Cenos Offshore Windfarm Limited

Cenos EIA

Appendix 7 - Marine & Physical Processes Modelling Report

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CONTENTS

ACRONYMS

ACRONYM	DEFINITION
1D	One Dimensional
2D	Two Dimensional
3D	Three Dimensional
°C	degrees Celsius
Cefas	Centre for Environment, Fisheries and Aquaculture Science
CNS	Central North Sea
CTD	Conductivity, Temperature and Depth
EIA	Environmental Impact Assessment
EIAR	Environmental Impact Assessment Report
EICC	Export/Import Cable Corridor
FTU	Floating Turbine Unit
GOTM	General Ocean Turbulence Model
GSW	Gibbs SeaWater
HDD	Horizontal Directional Drilling
HnTh	Hundreds of Thousands
HVDC	High Voltage Direct Current
IOC	Intergovernmental Oceanographic Commission
J	Joules
kg	Kilogram
km	Kilometre
KP	Kilometre Point
LAT	Lowest Astronomical Tide
m	Metre
mg/l	Milligrams per litre
MHWS	Mean High Water Springs
MLWS	Mean Low Water Springs
Mn	Millions
MPA	Marine Protected Area
m/s	Metres per Second
MW	Mega Watt
NM	Nautical mile

ACRONYM	DEFINITION
NW	North-west
NCMPA	Nature Conservation Marine Protected Area
OSCP	Offshore Substation and Converter Platform
OWF	Offshore Wind Farm
PDE	Project Design Envelope
PEA	Potential Energy Anomaly
PLGR	Pre-Lay Grapnel Run
PLONOR	Pose Little Or No Risk to the environment
PP	Primary Productivity
PSU	Practical Salinity Units
SPM	Suspended Particulate Matter
SSC	Suspended Sediment Concentration
SSM	Scottish Shelf Model
TKE	Turbulent Kinetic Energy
TnTh	Tens of Thousands
UK	United Kingdom
USA	United States of America
WCS	Worst-case Scenario

GLOSSARY

TERM	DEFINITION
2023 Scoping Opinion	Scoping Opinion received in June 2023, superseded by the 2024 Scoping Opinion.
2023 Scoping Report	Environmental Impact Assessment (EIA) Scoping Report submitted in 2023, superseded by the 2024 Scoping Report.
2024 Scoping Opinion	Scoping Opinion received in September 2024, superseding the 2023 Scoping Opinion.
2024 Scoping Report	EIA Scoping Report submitted in April 2024, superseding the 2023 Scoping Report.
Area of Opportunity	The area in which the limits of electricity transmission via High Voltage Alternating Current (HVAC) cables can reach oil and gas assets for decarbonisation. This area is based on assets within a 100 kilometre (km) radius of the Array Area.
Array Area	The area within which the Wind Turbine Generators (WTGs), floating substructures, moorings and anchors, Offshore Substation Converter Platforms (OSCPs) and Inter-Array Cables (IAC) will be present.
Cenos Offshore Windfarm ('the Project')	'The Project' is the term used to describe Cenos Offshore Windfarm. The Project is a floating offshore windfarm located in the North Sea, with a generating capacity of up to 1,350 Megawatts (MW). The Project which defines the Red Line Boundary (RLB) for the Section 36 Consent and Marine Licence Applications (MLA), includes all offshore components seaward of Mean High Water Springs (MHWS) (WTGs, OSCPs, cables, floating substructures moorings and anchors and all other associated infrastructure). The Project is the focus of this Environmental Impact Assessment Report (EIAR).
Cenos Offshore Windfarm Ltd. (The Applicant)	The Applicant for the Section 36 Consent and associated Marine Licences.
Cumulative Assessment	The consideration of potential impacts that could occur cumulatively with other relevant projects, plans, and activities that could result in a cumulative effect on receptors.

TERM	DEFINITION
Developer	Cenos Offshore Windfarm Ltd., a Joint Venture between Flotation Energy and Vårgrønn As (Vårgrønn).
Environmental Impact Assessment (EIA)	The statutory process of evaluating the likely significant environmental effects of a proposed project or development. Assessment of the potential impact of the proposed Project on the physical, biological and human environment during construction, operation and maintenance and decommissioning.
Environmental Impact Assessment Regulations	This term is used to refer to the Environmental Impact Assessment Regulations which are of relevance to the Project. This includes the Electricity Works (Environmental Impact Assessment) (Scotland) Regulations 2017, the Marine Works (Environmental Impact Assessment) (Scotland) Regulations 2017 (as amended); and the Marine Works (Environmental Impact Assessment) Regulations 2007.
Environmental Impact Assessment Report	A report documenting the findings of the EIA for the Project in accordance with relevant EIA Regulations.
Export/Import Cable	High voltage cable used to export/import power between the OSCPs and Landfall.
Export/Import Cable Bundle (EICB)	Comprising two Export/Import Cables and one fibre-optic cable bundled in a single trench.
Export/Import Cable Corridor (EICC)	The area within which the Export/Import Cable Route will be planned and the Export/Import Cable will be laid, from the perimeter of the Array Area to MHWS.
Export/Import Cable Route	The area within the Export/Import Export Corridor (EICC) within which the Export/Import Cable Bundle (EICB) is laid, from the perimeter of the Array Area to MHWS.
Floating Turbine Unit (FTU)	The equipment associated with electricity generation comprising the WTG, the floating substructure which supports the WTG, mooring system and the dynamic section of the IAC.
Flotation Energy	Joint venture partner in Cenos Offshore Windfarm Ltd.

TERM	DEFINITION
Habitats Regulations	The Habitats Directive (Directive 92/43/ECC) and the Wild Birds Directive (Directive 2009/147/EC) were transposed into Scottish Law by the Conservation (Natural Habitats &c) Regulations 1994 ('Habitats Regulations') (up to 12 NM); by the Conservation of Offshore Marine Habitats and Species Regulations 2017 ('Offshore Marine Regulations') (beyond 12 NM); the Conservation of Habitats and Species Regulations 2017 (of relevance to consents under Section 36 of the Electricity Act 1989); the Offshore Petroleum Activities (Conservation of Habitats) Regulations 2001; and the Wildlife and Countryside Act 1981. The Habitats Regulations set out the stages of the Habitats Regulations Appraisal (HRA) process required to assess the potential impacts of a proposed project on European Sites (Special Areas of Conservation, Special Protection Areas, candidate SACs and SPAs and Ramsar Sites).
Habitats Regulations Appraisal	The assessment of the impacts of implementing a plan or policy on a European Site, the purpose being to consider the impacts of a project against conservation objectives of the site and to ascertain whether it would adversely affect the integrity of the site.
High Voltage Alternating Current (HVAC)	Refers to high voltage electricity in Alternating Current (AC) form which is produced by the WTGs and flows through the IAC system to the OSCPs. HVAC may also be used for onward power transmission from the OSCPs to assets or to shore over shorter distances.
High Voltage Direct Current (HVDC)	Refers to high voltage electricity in Direct Current (DC) form which is converted from HVAC to HVDC at the OSCPs and transmitted to shore over longer distances.
Horizontal Directional Drilling (HDD)	An engineering technique for laying cables that avoids open trenches by drilling between two locations beneath the ground's surface.
Innovation and Targeted Oil & Gas (INTOG)	In November 2022, the Crown Estate Scotland (CES) announced the Innovation and Targeted Oil & Gas (INTOG) Leasing Round, to help enable this sector-wide commitment to decarbonisation. INTOG allowed developers to apply for seabed rights to develop offshore windfarms for the purpose of providing low carbon electricity to power oil and gas installations and help to decarbonise the sector. Cenos is an INTOG project and in November 2023 secured an Exclusivity Agreement as part of the INTOG leasing round.
Inter-Array Cable (IAC)	The cables which connect the WTGs to the OSCPs. WTGs may be connected with IACs into a hub or in series as a 'string' or a 'loop' such that

TERM	DEFINITION
	power from the connected WTGs is gathered to the OSCPs via a single cable.
Joint Venture	The commercial partnership between Flotation Energy and Vårgrønn, the shareholders which hold the Exclusivity Agreement with CES to develop the Cenos site as an INTOG project.
Landfall	The area where the Export/Import Cable from the Array Area will be brought ashore. The interface between the offshore and onshore environments.
Marine Licence	Licence required for certain activities in the marine environment and granted under the Marine and Coastal Access Act 2009 and/or the Marine (Scotland) Act 2010.
Marine Protected Area (MPA)	Marine sites protected at the national level under the Marine (Scotland) Act 2010 out to 12 NM, and the Marine and Coastal Access Act 2009 between 12-200 NM. In Scotland MPAs are areas of sea and seabed defined so as to protect habitats, wildlife, geology, underseas landforms, historic shipwrecks and to demonstrate sustainable management of the sea.
Marine Protected Area (MPA) Assessment	A three-step process for determining whether there is a significant risk that a proposed development could hinder the achievement of the conservation objectives of an MPA.
Mean High Water Springs (MHWS)	The height of Mean High Water Springs is the average throughout the year, of two successive high waters, during a 24-hour period in each month when the range of the tide is at its greatest.
Mean Low Water Springs (MLWS)	The height of Mean Low Water Springs is the average throughout a year of the heights of two successive low waters during periods of 24 hours (approximately once a fortnight).
Mitigation Measures	Measures considered within the topic-specific chapters in order to avoid impacts or reduce them to acceptable levels. • Primary mitigation - measures that are an inherent part of the design of the Project which reduce or avoid the likelihood or magnitude of an adverse environmental effect, including location or design; • Secondary mitigation – additional measures implemented to further reduce environmental effects to 'not significant' levels (where appropriate) and do not form part of the fundamental design of the Project; and

TERM	DEFINITION
	- Tertiary mitigation – measures that are implemented in accordance with industry standard practice or to meet legislative requirements and are independent of the EIA (i.e. they would be implemented regardless of the findings of the EIA). Primary and tertiary mitigation are referred to as embedded mitigation. Secondary mitigation is referred to as additional mitigation.
Mooring System	Comprising the mooring lines and anchors, the mooring system connects the floating substructure to the seabed, provides station-keeping capability for the floating substructure and contributes to the stability of the floating substructure and WTG.
Nature Conservation Marine Protected Area (NCMPA)	MPA designated by Scottish Ministers in the interests of nature conservation under the Marine (Scotland) Act 2010.
Offshore Substation Converter Platforms (OSCPs)	An offshore platform on a fixed jacket substructure, containing electrical equipment to aggregate the power from the WTGs and convert power between HVAC and HVDC for export/import via the export/import cable to/from the shore. The OSCPs will also act as power distribution stations for the Oil & Gas platforms.
Onward Development	Transmission projects which are anticipated to be brought forward for development by 3rd party oil and gas operators to enable electrification of assets via electricity generated by the Project. All Onward Development will subject to separate marine licensing and permitting requirements.
Onward Development Area	The area within which oil and gas assets would have the potential to be electrified by the Project.
Onward Development Connections	Oil and gas assets located in the waters surrounding the Array Area will be electrified via transmission infrastructure which will connect to the Project's OSCPs. These transmission cables are referred to as Onward Development Connections.
Project Area	The area that encompasses both the Array Area and EICC.
Project Design Envelope	A description of the range of possible elements that make up the Project design options under consideration and that are assessed as part of the EIA for the Project.

TERM	DEFINITION
Study Area	Receptor specific area where potential impacts from the Project could occur.
Transboundary Assessment	The consideration of impacts from the Project which have the potential to have a significant effect on another European Economic Area (EEA) state's environment. Where there is a potential for a transboundary effect, as a result of the Project, these are assessed within the relevant EIA chapter.
Transmission Infrastructure	The infrastructure responsible for moving electricity from generating stations to substations, load areas, assets and the electrical grid, comprising the OSCPs, and associated substructure, and the Export/Import Cable.
Vårgrønn As (Vårgrønn)	Joint venture partner in Cenos Offshore Windfarm Ltd.
Wind Turbine Generator (WTG)	The equipment associated with electricity generation from available wind resource, comprising the surface components located above the supporting substructure (e.g., tower, nacelle, hub, blades, and any necessary power transformation equipment, generators, and switchgears).
Worst-Case Scenario	The worst-case scenario based on the Project Design Envelope which varies by receptor and/or impact pathway identified.

APPENDIX 7 MARINE & PHYSICAL PROCESSES MODELLING REPORT

7.1 Introduction

ABPmer has been commissioned to undertake assessment of the potential impacts of the Cenos Offshore Wind Farm ('the Project') in relation to Marine Geology, Oceanography and Coastal Processes, which is a collective term for the following:

- Water levels;
- Currents;
- Waves (and winds);
- Water column stratification and frontal systems;
- Sediments and geology (including seabed sediment distribution and sediment transport);
- Seabed geomorphology; and
- Coastal geomorphology.

The Project is located in the Central North Sea (CNS) and comprises both the Array Area and the Export/Import Cable Corridor (EICC), which extends up to Mean High-Water Springs (MHWS) (Figure 7-1). The Array Area is approximately 333 square kilometres (km^2) located in a water depth between 82 metres (m) and 105 m Lowest Astronomical Tide (LAT). The Array Area will include up to 95 Floating Turbine Units (FTUs). Each FTU will have a WTG and a floating substructure, moored to the seabed to ensure station-keeping. Inter-Array Cables (IACs) will be used to gather electricity from the FTU's to up to two central Offshore Substation Converter Platforms (OSCPs). The IACs will have dynamic portions in the water column between the seabed and substructure, and static portions buried in the seabed. Included in the transmission assets are the OSCPs and the Export/Import Cable. The IACs will connect to the OSCPs to transmit power from the FTUs to the OSCPs. The Export/Import Cable will lie within the Export/Import Cable Corridor (EICC) which is approximately 230 km in length and will run from the OSCPs to the landfall.

The Study Area defined in Figure 7-1 is a zone of influence around the Project within which changes to Marine Geology, Oceanography and Coastal Processes could theoretically occur. More details of the basis for the extent of this Study Area are provided in **EIAR Vol. 3, Chapter 8: Marine Geology, Oceanography and Coastal Processes**.

This technical report provides a detailed assessment of:

- Potential changes to Suspended Sediment Concentrations (SSC's), bed levels and changes to sediment type as a consequence of sediment disturbance; and
- Potential changes to stratification and frontal systems as a consequence of FTUs.

The findings of this report have been summarised in **EIAR Vol. 3, Chapter 8: Marine Geology, Oceanography and Coastal Processes** and are used to inform assessments for other EIA receptor groups which may potentially be sensitive to changes in SSC, bed levels (sediment deposition) and water column stratification.

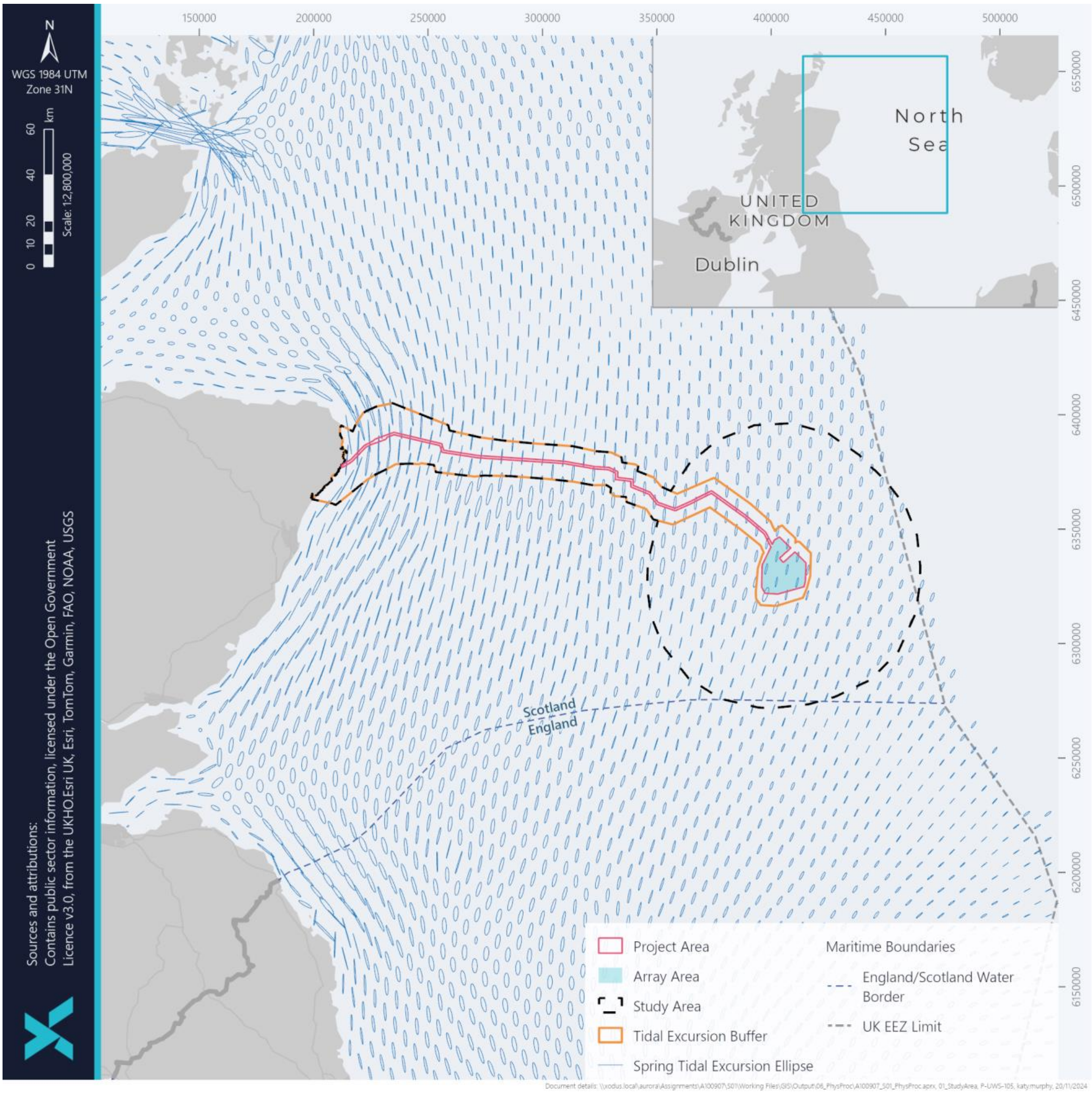


Figure 7-1 Marine Geology, Oceanography and Coastal Processes Study Area

7.2 Assessment of potential changes to suspended sediment concentrations, bed levels and sediment type

7.2.1 Introduction

Local increases in SSC may potentially result from the disturbance of sediment by construction related activities, namely due to:

- Seabed preparation by Pre-Lay Grapnel Run (PLGR) prior to IACs and Export/Import Cable burial;
- Seabed preparation by boulder clearance prior to IACs and Export/Import Cable burial;
- IACs and Export/Import Cable burial by ploughing, trenching and jetting; and
- Release of drilling fluid during Horizontal Directional Drilling (HDD) punch out at the Landfall.

Cable de-burial and/or removal during cable repair and/or remediation in the operation and maintenance phase may also cause some localised disturbance of sediment. However, this will be at a rate, scale and duration less than or similar to the activities described above and so are not explicitly assessed.

Any material mobilised by the activities listed above may be transported away from the disturbance location by the local tidal regime. According to the source-pathway-receptor model:

- Disturbance and release of sediment is considered as the source of potential changes to SSC in the water column;
- Tidal currents act as the pathway for transporting the suspended sediment; and
- The receptor is a feature potentially sensitive to any increase in SSC within the water column and/or the subsequent deposition of suspended sediments on the seabed.

The potential changes assessed in this technical annex are summarised in **EIAR Vol. 3, Chapter 8: Marine Geology, Oceanography and Coastal Processes**, alongside the activities giving rise to the change and the Project phases in which the potential change may occur. The magnitude, duration, rate of change and frequency of recurrence of changes to SSC and bed level are variable between operation types and in response to natural variability in the controlling environmental parameters.

In many cases, Marine Geology, Oceanography and Coastal Processes are not in themselves receptors but are, instead, 'pathways' which have the potential to indirectly impact other environmental receptors. Changes caused to SSC and associated sediment deposition are considered here as potential pathways of change that will be assessed by other EIA topics in relation to other sensitive receptors in particular:

- **EIAR Vol. 3, Chapter 9: Marine Water and Sediment Quality;**
- **EIAR Vol. 3, Chapter 10: Benthic Ecology;** and
- **EIAR Vol. 3, Chapter 13: Fish and Shellfish Ecology.**

7.2.2 Methodology

7.2.2.1 Baseline

The baseline understanding relevant to this impact assessment is mostly provided in EIAR Vol. 3, Chapter 8: Marine Geology, Oceanography and Coastal Processes. The data sources used, and any relevant analysis methodology are also outlined in that Chapter. A summary of relevant information is also provided in Section 7.2.3 of this report.

7.2.2.2 Impact assessment

7.2.2.2.1 Introduction

Sediment disturbed and released into the water column during the construction, operation and maintenance (cable repair/remediation events) and decommissioning phases will settle downwards at a rate depending upon its grain size. During settling, the sediment plume will be advected away from the point of release by any currents that are present and will be dispersed laterally by turbulent diffusion. The horizontal advection distance will be related to the flow speed and the physical properties of the sediment. The maximum near-bed level of SSC is expected to be found at the location and time of the activity causing the disturbance. If the source of the plume is initially located or directed away from the seabed, the maximum SSC will be where the main body of the settling plume of sediment reaches the seabed.

Coarse grained sediments (i.e. sand/gravel) will behave differently to fine grained sediments (i.e. silt/clay) when released into the water column. The disturbance of coarse grained or consolidated material is likely to give rise to high SSCs in the vicinity of the release location but is also likely to settle out of suspension quickly (e.g. in the order of seconds to minutes) so any sediment plumes are likely to be localised. In contrast, fine grained material will tend to remain in suspension for a longer period of time (in the order of hours to days), potentially resulting in an increase in SSC over a larger area, at a progressively reduced concentration, due to advection and dispersion from the original release location.

