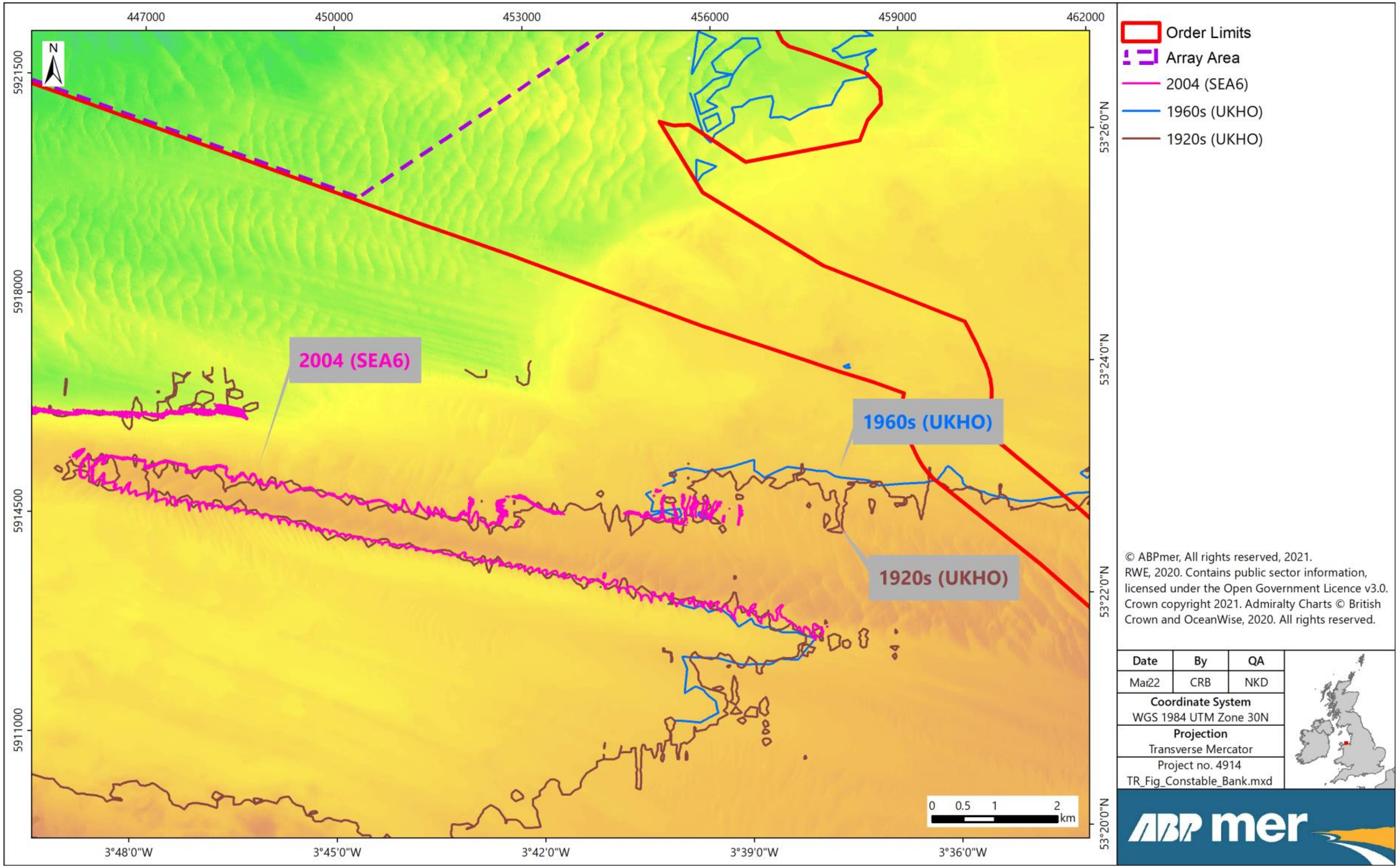


Figure 26. **Stability in the lateral position of Constable Bank over the period 1920 to 2004, based on analysis of the -10 mLAT contour**

