Vattenfall Wind Power Ltd

Thanet Extension Offshore Wind Farm

Annex 2-1: Marine Geology, Oceanography, Physical Processes Technical Report

June, 2018, Revision A

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Vattenfall Wind Power Ltd

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Annex 2-1: Marine Geology, Oceanography and Physical Processes Technical Report

June, 2018

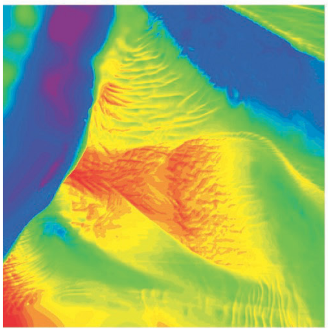
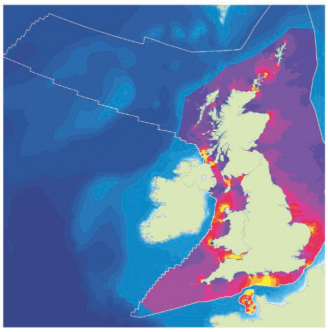
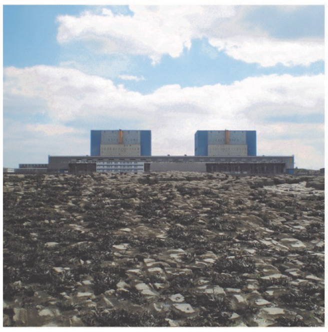
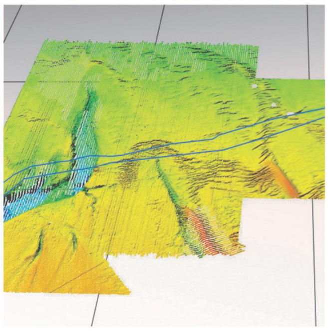
Drafted By:	ABPmer
Approved By:	Helen Jameson
Date of Approval	June 2018
Revision	A

GoBe Consultants Ltd.

Thanet Extension Offshore Wind Farm

Marine Geology, Oceanography and Physical Processes Technical Report

May 2018

Innovative Thinking - Sustainable Solutions

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Tony Brooks	David Lambkin	Heidi Roberts
[redacted]		

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Contributing Authors

Tony Brooks, David Lambkin, Ian Davidson

Acknowledgements

Bill Cooper (Cooper Marine Advisers)

Notice

ABPmer
Quayside Suite, Medina Chambers, Town Quay, Southampton, Hampshire SO14 2AQ
T: +44 (0) 2380 711844 W: http://www.abpmer.co.uk/

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1 Introduction

1.1 Overview

ABPmer has been commissioned to undertake the Environmental Impact Assessment (EIA) for the potential impacts of the Thanet Extension offshore wind farm ('Thanet Extension') on Marine Geology, Oceanography and Physical Processes (hereafter referred to as 'physical processes'). Physical processes is a collective term for the following:

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

Specifically, this assessment considers the potential impact of Thanet Extension seaward of Mean High Water Springs (MHWS) during its construction, operation and maintenance, and decommissioning phases.

The Thanet Extension array area would be located off the south east coast of Kent in the South East of England approximately 8 km offshore (at the closest point), in proximity to the operational Thanet Offshore Wind Farm (TOWF) (Figure 1). Electricity generated would be transported to the shore by offshore export cables installed within the proposed Thanet Extension Offshore Export Cable Corridor (OECC), making landfall in Pegwell Bay.

This technical report provides an assessment of the potential for change to physical processes as a consequence of the construction, operation and maintenance, and decommissioning of Thanet Extension, both on its own and in conjunction with other planned, consented and operational projects. These findings have subsequently been used to underpin the significance of effect assessments for physical processes receptors, presented in Volume 2, Chapter 2: Marine Geology, Oceanography and Physical Processes (Document Ref: 6.2.2). The results have also been used to inform assessments for other EIA receptor groups which may potentially be sensitive to changes in physical processes.