Similar differences are expected when considering any resulting changes in bed level due to settlement of the material in suspension. Coarser material will tend to give rise to thicker but more localised changes in bed levels whereas fine grained material may give rise to smaller changes in bed levels over a wider area. The exact pattern of re-deposition of sediment to the seabed will depend on the actual combination of operational methods and environmental conditions at the time of the event, which will be variable. The total volume of sediment disturbed is, however, known with greater certainty and a range of potential combinations of deposit shape, thickness and area (corresponding to the same total volume) can be more reliably provided, as a subset of all possible combinations.

7.2.2.2.2 Spreadsheet based numerical models

In order to inform the assessment of potential changes to SSC and bed levels arising from construction related activities, a number of spreadsheet based numerical models have been developed for use. Similar models were developed and used to inform the environmental impact assessments for similar activities at Burbo Bank Extension, Walney Extension, Navitus Bay, Thanet Extension, Hornsea Three, Erebus, Llyr, Rampion 2 and Five Estuaries Offshore Wind Farms (OWFs; DONG Energy, 2013a,b; Navitus Bay Development Ltd, 2014; Vattenfall, 2018; Ørsted, 2018; Blue Gem Wind, 2023; Floventis, 2024; RWE, 2024a,b respectively). The spreadsheet based numerical models used here are based upon the following information, assumptions and principles:

- Re-suspended coarser sediments (sands and gravels) will settle relatively rapidly to the seabed and their dispersion can therefore be considered on the basis of a 'snapshot' of the ambient conditions which are unlikely to vary greatly between the times of sediment release and settlement to the seabed. Re-suspended finer sediments may persist in the water column for hours or longer and so their dispersion is considered instead according to the longer-term net tidal current drift rate and direction in the area, which vary both temporally and spatially in speed and direction;
- A representative current speed for the Array Area is 0.25 metres per second (m/s), which is representative of higher tidal flow conditions occurring on most flood and ebb cycles for a range of spring and neap conditions. Assuming a higher value will increase dispersion, decrease SSC and reduce the thickness of subsequent deposits and *vice versa*;
- Lateral dispersion of SSC in the plume is controlled by the horizontal eddy dispersion coefficient, Ke, estimated as $Ke = \kappa u^* z$ (Soulsby, 1997), where, z is the height above the seabed (a representative value of half the water depth is used), κ is the von Kármán coefficient ($\kappa = 0.4$) and u^* is the friction velocity ($u^* = \sqrt{(\tau/\rho)}$). Where ρ is the density of seawater ($\rho = 1027$ kilograms (kg)/m^3) and τ is the bed shear stress, calculated using the quadratic stress law ($\tau = \rho C_d U^2$, Soulsby, 1997) using a representative current speed for the Study Area ($U = 0.25$ m/s) and a drag coefficient value for a rippled sandy seabed ($C_d = 0.006$);
- The interpreted geophysical data and sediment grab samples indicate that in general there are two characteristic surficial sediment types present, namely:
  - Where present, surficial sediments in the EICC are characterised as clayey, silty sand with occasional gravel and isolated to scattered cobbles and boulders. Sediments typically comprise mainly sand (80-90%) and fines (10-20%), with a small proportion of gravel (<1%).
  - In the Array Area, surficial sediments are characterised as clayey, silty sand with occasional gravel and isolated to scattered cobbles and boulders. Sediments typically comprise fine sand and coarse silt (50-65%) and fines (35-50%), with a small proportion of gravel (1-3%).
- To estimate the time-scale in suspension, sediment is assumed to settle downwards at a calculated (theoretical, from Soulsby, 1997) settling velocity for each grain size fraction (0.0001 m/s for fines, 0.001 m/s for fine sands and coarse silts, 0.05 m/s for medium sands and 0.5 m/s for gravels and generally coarser sediments, including clastic drill arisings).

The numerical model for SSC resulting from the release of sands and gravels is constructed as follows:

- The time required for sediment to settle at the identified settling velocity through a range of total water depths representative of the site is calculated, to yield the duration for settlement;
- The horizontal distance downstream that the plume is advected is found as the product of the representative ambient current speed and the duration for settlement;
- The horizontal footprint area of the plume at different water depths is calculated from the initial dispersion area, increasing at the horizontal dispersion rate over the elapsed time for the plume to reach that depth; and,
- The estimate of SSC at different elevations is found by dividing the sediment mass in suspension at a given water depth (the product of the sediment release rate and the duration of the impact, divided by the water depth) by the representative plume volume at that depth (horizontal footprint area at that depth x 1 m).

The numerical model for sediment deposition thickness resulting from the release of sands and gravels is constructed as follows:

- The area over which sediment is deposited depends on the lateral spreading of the sediment plume footprint with depth, but also with tidal variation in current speed and direction, including the possibility of flow reversal. This is an important factor if the release occurs for more than tens of minutes as it affects the distance and direction which the plume is advected from the source;
- The width of the footprint of (instantaneous) deposition onto the seabed is estimated as the square root of the near-bed plume footprint area (calculated using the model for SSC above). When drilling anchor piles, the point of sediment release is likely to be static and so the width of deposition is characterised based on the footprint of release and a small amount of lateral dispersion between surface and seabed prior to deposition;
- The length of the footprint of deposition onto the seabed over multiple tidal cycles is estimated as twice the advected distance of the plume at the representative current speed, representing the maximum length over consecutive flood and ebb tides. If the operation lasts less than 12.4 hours (one full tidal cycle), the length is reduced proportionally; and
- The average seabed deposition thickness is calculated as the total volume of sediment released, divided by the footprint area (width times length) of deposition.

This model provides a conservative estimate of deposition thickness as it assumes that the whole sediment volume is deposited locally in a relatively narrow corridor. In practice, the deposition footprint on the seabed will probably be normally wider and frequently longer than is assumed, and the proportion of all sediment deposited locally will vary with the distribution in grain size (leading to a greater area but a correspondingly smaller average thickness).

The numerical model for SSC resulting from dispersion of fine sediment is constructed on the basis of the initial dispersion into the receiving waters, and then further dispersion of the plume as a whole, as per the following example for drilling fluid release at the Landfall:

- Drilling fluid is discharged at the maximum concentration (e.g. 80 kg/m^3, 80,000 milligrams per litre (mg/l), for drilling fluid) into a representative nearbed plume with initial dimensions 10 m wide x 10 m long x 1 m high/deep = 100 m^3;
- The total sediment contained in the plume is 100 m^3 x 80 kg/m3 = 8,000 kg; and
- The initial concentration plume would then be subject to turbulent dispersion and dilution both laterally and vertically. Given the starting mass of sediment and water volume above, levels of SSC will vary rapidly in proportion to the dilution of the same sediment mass as the plume dimensions and volume increase, e.g. If the plume dimensions subsequently increase to 50 m wide x 10 m long x 5 m high/deep, the new volume is 2500 m^3 and the average concentration in that plume is 8,000 kg/2500 m^3 = 3.2 kg/m^3 = 3,200 mg/l (reduced from 80,000 mg/l).

7.2.3 Baseline characterisation

7.2.3.1 Overview

A description of the baseline environment across the Marine Geology, Oceanography and Coastal Processes Study Area is provided in EIAR Vol. 3, Chapter 8: Marine Geology, Oceanography and Coastal Processes, drawing upon the findings of the project-specific geophysical and geotechnical surveys, and other pre-existing measured and modelled data.

Based on the data sources described in EIAR Vol. 3, Chapter 8: Marine Geology, Oceanography and Coastal Processes, a summary of the relevant baseline characteristics within and nearby to the Array Area of the Project is provided below, for the following characteristics:

- Tidal Currents;
- Seabed sediment type;
- Suspended Sediment Concentration;
- Sediment Deposition; and
- Future Change.

7.2.3.2 Tidal currents

Tidal current speeds vary continuously in response to flood/ebb, spring/neap, equinox/solstice and other tidal cycles, as well as with depth and in conjunction with any non-tidal surge influence. Based on the site specific metocean survey in the Array Area and other hindcast data, peak depth averaged current speed on a mean spring tide within the Array Area is approximately 0.3 m/s, increasing gradually along the EICC to between approximately 0.6 and 0.8 m/s at the Landfall. Peak depth averaged current speed on a mean neap tide is approximately half the spring value.

Tidal currents disperse sediment plumes by advection. The path followed by tidal currents, and the maximum distance that tidal currents might displace water in one flood or ebb cycle from a given location, is a limiting factor in the maximum spatial extent of sediment plume effects. The tidal ellipse's shown in Figure 7-1 illustrate the approximate elliptical path (length, width and orientation) followed by water in the Study Area during a mean spring tidal cycle. During mean spring tidal conditions, the approximate overall tidal excursion distance is: 4.5 km in the Array Area; 7.5 km in the middle of the EICC; and 8 to 12 km inshore. Tidal excursion distances on a mean neap tide (not shown) are approximately half the corresponding mean spring value. The spring tidal excursion buffer in Figure 7-1 indicates the maximum extent of water displacement (and therefore any plume effects) arising from any location within the Array Area or EICC.

7.2.3.3 Suspended sediment concentration

Monthly averaged satellite imagery of Suspended Particulate Matter (SPM) suggest that average (surface) SPM concentration is generally and consistently very low (<1 mg/l) throughout the EICC and Array Area, throughout the year. Values are relatively (slightly) higher closer to the landfall and coastline, in closer proximity to shallower water, coastal erosion and other fluvial sources of fine sediment.

In practice, higher values (potentially several tens or hundreds of mg/l) are realistically anticipated in some shallower locations closer to the Landfall during larger spring tides and storm conditions. SSC naturally varies with height in the water column. Sediment is naturally re-suspended by the action of currents and waves at the seabed, so SSC levels are higher, lower in the water column. Sediment grains naturally settle downwards under gravity but are also re-suspended upwards by turbulence, which is greater nearer the seabed. This results in an equilibrium state, and a non-linear profile of SSC (i.e. rapidly decreasing with height above the seabed).

7.2.3.4 Seabed sediment type

A summary of the sediment types within the Array Area, EICC and at the Landfall is presented in Figure 8-8 within EIAR Vol. 3, Chapter 8: Marine Geology, Oceanography and Coastal Processes.

The surficial sediment thickness above the underlying hard substrate (Quaternary geology) has been interpreted from project specific shallow geophysical surveys (Rovco, 2023a,b). In the EICC, potentially mobile surficial sediment thickness is typically thin (<0.5 m) or absent (exposed erosion resistant glacial tills); the maximum local surficial sediment thickness is 2.4 m at around Kilometre Point (KP) 61 (Rovco, 2023a). In the Array Area, potentially mobile surficial sediment thickness is typically thin (approximately 0.5 to 3 m thick over erosion resistant glacial tills) (Rovco, 2023b).

Where present, surficial sediments in the EICC are characterised as clayey, silty sand with occasional gravel and isolated to scattered cobbles and boulders. Sediments typically comprise mainly sand (80-90%) and fines (10-20%), with a small proportion of gravel (<1%).

In the Array Area, surficial sediments are characterised as clayey, silty sand with occasional gravel and isolated to scattered cobbles and boulders. Sediments typically comprise fine sand and coarse silt (50-65%) and fines (35-50%), with a small proportion of gravel (1-3%). Note that no mud samples were recorded in any of the sediment grab samples within the Array Area, as per the standard BGS Folk classification scheme used to map the UK seabed in detail.

Within the surficial sediments of the EICC and Array Area, there is a frequent occurrence of cobbles and boulders.

7.2.3.5 Future change

No consistent measurable future changes to the tidal or wave regimes, patterns of naturally occurring suspended sediment concentrations, or naturally occurring seabed sediment type (beyond the normal and relatively wide ranges of natural variability), are reliably predicted as a consequence of long-term natural trends or as a foreseeable potential impact of climate change during the lifetime of the Project.

7.2.4 Impact assessment

7.2.4.1 Worst-case scenario

A range of design details and tool options for cable burial, pre-lay bed preparation are included in the Project Design Envelope (PDE). The realistic worst-case for impacts caused by sediment disturbance is associated with the realistic combination of PDE options resulting in either the highest rate of sediment disturbance (for SSC), or the largest total volume of sediment locally or regionally disturbed (for deposition). This is calculated by considering the expected envelope of options for the designs and tools that might be realistically used for these activities. The Worst-case Scenario (WCS) for sediment disturbance contributing to potential impacts on SSC and sediment deposition is summarised as follows:

- PLGR:
  - Total maximum width of PLGR operating corridor: 100 m;
  - Maximum number of grapnel passes within total max width: 10;
  - Maximum width of grapnel disturbance: 1 m;
  - Total width of disturbance within the corridor: 10 m; and
  - Maximum depth of grapnel disturbance: typically 0.5 m.
- Boulder clearance:
  - Boulder clearance method: plough or grab in Array Area and EICC.
- IACs installation:
  - Maximum total length of cable trenches: 280 km;
  - Maximum trench dimensions: 2 m wide (at seabed); 1.8 m deep;
  - Excavation method: ploughing, jetting, trenching; and
  - Indicative installation rate: 250 m/hr.
- Export/Import Cable installation:
  - Maximum number of Export/Import Cable trenches: 1;
  - Maximum total length of Export/Import Cable trenches: 230 km (single trench);
  - Maximum trench dimensions: 2 m wide (at seabed); 1.8 m deep [except within 12 nautical miles (NM) where 3 m wide trench for sections where pre-lay trenching via a plough];
  - Excavation method: ploughing, jetting, trenching;
  - Indicative installation rate: 250 m/hr; and
  - 100% cable burial within the East of Gannet and Montrose Fields Nature Conservation Marine Protected Area (NCMPA) except at cable/pipeline crossing.
- HDD/Drilling fluid release (at Landfall):
  - Number of boreholes/release events: 3;
  - Total HDD drilled length: 409 m;
  - Maximum volume of drilling fluid in one borehole: 1,000 m^3 with 6 m^3 of solid losses. (Maximum total release of fluid for all three HDDs is 3,000 m^3, with 18 m^3 of solid spoil losses);
  - Representative maximum concentration of bentonite in drilling fluid: 80 kg/m^3 (80,000 mg/l); and
  - Wet punch-out (i.e. an exit below Mean Low Water Springs (MLWS)) at approximately 26.5 m water depth (below MHWS).

7.2.4.2 Pre-lay grapnel run

7.2.4.2.1 Summary of potential impact

The potential impacts of PLGR operations relate to the direct disturbance of the seabed soils, and also to the localised and temporary re-suspension of sediment (increase in SSC in a plume) and subsequent settling of sediments (deposition causing smothering and/or changes to surficial sediment type or character).

The exact nature of this disturbance will be determined by the soil conditions within the Array Area and EICC, the length of installed cable route to clear and the number/spacing of the grapnel runs, the grapnel dimensions, and any other relevant aspects of the PLGR methodology employed. These potential impacts are quantitatively characterised in this Section for Export/Import Cable and IACs using spreadsheet based numerical models.

7.2.4.2.2 Evidence base

The evidence base with respect to PLGR activities is relatively limited. Although a routine part of subsea cable installation, there are few examples of PLGR specific impact monitoring. For the EIA, due to the relatively smaller amounts of sediment disturbed, and closely related or overlapping footprint and timescale, potential impacts of PLGR are not usually assessed independently of the main cable burial activity.

Examples of PLGR grapnel designs are shown in Figure 7-2.

Images from: https://www.dokai.co.jp/e/service06.html; https://www.dlm-uk.com/products/

Figure 7-2 Examples of PLGR Grapnel Designs

The WCS footprint of PLGR in this case is 10 runs of a 1 m wide tool, with a total width of disturbance of 10 m within the 100 m operating corridor. The footprint of direct and indirect impacts of PLGR will overlap to some extent, but will also likely extend beyond the footprint of the boulder clearance plough (up to 13 m wide direct effect, Section 7.2.4.3) and the cable burial tool (up to 20 m wide, including direct and indirect local effects, Section 7.2.4.4). However, the direct effect of the PLGR on the seabed will be largely confined to the 1 m width of each tool run on the seabed, with areas of unaffected seabed in-between.

The grapnels used for PLGR generally have a limited cross section to cause disturbance, because the force on the tool is proportional to the dimensions or cross section of the grapnel arms/flukes/tines penetrating the seabed. The grapnel must be designed to penetrate the seabed to the required depth, but then to also continuously pass through the seabed, without getting stuck or breaking the equipment.

In practice, the grapnel design used might vary according to the services supplier, the locally expected soil conditions and/or the type of debris likely to be present and requiring clearance. Examples of PLGR grapnel designs found in an online search tended to be either: wider but shorter tines (wider but shallower disturbance); or, longer, thinner tines (deeper but narrower disturbance); or, some intermediate combination. Some (typically deeper, narrower) designs include a frame or wheel/roller arrangement to maintain the desired penetration depth and orientation relative to the seabed surface.

The speed of the PLGR tow is relatively slow (typically quoted as 1 knot, approximately 0.5 m/s). As a result, the passage of the grapnel through the seabed sediments is not very energetic and will not necessarily lead to resuspension of sediment from the affected cross section.

7.2.4.2.3 Assessment of change

The realistic worst-case scenario for sediment disturbance caused by PLGR is characterised in Table 7-1. The potential effects of sediment disturbance due to PLGR are typically localised to the cable route or the active PLGR location. As such, the WCS information mainly considers the local PLGR work dimensions and rates of sediment disturbance.

Table 7-1 WCS for sediment release by PLGR

PARAMETER	WCS	JUSTIFICATION
Number of Export/Import Cable trenches	1	1 cable bundle comprising 2 High Voltage Direct Current (HVDC) cables and a fibre optic cable.
Length of Export/Import Cable trench	230 km	-
Maximum rate of boulder clearance	1,000 m/hr	Assumed value.
Total length of IACs on seabed	280 km	The maximum total length of IACs: will be installed into the seabed as multiple shorter lengths.
Methods of PLGR	Various grapnel shapes and dimensions	-
Maximum dimensions of grapnel	Up to 1 m wide Up to 1.5m deep	Assume grapnel affects 10% of the maximum possible width/depth cross section, 10% x (1 m x 1.5 m) = 0.15 m^2. Conservatively assume 100% of sediment material is ejected from the affected cross section. In practice, many tools and methods used will normally minimise the volume of sediment (other than boulders) disturbed by design, to minimise forces on the plough.
Volume of sediment disturbed per metre progress	0.15 m^3	10% x (1 m x 1.5 m) x 1 m forward progress.
Sediment mineral density	2,650 kg/m^3	Assumed value for quartz sand (Soulsby, 1997).
Consolidated packing density	0.6	Assumed value for a typical, medium sorted sand (Soulsby, 1997).
Sediment disturbance rate	123 kg/s	(0.15 m^3 x 2,650 kg/m^3 x 0.6) x (1852 m/hr divided by 3600 s/hr).

An assessment of potential changes to SSC and bed levels has been undertaken using the spreadsheet based numerical models introduced in Section 7.2.2.2.2. A conservative assumption has been made that sub-soil material with a different grain size distribution to surficial sediments may also be re-suspended.

The seabed and sub-seabed sediment composition within the Array Area and along the EICC is relatively heterogeneous. In most locations, the majority of disturbed material contributing to sediment disturbance impacts will be mostly (98% or more) fine sand, coarse silt, muds and clays. Disturbance of the underlying sub-soils (including poorly sorted glacial tills) may also release variable proportions of gravel, coarser sands and fine grained sediments, depending on the nature of the soil and the degree of disaggregation.

It is impractical to capture the full detail of sediment heterogeneity in detail within the context of this assessment, which instead considers a most likely scenario of a grapnel causing maximum meaningful sediment disturbance in a fine sediment mixture:

- PLGR in 100% fine sand and silt (10-100 µm, settling rate 0.001 m/s). Also representative of consolidated fines and fine sand/fines mixtures.

This scenario provides a representative potential range of change both in terms of the duration, spatial extent of changes to SSC, and maximum thicknesses of sediment deposition for the main sediment type that is present and likely to be disturbed by this activity. In practice, an energetic upward release comprising mostly of entirely gravel is very unlikely.

See Section 7.2.4.5 for a discussion of similar tables for the relatively higher magnitude impact of cable trenching.

Table 7-2 Suspended sediment concentration and thickness of sediment deposition as a result of PLGR in 100% fine sand or coarse silt (settling rate 0.001 m/s)

REPRESENTATIVE CURRENT SPEED (m/s)	HEIGHT OF EJECTION (m)	TIME FOR RESETTLEMENT (s)	DISTANCE PLUME ADVECTED BY CURRENT (m)	LIMITED LENGTH OF INFLUENCE ON SSC IN DOWNSTREAM DIRECTION (m)	LIMITED DURATION OF INFLUENCE ON SSC LOCALLY (s)	AVERAGE SSC IN THE LIMITED LENGTH/DURATION OF INFLUENCE (mg/L)*	AVERAGE THICKNESS OF SEABED DEPOSITION ** (m)
0.1	1	1000	100	0.2	1.9	HnTh	0.00
0.2	1	1000	200	0.4	1.9	HnTh	0.00
0.3	1	1000	300	0.6	1.9	HnTh	0.00
0.4	1	1000	400	0.8	1.9	HnTh	0.00
0.1	5	5000	500	0.2	1.9	TnTh	0.00
0.2	5	5000	1000	0.4	1.9	TnTh	0.00
0.3	5	5000	1500	0.6	1.9	TnTh	0.00
0.4	5	5000	2000	0.8	1.9	TnTh	0.00
0.1	10	10000	1000	0.2	1.9	TnTh	0.00
0.2	10	10000	2000	0.4	1.9	TnTh	0.00
0.3	10	10000	3000	0.6	1.9	TnTh	0.00
0.4	10	10000	4000	0.8	1.9	TnTh	0.00

* Key: TnTh – Tens of Thousands; HnTh – low to mid Hundreds of Thousands

**Average thickness based on the total volume of sediment released and the distance the plume is advected by the current. Each row of results is part of a continuous scale of possible outcomes.

7.2.4.3 Boulder clearance

7.2.4.3.1 Summary of potential impact

The potential impacts of pre-lay boulder clearance operations relate to the direct disturbance of the seabed soils, and also to the localised and temporary re-suspension of sediment (increase in SSC in a plume) and subsequent settling of sediments (deposition causing smothering and/or changes to surficial sediment type or character).