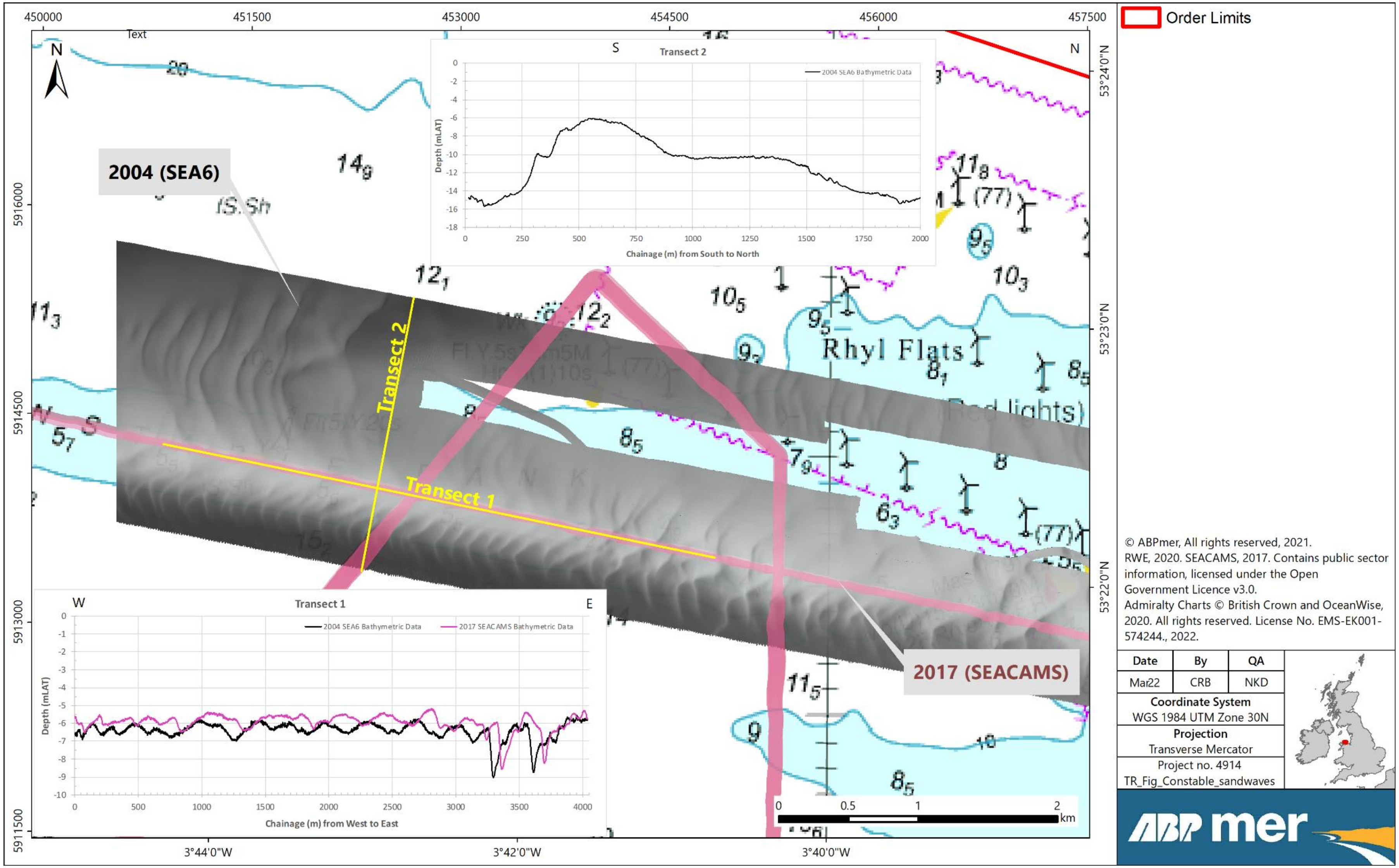


Figure 27. Migration of sand waves on Constable Bank over the period 2004 to 2017

Rhyl Flats

Rhyl Flats is an extensive subtidal sand flat complex attached to the coastline north of Rhyl and west of Prestatyn, to the southeast of the AyM array. Rhyl Flats is one named region within a wider system of inter-connected sandflats and sandbanks along the Liverpool Bay coastline. Rhyl Flats is the connection point between the eastern end of Constable Bank offshore sandbank and the coastal sedimentary system. To the east, Rhyl Flats merges gradually with other named areas including Chester Flats, Middle Patch and various large sandbank complexes in the approaches to the Dee estuary, through to Burbo Bank in the approaches to the Mersey estuary.

Other developments and infrastructure on or near to Rhyl Flats include: GyM export cable; Rhyl Flats offshore wind farm and export cable; Flat Holm offshore wind farm and export cable; Burbo Bank Extension export cable; and various other interconnector cables.

Rhyl Flats is generally shallow (-3 to -4 mLAT, shallowing to -1 to -2 mLAT in central parts). Larger sandwave features are present with wavelength 300 m and height up to 2 m in the region where Constable Bank merges with Rhyl Flats. Elsewhere, bedforms are likely widely present but smaller in wavelength and height; there is insufficient coverage of sufficiently high-resolution data to describe spatial variability.

Figure 28 shows a comparison of historical bathymetry (2005 to 2008) from the Rhyl Flats offshore wind farm. The wind farm is located on the northwestern edge of Rhyl Flats, just to the north of where Constable Bank and Rhyl Flats meet. Sandwave features are visible moving through the southern half of the site (wavelength approximately 120 to 250 m), from the area of Constable Bank. The sandwave crests are migrating eastward, by approximately ¼ wavelength (30 m) over the three-year survey interval, resulting in a migration rate of approximately 10 m per year in this period.

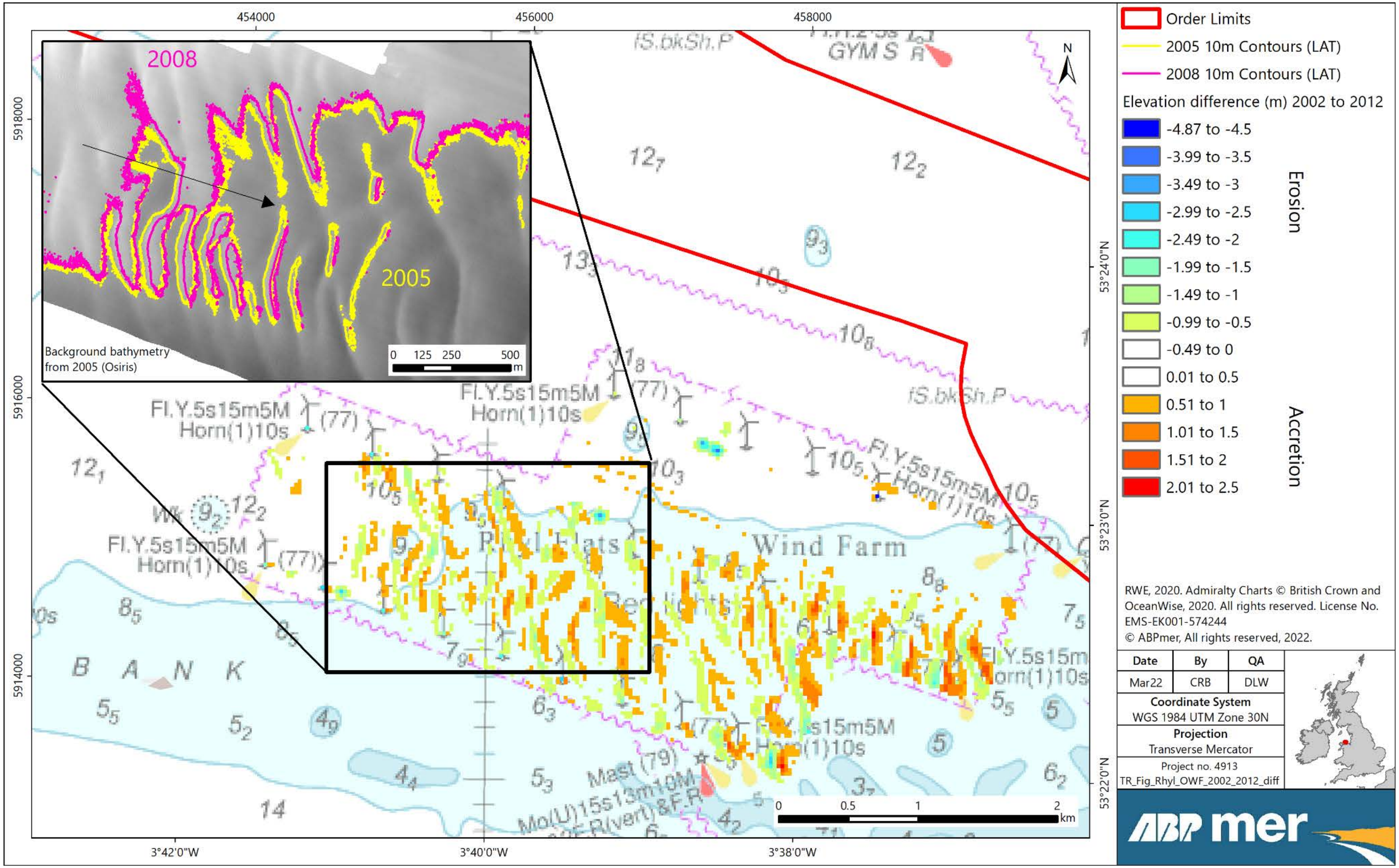


Figure 28. Migration of sand waves on outer Rhyl Flats over the period 2002 to 2012

5 Coastlines, Beaches and Nearshore Processes

5.1 Overview

The coastline within the study area extends from Carmel Head (in the west) to Southport (in the east) (Figure 1). The coastal characteristics are highly varied, ranging from rocky cliffs (e.g. Great Orme's Head) to low lying settings characterised by accumulations of soft unconsolidated sediments (such as the Dee estuary). The extension of Great Orme beyond the general alignment of the coastline provides a major drift divide, with easterly longshore sediment transport to the east, and westerly transport to the west of Great Orme.