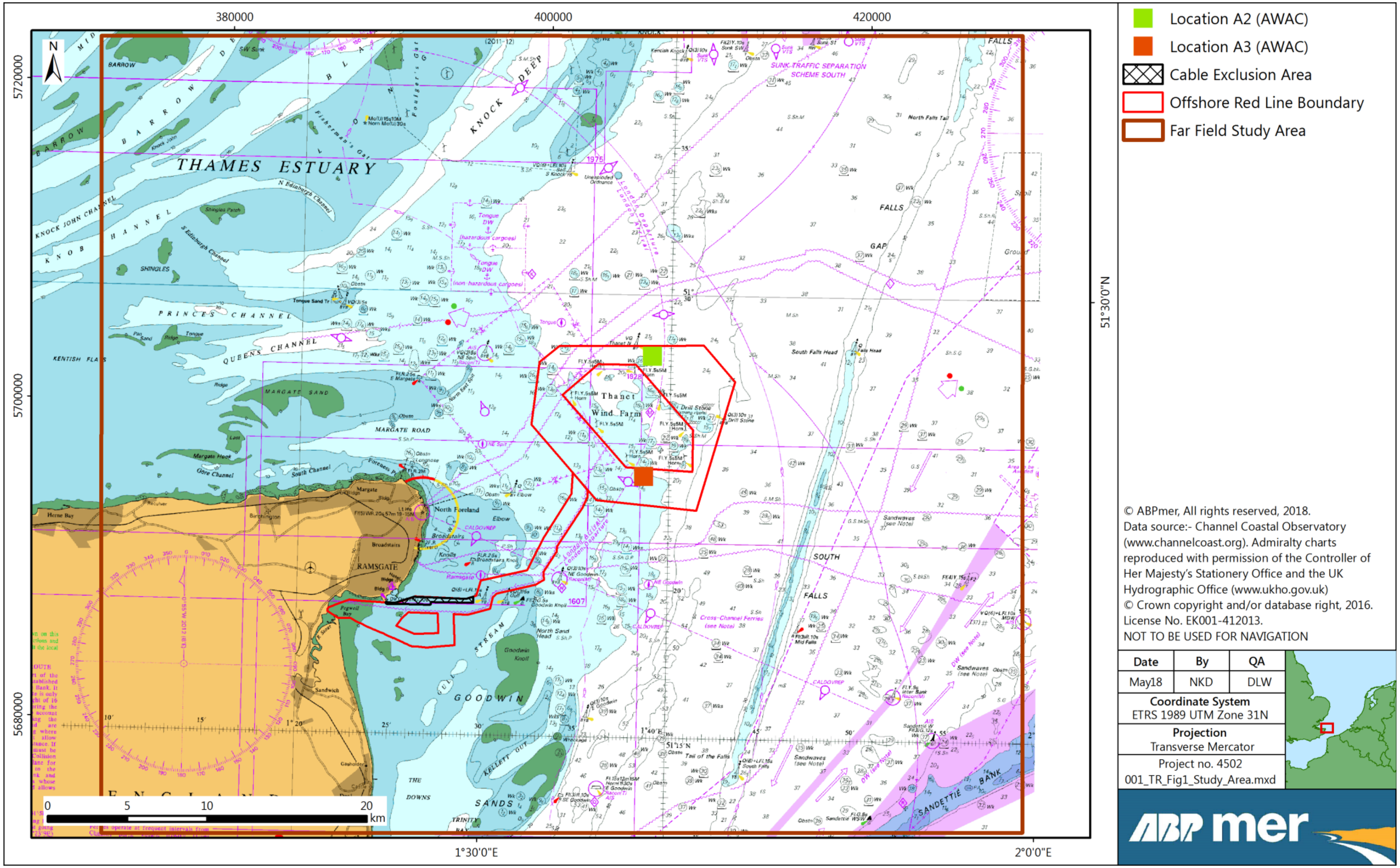


Figure 1. Thanet Extension offshore wind farm marine physical processes study area

1.2 Scope of assessment

The potential impacts to be assessed in relation to physical processes for Thanet Extension are summarised in the scoping report (Vattenfall, 2016) and listed in Table 1.

Table 1. Summary of potential impacts/ changes considered in the physical processes assessment

Potential Impact/ Change	Pathway (P)/ Receptor (R)
Construction	
Increases in Suspended Sediment Concentration (SSC) and deposition of disturbed sediments to the seabed due to dredging for seabed preparation prior to foundation installation.	P
Increases in SSC and deposition of disturbed sediments to the seabed due to the release of drill arisings during foundation installation.	P
Increases in SSC and deposition of disturbed sediment to the seabed due to cable installation within the Thanet Extension array area and within the export cable corridor.	P
Sandwave crest level preparation resulting in a change to local hydrodynamic, wave and sediment transport processes.	P
Impacts to sandbank receptors (due to construction activities).	R
Impacts to designated coastal feature receptors (due to construction activities).	R
Operation and Maintenance	
Changes to the tidal regime.	P
Changes to the wave regime.	P
Changes to sediment transport and sediment transport pathways.	P
Scour of seabed sediments.	P
Development of turbid wake features.	P
Impacts to sandbank receptors (due to wind farm operation).	R
Impacts to designated coastal feature receptors (due to wind farm operation).	R
Impacts to designated chalk feature receptors (due to wind farm operation).	R
Decommissioning	
Increases in SSC and deposition of disturbed sediment to the seabed within the Thanet Extension array area and the export cable corridor.	P
Impacts to designated coastal feature receptors (due to decommissioning activities).	R
Cumulative	
Cumulative temporary increases in SSC and seabed levels as a result of Thanet Extension export cable installation and dredge disposal activities.	P
Cumulative temporary increases in SSC and seabed levels as a result of Thanet Extension export cable installation and aggregate dredging activities.	P

The nature of the scoped in impacts are similar to that previously considered for the existing Thanet Offshore Wind Farm (TOWF) project. It should be recognised that in most cases, physical processes are not in themselves receptors but are, instead, 'pathways' which have the potential to indirectly impact other environmental receptors. Table 1 highlights which potential impacts/ changes are considered as pathways and which are considered as receptors. Notwithstanding this, three specific physical processes receptors have been identified within the Thanet Extension study area, namely:

- Designated coastal features:
  (Saltmarshes, intertidal flats and dune systems)

- Sandbanks:
  (South Falls, Goodwin Sands and Margate Sands); and

- Designated chalk features:
  (Cliffs, platforms and reefs).

This Annex provides the technical information underpinning each of the impacts listed in Table 1 and assessed within Volume 2, Chapter 2: Marine Geology, Oceanography and Physical Processes (Document Ref: 6.2.2). A search for relevant data/ literature to support the investigation has also been undertaken and is presented in Appendix A.

A description of the baseline environment across the marine processes study area is provided within in Volume 2, Chapter 2: Marine Geology, Oceanography and Physical Processes (Document Ref: 6.2.2). This draws upon the findings of the project-specific oceanographic, geophysical and geotechnical surveys (Table 2) as well as pre-existing data (Appendix A). Maximum adverse design scenarios used in the assessments presented in this Annex are also set out in Volume 2, Chapter 2: Marine Geology, Oceanography and Physical Processes (Document Ref: 6.2.2).

Table 2. Summary of project-specific survey data

Title	Overview	Reference
Bathymetric and geophysical survey	Sidescan sonar (SSS), single beam echo sounder (SBES), multibeam echo sounder (MBES), pinger (SBP), ultra-high resolution (UHR) multichannel and magnetometer (MAG) survey carried out within the Thanet Extension array area and export cable corridor between July and September 2016.	Fugro (2016a,b)
Geotechnical survey	Seabed cone penetration test (CPT) and vibrocores sampling operations were performed from 12 September to 16 September 2016. A total of 18 test locations were investigated in the Thanet Extension array area (10 CPT, 8 vibrocore). A total of 2 test locations were investigated in the Thanet Extension array area (1 CPT, 1 vibrocore).	Fugro (2016c)
Benthic survey	Survey undertaken between 11 November and 14 November. Particle Size Analysis (PSA) carried out on 28 grab samples. Drop down video acquired at 39 stations.	Fugro (2017)
Oceanographic survey	Wave, current, water and sediment data at two locations within the Thanet Extension array area. Two 600 kHz Nortek Acoustic Wave and Current meters (AWAC), a Datawell Waverider and two RBR OBS sensors were deployed on 16th and 17th December 2016 and recovered on 16th and 17th February 2018 (1 year and 2 months of data).	Partrac (2017)

1.3 Report structure and terminology

This Annex is structured around the potential impacts and effects requiring assessment, as identified during Scoping and through discussions held at the Marine Processes, Benthic Ecology and Fish and Shellfish Expert Working Group meetings:

Section 2: Assessment approach;
Section 3: Suspended sediment concentrations, bed levels and sediment type;
Section 4: Turbid wakes;
Section 5: Landfall;
Section 6: Tidal regime;
Section 7: Wave regime;
Section 8: Sediment transport regime;
Section 9: Scour and seabed alteration;
Section 10: Decommissioning; and
Section 11: Summary.

In this Annex, the following terminology is used to characterise geographical regions of the study area (Figure 1):

- Nearshore area (0 m Lowest Astronomical Tide (LAT) contour out to ~ -5 mLAT contour);
- Inshore area (~ -5 mLAT contour out to ~ -20 mLAT contour); and
- Offshore area (seaward of the ~ -20 mLAT contour).