The exact nature of this disturbance will be determined by the boulder distribution and soil conditions within the Array Area and EICC, the length of cable route to clear, the individual boulder dimensions, and the boulder clearance methodology employed. These changes are quantitatively characterised in this Section for the Export/Import Cable and IACs, using spreadsheet based numerical models.

7.2.4.3.2 Evidence base

The evidence base with respect to pre-lay boulder clearance activities is relatively limited. Although a routine part of subsea cable installation in affected areas, there are few examples of boulder clearance specific impact monitoring. For the EIA, due to the relatively smaller amounts of sediment disturbed, and the closely related or overlapping footprint and timescale, potential impacts of boulder clearance are not usually assessed independently of the main cable burial activity.

The WCS footprint of boulder clearance in this case is a single run of a 13 m wide plough tool, with a 20 m overall width of direct and indirect disturbance, along the cable route, and/or a remotely operated grab (typically for larger boulders). The plough or grab is used to locally relocate surface boulders laterally away from the cable route (by a distance in the order of a few tens of metres), prior to cable lay and burial. Boulders are not removed from the local area by the boulder clearance process.

The footprint of direct and indirect impacts of boulder clearance will overlap to some extent, and will likely be contained within, the footprint of the PLGR activities (10 runs of a 1 m wide tool, with a total width of disturbance of 10 m within the 100 m operating corridor, Section 7.2.4.2) and of the cable burial tool (up to 20 m wide, including direct and indirect local effects, Section 7.2.4.4). Where only a boulder clearance grab is used (instead of a plough), it is more likely to leave areas of unaffected seabed in-between points of local disturbance.

The ploughs used specifically for boulder clearance generally have a limited depth of penetration and so cross section of sediment disturbance by design, because the purpose of the tool is to displace surface boulders – not to create a trench or otherwise reduce the seabed surface elevation.

In practice, the plough or grab designs that might be used may vary according to the locally expected soil conditions and/or the size and density of boulders that are present and requiring clearance. Examples of boulder clearance plough and grab designs are shown in Figure 7-3 and Figure 7-4.

Images from: https://www.oceaneering.com/; https://globalmarine.group/

Figure 7-3 Examples of Boulder Clearance Plough Designs

Images from: www.utrov.com; https://www.hughes-subsea.com/

Figure 7-4 Examples of Boulder Clearance Grab Designs

The speed of tow for the boulder clearance plough is relatively slow (speeds in the order of 1000 m/hr are typical, approximately 0.28 m/s). As a result, the passage of the plough through the seabed sediments is not itself very energetic and will not necessarily lead to resuspension of sediment from the affected cross section. Resuspension is more likely to be associated with the tumbling passage of the boulders being displaced along the front face of the plough.

Boulder grabs will only be able to work with one (typically larger, up to 2.5 m) boulder at a time. The grab would manoeuvre into position above the target using small thrusters and the grab flukes close on the target. It is assumed that some of the seabed sediment around the boulder will be collected with the boulder. As the grab is lifted (assumed not more than 10 m above the seabed) and moved, some or all of the sediment on/in the grab might wash off/out as a sediment plume. In practice, some sediment (especially consolidated clays or clay rich soils, and any gravel) will either stay attached to/within the grab until the boulder is released, or, will simply return to the seabed directly as a singular clump or clast, not entering suspension or contributing meaningfully to SSC.

7.2.4.3.3 Assessment of change

Prior to installing the Export/Import Cable and IACs, pre-lay boulder clearance may be required. For the Project, the realistic WCS for sediment disturbance caused by boulder clearance is characterised in Table 7-3. The potential effects of sediment disturbance due to boulder clearance are typically localised to the cable route or the active boulder clearance location. As such, the WCS information mainly considers the local boulder clearance work dimensions and rates of sediment disturbance.

Table 7-3 WCS for sediment release by pre-lay boulder clearance

PARAMETER	WCS	JUSTIFICATION
Number of Export/Import Cable trenches	1	1 cable bundle comprising 2 High Voltage Direct Current (HVDC) cables and a fibre optic cable.
Length of Export/Import Cable trench	230 km	-
Maximum rate of boulder clearance		1 knot (1852 m/hr), assumed value.
Total length of IACs on seabed	280 km	The maximum total length of IAC: will be installed in multiple shorter lengths.
Methods of boulder clearance	Plough and grab	-
Maximum dimensions of boulder clearance	Plough up to 13 m wide	Assume plough 0.2m deep penetration along front edge. Assume grab up to 1 m diameter, penetration up to 0.5 m below seabed, 50% of total grab volume is surficial sediment. Plough - Conservatively assume 100% of sediment material is ejected from the affected cross section. In practice, many tools and methods used will normally minimise the volume of sediment (other than boulders) disturbed by design, to minimise forces on the plough.
Volume of sediment disturbed per metre progress	2.6 m^3	13 m wide x 0.2 m deep x 1 m forward progress.
Sediment mineral density	2,650 kg/m^3	Assumed value for quartz sand (Soulsby, 1997).
Consolidated packing density	0.6	Assumed value for a typical, medium sorted sand (Soulsby, 1997).
Sediment disturbance rate	2127 kg/s	(2.6 m^3 x 2,650 kg/m^3 x 0.6) x (1852 m/hr divided by 3600 s/hr).

An assessment of potential changes to SSC and bed levels has been undertaken using the spreadsheet based numerical models introduced in Section 7.2.2.2.2. A conservative assumption has been made that sub-soil material with a different grain size distribution to surficial sediments may also be re-suspended.

The seabed and sub-seabed sediment composition within the Array Area and along the EICC is relatively heterogeneous. In most locations, the majority of disturbed material contributing to sediment disturbance impacts will be mostly (98% or more) fine sand, coarse silt, muds and clays. Disturbance of the underlying sub-soils (including poorly sorted glacial tills) may also release variable proportions of gravel, coarser sands and fine grained sediments, depending on the nature of the soil and the degree of disaggregation.

It is impractical to capture the full detail of sediment heterogeneity in detail within the context of this assessment, which instead considers a most likely scenario of a grab causing maximum meaningful sediment disturbance in a fine sediment mixture:

- Boulder clearance in 100% fine sand and silt (10-100 μm, settling rate 0.001 m/s). Also representative of consolidated fines and fine sand/fines mixtures.

This scenario provide a representative potential range of change both in terms of the duration, spatial extent of changes to SSC, and maximum thicknesses of sediment deposition for the main sediment type that is present and likely to be disturbed by this activity. In practice, an energetic upward release comprising mostly of entirely gravel is very unlikely.

Table 7-4 Suspended sediment concentration and thickness of sediment deposition as a result of boulder clearance by plough in 100% fine sand or coarse silt (settling rate 0.001 m/s)

REPRESENTATIVE CURRENT SPEED (m/s)	HEIGHT OF EJECTION (m)	TIME FOR RESETTLEMENT (s)	DISTANCE PLUME ADVECTED BY CURRENT (m)	LIMITED LENGTH OF INFLUENCE ON SSC IN DOWNSTREAM DIRECTION (m)	LIMITED DURATION OF INFLUENCE ON SSC LOCALLY (s)	AVERAGE SSC IN THE LIMITED LENGTH/DURATION OF INFLUENCE (mg/L)*	AVERAGE THICKNESS OF SEABED DEPOSITION ** (m)
0.1	1	1000	100	0.2	1.9	HnTh	0.03
0.2	1	1000	200	0.4	1.9	HnTh	0.01
0.3	1	1000	300	0.6	1.9	HnTh	0.01
0.4	1	1000	400	0.8	1.9	HnTh	0.01
0.1	5	5000	500	0.2	1.9	TnTh	0.01
0.2	5	5000	1000	0.4	1.9	TnTh	0.00
0.3	5	5000	1500	0.6	1.9	TnTh	0.00
0.4	5	5000	2000	0.8	1.9	TnTh	0.00
0.1	10	10000	1000	0.2	1.9	TnTh	0.00
0.2	10	10000	2000	0.4	1.9	TnTh	0.00
0.3	10	10000	3000	0.6	1.9	TnTh	0.00
0.4	10	10000	4000	0.8	1.9	TnTh	0.00

* Key: TnTh – tens of thousands; HnTh – low to mid hundreds of thousands
**Average thickness based on the total volume of sediment released and the distance the plume is advected by the current. Each row of results is part of a continuous scale of possible outcomes.

Table 7-5 Suspended sediment concentration and thickness of sediment deposition as a result of boulder clearance by grab in 100% fine sand or coarse silt (settling rate 0.001 m/s)

REPRESENTATIVE CURRENT SPEED (m/s)	HEIGHT OF EJECTION (M)	TIME FOR RESETTLEMENT (s)	DISTANCE PLUME ADVECTED BY CURRENT (m)	LIMITED LENGTH OF INFLUENCE ON SSC IN DOWNSTREAM DIRECTION (m)	LIMITED DURATION OF INFLUENCE ON SSC LOCALLY (s)	AVERAGE SSC IN THE LIMITED LENGTH/DURATION OF INFLUENCE (mg/L)*	AVERAGE THICKNESS OF SEABED DEPOSITION ** (m)
0.1	1	1000	100	6.0	60.0	HnTh	0.00
0.2	1	1000	200	12.0	60.0	HnTh	0.00
0.3	1	1000	300	18.0	60.0	HnTh	0.00
0.4	1	1000	400	24.0	60.0	HnTh	0.00
0.1	5	5000	500	6.0	60.0	TnTh	0.00
0.2	5	5000	1000	12.0	60.0	TnTh	0.00
0.3	5	5000	1500	18.0	60.0	TnTh	0.00
0.4	5	5000	2000	24.0	60.0	TnTh	0.00
0.1	10	10000	1000	6.0	60.0	TnTh	0.00
0.2	10	10000	2000	12.0	60.0	TnTh	0.00
0.3	10	10000	3000	18.0	60.0	TnTh	0.00
0.4	10	10000	4000	24.0	60.0	TnTh	0.00

* Key: TnTh – tens of thousands; HnTh – low to mid hundreds of thousands
**Average thickness based on the total volume of sediment released and the distance the plume is advected by the current. Each row of results is part of a continuous scale of possible outcomes.

See Section 7.2.4.5 for a discussion of similar tables for the relatively higher magnitude impact of cable trenching.

7.2.4.4 Cable burial

7.2.4.4.1 Summary of potential impact

The potential impacts of cable burial (trenching) operations relate to the direct disturbance of the seabed soils, and also to the localised and temporary re-suspension of sediment (increase in SSC in a plume) and subsequent settling of sediments (deposition causing smothering and/or changes to surficial sediment type or character), (BERR, 2008).

The exact nature of this disturbance will be determined by the soil conditions within the Array Area and EICC, the length of installed cable, the burial depth and burial method. These potential impacts are quantitatively characterised in this Section for IACs and Export/Import Cable using spreadsheet based numerical models.

7.2.4.4.2 Evidence base

The evidence base with respect to subsequent cable burial activities is broad and includes a range of theoretical, numerical modelling and monitoring studies considering a range of installation methodologies, sediment types, water depths and other environmental conditions. The evidence base is widely applicable as the dimensions of the cables, the installation techniques used and the target depths of burial do not vary significantly with the scale of the development (small or large wind farm arrays) or the type of cable being installed (wind farm export, array or inter-connector cables, or non-wind farm electrical and communications cables).

SSC monitoring during cable laying operations has been undertaken at Nysted Wind Farm (ABPmer *et al*., 2007; BERR, 2008). During the works, both jetting and trenching were used, where the latter method involves pre-trenching and back-filling using back-hoe dredgers. Superficial sediments within the site were predominantly medium sands, approximately 0.5 m to 3 m in thickness, underlain by clay. SSC was recorded at a distance of 200 m from jetting and trenching activities and the following values were observed:

- Trenching – mean (14 mg/l) and max (75 mg/l); and
- Jetting – mean (2 mg/l) and max (18 mg/l).

The higher sediment concentrations from the trenching activities were considered to be a result of the larger volume of seabed strata disturbed during operations and the fact that the material disturbed during trenching was lifted to the surface for inspection. This meant that the sediment was transported through the full water column before being placed alongside the trench (BERR, 2008).

Cable laying monitoring also took place at Kentish Flats where ploughing methods were used to install three export cables (EMU Limited, 2005). The Centre for Environment, Fisheries and Aquaculture Science (Cefas) agreed pre-defined threshold limits against which SSC monitoring would be compared. The monitoring 500 m down-tide, i.e. where the concentrations will be greatest, of the cable laying activities showed:

- Marginal, short-term increases in background levels (approximately nine times increase to the background concentrations); and
- Peak concentrations occasionally reaching 140 mg/l (equivalent to peaks in the naturally occurring background concentrations).

The observations at Nysted and Kentish Flats provide confidence that cable laying activities do not create a long-term, significant disruption to the background sediment concentrations. Furthermore, it also illustrates that there is little sediment dispersal, indicating that there is unlikely to be much deposition on the seabed other than immediately adjacent to the cable route.

Reach (2007) describes plume dispersion studies for a cable laying jetting operation in Hong Kong with an assumption that 20% of a trench cross-section of 1.75 m^2 would be disturbed by the jetting process and the speed of the jetting machine would be 300 m/hour (0.083 m/s). ASA (2005) describes similar studies for a cable laying operation near Cape Cod in the United States of America (USA) and assumed that 30% of a trench cross-section of 3 m^2 would be disturbed by the jetting process and the speed of the jetting machine would be 91 m/hour (0.025 m/s). This latter study also assumed that any sand particles would quickly return to the bed and only the fine sediment particles (i.e. particles with a diameter less than 63 μm) would form a plume in the water column.

SeaScape Energy (2008) describes cable installation plume dispersion monitoring studies carried out in mainly sandy sediments at the Burbo OWF in Liverpool Bay, United Kingdom (UK):

- Three export cables were installed to a target depth of approximately 3 m by vertical injector ploughing while array cables were installed to a similar depth by jetting assisted ploughing;
- The monitoring demonstrated clearly that both cable installation techniques had only small scale impacts on localised SSC. Changes were measurable to a few hundreds of metres only and suspended sediment levels were not elevated more than five times background. Suspended sediment levels never approached the threshold level (3,000 mg/l) agreed with the competent authority beforehand, even in very close proximity to the works (< 50 m); and,
- Local changes in SSC over a relatively fine sediment seabed area (most likely to lead to plume impacts) was in the region of 250 to 300 mg/l within 200 m of the operation, falling to the measured baseline level (100 mg/l) by 700 m downstream. It is assumed, therefore, that coarser sediments were associated with even lower levels.

The post-burial impacts of cable burial on sandy seabed morphology were also considered by BERR (2008) with reference to a wide range of desktop and monitoring studies. The report concludes that impacts will also be limited in terms of both the thickness of re-deposited sediments and the potential for affecting the surficial sediment type:

> *"The low levels of sediment that are mobilised during cable laying mean that there will be only low levels of deposition around the cable route. The finer material will generally remain in suspension for longer but will settle and remobilise on each tide with no measurable material left in place. Coarser sediments are expected to settle within a few metres of the cable route and following disturbance is likely to recover rapidly, given similar communities in the vicinity." (BERR, 2008).*

7.2.4.5 Assessment of change

The Export/Import Cable and IACs may be installed by burial into the seabed by jetting, trenching or ploughing. For the Project, the WCS for sediment release caused by cable burial is characterised in Table 7-6.

The potential effects of sediment disturbance due to cable burial are typically localised to the cable route or the active cable burial location. As such, the WCS information mainly considers the local trench dimensions and rates of sediment disturbance.

Table 7-6 WCS for sediment release by cable burial

PARAMETER	WCS	WORKING AND OTHER ASSUMPTIONS
Number of Export/Import Cable trenches	1	1 cable bundle comprising 2 High Voltage Direct Current (HVDC) cables and a fibre optic cable.
Length of Export/Import Cable trench	230 km	-
Maximum rate of cable burial	250 m/hr	Fastest rate through softer sediments.
Total length of IACs on seabed	280 km	The maximum total length of IACs: will be installed as multiple shorter lengths.
Methods of IACs and Export/Import Cable burial	Ploughing Trenching Jetting	Jetting and similar methods have the greatest potential to energetically fluidise and eject material from the trench into suspension. By contrast, the other cable installation techniques described in the project design statement (e.g. ploughing) are expected to re-suspend a smaller amount of material into the water column. Due to spatial variation in the geotechnical properties of the underlying geology within this region, it is possible that a combination of techniques may be used.
Maximum dimensions of IACs and Export/Import Cable trench	Between MHWS and 12 NM: 3 m width where installation uses pre-lay trenching via a plough and 2 m width where jetting is utilised. Beyond 12 NM - up to 2 m wide. In all areas - up to 1.8 m deep with a 'U' shaped profile.	Jetting might be used at any location but in practice would only be used where surficial sediments are suitable. Target burial depth will typically be up to circa 1.8 m. Conservatively assume 100% of material is ejected from the trench. In practice, many tools and methods used for simultaneous lay and bury will normally retain the majority of sediment within the trench by design, to backfill and provide protective cover.
Volume of sediment disturbed per metre progress	3.6 m^3 (5.4 m^3)	Typically: 2 m wide x 1.8 m deep. (In some locations between MHWS and 12 NM, 3 m wide x 1.8 m deep.)
Sediment mineral density	2,650 kg/m^3	Assumed value for quartz sand (Soulsby, 1997).

PARAMETER	WCS	WORKING AND OTHER ASSUMPTIONS
Consolidated packing density	0.6	Assumed value for a typical, medium sorted sand (Soulsby, 1997).
Sediment disturbance rate	397.5 kg/s (596.3 kg/s)	Typically: (3.6 m^3 x 2,650 kg/m^3 x 0.6) x (250 m/hr divided by 3,600 s/hr). (In some locations between MHWS and 12 NM: (5.4 m^3 x 2,650 kg/m^3 x 0.6) x (250 m/hr divided by 3,600 s/hr)).

The jetting process normally fluidises an area of sediment within the seabed through which the cable is inserted. By design, the process is intended to bury the cable and so only a minimal proportion of the fluidised sediment is expected be actually ejected from the trench. The exact proportion ejected may vary. Values of 20 to 30% have been used in previous investigations of this type (ASA, 2005). Mass flow excavation tools may also fluidise the bed to a degree and may also be used to excavate an open trench for pre-lay trenching, in which case, a greater proportion of the material will be displaced. For the purposes of this investigation, it is conservatively assumed that 100% of the disturbed material is ejected.

An assessment of potential changes to SSC and bed levels has been undertaken using the spreadsheet based numerical models introduced in Section 7.2.2.2.2. A conservative assumption has been made that sub-soil material with a different grain size distribution to surficial sediments may also be re-suspended.

The seabed and sub-seabed sediment composition within the Array Area and along the EICC is relatively heterogeneous. In most locations, the majority of disturbed material contributing to sediment disturbance impacts will be mostly (98% or more) fine sand, coarse silt, muds and clays. Disturbance of the underlying sub-soils (including poorly sorted glacial tills) may also release variable proportions of gravel, coarser sands and fine grained sediments, depending on the nature of the soil and the degree of disaggregation.

It is impractical to capture the full detail of sediment heterogeneity in detail within the context of this assessment, which instead considers a series of realistic worst-case scenario 'end-member' scenarios. These are:

- Trenching through 100% coarse gravel (15,000 µm, settling rate 0.5 m/s);
- Trenching through 100% fine sand and silt (10-100 µm, settling rate 0.001 m/s); and
- Trenching through 100% fine mud and clay (<10 µm, settling rate 0.0001 m/s).

These three scenarios provide a representative potential range of change both in terms of the duration, spatial extent of changes to SSC, and maximum thicknesses of sediment deposition for the main sediment types that are present. In practice, a release comprising entirely gravel is very unlikely.

Cable burial through the underlying sub-soils may result in the release of a range of sediment grain sizes, depending on the local nature of sub-soil and cable burial method used. In practice, these soil types are unlikely to disaggregate entirely into the finest possible constituent particle sizes due to the cable burial methods being assessed. This is particularly true for non-jetting installation methods such as ploughing (Figure 7-5). Also, even when fully disaggregated, any hard subsurface layers present (including glacial tills) are unlikely to disaggregate into 100% fine grained material. Ploughing will result in a much lower rate of sediment re-suspension, hence this method has not been explicitly assessed.

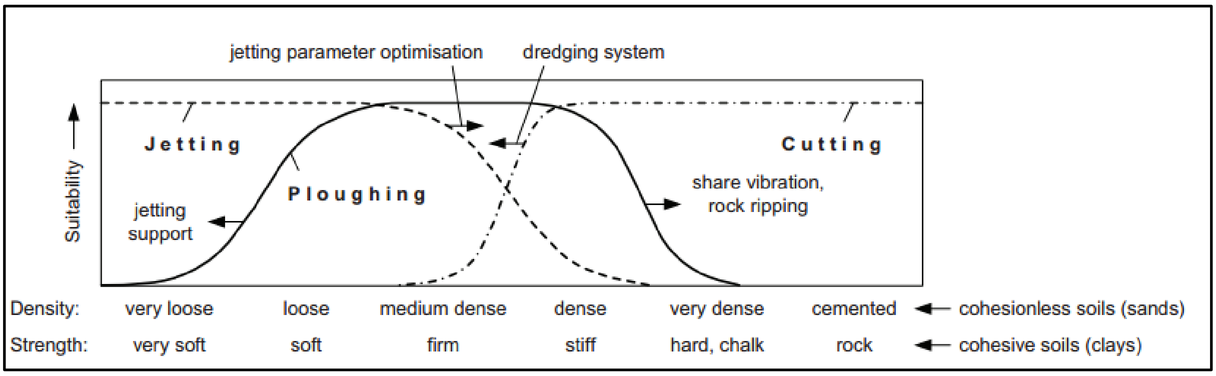


Figure 7-5 Indicative burial tool suitability in different ground conditions (DNV, 2014)

Results from the assessment scenarios outlined above are presented in Table 7-7 (for the gravel release scenario) and Table 7-8 (for the fine sand and silt release scenario); results for finer muds are effective similar to that for fine sands (Table 7-8) and are discussed further later in this Section. The predicted levels of SSC (locally and for the short duration before resettlement) are extremely high in absolute and relative terms, so only the overall order of magnitude is shown (millions to hundreds or tens of thousands of mg/l) rather than specific values. However, realistically, due to the relatively low height of ejection and rapid rate of resettlement, the extent and duration of such very high SSC levels are very limited and will only decrease rapidly thereafter due to ongoing dilution, dispersion and resettlement.