The shoreline management policy for much of the coastline is 'hold the line'. Indeed, several areas along the North Wales coast have a long history of sea defences, with seawalls, revetments, groynes and flood embankments preventing shoreline erosion and managing flood risk to coastal towns (e.g. Rhyl and Prestatyn).

The wave climate of the nearby offshore area (illustrated in Figure 8) was analysed to estimate the 'depth of closure' for the beaches and other shallow subtidal areas on this coastline as -5.1 mLAT. 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 significant bed level change or net sediment exchange between the nearshore and the offshore. 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 31 years of 3.3 m and associated wave period of 8.8 s (based on 31 years of modelled hindcast timeseries data).

Detailed descriptions and a summary of research relating to coastal morphology, coastal and beach processes, historical and contemporary coastal works and defences, and predictions of future evolution, are available in the North West England and North Wales SMP2 (Halcrow, 2011). This is summarised in the following sections and supplemented by the analysis of more recent topographic data.

5.2 Nearshore processes and sediment exchange

East of the River Clwyd to the Point of Ayr, tidal exchange with the Dee Estuary has a progressively stronger influence on local nearshore coastal processes in comparison to locations to the west. Local patterns of flow and sediment transport in the Welsh Channels passage of the Dee Estuary cause more complex nearshore and offshore sediment recirculation patterns. Despite the apparent complexity of effect, the position of the Welsh Channels passage has remained reasonable stable over the last 200 years.

There is thought to be exchange of (mainly sand) sediment, and so a degree of interdependency in patterns of longer-term morphological evolution, between the various larger sediment bodies present in the adjacent offshore and nearshore areas, namely:

- Alongshore (mainly eastward) transport along the beach upper foreshore from Abergele towards the Point of Ayr, at the mouth of the Dee estuary;
- Onshore movement of sediment from Constable Bank;
- Onshore movement of sediment from Rhyl Flats;
- Redistribution of sand and shingle from the nearshore seabed;

- Only limited alongshore sediment transport from the west (via Llandudno Bay, Penrhyn Bay and Colwyn Bay); and
- Only limited input of sediment from erosion of the (now mostly defended) cliffs and dunes.

The natural coastline between Abergele and Prestatyn is generally characterised by shingle ridges at the top of the beach and an extensive dune system behind, fronted by a wide sandy foreshore. As at the landfall, ridge and runnel features (bars and troughs) on the wide foreshore may vary in elevation and depth due to reworking and sediment redistribution over the beach by wave action. Some features are observed to migrate or change position, causing patterns of erosion and accretion. Some features appear less mobile due to the controlling influence of nearby coastal defences, groynes, jetties or other hard points on the beach.

Various (past, present and future) coastal engineering works and defences have and will continue to affect local beach processes and morphology in the area. More details may be found in Halcrow (2011). The construction of coastal defences and other historical activities has both reduced the rate of new sediment input and in some locations has directly reduced the volume of sediment present (e.g. the dredging of sand from near to Rhyl for the construction of Liverpool Docks), especially in the shingle ridges on the upper foreshore. Due to the dominant eastward transport and lack of replenishment, beach sediment volume is being gradually eroded in some locations, leading to: beach level lowering; loss of beach sediment volume; and the long-term landward movement of the low water mark along some defended stretches, i.e. coastal squeeze. The system is described as being 'out of equilibrium with the prevailing conditions' with respect to the position of the (presently defended) coastline.

5.3 Cable landfall

The landfall is located on a section of coast between Rhyl and Prestatyn, referred to in Halcrow (2011) as 'Rhyl Golf Links'. The beach at the landfall predominantly comprises sand, with areas of muddy sand interspersed across the mid shore. Areas of consolidated mud (peat) are present in the mid and upper shore with some clay also exposed in the upper shore (Figure 29). Areas of coarser sediments (i.e. pebbles and cobbles) which have been disturbed by wave action are largely confined to the upper shore.

A concrete/corrugated metal protected outflow pipe is present to the west of the survey area extending from the upper shore to the lower mid shore, with a muddy pool associated with the outflow. An area of concrete piles, boulders and bedrock is present in the upper beach at the east end of the landfall (Halcrow, 2011; Sefton Council, 2015; Fugro, 2020d).

Present day coastal defences are described as a stepped concrete revetment with wave return wall (originally built in 1951) and timber groynes (added between 1972 and 1975 in conjunction with other additional works) (Halcrow, 2011). It is noted that substantial new coastal defences are in the process of being installed in East Rhyl, immediately to the west of the landfall. These are being installed in response to the substantial flooding during winter 2013 caused by (approximately) 1 in 100-year extreme water levels which enabled wave overtopping of existing coastal defences (Denbighshire County Council, 2014). The new coastal defences involve placement of 128,000 tonnes of rock armour in front of the existing sea defences at East Rhyl, as well as 600 m of new sea defence wall and promenade.

The coastline at the landfall is orientated approximately south-southwest to east-northeast. This produces a relatively consistent angle of incidence between the coastline and the predominant westerly to northwesterly wave direction, resulting in a net eastward transport of sediment by winds and waves on the beach foreshore. Numerical modelling results of littoral (sand) transport rates at the landfall are summarised in Table 8, based on outputs from the Cell Eleven Tidal and Sediment Study (CETaSS) (Halcrow, 2010b).

Table 8. Modelled sediment transport rates at the landfall (Source: Halcrow, 2010b)

Average annual N/E transport (m³/year	Average annual S/W transport (m³/year)	Average annual net transport (m³/year)	Average annual gross transport (m³/year)	Standard deviation (net)(m³/year)	Average net winter transport (m³)	Average net summer transport (m³)	Wave height +10%, average annual net transport (m³/year)
-104000	6000	-99000	110000	26000	-73100	-25700	-120000
[Based on a grain size of 226 µm – fine sand]							

The River Clwyd discharges across the beach foreshore around 3 km to the west of the landfall in a shallow self-maintained channel; the location of the channel is fixed by the dominant eastward sediment transport direction and by a low training wall on its eastern margin. At the mouth of the Clwyd estuary, the shape of the coastline, the river channel, and a general accumulation of sediments in the nearshore, present a (relatively minor) discontinuity in the coastline and beach topography.