2 Assessment Approach

2.1 Overview

A Marine Geology, Oceanography and Physical Processes Method Statement was compiled by ABPmer (ABPmer, 2017) and reviewed by Regulators and stakeholders in April 2017. For the impact assessment, the following combination of approaches was proposed (as summarised in Table 3):

- Use of the 'evidence base' of monitoring data collected during the construction, operation and maintenance of other sufficiently analogous offshore wind farms, in particular the adjacent TOWF;
- Use of the 'evidence base' of results from pre-existing numerical modelling and desk based assessments undertaken to support EIA for other sufficiently analogous offshore wind farms (both in terms of project design and environmental setting);
- New analytical assessments of project-specific infrastructure design and activities, including the use of spreadsheet based tools; and
- Standard relationships describing (for example) hydrodynamic interactions with obstacles, sediment transport including settling and mobilisation, seabed scour, etc.

The proposed approach was broadly accepted by Regulators and stakeholders and therefore has been used to undertake the assessments documented in this Annex.

Table 3. Assessment approach for Thanet Extension

Issue	Assessment Approach for Thanet Extension
Suspended Sediment Concentrations, Bed Levels and Sediment Type	Spreadsheet based numerical model, validated against field observations and numerical modelling supporting analogues projects and activities.
Turbid wakes associated with foundations	Evidence base approach, drawing upon observational (direct and remotely sensed) data as well as published modelling considering the relationship between structure design and turbid wake development.
Landfall	Desk based assessment of historic variability at the landfall, informed by quantitative analysis of available topographic and bathymetric data.
Tidal Regime	Evidence base approach, drawing on the findings of hydrodynamic modelling undertaken to inform analogues projects, as well as field evidence.
Wave Regime	Evidence base approach, drawing on the findings of hydrodynamic modelling undertaken to inform analogues projects, as well as field evidence.
Sediment Transport Regime	Potential for Wind Turbine Generator (WTG) , offshore substation (if required) and meteorological mast (if required) foundations to influence patterns of sediment transport considered via desk based assessment drawing upon outputs from the analysis of potential changes to the tidal and wave regimes, in conjunction with wider understanding of baseline sediment transport.

Issue	Assessment Approach for Thanet Extension
	Potential for cable protection measures to influence patterns of sediment transport assessed conceptually, drawing upon the existing evidence base and empirical equations considering (for example) the extent of wave transformation for given water depths.
Scour and Seabed Alteration	Use of empirical equations to determine scour pit characteristics (horizontal extent and equilibrium scour depth) from foundation design.

From the outset, it is important to note that no new site specific wave, tide and sediment transport modelling has been carried out for the Thanet Extension physical processes assessment. There are several project specific reasons why such an approach is justified and these are set out in Section 2.2. Physical processes assessments have been carried out for a number of other UK offshore wind farm developments, without project specific numerical modelling of waves, tides and sediment transport. These include:

- Seagreen Phase 1 (consented in 2014);
- Burbo Round 2 extension (consented in 2014);
- Walney Round 2 extension (consented in 2014);
- Kentish Flats Extension (consented 2012); and
- Gunfleet Sands 2 and Demonstration sites (consented in 2008).

In addition to the above, the East Anglia THREE (Round 3) OWF EIA has been concluded without further project specific numerical modelling. Consent was granted for the project in August 2017.

2.2 Validation of assessment approach

The assessment approach used to inform this assessment is considered to be suitable and robust for the reasons set out below.

2.2.1 Availability of existing evidence

There is a large body of existing evidence available from analogous developments, especially the operational TOWF, which can be directly used to inform an understanding of the likely magnitude of change. This includes:

- Monitoring evidence from the construction and operational phases of offshore wind farms (e.g. Cefas, 2005; ABPmer *et al*., 2010; BERR, 2008; Titan, 2012a,b; 2013);

- Existing numerical modelling to inform EIA studies for offshore wind farm developments with analogous designs (in terms of foundation number and/or size) (e.g. ABPmer, 2002a, b; 2005); and

- Monitoring and modelling evidence from analogous activities and developments (e.g. aggregate extraction (e.g. TEDA, 2010).

2.2.2 Location of the development

As shown in Figure 1, the Thanet Extension array area surrounds the operational TOWF. Accordingly, the baseline conditions and processes that prevail within the TOWF site are similar in nature to that across the Thanet Extension array area. This observation underlines the appropriateness and value of using the observational evidence from the TOWF to directly inform the Thanet Extension assessment.

It should also be noted that, because the wind turbine foundations within the Thanet Extension array area will be distributed relatively uniformly in a narrow area around the existing TOWF site, the potential for further changes to waves and currents at locations outside of the TOWF and Thanet Extension array areas will be low. This is because the additional blockage will be minimal and because the directional distribution of foundations (blockage density) in any given direction will not be greatly different from the present TOWF alone condition.

2.2.3 Observational evidence from TOWF

The TOWF site (which has been operational since 2010) provides a close and in many respects a conservative analogue for the Thanet Extension project. No adverse morphological impacts (such as increased coastal change) have occurred that can be attributed to the operation presence of TOWF. This is consistent with the studies undertaken to support the TOWF marine processes EIA (Thanet Offshore Wind Limited, 2005). Turbid wake features have been observed although these are considered to have no adverse impacts on local sediment transport processes (Section 4).

2.2.4 Size of development and nature of the proposed foundation type

Up to 34 wind turbines may be installed within the Thanet Extension array area (Table 4). The overall scale of new infrastructure within the proposed development is therefore small, relative to both the existing TOWF (100 turbines) and many other built and consented UK offshore wind farm projects.

Table 4. Summary of key metrics for the Thanet Extension and (operational) TOWF projects

Metric	Thanet Extension	TOWF
Array area	72.8 km^2	35 km^2
Water depth range (mLAT)	-11.5 to -45 m	-14 to -23 m
Max. no of turbines	34	100
Turbine capacity	8 to 12+ MW	3 MW
Project capacity	340 MW	300 MW
Foundation options	Monopiles 3 or 4 legged tri/quadropods (pin piles) 3 or 4 legged tri/quadropods (suction caissons)	Monopiles
Turbine separation distance	716 m x 480 m	480 m (each row) 716 m (between rows)
Indicative turbine density	0.5 turbines/ km^2	2.9 turbines/ km^2

Wind turbines within the Thanet Extension array area will be supported by monopile, quadropod (jacket) and/or suction caisson foundations. Summary descriptions of the presently proposed dimensions of these foundation types are provided in Table 5. Individual foundations may potentially present greater blockage than the 4.1 and 4.9 m diameter monopile foundations installed in the operational TOWF site although overall numbers are lower. More information on this aspect is provided in Appendix B.