Table 7-7 Suspended sediment concentration and thickness of sediment deposition as a result of cable burial in 100% gravel (settling rate 0.5 m/s)

REPRESENTATIVE CURRENT SPEED (m/s)	HEIGHT OF EJECTION (m)	TIME FOR RESETTLEMENT (s)	DISTANCE PLUME ADVECTED BY CURRENT (m)	LIMITED LENGTH OF INFLUENCE ON SSC IN DOWNSTREAM DIRECTION (m)	LIMITED DURATION OF INFLUENCE ON SSC LOCALLY (s)	AVERAGE SSC IN THE LIMITED LENGTH/DURATION OF INFLUENCE (mg/L)*	AVERAGE THICKNESS OF SEABED DEPOSITION ** (m)
0.1	1	2	0.2	0.2	2.0	Mn	0.75 (1.125)
0.2	1	2	0.4	0.4	2.0	Mn	0.38 (0.57)
0.3	1	2	0.6	0.6	2.0	Mn	0.25 (0.38)
0.4	1	2	0.8	0.8	2.0	Mn	0.19 (0.29)
0.1	5	10	1.0	1.0	10.0	HnTh	0.15 (0.23)
0.2	5	10	2.0	2.0	10.0	HnTh	0.08 (0.12)
0.3	5	10	3.0	3.0	10.0	HnTh	0.05 (0.08)
0.4	5	10	4.0	4.0	10.0	HnTh	0.04 (0.06)
0.1	10	20	2.0	1.4	14.4	HnTh	0.08 (0.12)
0.2	10	20	4.0	2.9	14.4	HnTh	0.04 (0.06)
0.3	10	20	6.0	4.3	14.4	HnTh	0.03 (0.05)
0.4	10	20	8.0	5.8	14.4	HnTh	0.02 (0.03)

* Key: HnTh – hundreds of thousands; Mn – low millions.

** Average thickness based on the total volume of sediment released and the distance the plume is advected by the current. Large deposit thicknesses (e.g. >5 to 10 m) in combination with relatively small footprints will more realistically correspond to a broader and less thick deposit with slopes at the angle of repose for the sediment. Each row of results is part of a continuous scale of possible outcomes. Values for 2 m trench width, also (in brackets), for 3 m trench width which may occur in some locations between MHWS and 12 NM offshore.

Table 7-8 Suspended sediment concentration and thickness of sediment deposition as a result of cable burial in 100% fine sand, coarse silt and fines (settling rate 0.001-0.0001 m/s)

REPRESENTATIVE CURRENT SPEED (m/s)	HEIGHT OF EJECTION (m)	TIME FOR RESETTLEMENT (s)	DISTANCE PLUME ADVECTED BY CURRENT (m)	LIMITED LENGTH OF INFLUENCE ON SSC IN DOWNSTREAM DIRECTION (m)	LIMITED DURATION OF INFLUENCE ON SSC LOCALLY (s)	AVERAGE SSC IN THE LIMITED LENGTH/DURATION OF INFLUENCE (mg/L)*	AVERAGE THICKNESS OF SEABED DEPOSITION ** (m)
0.1	1	1000	100	1.4	14.4	Mn	0.04 (0.06)
0.2	1	1000	200	2.9	14.4	Mn	0.02 (0.03)
0.3	1	1000	300	4.3	14.4	Mn	0.01 (0.02)
0.4	1	1000	400	5.8	14.4	Mn	0.01 (0.01)
0.1	5	5000	500	1.4	14.4	HnTh	0.01 (0.01)
0.2	5	5000	1000	2.9	14.4	HnTh	0.00 (0.01)
0.3	5	5000	1500	4.3	14.4	HnTh	0.00 (0.00)
0.4	5	5000	2000	5.8	14.4	HnTh	0.00 (0.00)
0.1	10	10000	1000	1.4	14.4	HnTh	0.00 (0.01)
0.2	10	10000	2000	2.9	14.4	HnTh	0.00 (0.00)
0.3	10	10000	3000	4.3	14.4	HnTh	0.00 (0.00)
0.4	10	10000	4000	5.8	14.4	HnTh	0.00 (0.00)

* Key: HnTh – hundreds of thousands; Mn – low millions.

**Average thickness based on the total volume of sediment released and the distance the plume is advected by the current. Each row of results is part of a continuous scale of possible outcomes. Values for 2 m trench width, also (in brackets), for 3 m trench width which may occur in some locations between MHWS and 12 NM offshore.

Results are presented for a range of representative current speeds, noting that cable burial will continue through all states of the tide, frequently including times when current speed is lower than the highest locally possible (peak) value. Because of the uncertainty with regards to how high into the water column from the bed material may be ejected or re-suspended, results are provided for a realistic range of heights (1, 5 and 10 m). A greater height of ejection will lead to a potentially longer plume duration and a greater distance of influence, but also a corresponding reduction in SSC and deposition thickness. Because the cable burial tool will be moving (representative rate 250 m/hr), any influence of the plume experienced immediately downstream will be similarly limited in duration to the order of approximately 14 seconds, after which time, the plume will have been advected downstream past the location of the receptor or will be instead affecting an area of seabed elsewhere. A slower moving tool would cause a longer duration of increased SSC, however, with a proportionally reduced level of SSC due to the lower rate of disturbance.

Following the same principles, changes associated with cable burial into 100% fine grained sediment will be similarly high to that described for fine sand and silt in Table 7-8. The limited plume length in a downstream direction (order of 10 m), the duration of change to SSC locally (order of 10 s) and the average level of SSC (hundreds of thousands of mg/l) will be the same for fines in areas near to active cable burial. Fine sediment may persist in suspension for longer than sands (order of days) during which time the plume will be subject to significant dispersion, affecting a progressively larger area, but proportionally reducing the change to SSC to tens of mg/l or less in the same timeframe. As a result of advection and dispersion during the days before settlement, no measurable thickness of fine sediment accumulation is expected.

The main findings of the assessment can be summarised as follows:

- Medium to coarse sand and gravels (where present as consolidated glacial tills at or close below the seabed) are likely to result in a temporally and spatially limited plume affecting SSC levels (and settling out of suspension) in close proximity to the point of release. SSC will be locally elevated within the plume close to active cable burial up to tens or hundreds of thousands of mg/l. However, the change will only be present for a very short time locally, in the order of seconds to tens of seconds for coarser sand or gravel, before the material resettles to the seabed. Depending on the height to which the material is ejected and the current speed at the time of release, changes in SSC and deposition will be spatially limited to within metres (up to 25 m) downstream of the cable for gravels and within tens of metres (up to a few hundred metres) for coarser sands;
- Finer material (fine sands, clays and muds, present as surficial sediment layers in high proportions in some locations) will be advected away from the release location by the prevailing tidal current. High initial concentrations (similar to sands and gravels) are to be expected but will be subject to rapid dispersion, (dependant on the prevailing current conditions) both laterally and vertically, to near-background levels (tens of mg/l) within hundreds to a few thousands of metres of the point of release. In practice, only a small proportion of the material disturbed is expected to be fines, with a corresponding reduction in the expected levels of SSC;
- Irrespective of sediment type, the volumes of sediment being displaced and deposited locally are relatively limited (up to 3.6 m^3 per metre of cable burial) which also limits the combinations of sediment deposition thickness and extent that might realistically occur; and
- Fundamentally, the maximum distance from each metre of cable trench over which 3.6 m^3 of sediment can be spread to an average thickness of (for example) 0.05 m is 72 m; any larger distance would correspond to a smaller average thickness. The assessment suggests that the extent and so the area of deposition will normally be much smaller for sands and gravels (although leading to a greater average thickness of deposition in the order of tens of centimetres to a few metres) and that fine material will be distributed much more widely, becoming so dispersed that it is unlikely to settle in measurable thickness locally.

7.2.4.6 Drilling fluid release during HDD at the landfall

7.2.4.6.1 Summary of potential impact

HDD is the preferred option to transition the Export/Import Cable to the onshore export cable at the Landfall. The drill punch-out location will be in the subtidal inshore area, approximately 26.5 m below MHWS. The total drilled length will be up to approximately 409 m from entry to exit point. Up to three boreholes will be drilled (not simultaneously).

The release of drilling fluid (a suspension of natural bentonite clay in water) into the coastal waters at the punch-out location may cause a sediment plume in the inshore area.

7.2.4.6.2 Evidence base

Drilling fluid or drilling mud is a suspension of mainly bentonite clay in water with the following functions:

- To remove cuttings from in front of the drill bit;
- Power the mud motor;
- To transport cuttings from the drill face through the annular space towards the surface;
- Lubricate the drill string during drilling phases and any conduit liners or cables during pull back;
- Cooling the reamers (cutting tools);
- Hole stabilization; and
- Creation of a filter cake against the wall of the hole to minimize the risk of loss of drilling fluid or influx of groundwater penetration into the borehole.

The drilling fluid typically consists of a low concentration bentonite – water mixture. Depending on the formation to be drilled through, the concentration is typically between 13 litres (30 kg) and 35 litres (80 kg) of dry bentonite clay per m^3 of water (30,000 to 80,000 mg/l).

The use of bentonite has several benefits:

- It is a natural material;
- It is recyclable;
- It is on the Pose Little or No Risk to the environment (PLONOR) list, so its discharge is not a danger to the environment.

7.2.4.6.3 Assessment of change

The maximum volume of drilling mud that might be release from one borehole is estimated to be up to 1,000 m^3; a small additional quantity (approximately 6 m^3) of drill cuttings may also be present in the fluid. Several stages of drilling (pilot hole drilling and stages of reaming) may result in smaller release events separated in time. The installation of the HDD conduit duct may result in a larger release of fluid from the HDD conduit (up to the total volume), however, in practice, the fluid present at this stage may have been replaced or otherwise reduced to a concentration lower than required for drilling.

The realistic worst-case considered is a release of full concentration drilling mud (80,000 mg/l), up to the total volume (1,000 m^3), in a relatively short period of time (minutes to hours). The WCS is summarised as Table 7-9.

Table 7-9 WCS for bentonite release during HDD at the Landfall

PARAMETER	WORST-CASE SCENARIO	WORKING AND OTHER ASSUMPTIONS
HDD borehole	3	Maximum number of HDD boreholes exiting in the subtidal area (not simultaneous).
Representative total length of HDD drilling	409 m	-
Representative water depth at offshore HDD exit	Approximately 26.5 m below MHWS	-
Maximum volume of drill fluid in one HDD borehole	1,000 m^3	Based on working assumptions regarding HDD length, diameter and expected operational methods.
Maximum concentration bentonite in drill fluid	80,000 mg/l	80 kg per m^3.
Maximum total mass bentonite in one HDD borehole	80,000 kg	1,000 m^3 x 80kg per m^3.

Because of the time required to drill and finalise each HDD, it is assumed that the releases would not happen simultaneously and with a sufficiently long-time gap between punch out events that no overlapping or cumulative changes to SSC are expected (may be up to a year between the two events). The following assessment considers the change caused for one HDD borehole.

The initial plume will likely have a very high SSC of bentonite (up to the concentration of the drilling fluid itself) but will have a correspondingly small footprint. The plume will subsequently be advected in the general direction and speed of the ambient currents at the time of the release and will be gradually dispersed both horizontally and vertically by the natural processes of diffusion. The maximum mass of bentonite in the whole plume is finite (approximately 80,000 kg) and so SSC within the plume will become diluted and reduced in proportion to the increase in the overall volume of the plume. The spreadsheet model results in Table 7-10 shows that concentrations of bentonite will be reduced to naturally occurring background levels when the plume has dispersed to even a relatively small footprint in the order of 500 m across. A larger extent would correspond to a smaller SSC.

Table 7-10 SSC as a result of bentonite drill fluid release during HDD

PLUME WIDTH (m)	PLUME DEPTH (m)	PLUME SECTION LENGTH * (m)	RESULTING SSC (mg/L) *
20	2.5	20	80,000
40	5	40	10,000
100	10	100	800
250	15	250	85
500	20	500	16

* Single plume containing the maximum total mass of bentonite from one HDD borehole. Plume subject to progressive lateral and vertical dispersion, from an initial local plume of minimum dimensions and maximum concentration (undiluted drilling mud 80,000 mg/l), up to 500 x 500 m footprint (or equivalent dimensions for same area) and a representative inshore depth (20-30 m). The actual dimensions of the plume will vary depending on the prevailing current speed and surrounding bathymetry/coastline topography at the time and location of the release, and so cannot be predicted more accurately in advance.

The time required to achieve such dispersion cannot be calculated with certainty but is estimated to be in the order of hours based on normal tidally induced turbulence. If waves are active at the time of the release, wave induced turbulence at the seabed and wave breaking inshore would result in much higher rates of dispersion.

The maximum total mass of bentonite in suspension is assumed to remain constant over the time frame of this model, which is realistic as the bentonite is a fine-grained clay suspension that is expected take at least hours, if not days or longer to settle out of suspension under suitable conditions. If any bentonite does settle out of suspension more rapidly, then SSC in a plume of the same dimensions would be reduced proportionally. If the released drilling fluid does behave as a denser fluid for any reason, some or all may accumulate in the exit point (possibly becoming locally consolidated over days to weeks but more likely reworked and dispersed to not-measurable thicknesses over time) and/or some or all may move over the adjacent seabed downslope under gravity, i.e. in an offshore direction and away from the inshore areas.

The effects of the plume will also be of very short duration and temporary at any given location, limited to the time over which the release occurs (not presently known but estimated to be in the order of hours and less than one day).

The main findings of the assessment can be summarised as follows:

- The release of bentonite and drill cuttings in the form of drilling fluid from the planned HDD operations will result in a localised and temporary plume of elevated SSC specifically comprising bentonite clay (a natural non-toxic mineral). Where the plume has measurable SSC that might be of concern (e.g. to water quality), the duration and footprint of the plume will be small in absolute and relative terms (e.g. order of <20 mg/l over footprints larger than 500 m over a period of days; or, order of tens to low hundreds of mg/l over footprints less than 500 m over a period of minutes to one hour);
- In any case, the HDD exit point is located in relatively deep water several hundred metres offshore. The majority of the plume will be advected in the direction of the ambient tidal currents, which are aligned parallel with the adjacent coastline. The direction and speed of transport (north or south along the coast) will depend on the state

of the tide (flood or ebb) at the time of the release. It is expected that the plume would be dispersed to relatively low concentrations within hours of release and to background concentrations within a few tidal cycles (i.e. 1 day);
- The bentonite in the drilling fluid is expected to remain in suspension for at least hours or days and will be widely dispersed to very low concentrations before settling. Therefore, bentonite is not expected to accumulate anywhere in measurable thicknesses. If, however, a sufficiently dense mixture of bentonite and/or drill cuttings did accumulate in or around the HDD exit point, the accumulated material is expected to be reworked and redistributed to not-measurable concentrations and thicknesses over time by wave and tidal action; and
- The bentonite in the drilling fluid normally has an overall density and viscosity similar to seawater and so is expected to behave (advect, mix and disperse) in a similar manner. If (some of) the drilling fluid behaves as a relatively denser fluid, it might accumulate around the HDD exit point or flow over the adjacent seabed downslope under gravity, i.e. in an offshore direction and away from inshore areas, prior to being reworked and redistributed to not-measurable concentrations and thicknesses over time by wave and tidal action.

7.2.5 Summary

7.2.5.1 Pathways of Change or Effect

This Section provides a description of the realistically possible combinations of magnitude and extent of impact for local increases in SSC and seabed deposition, due to sediment disturbance potentially caused by:

- Seabed preparation by PLGR prior to cable burial;
- Seabed preparation by boulder clearance prior to cable burial;
- Cable burial by ploughing, trenching and jetting; and
- Release of drilling fluid during HDD punch out at the Landfall.

The actual magnitude and extent of such impacts will depend in practice on a range of factors, such as the actual total volumes and rates of sediment disturbance, the local water depth and current speed at the time of the activity, the local sediment type and grain size distribution, the local seabed topography and slopes, etc. There will be a wide range of possible combinations of these factors and so it is not possible to predict specific dimensions with complete certainty. To provide a robust assessment, a range of realistic combinations have been considered, based on conservatively representative location (environmental) and project (WCS) specific information, including a range of water depths, heights of sediment ejection/initial resuspension, and sediment types.

This wider range of results can be summarised broadly in terms of four main zones of effect, based on the distance from the activity causing sediment disturbance. These zones are consistent with the results of observational (monitoring) evidence and recent numerical modelling of analogous activities (e.g. BERR, 2008; TEDA, 2010; Navitus Bay Development Ltd, 2014; Awel y Môr OWF Ltd, 2022):

- 0 to 50 m – zone of highest SSC increase and greatest likely thickness of deposition. All gravel sized sediment likely deposited in this zone, and a large proportion of any coarser sand grains that are not resuspended high into the water column. Plume dimensions and SSC, and deposit extent and thickness, are primarily controlled by the volume of sediment released and the manner in which the deposit settles:
  - at the time of active disturbance - very high SSC increase (tens to hundreds of thousands of mg/l) lasting for the duration of active disturbance plus up to 30 minutes following end of disturbance; where dominant (e.g. areas of outcropping glacial material), coarse sands and gravels, or larger clasts of still consolidated cohesive silts, may deposit in local thicknesses of tens of centimetres to several metres; unconsolidated finer sediment (i.e. muddy fine sands) is unlikely to deposit in measurable thickness; and
  - more than one hour after the end of active disturbance – no remaining change to SSC; no measurable ongoing deposition.
- 50 to 500 m – zone of measurable SSC increase and measurable but lesser thickness of deposition. Mainly sands that are released or resuspended higher in the water column and resettling to the seabed whilst being advected by ambient tidal currents. Plume dimensions and SSC, and deposit extent and thickness, are primarily controlled by the volume of sediment released, the height of resuspension or release above the seabed, and the ambient current speed and direction at the time:
  - at the time of active disturbance - high SSC increase (hundreds to low thousands of mg/l) lasting for the duration of active disturbance plus up to 30 minutes following end of disturbance; sands and gravels may deposit in local thicknesses of up to tens of centimetres; fine sediment is unlikely to deposit in measurable thickness; and
  - more than one hour after end of active disturbance – no change to SSC; no measurable ongoing deposition.
- 500 m to the tidal excursion buffer distance – zone of lesser but measurable SSC increase and no measurable thickness of deposition. Mainly fines that are maintained in suspension for more than one tidal cycle and are advected by ambient tidal currents. Plume dimensions and SSC are primarily controlled by the volume of sediment released, the patterns of current speed and direction at the place and time of release and where the plume moves to over the following 24 hours:
  - at the time of active disturbance – low to intermediate SSC increase (tens to low hundreds of mg/l) as a result of any remaining fines in suspension, only within a narrow plume (tens to a few hundreds of metres wide, SSC decreasing rapidly by dispersion to ambient values within one day after the end of active disturbance; fine sediment is unlikely to deposit in measurable thickness;
  - one to six hours after end of active disturbance – decreasing to low SSC increase (tens of mg/l); fine sediment is unlikely to deposit in measurable thickness; and
  - six to 24 hours after end of active disturbance – decreasing gradually through dispersion to background SSC (no measurable local increase); fine sediment is unlikely to deposit in measurable thickness. No measurable change from baseline SSC after 24 to 48 hours following cessation of activities.
- Beyond the tidal excursion buffer distance or anywhere not tidally aligned to the active sediment disturbance activity – there is no expected measurable impact or change to SSC nor any measurable sediment deposition.

Figure 7-6 provides an example schematic illustration of the footprint of effect for installation of approximately 7.5 km of IACs, causing local short-term sediment disturbance. In practice the WCS impact will be a limited number of discrete areas of effect (similar to that shown in the example), separated by areas of lesser impact.