Historically, beach lowering has occurred along the Rhyl frontage, with landward movement of mean low water (beach narrowing) between 1871 and 1900. At the same time, two million tonnes of sand and gravel were removed from the foreshore for the construction of Liverpool Docks. Prior to 1959, the frontage experienced rapid erosion, however this rate reduced following the construction of the groynes in the 1970’s.

More recent imagery of the beach at the landfall (between 2006 and 2021) is shown in Figure 30 to Figure 34. The figures illustrate the coastal defences, the rocky/shingle bank on the upper beach (often partially buried in sand) and large ridge and runnel features on the sandy lower foreshore, trending approximately parallel to the coastline. The outfall (also partially buried on the upper beach) extends from the shoreline to beyond the groynes on the western side of the landfall area. Comparing the available historical images, the timber groynes closely control the position of ridge and runnel features on the upper foreshore. Seaward of the groynes in the intertidal area, there is visible change in beach morphology over time, suggesting a greater likelihood of local beach level variation due to natural evolution of the ridge and runnel features. It is understood that movement of these features regularly exposes the underlying cohesive deposits (Sefton Council, 2015).

The beach foreshore at the landfall is described as having an erosional trend (at an unspecified rate) (Sefton Council, 2015); however, the upper foreshore beach level is also (currently) relatively high due to the presence of the groynes (locally retaining sediment volume) and as a result of the foreshore training wall for the River Clwyd (which prevents meandering of the river channel across the Rhyl foreshore).

Source: Fugro, 2020d

Figure 29. Photographs of the landfall, taken during the benthic intertidal survey

Source: Google Earth

Figure 30. Satellite imagery of the landfall (1 January 2006)

Source: Google Earth

Figure 31. Satellite imagery of landfall (20 April 2009)

Source: Google Earth

Figure 32. Satellite imagery of the landfall (10 April 2011)

Source: Google Earth

Figure 33. Satellite imagery of the landfall (14 May 2016)

Figure 34. Satellite imagery of the landfall (20 Sept 2021)

Cross shore transects available from (i) the project-specific topographic survey of the landfall (undertaken in 2020) (Figure 35); (ii) LiDAR data covering Ffrith beach (collected 2004 to 2015); and (iii) beach topographic survey data (collected by the Northwest Regional Coastal Monitoring Programme in 2020) are shown in Figure 36. Spatial variation in the range of observed beach levels over the same period is shown in Figure 37. The analysis indicates that:

- No clear longer-term trends are evident based on this snapshot comparison (over a 16-year interval);
- The greatest magnitude of beach level change observed over larger areas is in the order of 1.75 to 2.25 m;
- The groynes generally retain sediment volume within the groyne bays, but do not prevent patterns of erosion and accretion over time;
- Larger changes are associated with the seaward face of ridge features on the foreshore likely in response to storm events. The elevation of the top and landward edges of ridge features appear more stable indicating overall beach stability; and
- The depth of runnel features also appear to be stable, indicating limited or no overall beach lowering.

The future evolution of the coastline will be highly dependent on the management of the coastal defences and/or activities that propagate to larger scale changes of behaviour of the Clwyd or Dee estuaries. The Futurecoast (Halcrow, 2002) prediction for a 'with present management' scenario is that the shoreline would continue to be maintained in its present position by defences. There would be little change from the present circumstances, with the continuation of present drift patterns and maintenance of foreshore width and beach levels. This prediction is largely dependent on the ongoing presence and action of the coastal defences, so will likely remain valid for as long as the defences remain.

The training wall along the River Clwyd is described as potentially susceptible to breaching and reports suggest that, should a breach occur, the river would revert to its old course along the Rhyl frontage resulting in a reduction in beach levels and thereby increasing the risk of (localised) overtopping or breaching of the defences. However, it is considered here that there is sufficient distance between the River Clwyd mouth and the landfall that such a breach should not necessarily pose an immediate risk, but (if not rectified) would have consequences for short to long term evolution of the seabed around the landfall area, potentially including periods of accretion as well as erosion.

The Shoreline Management Plan policy for this area (Halcrow, 2011) is:

- 0-20 years (short term) – Hold the Line
    - Maintaining and improving /raising/ widening the existing defences;
    - Investigations into ways of further reducing flood risk in the large flood risk area such as the possibility of building a secondary set-back defence in addition to the primary defence.
- 20-50 years (medium term) – Hold the Line
    - Maintaining and improving /raising/ widening the existing defences;
    - Potential options to further reduce flood risk in the large flood risk area in the form of a secondary set-back defence in addition to a less substantial primary defence.
- 50-100 years (long term) – Hold the Line
    - Maintaining and improving /raising/ widening the existing defences;
    - Potential options to further reduce flood risk in the large flood risk area in the form of a secondary set-back defence in addition to a less substantial primary defence.