Specifically, the project design statement for Thanet Extension does not include an option for gravity base or similar large volume foundations. Gravity base foundations would typically present a much larger blockage effect than other foundation types (such as monopiles and quadropod foundations) and, if included, usually represent the 'worst case' option in assessments of effect on waves, currents and sediment transport.

Table 5. Thanet Extension foundation descriptions

Foundation Type	Description
Monopile	Cylindrical steel pile with conical transitions - up to 10 m diameter Penetration up to 75 m depth below seabed level (average drilling depth 30 m)
Three legged tripod on either pin piles or suction caisson anchoring	Typically single large diameter vertical column supported by three braces Steel pin piles - diameter up to 4 m Seabed penetration of up to 70 m (average drilling depth 25 m) Spacing between legs up to 40 m Caisson bucket diameter up to 20 m
Four legged quadropods on pin piles or suction caisson anchoring	Numerous design variants available, typically, lattice structure comprising steel tubular sections Steel pin pile - diameter up to 4 m Seabed penetration of up to 70 m (average drilling depth 25 m) Spacing between legs up to 40 m Caisson bucket diameter up to 20 m

2.2.5 Proposed method of foundation installation

Bed preparation may be required if suction caisson structures are used. These activities would be carried out using standard dredging techniques for which a large body of information is already available from the offshore wind, aggregate dredging and port industry in the Greater Thames region.

3 Assessment of Suspended Sediment Concentrations, Bed Levels and Sediment Type

3.1 Overview

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

- Drilling of monopile foundations and pin piles for quadropod foundations;
- Seabed preparation by dredging prior to quadropod suction caisson foundation installation;
- Sandwave clearance (prior to cable burial); and
- Cable burial.

The mobilised material 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 suspended sediments and consequential deposition.

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.

3.2 Baseline conditions

A summary of the baseline characteristics within and nearby to the Thanet Extension array area is provided below, based on existing publically available information.

- Depth averaged mean spring currents within the Thanet Extension array area are in the approximate range 0.7 m/s to 1.2 m/s. Throughout inshore and offshore parts of the export cable route corridor mean spring peak currents are predominantly between approximately 0.9 m/s and 1.1 m/s but reach approximately 1.3 m/s in localised areas (Partrac, 2017; ABPmer *et al.*, 2008);

- Monthly averaged satellite imagery of suspended particulate matter (SPM) suggests that within the Thanet Extension array area average (surface) SPM is generally greater than 10 mg/l, increasing markedly throughout winter months to values between 30-80 mg/l (Eggleton *et al.*, 2011; Cefas, 2016), occasionally reaching up to 100 mg/l. Higher values (potentially several hundred) are anticipated during spring tides and storm conditions, with the greatest concentrations encountered close to the bed;

- SSC will naturally vary with height in the water column. Sediment is naturally re-suspended by the action of currents and waves at the seabed and so SSC is highest at the seabed. Sediment naturally settles downwards under gravity but is also re-suspended upwards by turbulence which is greater nearer the seabed. This results in a non-linear (power-law) profile of SSC (i.e. rapidly decreasing with height above the seabed);

- Seabed sediments within and nearby to the Thanet Extension array area are typically characterised by the presence of fine to coarse sands, with smaller areas of muddy sand and sandy gravel (Fugro, 2016a; Thanet Offshore Wind Limited, 2005; Nemo Link, 2011);

- Seabed sediments along the corridor are predominantly characterised by sands and gravels with varying contributions of each (Fugro, 2016b);

- Sediments in Pegwell Bay comprise medium to silty sands overlying chalk (Rees Jones, 1998; Dussart and Rodgers, 2002; Thanet Offshore Wind Limited, 2005);

- The thickness of seabed surficial sediment cover is highly variable, ranging from 0 to ~ 8 m, in the vicinity of mobile bedform features; and

- Extensive areas of Cretaceous chalk are covered by varying thicknesses of Tertiary marine sediments (Woolwich Formation, Thanet Formation) and Holocene sediments (Southern Bight and Elbow). These include mudstones and fine grained muddy sands. A summary of the interpreted geology within the array area is presented in Figure 2a and b.