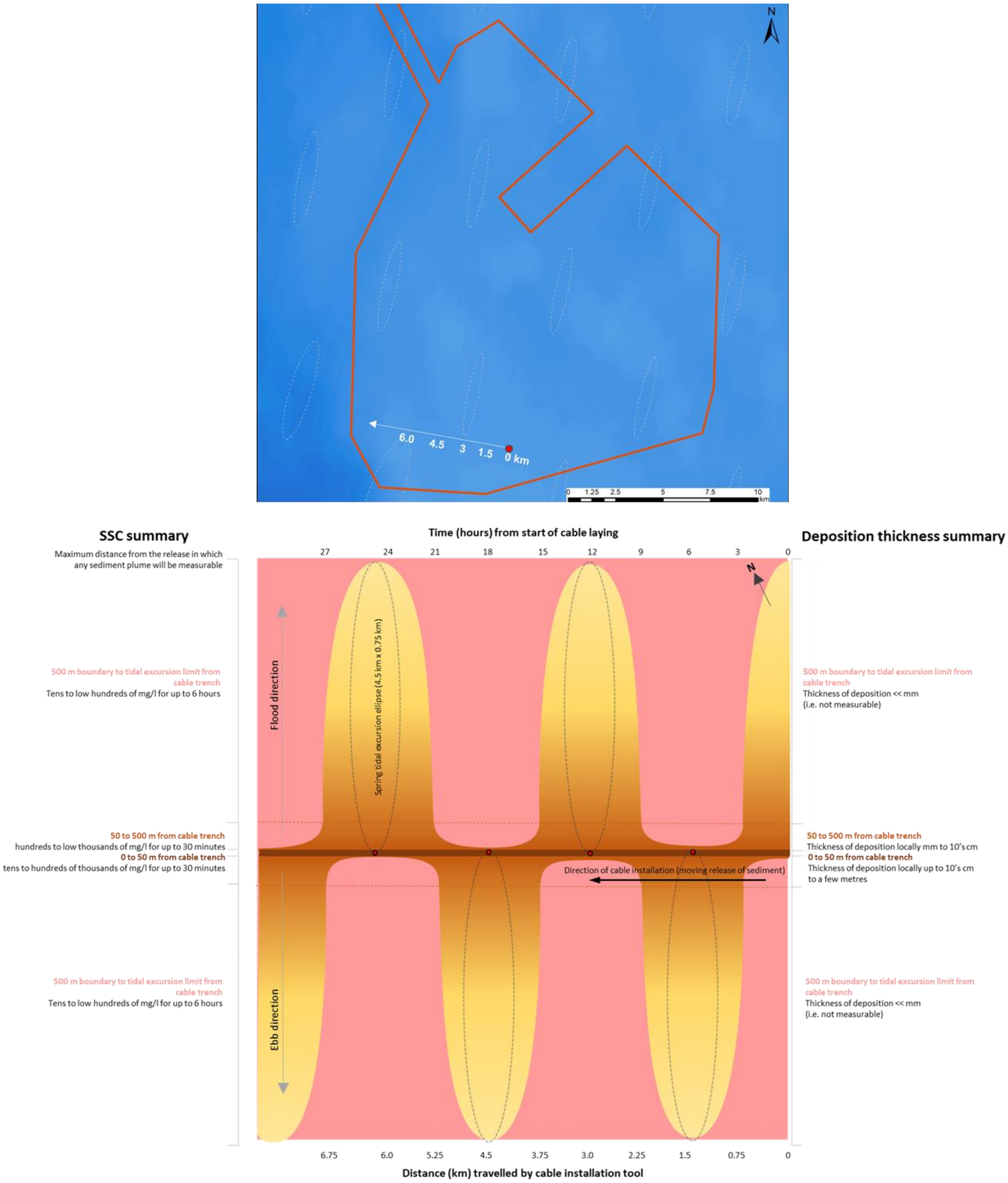


Figure 7-6 Zones of elevated SSC and sediment deposition associated with cable installation. Example shown is for an indicative release within the Array Area

7.2.5.2 East of Gannet and Montrose Fields NCMPA

The Array Area is located within the East of Gannet and Montrose Fields NCMPA. Within the extent of the NCMPA, 280 km of IACs and 35 km of Export/Import Cable will be installed, potentially requiring PLGR, boulder clearance and cable burial.

The footprint of *direct* physical disturbance impact is quantified within EIAR Vol. 3, Chapter 8: Marine Geology, Oceanography and Coastal Processes.

The absolute and relative spatial footprint of *indirect* impacts due to sediment disturbance (deposition) can be estimated as follows:

- The total footprint of the East of Gannet and Montrose Fields NCMPA is 1,839,000,000 m^2 (1,839 km^2);
- The total footprint of the Array Area is 332,709,534 m^2 (333 km^2);
- PLGR (WCS details in Table 7-1):
  - Total distance of PLGR in NCMPA = (280,000 m + 35,000 m) x 10 runs = 3,150,000 m;
  - Volume of sediment disturbed per metre progress = 0.15 m^3/m;
  - Total volume of sediment disturbed in NCMPA = 3,150,000 m x 0.15 m^3/m = 472,500 m^3;
  - Maximum area that can be subject to 0.05 m thick deposition in NCMPA = 472,500 m^3/0.05 m = 9,450,000 m^2;
  - Maximum area as a proportion of the East of Gannet and Montrose Fields NCMPA = 9,450,000 m^2/1,839,000,000 m^2 = 0.514%; and
  - Maximum area as a proportion of the Array Area = 9,450,000 m^2/332,709,534 m^2 = 2.840%.
- Pre-lay boulder clearance (WCS details in Table 7-3):
  - Total distance of boulder clearance by plough in NCMPA = (280,000 m + 35,000 m) x 1 run = 315,000 m;
  - Volume of sediment disturbed per metre progress = 2.6 m^3/m;
  - Total volume of sediment disturbed in NCMPA = 315,000 m x 2.6 m^3/m = 819,000 m^3;
  - Maximum area that can be subject to 0.05 m thick deposition in NCMPA = 819,000 m^3/0.05 m = 16,380,000 m^2;
  - Maximum area as a proportion of the East of Gannet and Montrose Fields NCMPA = 16,380,000 m^2/1,839,000,000 m^2 = 0.891%; and
  - Maximum area as a proportion of the Array Area = 16,380,000 m^2/332,709,534 m^2 = 4.923%.
- Cable burial (WCS details in Table 7-6):
  - Total distance of cable burial in NCMPA = (280,000 m + 35,000 m) x 1 run = 315,000 m;
  - Volume of sediment disturbed per metre progress = 3.6 m^3/m;
  - Total volume of sediment disturbed in NCMPA = 315,000 m x 3.6 m^3/m = 1,134,000 m^3;
  - Maximum area that can be subject to 0.05 m thick deposition in NCMPA = 1,134,000 m^3/0.05 m = 22,680,000 m^2;
  - Maximum area as a proportion of the East of Gannet and Montrose Fields NCMPA = 22,680,000 m^2/1,839,000,000 m^2 = 1.233%; and
  - Maximum area as a proportion of the Array Area = 22,680,000 m^2/332,709,534 m^2 = 6.817%.

The mobility potential of surficial sediments within the Array Area is very low, due to the weak tidal currents and infrequent wave action at the seabed due to the water depth. This means that the seabed has limited ability to recover to its 'natural' state following site preparation activities and/or cable laying, with natural recovery of surface scars etc potentially taking many years/ decades. However, it is important to note that the activities described will locally disturb or displace, rather than remove sediment and the physical disturbance action itself will only be temporary. The significance of this for the designated biodiversity interests within the East of Gannet and Montrose Fields NCMPA (in particular ocean quahog (*Arctica islandica*) is considered separately, within EIAR Vol. 3, Chapter 10: Benthic Ecology.

7.2.5.3 Southern Trench NCMPA

The EICC passes through the Southern Trench NCMPA. Within the extent of the NCMPA, 19.2 km of Export/Import Cable will be installed, potentially requiring PLGR, boulder clearance and cable burial.

The footprint and volume of *direct* physical disturbance impact is quantified within EIAR Vol. 3, Chapter 8: Marine Geology, Oceanography and Coastal Processes.

The absolute and relative spatial footprint of *indirect* impacts due to sediment disturbance (deposition) can be estimated as follows:

- The total footprint of the Southern Trench NCMPA is 2,398,000,000 m^2 (2,398 km^2);
- PLGR (WCS details in Table 7-1):
  - Total distance of PLGR in NCMPA = (19,200 m) x 10 runs = 192,000 m;
  - Volume of sediment disturbed per metre progress = 0.15 m^3/m;
  - Total volume of sediment disturbed in NCMPA = 192,000 m x 0.15 m^3/m = 28,800 m^3;
  - Maximum area that can be subject to 0.05 m thick deposition in NCMPA = 28,800 m^3/0.05 m = 576,000 m^2; and
  - Maximum area as a proportion of the Southern Trench NCMPA = 576,000 m^2/2,398,000,000 m^2 = 0.024%.
- Pre-lay boulder clearance (WCS details in Table 7-3):
  - Total distance of boulder clearance by plough in NCMPA = (19,200 m) x 1 run = 19,200 m;
  - Volume of sediment disturbed per metre progress = 2.6 m^3/m;
  - Total volume of sediment disturbed in NCMPA = 19,200 m x 2.6 m^3/m = 49,920 m^3;
  - Maximum area that can be subject to 0.05 m thick deposition in NCMPA = 49,920 m^3/0.05 m = 998,400 m^2; and
  - Maximum area as a proportion of the Southern Trench NCMPA = 998,400 m^2/2,398,000,000 m^2 = 0.042%.
- Cable burial (WCS details in Table 7-6):
  - Total distance of cable burial in NCMPA = (19,200 m) x 1 run = 19,200 m;
  - Volume of sediment disturbed per metre progress = 3.6 m^3/m;
  - Total volume of sediment disturbed in NCMPA = 19,200 m x 3.6 m^3/m = 69,120 m^3;
  - Maximum area that can be subject to 0.05 m thick deposition in NCMPA = 69,120 m^3/0.05 m = 1,382,400 m^2; and
  - Maximum area as a proportion of the Southern Trench NCMPA = 1,382,400 m^2/2,398,000,000 m^2 = 0.057%.

7.3 Assessment of potential changes to stratification and frontal systems

7.3.1 Introduction

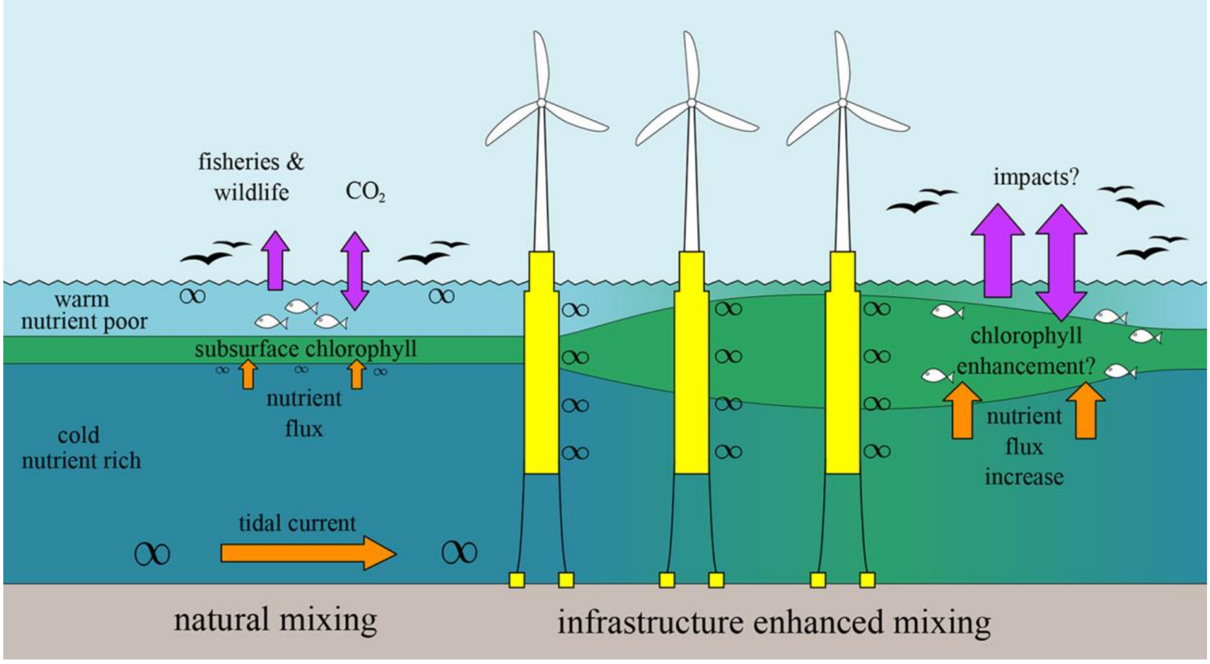
This Section presents detailed baseline characterisation and assessment of stratification and frontal systems across the Marine Geology, Oceanography and Coastal Processes Study Area (Figure 7-1). The findings from this assessment will be used to inform significance of effect assessments presented in other chapters of the EIAR, in particular:

- EIAR Vol. 3, Chapter 10: Benthic Ecology;
- EIAR Vol. 3, Chapter 11: Marine Mammal Ecology;
- EIAR Vol. 3, Chapter 12: Offshore Ornithology; and
- EIAR Vol. 3, Chapter 13: Fish and Shellfish Ecology.

There has been increasing interest in the scientific literature on the impact of OWF developments on stratification, e.g. Carpenter *et al.*, (2016), Cazenave, *et al.*, (2016) and Dorrell *et al.*, (2022). This interest has been driven at least in part by the proliferation and potential cumulative impacts of proposed floating OWFs: these projects are located further offshore and in deeper water than fixed bottom projects and it is these settings which are characterised by seasonal water column stratification (Figure 7-8) and which could therefore potentially be impacted by the installation of OWF infrastructure. Floating and fixed bottom foundation structures remove power from the flow that is fed into turbulent mixing in the wake downstream of the structure. Wake turbulence mixes cold nutrient rich bottom water with warm nutrient poor surface water, reducing the strength of stratification as illustrated in the schematic in Figure 7-7 (Dorrell *et al.*, 2022).

The aim of the assessment of potential changes to stratification and frontal systems technical report is to:

- Characterise the baseline stratification timing and strength within and surrounding the Project;
- Characterise the baseline tidal mixing front dynamics within and surrounding the Project; and
- Conduct a Project-specific EIA for the WCS for wind farm infrastructure in the Array Area.



The swirl symbol (∞) indicates locations where turbulence is generated as a result of near bed, near surface and flow-structure induced shear. Wake turbulence mixes cold nutrient rich bottom water with warm nutrient poor surface water, reducing the strength of stratification and potentially enhancing plankton growth in the subsurface chlorophyll layer. Changes in the subsurface chlorophyll layer would have further impacts on nutrient pathways, ecosystem functioning and oceanic carbon sequestration.

Figure 7-7 Schematic of processes contributing to natural stratification, and the effect of additional turbulence generated by OWF infrastructure (from Dorrell et al., 2022).

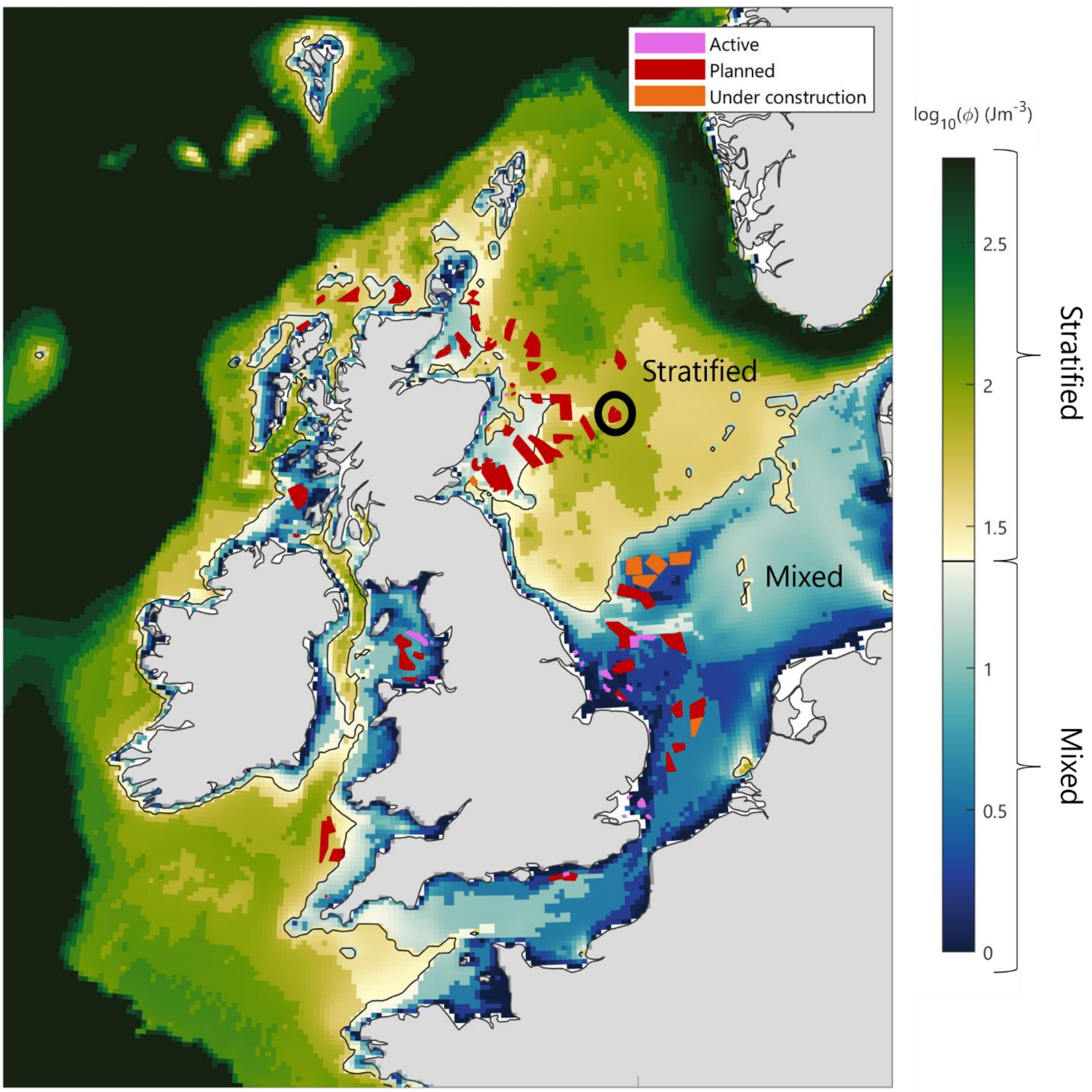


Figure 7-8 Northwest Europe summer potential energy anomaly, ϕ, a measure of the amount of stratification, calculated from Copernicus model output. The black circle denotes the location of the Array Area

7.3.2 Methodology

In order to provide a robust assessment of the potential impact of FTUs and OSCPs in the Array Area this study provides:

- A more detailed baseline characterisation of stratification (approach summarised in Section 7.3.2.1), including:
  - An overview of terminology and the natural processes causing or affecting stratification in shelf seas and in the general vicinity of the Array Area;
  - A quantitative characterisation of stratification strength over the Northwest European Shelf and within the Marine Geology, Oceanography and Coastal Processes Study Area, including general patterns of spatial and temporal (seasonal) variation, and interannual variability;
  - The characteristics and natural processes causing or affecting tidal mixing fronts (between areas of relatively more mixed and more stratified water); and
  - Projected changes to the future baseline characterisation of stratification, due to the effects of climate change.
- A Project-specific EIA (approach summarised in Section 7.3.2.2) for the WCS wind farm infrastructure in the Array Area, addressing the following questions:
  - How might the FTUs and OSCPs change mixing?
  - How might this change in mixing influence the timing of seasonal stratification and frontal positions?
  - What impacts could this have on primary production and the wider ecosystem? and
  - What impacts could change in near-surface wind speeds have on water column mixing and stratification?

7.3.2.1 Baseline

The baseline understanding of the existing temporal/spatial pattern of stratification and positioning of tidal mixing fronts has been developed using Conductivity, Temperature and Depth (CTD) profiles collected in the Array Area during later summer (August/September 2023) and readily available three-dimensional (3D) numerical model outputs from Copernicus Marine Service (Copernicus, 2024a and Copernicus 2024b).

Temperature, salinity and chlorophyll-a reanalysis datasets across the North-west (NW) European Shelf were generated by integrating past observations from satellites and in-situ measurements with coupled physical-biogeochemistry model systems. This dataset provides timeseries from 2010 to 2024, at a 7 km horizontal resolution and over 24 standard Intergovernmental Oceanographic Commission (IOC) of UNESCO geopotential levels, concentrated in the upper 200 m of the water column. A detailed description of the model production, calibration and validation is available in Tonani *et al., (*2022) and Ciavatta *et al.*, (2018) for the physical and biogeochemical models, respectively.

The use of Copernicus reanalysis data allowed for a detailed examination of spatial and temporal variability over a range of scales, from broader seasonal and inter-annual changes to shorter term fluctuations occurring over a tidal cycle. Vertical temperature and salinity profiles facilitated the calculation of density profiles, which were used to assess stratification strength through the Potential Energy Anomaly (PEA), as discussed in Section 7.3.3.2. Chlorophyll-a profiles served as a proxy for primary productivity, with elevated concentrations often indicating increased productivity linked to the onset of stratification or the positioning of tidal mixing fronts, discussed in greater detail in Section 7.3.3.3.

The Scottish Shelf Model (SSM) 3.02 Reanalysis hindcast is another potential data source for establishing the stratification baseline and conducting impact assessments for the Marine Geology, Oceanography and Coastal Processes Study Area. The SSM provides hourly data on horizontal currents and water elevations, as well as daily averages of three-dimensional currents, temperature, and salinity. However, at the time of writing, the server hosting the SSM data was down, meaning it was unavailable for the analysis in this report. Since the SSM is forced by the same Copernicus data used here, the two model outputs are expected to be similar. Additionally, the Copernicus model output offers higher temporal resolution, providing hourly 3D data (as opposed to daily in the SSM), which allows for a more detailed assessment of stratification variability over shorter timescales, such as diurnal tidal cycles.

7.3.2.2 Impact Assessment

To assess the impact of FTUs and OSCPs on water column mixing and stratification, the method outlined by Carpenter *et al.*, (2016) was employed. This approach uses empirical equations to estimate two key timescales: the mixing timescale, which predicts the time required for complete mixing of stratified layers due to increased Turbulent Kinetic Energy (TKE) generated by the FTUs, and the advective timescale, which quantifies how long a water parcel remains within the Array Area, experiencing enhanced TKE. These estimates provide insight into the influence of FTUs on local stratification and are discussed in more detail in Section 7.3.4.2.

One-dimensional depth-profile models, such as the General Ocean Turbulence Model (GOTM), could offer a more detailed analysis of mixing processes within a limited distance of individual foundations at the site. However, the absence of sufficient measured data for model validation poses a significant challenge, limiting the usefulness of the results. A one-dimensional (1D) modelling approach would not provide a suitably realistic description of the two-dimensional (2D) or 3D result of localised turbulent interaction between the flow and individual foundations in an array of widely spaced foundations, and where water passing through the site may or may not be repeatedly affected. Whilst a bespoke 1/2/3-D model might be theoretically possible, the extensive effort required to develop, calibrate/validate, and implement such a model would be disproportionate to the findings, as the baseline analysis indicates only minimal potential for changes to stratification within the Array Area.

7.3.3 Baseline characterisation

7.3.3.1 Overview

Stratification is a naturally occurring seasonal hydrodynamic process related to the vertical and horizontal distribution of seawater temperature and salinity. Where present, stratification plays a key role in nutrient availability and the distribution of marine flora and fauna.