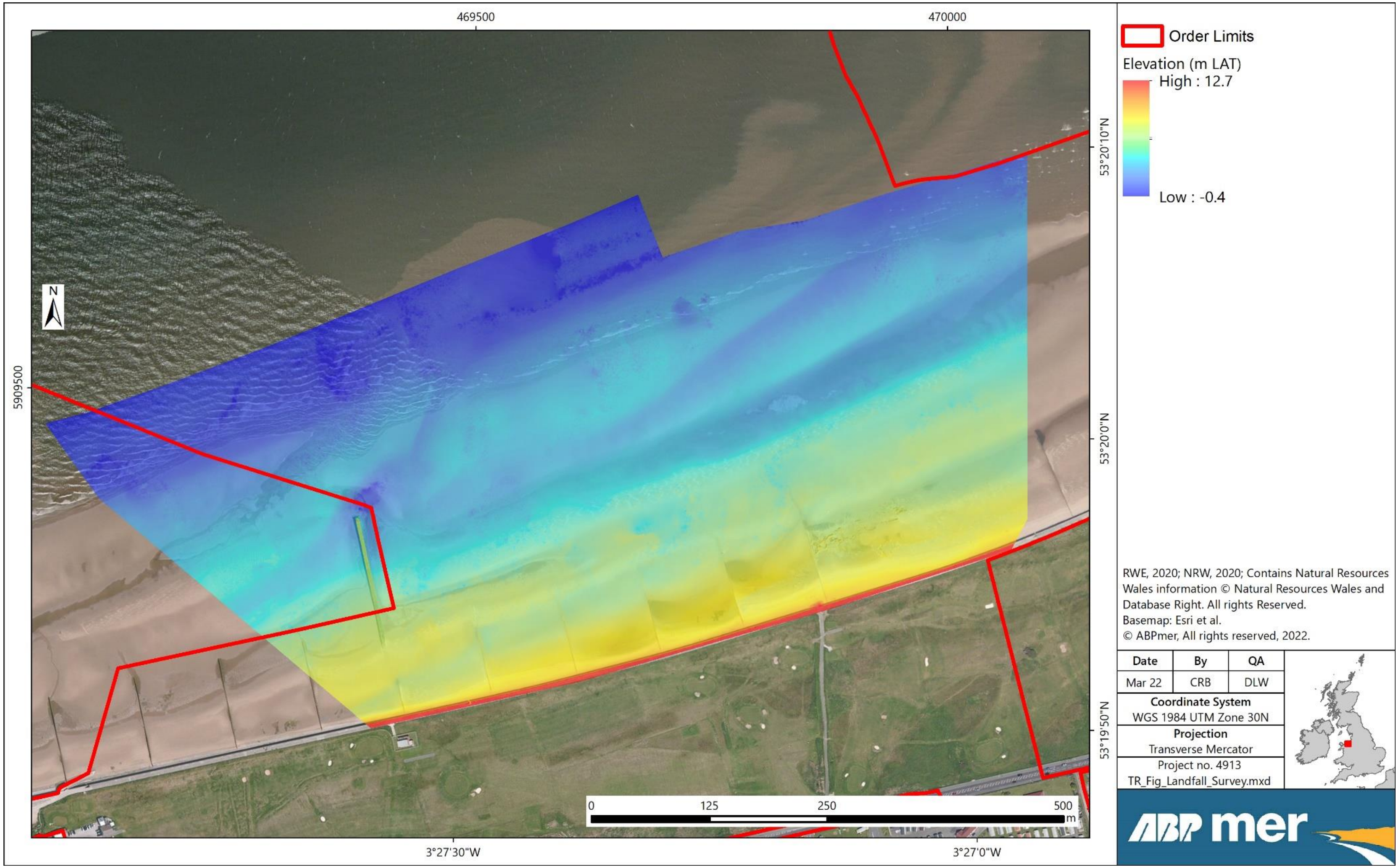


Figure 35. Project specific UAV-based survey of the landfall at Ffrith (undertaken in 2020)

Figure 36. Transects showing change in beach topography over the period 2004 to 2020

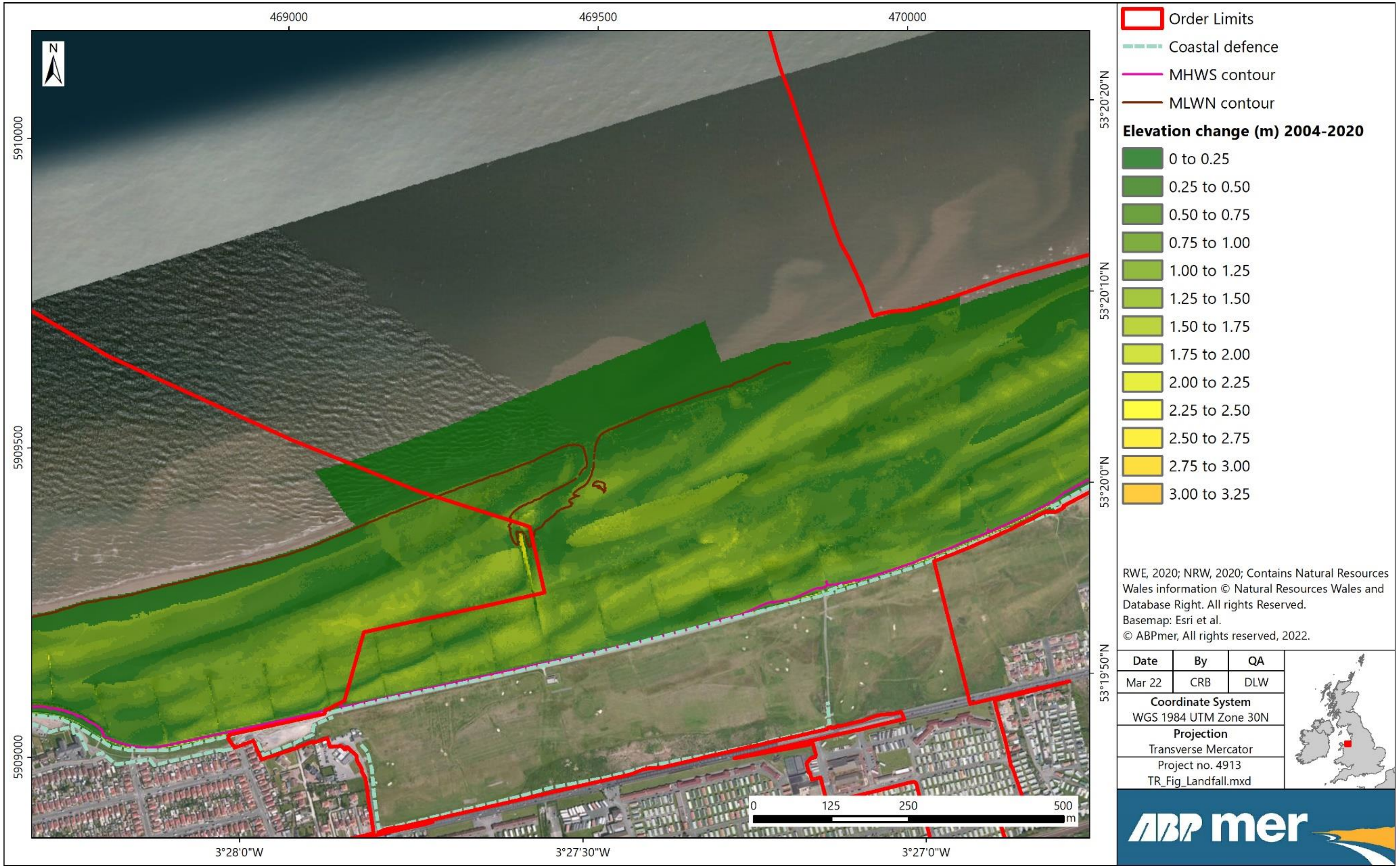


Figure 37 **Range of observed beach levels (difference [maximum – minimum] local elevation) in the period 2004 to 2020.**

6 References

ABPmer (2009). Gwynt y Môr Offshore Wind Farm: Assessment of Seabed Variability. R1546.