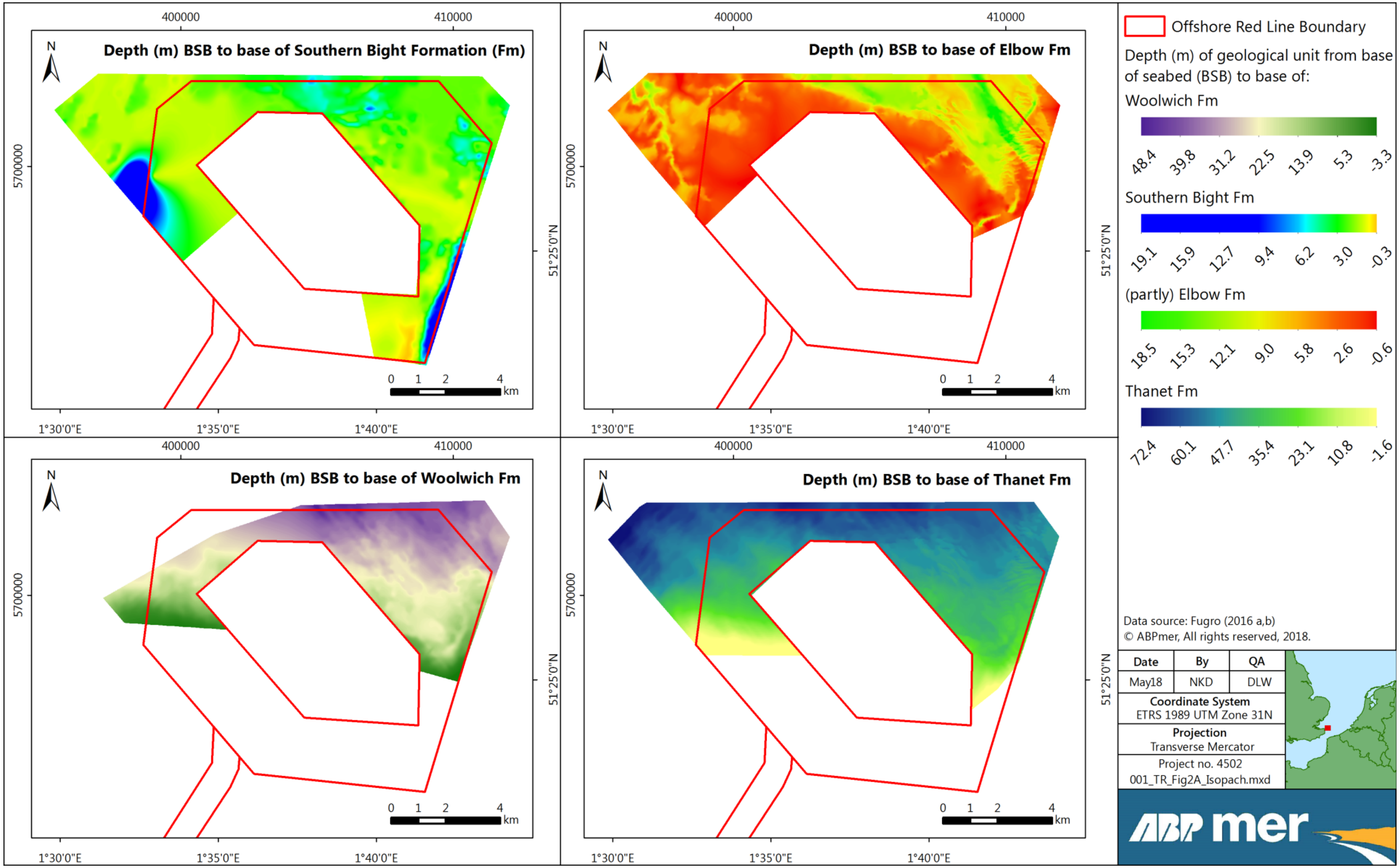


Figure 2a. Distribution and thickness of geological units within the Thanet Extension offshore wind farm array area

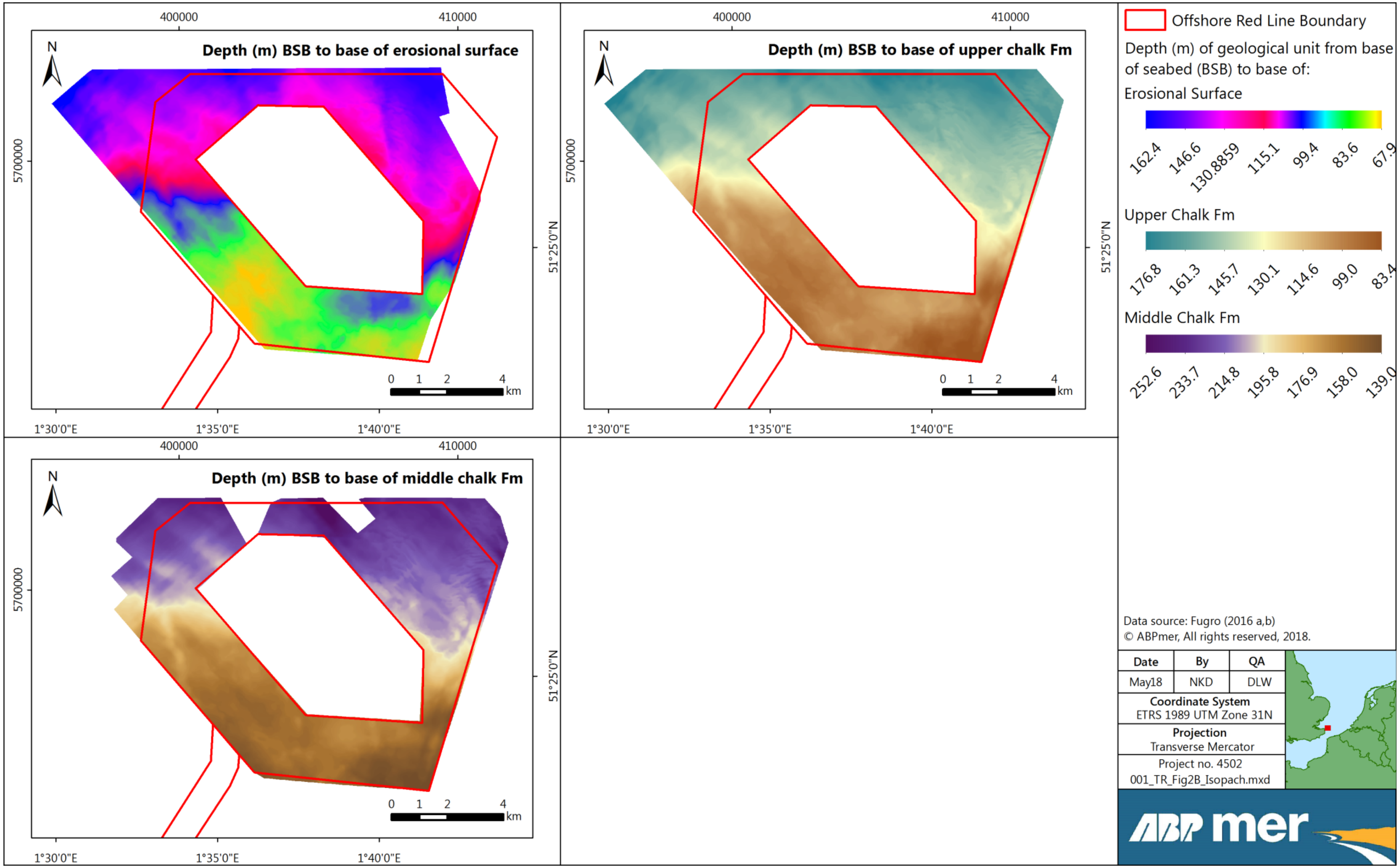


Figure 2b. **Distribution and thickness of geological units within the Thanet Extension array area**

3.3 Assessment

3.3.1 Methodology

Sediment disturbed and released into the water column during construction 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 where the main body of the settling plume of sediment reaches the seabed.

Coarse grained (i.e. sand/ gravel) sediments will behave differently to fine grained (i.e. silt/ clay) sediments 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 resettlement 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.

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 and Navitus Bay offshore wind farms (DONG Energy, 2013a, b; and Navitus Bay Development Ltd, 2014, 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 Thanet Extension array area is 0.5 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 = κu*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 (κ = 0.4) and u* is the friction velocity (u* = √(τ/ρ). Where ρ is the density of seawater (ρ = 1027 kg/m^3) and τ is the bed shear stress, calculated using the quadratic stress law (τ = ρ C_d U2, Soulsby, 1997) using a representative current speed for the Thanet Extension site (U = 0.25 m/s) and a drag coefficient value for a rippled sandy seabed (C_d = 0.006);

- The interpreted geophysical data from the Thanet Extension array area indicate that in general there are three characteristic surficial sediment types present, namely:
  - Clayey to silty sand;
  - Fine to coarse sand; and
  - Sandy gravel.