During summer, solar heating and higher air temperatures warm the surface waters, creating a marked temperature difference between the warmer, buoyant upper layer and the colder, denser bottom waters. In the North Sea, this temperature difference can reach up to 10 degrees Celsius (°C), forming a sharp vertical density gradient, or pycnocline, which acts as a physical barrier to vertical mixing. This separation limits the upward transport of nutrients from deeper waters, which can limit primary production in surface waters as nutrients become depleted over time.

The development of stratification is counterbalanced by turbulent mixing, which is generated at the seabed by tidal currents and at the surface by wind and wave action. Consequently, stratification is more likely to form in deeper waters, but can also occur in shallower areas with low current speeds and limited wind exposure. The interplay between these forces determines whether stratification will persist or break down, affecting the overall productivity of the ecosystem.

Tidal mixing fronts form at the boundaries between well-mixed and stratified waters, creating regions of enhanced biological activity. These fronts, common in shelf seas like the North Sea (Hill *et al.*, 2005; 2008), facilitate nutrient exchange between surface and deeper layers, promoting primary production through the stimulation of phytoplankton growth. Fronts act as biological hotspots, concentrating nutrients and attracting higher trophic levels, making them important features for fisheries and marine biodiversity. The strength and position of these fronts are influenced by factors such as tidal current speeds, freshwater inputs, and wind patterns, which can vary on timescales ranging from hours to years.

The North Sea is characterised by significant spatial and temporal variation in the vertical distribution of temperature and salinity. An assessment of intra-annual patterns of stratification in the North Sea has been undertaken by van Leeuwen *et al.*, (2015), using a long-term (51-year) regional scale hydro-biogeochemical model simulation. The Array Area is located in an area described by van Leeuwen *et al.*, (2015) as being "seasonally stratified", defined as > 120 days in the year where the water column is stratified and > 90 days in the year where the water column is fully mixed.

Further details of the baseline environment with respect to stratification and frontal systems can be found in EIAR Vol. 3, Chapter 8: Marine Geology, Oceanography and Coastal Processes.

7.3.3.2 Stratification

CTD upcast profiles of temperature and salinity collected during August to September 2023 in the Array Area are presented in Figure 7-9. During late summer, the thermocline in this area is well defined. Temperature profiles are consistent across the sampling locations, showing that the upper ~25 m of the water column is thermally well-mixed, with surface temperatures exceeding 15°C. From 25 m to 35 m, temperatures decrease rapidly. The rate of temperature decline slows from 35 m to 45 m. Deeper than 45 m the temperature stabilises and remains consistent down to the seabed.

Salinity profiles show less variability, suggesting stratification is primarily driven by temperature differences. In the top 30 m, salinity values are ~35 Practical Salinity Units (PSU). At approximately 30 m depth, salinity increases slightly across all ten profiles, peaking at ~36 PSU at 35 m depth. Below this, salinity returns to surface values and remains stable to the seabed. This minor salinity fluctuation coincides with the thermocline and may indicate the seasonal weakening of the halocline.

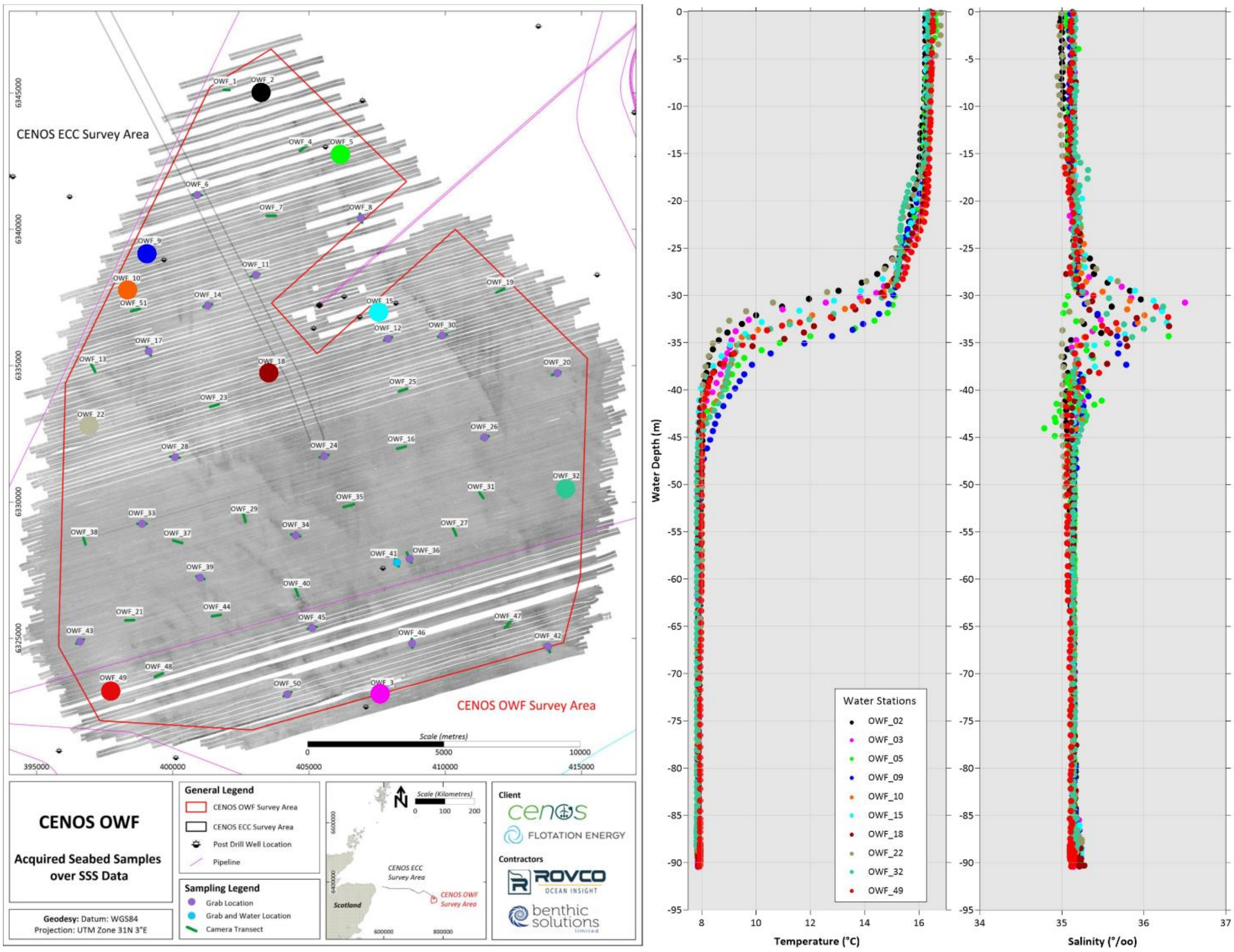


Figure 7-9 CTD upward cast location (left) and temperature (middle) and salinity (right) profiles

The measured CTD data provides insight into the degree of stratification across the Array Area at a single point in time (Aug-Sep 2023). However, to assess temporal and spatial variability, the Copernicus model output is used.

The PEA provides a measure of the amount of energy (Joules (J)) per unit volume (J/m^3) required to completely mix a stratified water column, making density vertically homogenous. The significance of PEA lies in its ability to provide a single, scalar value that captures the complexity of stratification in terms of both temperature and salinity gradients. It is widely used in oceanography to assess how stratified a water body is, e.g. Simpson, 1981; Gowan *et al.*, 1995; Yamaguchi *et al.*, 2019; Dorell *et al.*, 2022.

PEA (ϕ) is calculated as:

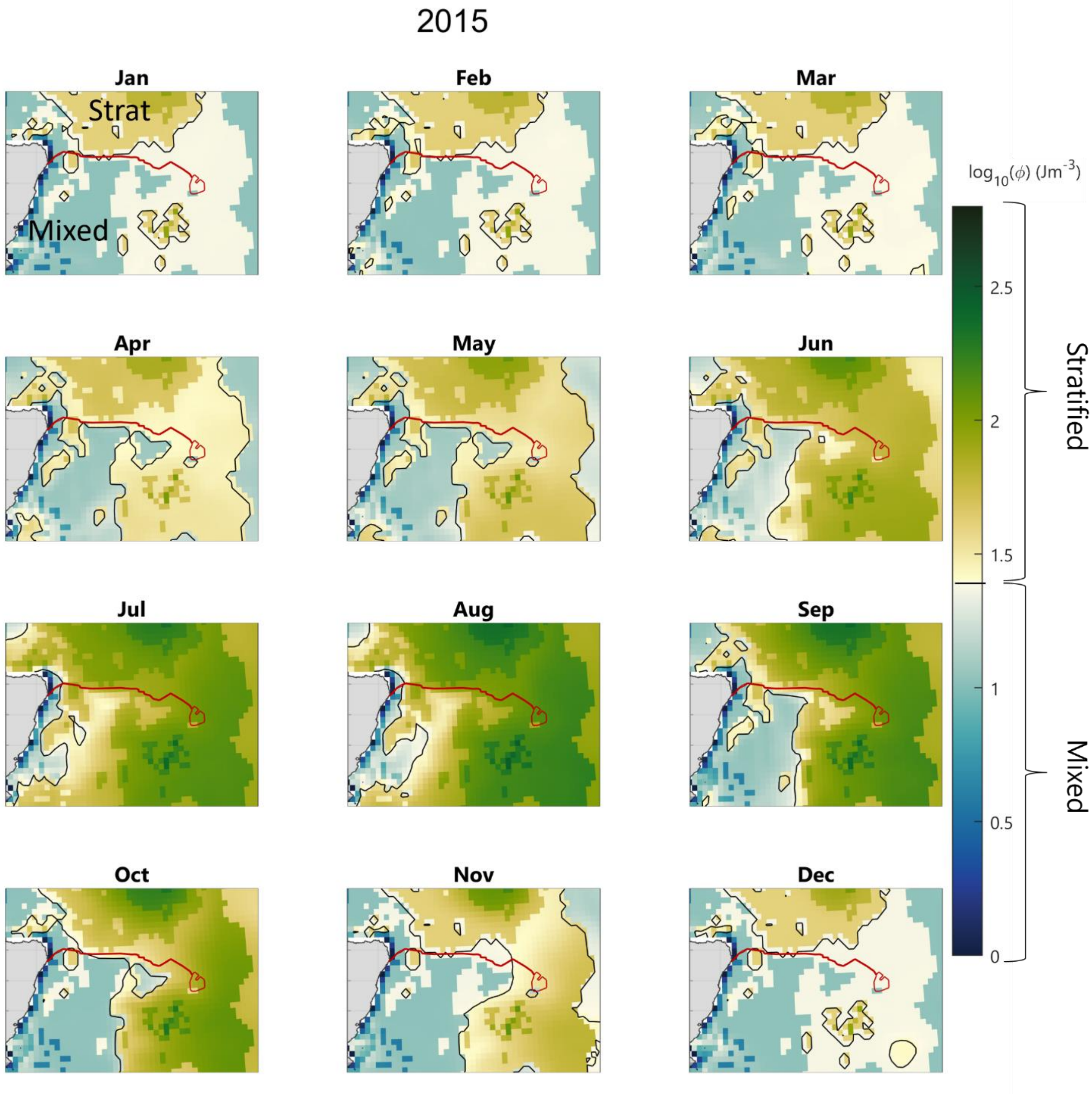
$$\phi = \frac{g}{h} \int_{-h}^{0} (\rho - \bar{\rho})\, z \cdot dz$$

where h is the water depth, g is acceleration due to gravity (9.81 m/s^2), ρ is the water density and $\bar{\rho}$ is the density calculated using the depth-mean water temperature and salinity. To calculate water density, the Gibbs SeaWater (GSW) Matlab toolbox is used alongside 3D temperature and salinity data available from the Copernicus reanalysis dataset.

The threshold values of PEA can vary depending on the specific water body. Based on the density profiles and calculated PEA values for the Marine Geology, Oceanography and Coastal Processes Study Area and its surrounding regions, along with thresholds used in the literature (Gowan *et al.*, 1995; Dorrell *et al.*, 2022), the following PEA classifications are applied in this study:

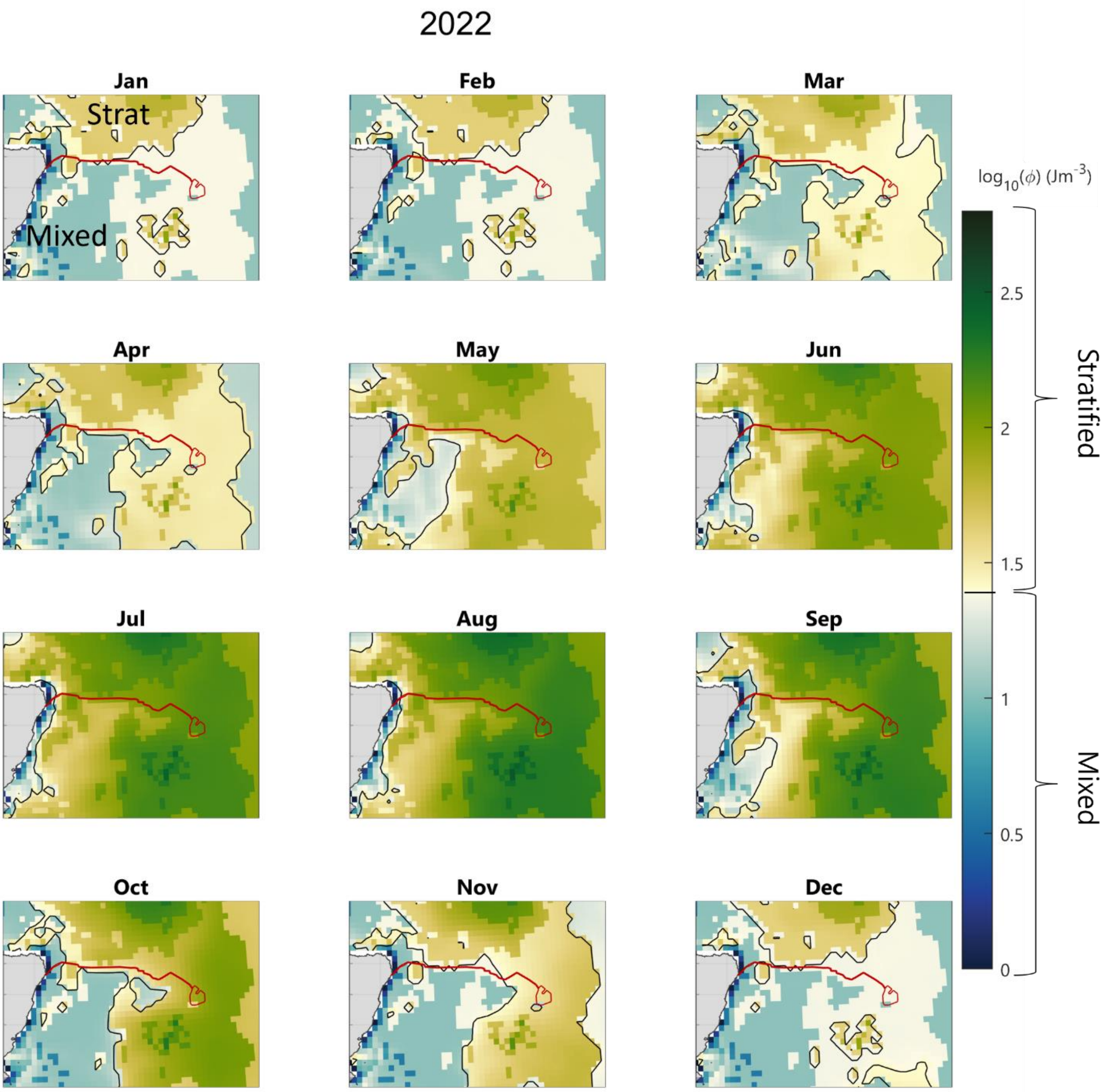
- Mixed water column: $\phi < 25$ J/m^3;
- Weakly stratified water column: $25 \le \phi < 50$ J/m^3;
- Moderately stratified water column: $50 \le \phi < 100$ J/m^3; and
- Strongly stratified water column: $\phi > 100$ J/m^3.

PEA values were calculated for the Marine Geology, Oceanography and Coastal Processes Study Area and its surrounding region at monthly intervals, from January 2010 to December 2023. This approach enabled the assessment of both seasonal and inter-annual variability in stratification strength. Figure 7-10 and Figure 7-11 illustrate the results for two specific years, 2015 and 2022, representing a year with weaker stratification and a year with stronger stratification, respectively.



Seas are partitioned into those defined as mixed (ϕ<25 J/m3) and stratified (ϕ≥25 J/m3). The Array Area and EICC are outlined in red.

Figure 7-10 Calculated potential energy anomaly (ϕ), based on the Copernicus reanalysis monthly temperature and salinity data for 2015



Seas are partitioned into those defined as mixed (ϕ<25 J/m3) and stratified (ϕ≥25 J/m^3). The Array Area and EICC is outlined in red.

Figure 7-11 Calculated potential energy anomaly (ϕ), based on the Copernicus reanalysis monthly temperature and salinity data for 2022

During the winter months (December to February), reduced solar heating and increased turbulent mixing from wind and waves result in mixed waters in the Array Area, characterised by homogeneous temperature and density profiles, with PEA values <20 J/m^3. With the onset of spring and summer, calmer weather and longer, warmer days enhance stratification, overcoming the mixing effects of tides. From March to November, this leads to a vertical temperature gradient and an increase in PEA values. Over the 14-year analysis period (2010 to 2023), PEA typically reaches around 200 J/m^3 in mid-summer, indicating a strongly seasonally stratified water column, consistent with the findings of van Leeuwen *et al.*, (2015). To the west of the Array Area, shallower depths and stronger tidal currents result in reduced stratification. Approximately 180 km west of the Array Area, the water column remains well-mixed throughout the year.

There is some variability in the strength and timing of seasonal stratification from year to year, with mid-summer PEA values ranging from approximately 180 J/m³ in 2015 to approximately 220 J/m³ in 2022 (Figure 7-12), however even during the "weaker" stratification years, PEA values exceed the threshold for strong stratification (ϕ > 100 J/m³).

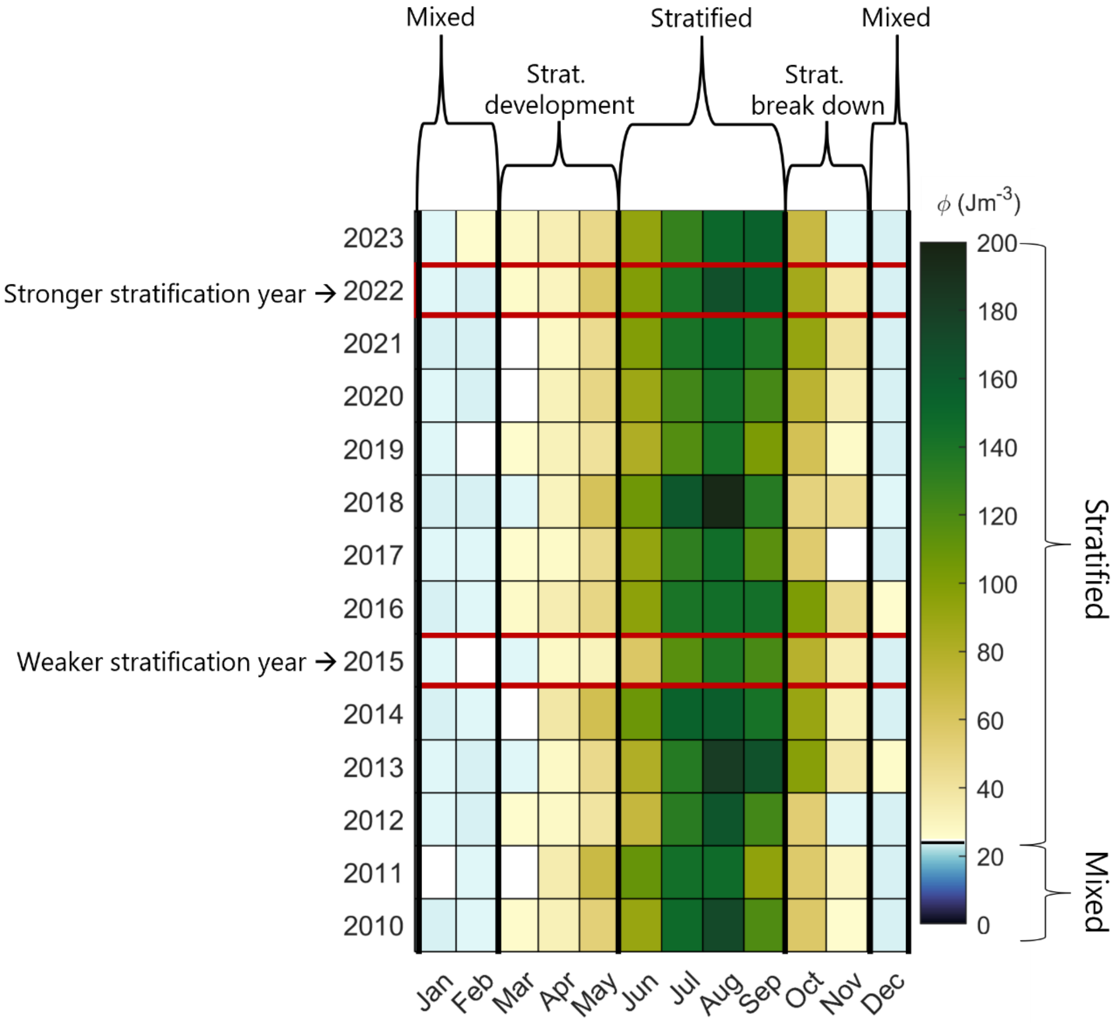


Figure 7-12 Monthly potential energy anomaly (ϕ) values in the Array Area from 2010 to 2023

7.3.3.3 Tidal mixing fronts

Miller and Christodoulou (2014) applied front detection and aggregation techniques to high resolution satellite ocean colour data to describe frequently occurring fronts near to the Scottish coast. Key frontal zones were selected through detailed analysis of the seasonal chlorophyll and thermal front distributions. The coast from Aberdeenshire to the Firth of Forth was identified as a potential frontal hotspot. Figure 7-13 shows a seasonally averaged front frequency map for summer months based on an interpretation of ten years of satellite data (between 1998 to 2008; Miller and Christodoulou, 2014). There is an area of high potential for front formation ~5 km to ~110 km from the coastline within the Study Area. Here, over the analysed ten-year period, fronts occurred 60 - 1012 times during the summer. In contrast, the potential for tidal mixing front formation within the Array Area is significantly lower.