ABPmer (2005). Gwynt Y Mor Offshore Wind Farm: Coastal Process Study - Phase 1: Determining Scope. ABPmer Report R.1177.

ABPmer, Met Office and POL (2008). Atlas of UK Marine Renewable Energy Resources: Atlas Pages. A Strategic Environmental Assessment Report, March 2008. Produced for BERR. Report and associated GIS layers available at: [redacted]

Barne JH., Robson CF., Kaznowska, SS., Doody, JP., Davidson NC. (1996). Coasts and seas of the United Kingdom. Region 13 Northern Irish Sea: Colwyn Bay to Stranraer, including the Isle of Man, ed. by J.H. Barne, C.F. Robson, S.S. Kaznowska, J.P. Doody, & N.C. Davidson, 63-66. Peterborough, Joint Nature Conservation Committee.

Belderson RH., Johnson MA., Kenyon NH. (1982). Bedforms. In: Stride AH (ed.) Offshore tidal sands, processes and deposits. Chapman and Hall Ltd, London, UK pp 27-57

BGS (1984). Liverpool Bay Sheet 53 N - 04 W Sea Bed Sediments and Quaternary.

Bide, T P, Campbell, E, Cave, M, Balson, P S and Green, S. (2013). The Marine Mineral Resources of the UK Continental Shelf: Final Report. British Geological Survey Commissioned Report, CR/13/020. 75pp

Bowers, D.G., Boudjelas, S., Harker, G.E.L. (1998). The distribution of fine suspended sediments in the surface waters of the Irish Sea and its relation to tidal stirring. International Journal of Remote Sensing 19 (14), 2789 to 2805.

Brooks, AJ., Whitehead, PA., Lambkin, DO. (2018). Guidance on Best Practice for Marine and Coastal Physical Processes Baseline Survey and Monitoring Requirements to inform EIA of Major Development Projects. NRW Report No: 243, 119 pp, Natural Resources Wales, Cardiff.

Cefas (2016). Suspended Sediment Climatologies around the UK. Report for the UK Department for Business, Energy & Industrial Strategy offshore energy Strategic Environmental Assessment programme.

Coughlan, M., Guerrini, M., Creane, S., O'Shea, M., Ward, S.L., Van Landeghem, K.J.J., Murphy, J., Doherty, P., (2021) A new seabed mobility index for the Irish Sea: Modelling seabed shear stress and classifying sediment mobilisation to help predict erosion, deposition, and sediment distribution, Continental Shelf Research, doi[redacted]

Denbighshire County Council (2014). Rhyl Coastal Defence Assessment.

Dŵr Cymru Welsh Water (DCWW) (2016). Oceanographic monitoring around the Welsh Coast: data from ADCP deployments.

Environment Agency (2019). Coastal flood boundary conditions for the UK: update 2018. Project SC060064.

Flather, R. A. (1987). Estimates of extreme conditions of tide and surge using a numerical model of the northwest European continental shelf. Estuarine, Coastal and Shelf Science, 24, pp.69-93.

Fugro (2020a). WPM1 Main Array Area -Seafloor and Shallow Geological Results Report. Doc Ref 003616043-04

Fugro (2020b). WPM2& WPM3 – ECR East A and B- Seafloor and Shallow Geological Results Report. Doc Ref 003700854-02

Fugro (2020c). Fugro -WPM4 – Export Cable Routes (Onshore) – Processing & results – UAV photogrammetry. Doc Ref 0037000849-04.

Fugro (2020d). Fugro -WPM4 – Export Cable Routes (Onshore) – Benthic Intertidal Results Report. Doc Ref 003700858-03

Fugro (2002). Rhyl Flats Bathymetric Survey. Client Confidential.

Halcrow (2011). North West England and North Wales Shoreline Management Plan SMP2. [redacted] Accessed 15/02/2021

Halcrow (2010a). Cell 11 Regional Monitoring Strategy (CERMS). 2010 Monitoring Update Report

Halcrow (2010b). Cell Eleven Tidal and Sediment Study (CETaSS) Phase 2 (ii.

Halcrow (2010c). North West England and North Wales Shoreline Management Plan SMP2 Supporting Studies Cell Eleven Tidal and Sediment Study (CETASS) Phase 2 (ii) Appendix C – Sandbanks Study

Halcrow (2002). Futurecoast. Now available from [redacted]

Holmes, R, and Tappin, D R. (2005). DTI Strategic Environmental Assessment Area 6, Irish Sea, seabed and surficial geology and processes. British Geological Survey Commissioned Report, CR/05/057.

Howarth, M J. (2005). Hydrography of the Irish Sea. Proudman Oceanographic Laboratory Internal Document, 174.

Hubbard, A., Bradwell, T., Colledge, N., Hall, A., Patton, H., Sugden, D., Cooper, R., and Stoker, M. (2009). Dynamic cycles, ice streams and their impact on the extent, chronology and deglaciation of the British-Irish ice sheet, Quaternary Science Reviews, Vol. 28, 758-776.

Kenyon, N.H. and Cooper, W.S. (2005). Sandbanks, sand transport and offshore wind farms. pp106.

Mellet, C. L., Long, D., Carter, G., Chiverell, R., C., and Van Landeghem, K. J. J. (2015). Geology of the seabed and shallow surface: the Irish Sea, Energy and Marine Geoscience Programme, Commissioned Report CR/15/057, British Geological Survey, Edinburgh

Motyka, J. M. and Brampton, A. H. (1993). Coastal Management, Mapping of littoral cells. HR Wallingford, Report SR 328, January 1993, pp102.

Nicholls, R.J., Birkemeier, W.A., Hallermeier, R.J. (1996). Application of the Depth of Closure Concept. Coastal Engineering Proceedings, 25. doi.org/10.9753/icce.v25.%p

Norman, D.L.., Brown, J.M., Amoudry, L.O., Souza, A.J. (2014). Processes controlling stratification in Liverpool Bay. Southampton, National Oceanography Centre, 18pp. (National Oceanography Centre Internal Document, No. 10)

Npower Renewables (2004). GyM Offshore Wind Farm, Scoping report

Npower Renewables (2005). GyM Offshore Wind Farm, Environmental Statement. Chapter 5 The physical environment

Osiris (2003a). Gwynt Y Môr Proposed Offshore Wind Farm Development Geophysical Surveys Phase 1 Survey Report C2018 – 01

Osiris (2003b). Gwynt Y Môr Proposed Offshore Wind Farm Development Geophysical Surveys Phase 2 Survey Report C3008

Osiris (2004). Gwynt Y Môr Proposed Offshore Wind Farm Development Geophysical Surveys Phase 3 Survey Report C4009

Osiris (2005). Rhyl Flats Offshore Wind Farm Development. Pre-construction and Cable Route Survey. Report C5025. Client Confidential.