- To estimate the time-scale in suspension, sediment is assumed to settle downwards at a calculated (theoretical) settling velocity for each grain size fraction (0.0001 m/s for fines, 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[1] 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). For monopile foundations, the point of sediment release is likely to be static and so the width of deposition is characterised directly as the footprint of deposition. For quadropod suction caisson foundations, the point of sediment release is likely to move within an area equivalent

[1] Defined here as the average flow observed during the Thanet Extension oceanographic survey (Partrac, 2017)

to the size of the quadropod foundation or dredged area, in which case the overall width of deposition is characterised as the footprint of deposition plus the diameter of the suction caisson foundation;

- 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;
- The average seabed deposition thickness is calculated as the total volume of sediment released, divided by the footprint area (width times length) of deposition; and
- 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 as per the following example:

- The vessel is likely to be stationary during precision dredging operations so the water movement relative to the vessel is dominantly tidal (at the representative current speed 0.5 m/s);
- Sediment is discharged at a representative rate (e.g. 30 kg/s for dredging over-spill) into a minimum volume of water 100 m^3 = 10 m x 10 m x 1 m deep;
- This volume of water will be refreshed every 20 seconds (10 m / 0.5 m/s);
- The total sediment input is 20 s x 30 kg/s = 600 kg;
- The resulting initial concentration in the receiving water is 600 kg / 100 m^3 = 6 kg/m^3 = 6,000 mg/l;
- The initial concentration would then be subject to turbulent dispersion 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; and
- Assuming a faster current speed, faster vessel motion or larger footprint of release would reduce the mass of sediment introduced to the fixed volume of the receiving waters (and so SSC) at the point of initial dispersion, and *vice versa*.

3.3.2 Drilling of monopile foundations and pin piles for quadropod foundations

Summary

Monopile foundations and pin piles for quadropod foundations will be installed into the seabed using standard piling techniques. In some locations, the particular geology may present some obstacle to piling, in which case, some or all of the seabed material might be drilled from within the pile footprint to assist in the piling process. It is noted here though, that all monopiles within TOWF were successfully installed using piling techniques and no drilling was required to assist the installation works.

The impact of drilling operations mainly relates to the release of drilling spoil at or above the water surface which will put sediment into suspension and the subsequent re-deposition of that material to the seabed. The nature of this disturbance will be determined by the rate and total volume of material to be drilled, the seabed and subsoil material type, and the drilling method (affecting the texture and grain size distribution of the drill spoil). These changes are quantitatively characterised in this section using the spreadsheet based numerical models described in Section 3.3.1.

Evidence base

The evidence-base does not presently include many measurements of SSC resulting from drilling operations for monopile or pin pile installation. This is due to the relatively small number of occasions that such works have been necessary.

Limited evidence from the field is provided by the during- and post-construction monitoring of monopile installation using drill-drive methods into chalk at the Lynn and Inner Dowsing offshore wind farms (CREL, 2008). Although broadly similar geology to the Thanet Extension array area, it is recognised that the foundation dimensions and drilling apparatus will differ. In the Thanet Extension array area, it is also not yet known how the drilled sub-soils will disaggregate. All of the above factors limit the extent to which the Lynn and Inner Dowsing monitoring evidence can be considered to be indicative of the proposed construction activities for Thanet Extension.

The installation of steel monopiles (4.7 m diameter and up to 20 m penetration depth) was assisted in some cases by a drill-drive methodology. The drill arisings were mainly in the form of rock (chalk) chippings that were released onto the seabed a short distance away in a controlled manner using a pumped riser. The particular concern in that case was the possibility of sub-surface chalk arisings leading to high levels of SSC of an atypical sediment type. The result of sediment trap monitoring (located as close as 100 m from the operation) was that the chalk was not observed to collect in significant quantities. However, direct measurements of SSC were not possible at the time of the operation.

The dimensions of the chalk drill arisings deposit created was measured by geophysical survey and characterised as a conical mound, approximately 3 m thick at the peak, extending laterally (from the peak to ambient bed level) up to 10 m in what is assumed the downstream direction and 5 m in the other. The volume of the deposit (measured as approximately 290 m^3) was similar to the total volume of the drilled hole (347 m^3) indicating that the majority of the total drill arisings volume had been deposited locally. The difference in volumes might be partially explained by different patterns of settling or transport leading to some material settling away from the main deposit location. It is also possible that the combination of drill and drive did not necessarily release a volume of material equivalent to 100% of the internal volume of the pile, or that the full burial depth may not have been achieved in this example. Seabed photographs indicate that the material in the deposit is clearly horizontally graded, with the largest clasts closer to the centroid of the deposit.

Assessment of change

The greatest SSC and thickness of sediment deposition is associated with drilling activities associated with monopile installation (Volume 2, Chapter 2: Marine Geology, Oceanography and Physical Processes (Document Ref: 6.2.2)). The maximum adverse scenario occurs as a result of fully drilling (100% of the volume of) a single turbine monopile foundation, for a 12 MW WTG, (7.5 drill diameter, 30 m average depth, drilling rate 5 m/hour). For the array as a whole, the maximum adverse scenario is associated with a layout comprising up to 28 x 10 MW turbine foundations (7 m drill diameter; 716 m x 480 m spacing), one Offshore Substation (OSS) and one met mast. However, due to ground conditions only up to 50% of the total number of turbine foundations might be fully drilled (100% of the monopile volume).

The distribution of grain/clast sizes in the drill arisings for individual WTG foundations is not known in advance, so results are provided separately for scenarios where 100% of the material is assumed to be either fines, (medium) sand or (coarse) gravel sized. In practice, depending on the actual ground conditions and drilling tools used, the distribution of grain/clast size in the spoil will be some variable mixture of these with a corresponding intermediate duration, extent and magnitude of change.

The maximum adverse scenario for sediment release by drilling activities is summarised in Table 6.

Table 6. Maximum adverse scenario for sediment release by drilling monopiles

Parameter	Maximum Adverse Scenario	Working and Other Assumptions
Turbine Monopiles		
Number of turbine monopiles to be drilled	17	Up to 50% of 34 turbine monopiles may be drilled to an average depth of 30 m
Maximum drill diameter used for (12 MW) monopile installation	7.5 m	100 % of the monopile internal area will be drilled
Total volume of drill arisings from one (12 MW) turbine monopile	1,325 m^3	7.5 m drill diameter, 30 m depth
Total volume of drill arisings for entire array (corresponds to array of 34 x 10 MW turbine monopiles)	19,627 m^3	1,154.5 m^3 x 17 turbine foundations
Sediment mineral density	2,650 kg/m^3	Assumed value for quartz sand (Soulsby, 1997).
Total mass of drill arisings from one (12 MW) turbine monopile	3,511,250 kg	1,325 m^3 x 2,650 kg/m^3 Assuming the drilled material is fully consolidated with minimal voids
Total mass of drill arisings from all (10 MW) turbine monopiles	52,011,550 kg	19,627 m^3 x 2,650 kg/m^3 Assuming the drilled material is fully consolidated with minimal voids
Drilling rate	5 m/hour	6 hours to install 1 monopile (30 m divided by 5 m/hour)
Maximum sediment release rate whilst drilling	163 kg/s	7.5 m diameter, 5 m/hour = 221 m^3/hr = 0.06 m^3/s x 2,650 kg/m^3 Assuming the drilled material is fully consolidated with minimal voids
Consolidated packing density	0.6	Assumed value for a typical, medium sorted sand (Soulsby, 1997).
Total (consolidated) volume of drill arisings from one (12 MW) turbine monopile	2,208 m^3	1,325 m^3 divided by 0.6
Total (consolidated) volume of drill arisings from all 17 (10 MW) turbine monopiles	32,712 m^3	19,627 m^3 divided by 0.6