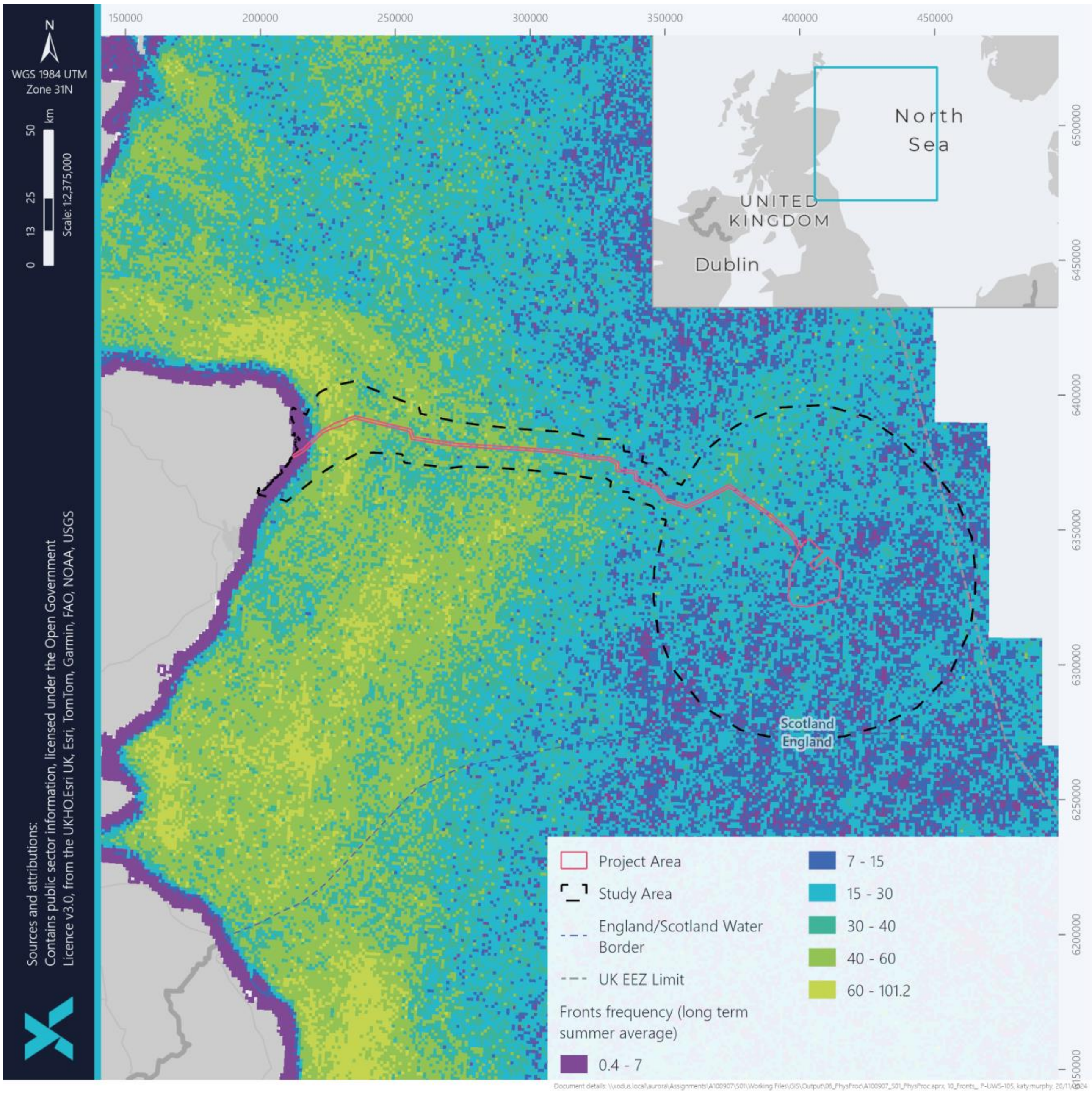
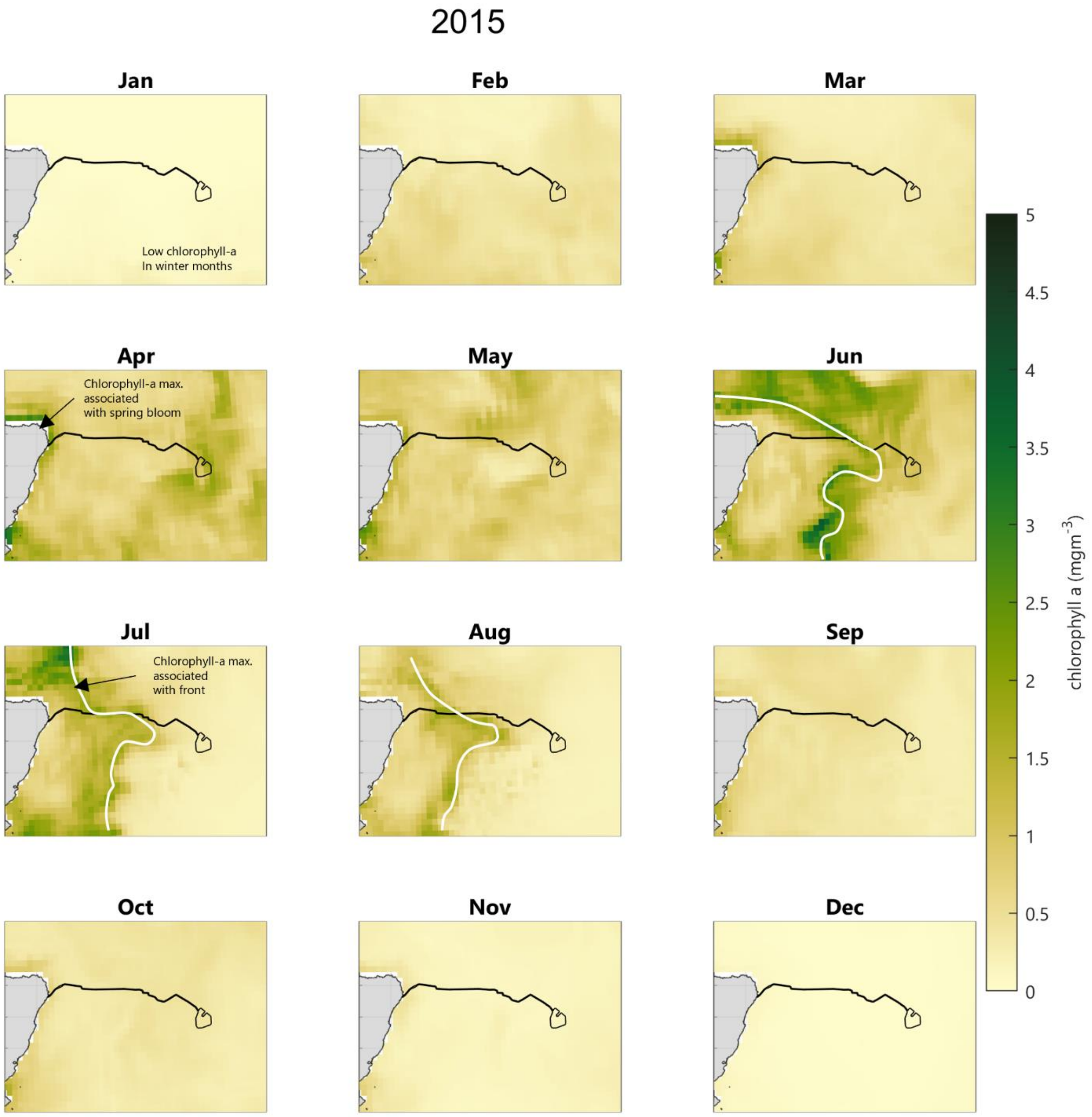


Figure 7-13 Potential for formation of fronts across the Marine Geology, Oceanography and Coastal Processes Study Area (Miller and Christodoulou, 2014)

Chlorophyll-a is the green substance used by plants to photosynthesise (creating sugars from basic chemical building blocks), using sunlight. The relative abundance of chlorophyll-a is proportional to phytoplankton biomass, and local patterns or gradients in concentration can serve as an effective proxy indicator for locating tidal mixing fronts (Garcia-Nieto *et al.*, 2024).

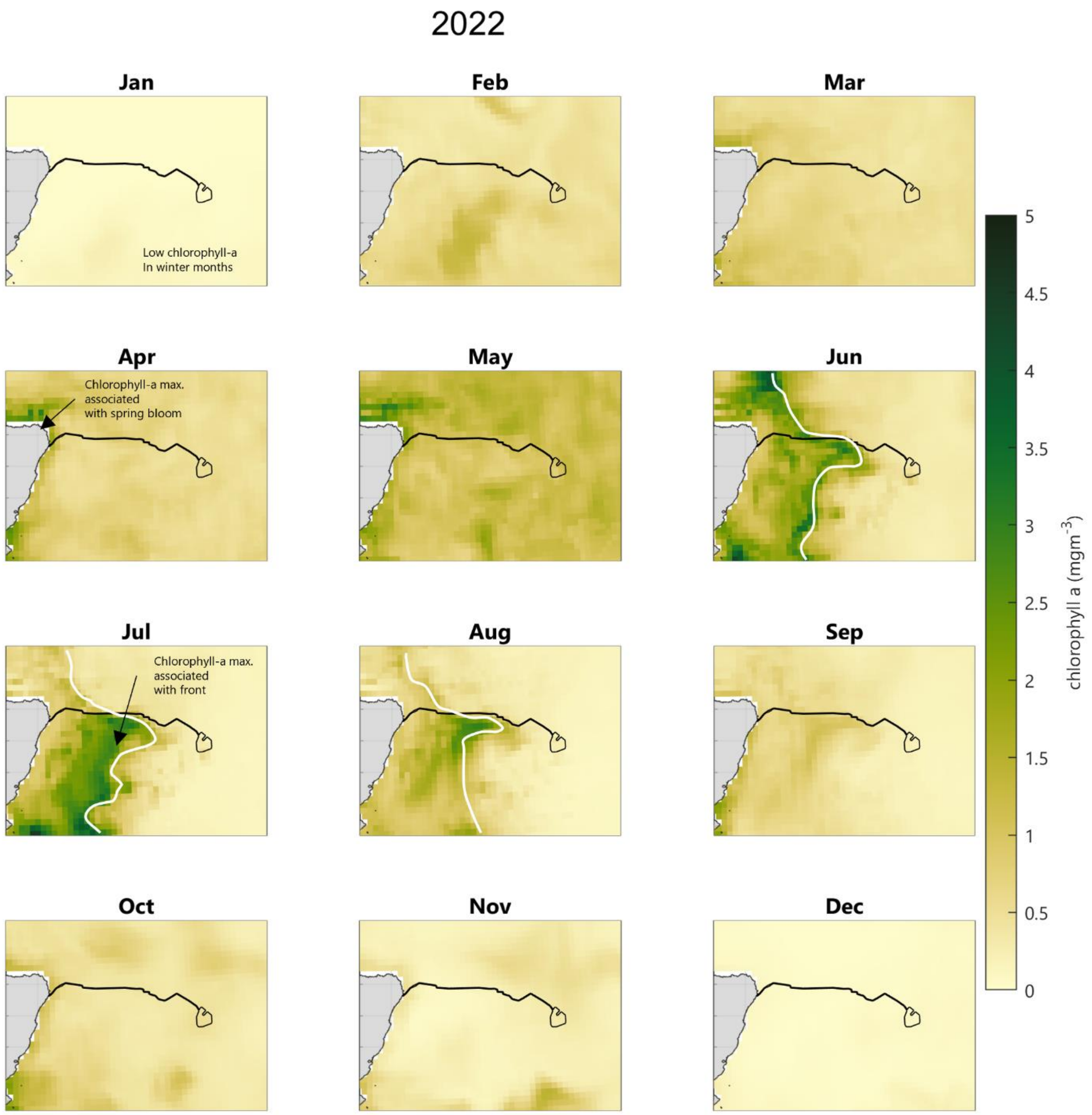
Phytoplankton rely on sunlight and nutrients for photosynthesis and thrive in areas where both are readily available. In stratified waters, nutrients tend to be trapped below the thermocline, making them inaccessible to phytoplankton in the sunlit surface layer. The physical mixing at fronts locally supplies a relatively higher concentration of nutrients into the sunlit surface layer, therefore creating more favourable conditions for phytoplankton growth by preventing nutrient depletion in the surface layers. As a result, these areas often support higher levels of primary production (and chlorophyll-a) compared to both the mixed and stratified waters on either side of the front.

Figure 7-14 and Figure 7-15 show the maximum chlorophyll-a concentrations within the upper 30 meters of the water column for the years 2015 and 2022, capturing both deep chlorophyll maxima and surface peaks. Elevated chlorophyll-a concentrations, likely associated with a tidal mixing front, are consistently observed west of the Array Area during the summer months. This pattern, evident across all years analysed (2010 to 2023), suggests higher primary production occurring at the boundary between the weakly stratified/mixed waters inshore and the more strongly stratified waters proximal to where the Array Area is located. These findings align well with the high front frequency region predicted by Miller and Christodoulou (2014) in Figure 7-13.



The Array Area and EICC are outlined in black.

Figure 7-14 Copernicus reanalysis monthly maximum chlorophyll-a concentration in the upper 30 m for 2015.



The Array Area and EICC are outlined in black.

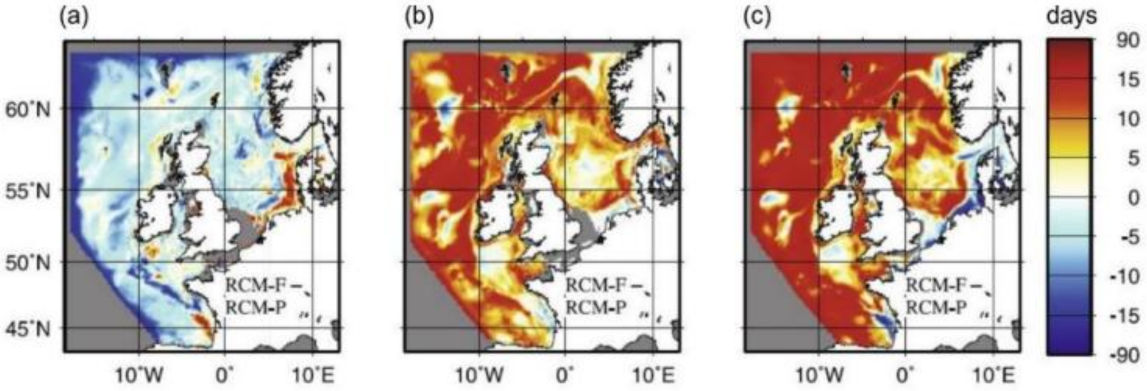
Figure 7-15 Copernicus reanalysis monthly maximum chlorophyll-a concentration in the upper 30 m for 2022

7.3.3.4 Future change

The stratification dynamics in the CNS are expected to undergo significant changes due to the changing climate. With the Project potentially beginning commercial operation in 2031, and a Project lifetime of ~40 years, it is important to consider how the timing and strength of stratification will evolve during this time.

The timing of stratification is influenced by the interplay between solar heating and tidal mixing, with a smaller but notable contribution from wind-driven mixing. Global warming and changes to meteorological conditions, is likely to alter the timing of spring stratification, and subsequently the timing of the spring phytoplankton bloom.

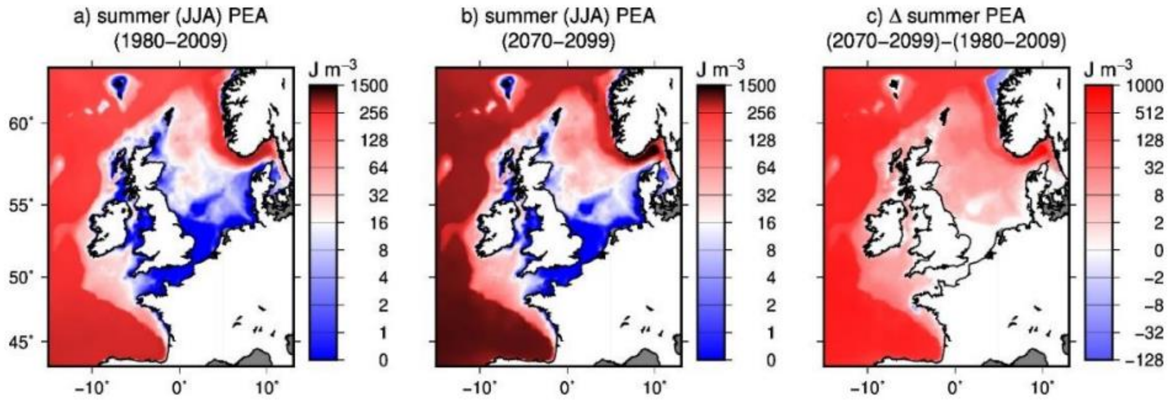
Model projections suggest that by 2100, the thermal stratification period in UK shelf seas will extend by approximately two weeks, with stratification occurring about one week earlier and breaking down 5 to 10 days later than present (Sharples *et al.*, 2022). The dominant driver behind this shift is the increase in air temperature, which accelerates solar heating of the surface waters and thus strengthens thermal gradients. Historically, stratification timing in the central/north-western North Sea has advanced by about 0.5 days per year since the late 1980s, based on analyses from 1974-2003 (Sharples *et al.*, 2006; Holt *et al.*, 2012). While these observed trends in stratification timing are relatively weak and difficult to separate from inter-annual variability (Jardine *et al.*, 2022), they offer some indication of potential future patterns (Figure 7-16).



The future prediction was based on a 'business as usual' climate projection. a) Change in timing (days) of the onset of seasonal stratification. b) Change in timing (days) of the autumn/winter breakdown of stratification. c) Change in the total number of days of stratification during one year.

Figure 7-16 Comparison between present-day (1961-1990) and future (2070-2098) timing of stratification (from Sharples et al., 2022)

Model projections also suggest that seas across the northwest European shelf, including the Central/Northern North Sea, will experience greater surface-to-bottom temperature differences as the seasonal heating cycle intensifies (Tinker *et al.*, 2016), resulting in stronger stratification (Figure 7-17). This increase in stratification strength reduces vertical mixing, limiting the upward transport of nutrients from the deep layers to the surface, where they fuel primary production. This could lead to a decline in overall Primary Productivity (PP), as suggested by Chust *et al.*, (2014).



a) Present day average strength of stratification. b) Predicted strength of stratification towards the end of the century. c) Predicted change in stratification towards the end of the century.

Figure 7-17 Present day and predicted strength of stratification (from Sharples et al., 2022)

7.3.4 Impact assessment

7.3.4.1 Worst-case scenario

Several layout and foundation options detailed in the PDE were considered. The realistic worst-case for impacts to stratification and frontal systems is associated with the PDE design option providing the largest hydrodynamic blockage within the water column. This is calculated by considering the floating substructure type, dimensions, and number, mooring configuration, anchor system and electrical cabling. The WCS for subsurface blockage contributing to potential impacts on stratification is summarised as follows:

- 95 x 15 Mega Watt (MW) FTU:
  - Minimum horizontal spacing of 928 m;
  - Floating platform substructure type: semi-submersible;
  - Maximum width of floating substructure is 112 m;
  - Draft of floating substructure below surface is 20 m;
  - Six mooring lines per floating substructure;
  - Mooring line diameter of 302 mm;
  - Mooring line length in water column of 422 m;
- Two dynamic IACs sections in the water column per FTU:
  - IACs diameter of 350 mm; and
  - Total IACs length in water column for all FTUs: 70 km;
- 2 x OSCPs:
  - OSCPs foundation type: jacket;
  - Maximum diameter of OSCPs jacket leg is 4 m; and
  - Maximum width of OSCPs jacket is 50 m.

To the best of the authors knowledge, all of the academic analysis to date which considers potential impacts from windfarms on mixing processes has focused on flow around monopile (i.e. simple fixed bottom) foundations (e.g. Carpenter *et al.*, 2016, Cazenave *et al.*, 2016; and Dorrell *et al.*, 2022), not floating foundations such as those which may be installed in the Array Area. The assessment presented in this Section draws upon this research, (pertaining to fixed bottom foundations), therefore can be seen as a worst-cast estimate of blockage effects, as a monopile structure through the whole water column is likely to impact the vertical structure more than a floating structure near the surface.

7.3.4.2 How might FTUs and OSCPs change mixing?

Turbulent mixing acts to breakdown stratification, it is a naturally occurring, omnipresent process driven at the seabed by tidal currents and at the surface by wind and wave action. Flow past floating and fixed bottom substructure foundations within the Array Area will provide another source of turbulence generation, driving additional water column mixing compared to the baseline scenario. In the following assessment, the contribution of one OSCP is equivalent to one additional FTU, and with similar or greater minimum separation and spacing within the array. The assessment is therefore described in terms of the effect of the FTUs, but this does include the effect of up to two OSCPs.

To assess the impact of the FTUs on the strength of localised water column mixing, the method outlined by Carpenter *et al.*, (2016) was employed. This approach uses empirical equations to estimate two key timescales: the mixing timescale, which predicts the time required for complete mixing of stratified layers due to increased TKE generated by the FTUs, and the advective timescale, which quantifies how long a water parcel remains within the Array Area, experiencing enhanced TKE.

Power is removed from the flow as it is forced around an OWF foundation, this can be expressed as power consumption per unit area (P_{str}) in W/m^2 by the following equation:

$$P_{str} = \frac{\rho_0 C_D A \langle |\bar{u}|^3 \rangle}{2L^2}$$

Where: ρ_0 is the water density (1,026 kg/m^3); C_D is the drag coefficient; A is the cross-sectional area of the turbine foundation in the water column; L is the distance between equally spaced wind turbines; and, $|\bar{u}|^3$ is the time mean, depth-mean current velocity, cubed (i.e. a measure of the power of the current throughout the year).