Osiris (2008). Rhyl Flats Bathymetric Survey. Client Confidential.

Osiris (2012). Rhyl Flats Bathymetric Survey. Client Confidential.

Palmer, M., Howard, T., Tinker, J., Lowe, J., Bricheno, L., Calvert, D., Edwards, T., Gregory, J., Harris, G., Krijnen, J., Pickering, M., Roberts C. and Wolf J. (2018). UK Climate Projections Science Report: UKCP18 Marine report. Met Office Hadley Centre: Exeter.

Parson, J., Pugh-Thomas, M. (1979) Notes on the ecology of the Clwyd estuary. North Wales. Journal of Natural History 13, 725-734.

Pye, K. & Blott, S.J. (2017). Barkby Beach to Point of Ayr: Geomorphology Review. Report to Flintshire Council and Denbighshire Council. KPAL Report 21009, July 2017.

Robins PE., Neill., SP., Lewis., MJ. (2014). Impact of tidal-stream arrays in relation to the natural variability of sedimentary processes. Renewable Energy 72: 311-321.

Royal Haskoning (2010). West of Wales SMP2.
[redacted]

RWE Npower (2005). Gwynt y Môr Offshore Wind Farm Environmental Statement.

Sager, G. and Sammler, R. (1975). Atlas der Gezeitenstrome fiir die Nordsee, den Kanal und die Irische See. Seehydro:Jraphischer Dienst der Deutschen Demokratischen Republik, Rostock.

SEACAMS (2014). Multibeam bathymetry data collected between Colwyn Bay to Prestatyn. Available from [redacted]

Sefton Council (2015). North West Strategic Monitoring Regional Sediment Analysis and Reporting 2015. Intertidal Report November 2015. CEUK Project Ref: 08/1410

Sutton, G. (2008). Irish Sea Marine Aggregate Initiative (IMAGIN) Project Synthesis Report Including: Geological Assessment, Environmental Assessment, Morphodynamic Modelling Web-based GIS System, Cost Benefit Analysis, Aggregate Resources and Markets-Wales. Marine Environment and Health Series, No. 36. 2008.

UKHO (2021). Admiralty TotalTide. [redacted]

UKHO (2019). Multibeam bathymetry data collected between Little Ormes Head to Hilbre Point. Available from [redacted]

Van Landeghem, K.J..J. (2012). Irish Sea, R3 Wind Farm Development Zone. Prediction of sediment wave migration. Document Number R3-D-EV-027-0132-000000-001. Prepared for Centrica plc

Van Landeghem, K.J..J., Baas, J.H., Mitchell, N.C., Wilcockson, D., Wheeler, A.J. (2012). Reversed sediment wave migration in the Irish Sea, NW Europe: A reappraisal of the validity of geometry-based predictive modelling and assumptions. Marine Geology, Vol 295-298, p95–112, doi:10.1016/j.margeo.2011.12.004Van

Van Landeghem, K.J..J., Wheeler, A.J., Mitchell, N.C., Sutton, G. (2009). Variations in sediment wave dimensions across the tidally dominated Irish Sea, NW Europe. Marine Geology, Vol 263, p108–119, doi:10.1016/j.margeo.2009.04.003.

Vincent, M.A., Atkins, S.M., Lumb, C.M., Golding, N., Lieberknecht, L.M. and Webster, M. (2004). Marine nature conservation and sustainable development - the Irish Sea Pilot. Report to Defra by the Joint Nature Conservation Committee, Peterborough.

White M, Gaffney S, Bowers DG, Bowyer P. (2003). Interannual variability in Irish sea turbidity and relation to wind strength. Biol Environ Proc R Ir Acad 103B:83-90.