Parameter	Maximum Adverse Scenario	Working and Other Assumptions
Area over which sediment is released at or above the water surface (12 MW turbine monopiles)	44 m^2	Assumed value – sediment is released at or above the water surface in an area approximately equal to the area of the drilled hole (7.5 m diameter). Using a larger value will increase initial dispersion, decrease SSC and reduce the thickness of subsequent deposits and *vice versa*.
Offshore Substation		
Number of monopiles to be drilled	1	Average depth penetration depth of 30 m
Maximum drill diameter used for monopile installation	6	100 % of the monopile internal area will be drilled
Total volume of drill arisings	900 m^3	-
Sediment mineral density	2,650 kg/m^3	Assumed value for quartz sand (Soulsby, 1997).
Total mass of drill arisings from one (12 MW) turbine monopile	2,385,000	900 m^3 x 2,650 kg/m^3 Assuming the drilled material is fully consolidated with minimal voids
Drilling rate	5 m/hour	6 hours to install 1 monopile (30 m divided by 5 m/hour)
Maximum sediment release rate whilst drilling	104 kg/s	6 m diameter, 5 m/hour = 167 m^3/hr = 0.05 m^3/s x 2,650 kg/m^3 Assuming the drilled material is fully consolidated with minimal voids
Consolidated packing density	0.6	Assumed value for a typical, medium sorted sand (Soulsby, 1997).
Total (consolidated) volume of drill arisings	1,500 m^3	900 m^3 divided by 0.6
Area over which sediment is released at or above the water surface	28.3 m^2	Assumed value – sediment is released at or above the water surface in an area approximately equal to the area of the drilled hole (6 m diameter). Using a larger value will increase initial dispersion, decrease SSC and reduce the thickness of subsequent deposits and *vice versa*.
Met Mast		
Number of monopiles to be drilled	1	Average depth penetration depth of 30 m
Maximum drill diameter used	7.5 m	100 % of the monopile internal area will be drilled
Total volume of drill arisings from one monopile	1,325 m^3	7.5 m drill diameter, 30 m depth
Sediment mineral density	2,650 kg/m^3	Assumed value for quartz sand (Soulsby, 1997).
Total mass of drill arisings from one monopile	3,511,250 kg	1,325 m^3 x 2,650 kg/m^3 Assuming the drilled material is fully consolidated with minimal voids

Parameter	Maximum Adverse Scenario	Working and Other Assumptions
Drilling rate	5 m/hour	6 hours to install 1 monopile (30 m divided by 5 m/hour)
Maximum sediment release rate whilst drilling	163 kg/s	7.5 m diameter, 5 m/hour = 221 m^3/hr = 0.06 m^3/s x 2,650 kg/m^3 Assuming the drilled material is fully consolidated with minimal voids
Consolidated packing density	0.6	Assumed value for a typical, medium sorted sand (Soulsby, 1997).
Total (consolidated) volume of drill arisings from one monopile	2,208 m^3	1,325 m^3 divided by 0.6
Area over which sediment is released at or above the water surface	44 m^2	Assumed value – sediment is released at or above the water surface in an area approximately equal to the area of the drilled hole (7.5 m diameter). Using a larger value will increase initial dispersion, decrease SSC and reduce the thickness of subsequent deposits and *vice versa*.

Levels of SSC resulting from drilling of the different foundation types (with different rates of release) assuming 100% of the drill arisings are fines are shown in Table 7 for the range of dispersion scenarios listed below.

- Source concentration at the point of release (total mass evenly dispersed in a volume of water 10 m wide, 10 m length, 1 m depth);
- Vertical diffusion to 5 m, 20 m lateral spread in footprint dimensions (30 seconds to one minute after release, 15 to 30 m downstream);
- Vertical diffusion to 15 m (from surface to approximately half water depth), 50 m lateral spread in footprint dimensions (five to ten minutes after release, 150 m to 300 m downstream); and
- Vertical diffusion to 25 m (so affecting the seabed), 100 m lateral spread in footprint dimensions (30 minutes after release, 900 m downstream).

Table 7. Suspended sediment concentration as a result of drilling 100% of the volume of one 12 MW turbine monopile foundation (100% drill arisings as fines)

Parameter			12 MW Turbine Monopile Foundation
Rate of sediment release (kg/s)			163
Total mass released into receiving water (kg/s)			3,252
Representative current speed (m/s)			0.5
Plume Width (m)	Plume Depth (m)	Plume Section Length (m)	Resulting SSC (mg/l)
10	1	10	32,520
20	5		3,252
50	15		434
100	25		130

The approximate timeframe and distance downstream from the point of release for each dispersion scenario is indicated, based on the representative rates of settling, lateral dispersion and current speeds previously described in Section 3.3.1.

Levels of SSC and the estimated area and average thickness of sediment thickness resulting from drilling assuming 100% of the drill arisings are sands or gravels are shown in Table 8 for a single large (12 MW) turbine.

Table 8. Suspended sediment concentration and sediment deposition as a result of drilling 100% of the volume of one 12 MW turbine monopile foundation (100% drill arisings as sands or gravels)

Sediment Type	Water Depth (m)	Settling Rate (m/s)	Duration of Settlement (s)	Distance Plume Advected by Peak Current (m)	Maximum Mass in Suspension (kg)	Area of Seabed Deposition (m^2)	Average Thickness of Seabed Deposition (m)
100% Sand	14	0.05	280	140	45,529	2,229	0.99
	25		500	250	81,301	5,845	0.38
	36		720	360	117,073	11,102	0.20
	47		940	470	152,846	17,999	0.12
100% Gravel	14	0.5	28	14	4,553	132	16.73
	25		50	25	8,130	295	7.49
	36		72	36	11,707	509	4.34
	47		94	47	15,285	776	2.85
Sediment Type	**Water Depth (m)**	**Diameter of Midwater SSC Influence (m)**	**Area of Midwater SSC Influence (m^2)**	**Midwater Average SSC (mg/l)**	**Diameter of Near-Bed SSC Influence (m)**	**Area of Near-Bed SSC Influence (m^2)**	**Near-Bed Average SSC (mg/l)**
100% Sand	14	15	184	17,630	19	271	12,012
	25	21	362	8,980	27	584	5,571
	36	28	599	5,427	36	1,015	3,203
	47	34	896	3,631	45	1,566	2,077
100% Gravel	14	10	78	4,162	11	95	3,422
	25	12	112	2,915	14	148	2,190
	36	14	151	2,155	16	214	1,521
	47	16	196	1,657	19	291	1,118