The drag coefficient of a structure is highly variable, dependent on a range of factors such as roughness length scale and turbulence in the approaching flow. A range of values for C_D have been applied in previous studies. The highly conservative value of $C_D = 1$, as used by Carpenter *et al.*, (2016) and similar to values suggested by Faltinsen (1990) for floating structures and ships, is applied here. The cross-sectional area of each foundation type provided in the design envelope was calculated, and the maximum area used – this was for a platform floating substructure type which gave an individual substructure area of 3,262 m^2 (including mooring lines and IACs), equivalent to a monopile of 34.9 m diameter in 93.5 m of water (mean water depth across the Array Area). The OSCPs have a similar equivalent monopile diameter and account for only a small proportion of the total blockage effect. The smallest FTU spacing distance provided in the design envelope, 928 m, was used as L. The mean current velocity for the Array Area, averaged over the period 1979 to 2023 was 0.17 m/s. These values and assumptions provide an estimate of power removal per unit area across the Array Area of 0.01 W/m^2.

The estimate of the power removed by an OWF foundation structure is assumed to be equal to the power put into TKE production (Carpenter *et al.*, 2016), which mixes the water column stratification. Therefore, given the strength of the stratification, represented by the PEA, a timescale to mix a water column completely by only the TKE generated by wind turbine structures (T_{mix}) can be estimated by:

$$T_{mix} = \frac{\phi_{max} h}{R_f P_{str} b}$$

where: R_f is the Richardson number, a value of 0.17 is commonly used in oceanographic studies; h is the water depth (93.5 m); ϕ_{max} is the PEA value for the maximum stratification case, for the Array Area this was ~220 J/m^3 in August 2010, 2013, 2018 and 2022; and, b is the thickness of the pycnocline region during maximum stratification (20 m).

The calculated mixing timescale for the Array Area is approximately 7.3 days. To provide context for this value, it is necessary to determine a timescale of advection (T_{adv}), i.e. how long a parcel of water is likely to experience enhanced turbulent mixing induced by the OWF structures. This was estimated using the mean residual current speed across the Array Area (0.05 m/s, PhysE, 2023) and the Array Area's length scale (25 km), resulting in a T_{adv} value of 5.8 days. This indicates that a parcel of water is not exposed to the elevated TKE from the OWF structures for a sufficient duration to fully break down the strong stratification present in the water column.

The foundation-induced mixing described in this Section will primarily occur directly behind individual FTUs, resulting in narrow wakes that extend only a short distance downstream. These localised foundation wakes have a limited spatial footprint, meaning not all water parcels within the Array Area will pass through these zones of enhanced mixing. As a result, the wakes will create spatially confined regions of more weakly stratified water, surrounded by unaffected, strongly stratified waters. This may create small pockets of elevated primary production within the Array Area, where mixing and weakening of the stratification in the FTU wakes acts to vertically mix nutrients into the nutrient depleted, sunlit surface layers of the surrounding stratified waters.

Over time and with increasing distance from the FTUs, the localised mixing effects will dissipate into the surrounding waters. This means the more weakly stratified wake regions will gradually recover, returning to a state of strong stratification. Research by Miles *et al.*, (2017) using scaled flume tank models found that while monopile foundations initially reduced flow velocity and increased turbulence in their wake, these effects largely dissipated within 8.3 pile diameters downstream. This limited spatial influence on flow and turbulence suggests that the impact of floating foundations on stratification will also be spatially constrained, affecting only small portions of the shelf sea and minimising the likelihood of cumulative impacts with other planned OWFs.

7.3.4.3 How might this change in mixing influence the timing of seasonal stratification and frontal positions?

The impact of the FTUs on seasonal stratification and frontal positions is expected to be minimal. The mixing induced by the FTUs is unlikely to be strong enough to fully break down stratification within the timescale that water parcels are exposed to this enhanced mixing. Additionally, the dominant tidal mixing front is located over 30 km west of the Array Area at its closest point, and during years of stronger stratification, this distance between Array Area and front increases as the front typically forms even farther inshore. The onset of stratification in spring depends on surface heating overcoming vertical mixing. The FTU-induced mixing could theoretically delay the onset of stratification. Similarly, the breakdown of stratification in autumn may be slightly accelerated by the FTUs' enhanced TKE. However, in years where stratification is naturally weak, stratification typically develops later and breaks down earlier. Therefore, the FTUs' influence on seasonal timing is expected to be small, falling within the natural variability of the system.

Frontal systems form at boundaries between mixed and stratified waters, and their position and intensity can be influenced by vertical mixing. The added turbulence from the floating substructure will act to locally weaken, but not fully break down stratification, within the wakes of FTUs. This may create small pockets of elevated primary production within the Array Area, where mixing and weakening of the stratification in the FTU wakes acts to vertically mix nutrients into the nutrient depleted, sunlit surface layers of the surrounding stratified waters.

7.3.4.4 What impacts could this have on primary production and the wider ecosystem?

Potential impacts on primary production and the wider marine ecosystem will be reported on separately, within other chapters of the EIAR, notably EIAR Vol. 3, Chapter 12: Offshore Ornithology and EIAR Vol. 3, Chapter 13: Fish and Shellfish Ecology. However, the potential impact of the FTUs on primary production and the wider ecosystem is expected to be small, especially when considering the mixing/advection timescales, natural variability and existing patterns of productivity in the region.

Elevated primary production consistently occurs to the west of the Array Area, near the boundary between areas of relatively weaker and more strongly stratified waters (Figure 7-14 and Figure 7-15), and is indicative of the tidal mixing front location. The Array Area is located outside this key area of productivity, which limits the potential for any direct impacts (i.e. direct local mixing at the location of the front). Any indirect advected effect of additional mixing reducing stratification extending from the Array Area is unlikely to overlap or significantly alter the nutrient dynamics at the existing front, because there is no clear hydrodynamic pathway connecting the two locations: the front is not aligned to the Array Area along the tidal current axis or within one tidal excursion distance (PhysE, 2023); and, the residual current direction from the Array Area is away from the front towards the north (PhysE, 2023).In terms of the wider ecosystem, the localised mixing effects near the FTU are unlikely to affect ecosystem processes beyond the immediate vicinity of the Array Area. The present day and recent historical primary production hotspots and associated biological activities, such as zooplankton blooms and fish aggregations, are concentrated at the tidal front, which is and will continue to be created and controlled by natural processes and will be subject to natural variation in strength and timing, unaffected by the FTUs' influence.

The strength and duration of stratification in the CNS is predicted to increase from now until 2100 predominantly due to increased air temperatures (see Section 7.3.3.4). This means the front's position will likely be pushed further west, closer to the coastline and further from the Array Area, as previously mixed waters become stratified. This further limits the potential for any direct impacts of the FTUs on the front over the Project's lifetime.

7.3.4.5 What impacts could change in near-surface wind speeds have on water column mixing & stratification?

Another potential influence on mixing is the change in near sea surface wind speeds due to the FTUs. This has been investigated by Christiansen *et al.*, (2022). A detailed hydrodynamic model was set up to simulate the seasonal cycle of summer stratification in the southern North Sea, with multiple OWFs in operation. The simulations show the emergence of large-scale attenuation in the wind forcing and associated alterations in the local hydro- and thermodynamics. Induced changes in the vertical and lateral flow were found to be sufficiently strong to influence the residual currents and entail alterations of the temperature and salinity distribution in areas of OWF operation. Ultimately, these were found to affect the stratification development in the southern North Sea. In the German Bight in particular, the reduction of mixing at OWFs was found to enhance or maintain stratification strength during the autumn breakdown phase of summer stratification.

However, whilst the modelling analyses of Christiansen *et al.*, (2022) provide theoretical evidence for atmospheric OWF wakes to impact water column stratification, the findings are based on the presence of a very large number of OWFs (>50) in relatively close proximity with a large total number of turbines (>2,500) present within the theoretical scenario Study Area. In contrast, the Project is further offshore and is not part of a large group of closely spaced OWFs and is itself much smaller (up to 95 FTU). Any associated wind wake effects are therefore only expected to have a very limited aggregated spatial footprint. The potential for widespread changes in the rate of surface mixing and associated water column stratification is therefore considered to be very low and within the range of natural variability.

7.3.5 Summary

The assessment of potential changes to stratification and frontal systems caused by the FTUs indicates that the FTUs will have minimal impacts.

The baseline conditions show that the Array Area experiences strong seasonal stratification, with significant seasonal and inter-annual variability. Stratification typically peaks during mid-summer when warmer surface waters are separated from colder bottom waters by a thermocline (temperature gradient) and associated pycnocline (density gradient). The region to the west of the Array Area experiences weaker stratification, with waters becoming increasingly mixed with proximity to the coast. The boundary between stratified and weakly stratified/mixed waters occurs to the west of the Array Area and supports higher levels of primary production, indicative of a tidal mixing front. In contrast, the Array Area itself is characterised by stronger stratification and lower levels of primary productivity.

The installation of floating substructures and OSCP jacket foundations will generate additional turbulence alongside naturally occurring turbulence generated at the seabed by tidal currents and the surface by wind/wave action. The foundation induced TKE will enhance vertical mixing in the water column, acting to weaken stratification. However, this mixing effect is expected to be spatially limited, occurring in narrow wakes downstream of FTUs.

The estimated mixing timescale for the area during a strong stratification period (August 2022) is approximately 7.3 days. The estimated time a water parcel spends within the Array Area experiencing enhanced mixing is 5.8 days. This indicates that a parcel of water is not exposed to the elevated TKE from the FTUs for a sufficient duration to fully break down the strong stratification present in the water column.

The FTUs are not expected to significantly influence the timing of seasonal stratification or the positioning of tidal mixing fronts. While additional mixing may theoretically delay the onset of stratification in spring or accelerate its breakdown in autumn, any changes would be subtle and fall within the bounds of natural variability. Similarly, shifts in frontal systems—regions where mixed and stratified waters meet—are expected to be highly localised.

Impacts on primary production and the wider ecosystem are also expected to be minimal. The most productive area, located west of the Array Area within the more weakly stratified waters, is located outside the direct influence of the Array Area. Small pockets of elevated primary production maybe generated within the Array Area, where mixing and weakening of the stratification in the FTU wakes acts to vertically mix nutrients into the nutrient depleted, sunlit surface layers of the surrounding stratified waters.

Finally, while changes in near-surface wind speeds due to the FTUs could theoretically influence water column mixing, the scale of these effects is expected to be negligible. Large-scale OWFs have been shown to reduce surface mixing and enhance stratification in some studies, but the relatively small size of the Project makes widespread impacts unlikely.

7.4 References

ABPmer, Cefas and HR Wallingford. (2007). Review of Round 1 Sediment process monitoring data - lessons learnt. (Sed01).

ASA (2005). Estimates of seabed scar recovery from jet plough cable burial operations and possible cable exposure on Horseshoe Shoal from sand migration. Report prepared by ASA for Cape Wind Associates, ASA Report 5-128, October.

Awel y Môr OWF Ltd (2022). Category 6: Environmental Statement. Volume 2, Chapter 2: Marine Geology, Oceanography and Physical Processes. April 2022. Available online at: https://infrastructure.planninginspectorate.gov.uk/wp-content/ipc/uploads/projects/EN010112/EN010112-000188-6.2.2_AyM_ES_Volume2_Chapter2_MarinePhysProc_vFinal.pdf [Accessed on 05/11/2024]

Blue Gem Wind (2023). Erebus Floating Offshore Wind Farm Environmental Statement. Available online at: https://www.bluegemwind.com/wp-content/uploads/2020/07/EREBUS-NON-TECHNICAL-SUMMARY-Interactive.pdf [Accessed on 05/11/2024].

Department for Business Enterprise and Regulatory Reform (BERR) (2008). Review of Cabling Techniques and Environmental Effects applicable to the Offshore Wind farm Industry. Technical Report. January 2008. In association with Defra. Available online at: https://tethys.pnnl.gov/sites/default/files/publications/Cabling_Techniques_and_Environmental_Effects.pdf [Accessed on 05/11/2024].

Carpenter, J. R., Merckelbach, L., Callies, U., Clark, S., Gaslikova, L. and Baschek, B. (2016). Potential Impacts of Offshore Wind Farms on North Sea Stratification. PLoS ONE 11(8).

Casenave, P. W., Torres, J. and Icarus Allen, J. (2016). Unstructured grid modelling of offshore wind farm impacts on seasonally stratified shelf seas. Progress in Oceanography 145, pp. 25-41.

Christiansen, N., Daewl, U., Djath, B. and Schrum, C. (2022). Emergence of Large-Scale Hydrodynamic Structures Due to Atmospheric Offshore Wind Farm Wakes. Frontier Marine Science, Vol. 9.

Chust, G., Allen, J. I., Bopp, L., Schrum, C., Holt, J., Tsiaras, K., Zavatarelli, M., Chifflet, M., Cannaby, H., Dadou, I., Daewel, U., Wakelin, S. L., Machu, E., Pushpadas, D., Butenschon, M., Artioli, Y., Petihakis, G., Smith, C., Garçon, V., Goubanova, K., Le Vu, B., Fach, B. A., Salihoglu, B., Clementi, E. and Irigoien, X. (2014). Biomass changes and trophic amplification of plankton in a warmer climate. Global Change Biology, 20(7), 2124-2139, doi: 10.1111/gcb.12562.

Ciavatta, S., Brewin, R. J. W., Skákala, J., Polimene, L., de Mora, L., Artioli, Y., and Allen, J. I. (2018). Assimilation of ocean-color plankton functional types to improve marine ecosystem simulations. Journal of Geophysical Research: Oceans, 123, 834–854.

Copernicus Marine Service (Copernicus) (2024a). Atlantic- European Northwest Shelf- Ocean Physics Reanalysis. Available online at: https://data.marine.copernicus.eu/product/NWSHELF_MULTIYEAR_PHY_004_009 [Accessed on 05/11/2024].

Copernicus (2024b). Atlantic- European Northwest Shelf- Ocean Biogeochemistry Reanalysis. Available online at: https://data.marine.copernicus.eu/product/NWSHELF_MULTIYEAR_BGC_004_011/description?view=-&option=-&product_id=- [Accessed on 05/11/2024].

Det Norske Veritas (DNV), (2014). Subsea Power Cables in Shallow Water Renewable Energy Applications. Recommended Practice DNV-RP-J301. 145pp.

DONG Energy (2013a). Burbo Bank Extension Offshore Wind Farm Environmental Statement. Available online at: https://tethys.pnnl.gov/publications/burbo-bank-extension-offshore-wind-farm-volume-2-es-biological-environment [Accessed on 05/11/2024].

DONG Energy (2013b). Walney Extension Environmental Statement. Available online at: https://orsted.co.uk/energy-solutions/offshore-wind/our-wind-farms/walney-extension [Accessed on 05/11/2024].

Dorrell, R. M., Lloyd, C. J., Lincoln, B. J., Rippeth, T. P., Taylor, J. R., Caulfield, C. P., Sharples, J., Polton, J. A., Scannell, B. D., Greaves, D. M., Hall, R. A. and Simpson, J. H. (2022). Anthropogenic Mixing in Seasonally Stratified Shelf Seas by Offshore Wind Farm Infrastructure. Front. Mar. Sci. 9:830927.

EMU Limited (2005). Kentish Flats Monitoring Programme: Turbidity Monitoring. Report No. 05/J/1/01/0733/0500. Report to Kentish Flats Ltd. 13pp.

Faltinsen, O. M. (1990). Sea Loads on Ships and Offshore Structures. Cambridge University Press, Cambridge, CB2 1RP, UK.

Floventis (2024). Llyr Floating Offshore Wind Farm Environmental Statement. Available online at: https://www.gov.wales/environmental-impact-assessment-eia-deferral-directions-section-36-electricity-act-llyr-offshore [Accessed on 05/11/2024].

Garcia-Nieto, P. J., Garcia-Gonzalo, E., Fernandez, J. R. A, Muiz, C. D. (2024), Forecast of chlorophyll-a concentration as an indicator of phytoplankton biomass in El Val reservoir by utilizing various machine learning techniques: A case study in Ebro River basin, Spain. Journal of Hydrology, 639.

Gowen, R., Stewart, B., Mills, D., and Elliott, P. (1995). Regional differences in stratification and its effect on phytoplankton production and biomass in the northwestern Irish Sea. J. Plankton Res. 17, 753–769.

Hill, V. and Cota, G. (2005). Spatial patterns of primary production on the shelf, slope and basin of the Western Arctic in 2002. Deep Sea Res. II 52, 3344–3354.

Hill, A. E., Brown, J. Fernand, L. Holt, J., Horsburgh, K. J., Proctor, R., Raine R. and Turrell, W. R. (2008). Thermohaline circulation of shallow tidal seas. Geophysical Research Letters, 35(11).

Holt, J., Hughes, S., Hopkins, J., Wakelin, S.L., Holliday, N.P., Dye, S., González-Pola, C., Hjøllo , S.S., Mork, K.A., Nolan, G., Proctor, R., Read, J., Shammon, T., Sherwin, T., Smyth, T., Tattersall, G., Ward, B., Wiltshire, K.H. (2012). Multi-decadal variability and trends in the temperature of the northwest European continental shelf: A model-data synthesis, Progress in Oceanography, 106, 96-117. https://doi.org/10.1016/j.pocean.2012.08.001.

Jardine, J. E., Palmer, M.R., Mahaffey, C., Holt, J., Wakelin, S. and Artioli, Y. (2022). Climatic controls on the spring phytoplankton growing season in a temperate shelf sea. Journal of Geophysical Research: Oceans, e2021JC017209.

Miles, J., Martin, T., Goddard, L. (2017). Current and wave effects around windfarm monopile foundations. Coastal Engineering 121, 167-178.

Miller, P. I. and Christodoulou, S. (2014). Frequent locations of oceanic fronts as an indicator of pelagic diversity: Application to marine protected areas and renewables. Marine Policy, 45, pp. 318-329.

Navitus Bay Development Ltd (2014). Navitus Bay Wind Park Environmental Statement. Available online at: https://tethys.pnnl.gov/sites/default/files/publications/Navitus-Bay-Wind-ES.pdf [Accessed on 05/11/2024].

Ørsted (2018). Hornsea Three Offshore Wind Farm: Environmental Impact Assessment. Available online at: https://national-infrastructure-consenting.planninginspectorate.gov.uk/projects/EN010080/documents [Accessed on 05/11/2024].

PhysE (2023). Cenos Metocean Criteria Volume 2 – Operational Presentations. Document code: FLO-CEN-REP-0014

Reach (2007). Asia-America Gateway (AAG) Cable Network, South Lantau, Project Profile 2007. report prepared by Atkins and EGS for Reach Networks Hong Kong Ltd.

Rovco (2023a). EICC Geophysical Results Report. Cenos OWF Array and Export Cable Corridor Geophysical Survey. Doc: CEN001-ROV-01-CON-GPH-RPT-0015.

Rovco (2023b). OWF Geophysical Results Report. Cenos OWF Array and Export Cable Corridor Geophysical Survey. Doc: CEN001-ROV-01-CON-GPH-RPT-0013.

RWE (2024a). Rampion 2 Offshore Wind Farm Environmental Statement. Available online at: https://national-infrastructure-consenting.planninginspectorate.gov.uk/projects/EN010117/documents [Accessed on 05/11/2024].

RWE (2024b). Five Estuaries Offshore Wind Farm Environmental Statement. Available online at: https://national-infrastructure-consenting.planninginspectorate.gov.uk/projects/EN010115/documents?lang=en [Accessed on 05/11/2024].

SeaScape Energy (2008). Burbo Offshore Wind Farm: Construction Phase Environmental Monitoring Report. CMACS for SeaScape Energy. April 2008.

Sharples, J., Ross, O. N., Scott B. E., Greenstreet, S. P. R. and Fraser, H. (2006). Inter-annual variability in the timing of stratification and the spring bloom in the North-western North Sea. Continental Shelf Research, 26(6), 733–751, doi:10.1016/j.csr.2006.01.011.

Sharples, J., Holt, J., Wakelin, S., Palmer, M. R. (2022). Climate change impacts on stratification relevant to the UK and Ireland. Marine Climate Change Impacts Partnership Science Review, 11pp.

Simpson, J. H. and Bowers, D. (1981). Models of stratification and frontal movement in shelf seas. Deep Sea Research Part A. Oceanographic Research Papers. 28, 7, pp. 727-738.

Soulsby, R.L. (1997). Dynamics of marine sands. A manual for Practical Applications. Thomas Telford, London.

Thames Estuary Dredging Association (TEDA) (2010). 'MAREA: High-level plume study'. Technical note DDR4318-03. http://marine-aggregate-rea.info/sites/www.marine-aggregate-rea.info/files/private/appendix-3plume-study.pdf [Accessed on 05/11/2024].

Tinker, J., J. Lowe, A. Pardaens, J. Holt, and R. Barciela (2016). Uncertainty in climate projections for the 21st century northwest European shelf seas, Progress in Oceanography, 148(Supplement C), 56-73. doi: https://doi.org/10.1016/j.pocean.2016.09.003.

Tonani, M., Ascione, I. and Saulter, A. (2022). Product User Manual v.1.3 – Ocean Physical and Biogeochemical reanalysis. Copernicus Marine Service.

van Leeuwen, S., Tett, P., Mills, D., and van der Molen, J. (2015). Stratified and nonstratified areas in the North Sea: Long-term variability and biological and policy implications. Journal of Geophysical Research-Oceans, 120(7), 4670-4686.

Vattenfall (2018). Thanet Extension Offshore Wind Farm: Environmental Impact Assessment. Available online at: https://national-infrastructure-consenting.planninginspectorate.gov.uk/projects/EN010084/documents [Accessed on 05/11/2024].

Yamaguchi, R., Toshio, S., Richards, K. J. and Qiu, B. (2019). Diagnosing the development of seasonal stratification using the potential energy anomaly in the North Pacific. Climate Dynamics.