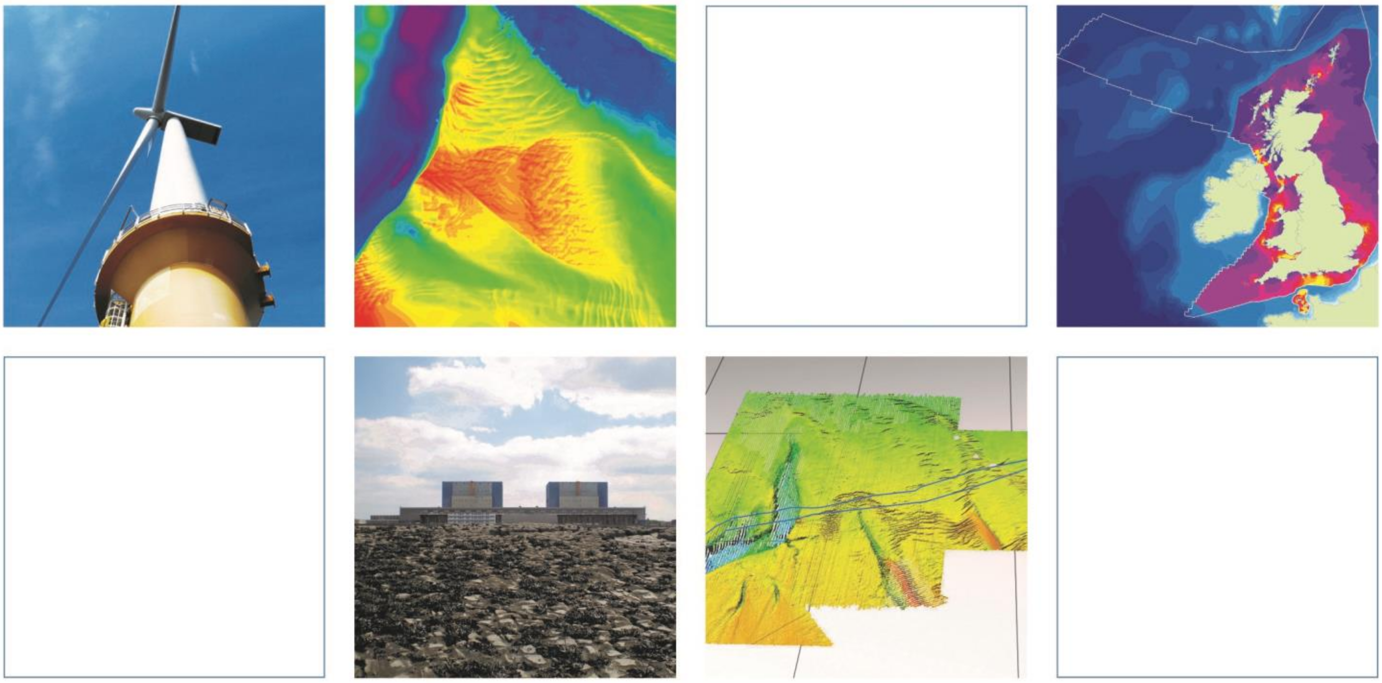
7 Abbreviations and Acronyms

AmSedIS	Amplified Sediment Waves in the Irish Sea (research project)
AyM	Awel y Môr (Offshore Wind Farm)
BGS	British Geological Survey
BODC	British Oceanographic Data Centre
CBF	Cardigan Bay Formation
CD	Chart Datum
Cefas	Centre for Environment, Fisheries and Aquaculture Science
CERMS	Cell 11 Regional Monitoring Strategy
CETaSS	Cell Eleven Tidal and Sediment Study
CTD	Conductivity, Temperature and Depth
DCWW	Dŵr Cymru Welsh Water
DTI	Department of Trade and Industry
ECC	Export Cable Corridor
EIA	Environmental Impact Assessment
GIS	Geographic Information System
GoBe	GoBe Consultants
GyM	Gwynt y Môr
IMAGIN	Irish Sea Marine Aggregate Initiative
IMARDIS	Integrated Marine Data and Information System
ISIS	Irish Sea Ice Stream
JNCC	Joint Nature Conservation Committee
LAT	Lowest Astronomical Tide
LiDAR	Light Distance and Ranging
NRW	Natural Resources Wales
NTSLF	National Tide and Sea Level Facility
OBS	Optical Backscatter
ODN	Ordnance Data Newlyn
OWF	Offshore Wind Farm
RCP	Representative Concentration Pathway
RP	Return Period
RWE	RWE Renewables UK
SAC	Special Areas of Conservation
SEA	Strategic Environmental Assessment
SEACAMS	Sustainable Expansion of the Applied Coastal and Marine Sectors (research project)
SI	The International System of Units (Système international (d'unités))
SMP	Shoreline Management Plan
SPA	Special Protection Area
SPM	Suspended Particulate Matter
SSC	Suspended Sediment Concentration
SSF	Surface Sands Formation
SSS	Side Scan Sonar
SSSI	Sites of Special Scientific Interest
Tp	Peak wave period
UK	United Kingdom
UKCP18	UK Climate Projections
UKHO	United Kingdom Hydrographic Office
WIS	Western Irish Sea Formation

Cardinal points/directions are used unless otherwise stated.

SI units are used unless otherwise stated.

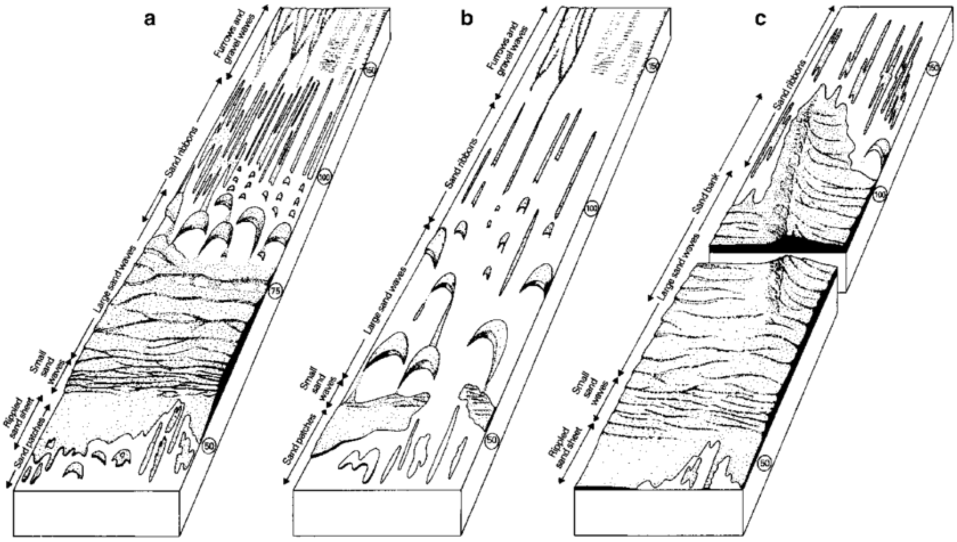
Appendix



Innovative Thinking - Sustainable Solutions

A Distribution of Bedform Zones Along Tidal Current Transport Paths (Belderson *et al.*, 1982)

The following table and figure are from the published research of Belderson *et al*, (1982).[1]



From Belderson *et al.* (1982)

Figure A1. Distribution of bedform zones along tidal current transport paths: (a) general model (intermediate sand supply); (b) low sand supply model, and (c) high sand supply model

Table A1. Interpretation of Figure A1 – bedforms resulting from categories of peak surface current speed on a mean spring tide depending on sediment abundance

Current Speed (m/s)		Sedimentary Environment		
Lower	**Upper**	**Abundant Sediment**	**Intermediate**	**Limited Sand**
0	0.3	Limited to no transport of sands.	Limited to no transport of sands.	Limited to no transport of sands.
0.3	0.5	Superficial ripples.	Mobile sand patches with ripples	Mobile sand patches
0.5	0.6	Megaripples and small sand waves	Patchy megaripples and small sand waves	Isolated megaripples and small sand waves
0.6	0.75	Large sandwaves	Larger sandwaves	Isolated sandwaves and dunes
0.75	1	Sandbanks and sandwaves	Sandwaves and sand ribbons	Sand ribbons
1	1.25	Sandbanks, sandwaves and sand ribbons	Sand ribbons if sand still present	Sand ribbons if sand still present
1.25	1.5	Sand ribbons if sand still present	Furrows and gravel waves	Furrows and gravel waves

.

[1] Belderson RH., Johnson MA., Kenyon NH. 1982. Bedforms. In: Stride AH (ed.) Offshore tidal sands, processes and deposits. Chapman and Hall Ltd, London, UK pp 27-57

Contact Us

ABPmer

Quayside Suite,
Medina Chambers
Town Quay, Southampton
SO14 2AQ

T +44 (0) 23 8071 1840
F +44 (0) 23 8071 1841
E enquiries@abpmer.co.uk

www.abpmer.co.uk

Fferm Wynt Alltraeth
AWEL Y MÔR
Offshore Wind Farm

RWE Renewables UK
Swindon Limited

Windmill Hill Business Park
Whitehill Way
Swindon
Wiltshire SN5 6PB
T +44 (0)8456 720 090
www.rwe.com

Registered office:
RWE Renewables UK
Swindon Limited Windmill
Hill Business Park Whitehill
Way
Swindon