Estimates of the area and average thickness of sediment deposition are provided in the preceding tables based on the approximate footprint of the plume and tidal advection factors. The extent, thickness and shape of sediment deposits on the seabed will be highly variable in practice. However, given the total volume of sediment, a range of potential alternative combinations can be calculated. For a given volume of sediment, a smaller area of extent will correspond to a greater thickness of accumulation, and *vice versa*. A steeper sided cone shape deposit will have a greater thickness and a smaller area of change than a less steep sided cone or flat deposit shape. A range of possible value combinations are provided in Table 9 for the largest (12 MW) foundation. The table demonstrates the changing spatial scale of the impact between two end members of: (i) maximum possible thickness (although also the smallest footprint or extent of impact); and (ii) the most extensive accumulation (to a smallest thickness of 0.05 m).

Table 9. Alternative potential extents and thicknesses of sediment deposition as a result of drilling 100% of the volume of one 12 MW turbine monopile foundation (100% drill arisings as sands or gravels)

Foundation Type / Operation	Deposition Scenario	Nominal Diameter of Influence (m) as a Result of Drilling for One 12 MW Foundation	Thickness of Deposit (m)*
Drilling of largest (12 MW) (1,325 m^3 drill arisings per foundation; equivalent volume when deposited at seabed = 2,209 m^3 (based on a packing density of 0.6)).	Cone	30 (steepest) 60 90	9.4 2.3 1.0
	Uniform thickness	70 99 221	0.5 0.25 0.05

* Height of peak for cones and average uniform thickness. The dimensions of the steepest cone are provided here to indicate the smallest possible area that could be impacted. It is not realistically expected that cone deposits of greater thicknesses (e.g. >5 to 10 m) will be allowed to accumulate in practice. All value pairs are part of a continuous scale of possible outcomes.

More concentrated and localised deposits (associated with coarse gravels and large clastic materials) are assumed to deposit naturally into a cone shape where the maximum thickness is in the centre of the deposit and decreases linearly to zero at the edges. Operationally, very thick deposits may affect safe navigation or other engineering considerations and so would not be planned or allowed to occur. The greatest possible thickness (at the central point of the cone, also corresponding to the smallest possible area) is associated with a cone that has the steepest possible slope angle (i.e. the angle of repose for such loose sediments = 32°). The height of cones with two and three times the extent of the steepest cone are provided for comparison. The largest possible areas impacted by uniformly distributed thicknesses of 0.5 m, 0.25 m and 0.05 m (more likely associated with sand sized material) are also provided (making no assumptions regarding the shape of the area).

The following observations based on the spreadsheet based numerical model results set out in Table 7 to Table 9, are consistent with similarly modelled patterns of change in assessments for other wind farms, and the wider monitoring evidence base.

Assuming that a mixture of sediment grain sizes are present, the overall spatial pattern of change due to drilling of a single monopile foundation is summarised as follows:

- SSC will be increased by tens to hundreds of thousands of mg/l at the point of sediment release (for a period of seconds to a few minutes), which is at or near the water surface;
- SSC of low tens of mg/l will be present in a narrow plume (tens to a few hundreds of metres wide, up to one tidal excursion in length (up to ~13 km on spring tides and 7 km on neap tides; Figure 3) aligned to the tidal stream downstream from the source;
- If drilling occurs over more than one flood or ebb tidal period, the plume feature may be present in both downstream and upstream directions;
- Outside of the area up to one tidal excursion upstream and downstream of the foundation location, SSC less than 10 mg/l may occur more widely due to ongoing dispersion and dilution of material;
- Sufficiently fine sediment may persist in suspension for hours to days or longer, but will become diluted to very low concentrations (<5 mg/l, indistinguishable from natural background levels and variability) within timescales of around one day; and

- Over longer timescales, net movement of any fine grained material persisting in suspension would generally be in an approximate southerly (south-easterly through south-westerly) direction across most of the array area in accordance with the direction of longer term net tidal current drift in this area (see baseline description provided in Volume 2, Chapter 2: Marine Geology, Oceanography and Physical Processes (Document Ref: 6.2.2)).

Sediment deposition as a result of drilling for a single foundation installation are characterised as follows:

- Deposits of mainly coarse grained and clastic sediment deposits will be concentrated within an area in the order of approximately 10 to 100 m downstream/upstream and a few tens of metres wide from individual foundations, with an average thickness in the order of one to ten metres (limited to realistically likely values);

- Deposits of mainly sandy sediment deposits will be concentrated within an area in the order of approximately 150 m to 500 m downstream/upstream and tens to one hundred metres wide from individual foundations, with an average thickness in the approximate order of tens of centimetres to approximately one metre;

- Fine grained material will be dispersed widely within the surrounding region and will not settle with measurable thickness; and

- The absolute width, length, shape and thickness of local sediment deposition as a result of drilling is estimated above. It cannot however, be predicted with certainty and are likely to vary due to the nature of the drill spoil, the local water depth and the ambient environmental conditions during the drilling activity. Other possible combinations of shape, area and thickness of sediment deposition are provided in Table 9.

The local patterns of change to SSC and sediment deposition are described above, as a result of drilling activities for individual foundations of any type. In the array area, up to 17 (50% of 34) 10 MW monopile foundations for turbines may be installed using drilling, as well as one Offshore Substation (OSS) and one met mast. The total sediment volume potentially released by drilling 50% of all turbine foundations has also been assessed with respect to the total potential extent and thickness of sediment deposition, as summarised below.

The actual shape, width, length and thickness of local or regional sediment deposition as a result of drilling cannot be predicted with certainty and is likely to vary according to the final distribution of foundations, the local nature of the drill spoil, the local water depth and the ambient environmental conditions during the drilling activity. However, the maximum total volume that could theoretically be released from drilling 50% of all foundations (17 monopile turbine foundations, 1 monopile OSS foundation and one met mast) is 21,852 m^3 and it is found that:

- If the total volume of drill arisings from all foundations was distributed equally across the array area (72.8 km^2), the average increase in bed elevation would be 0.0005 m (i.e. <1 mm) (assuming a packing density of the deposited material of 0.6); and

- An area equal to approximately 1.0% of the array area could potentially be covered by an average thickness of 0.05 m of material (assuming a packing density of the deposited material of 0.6).

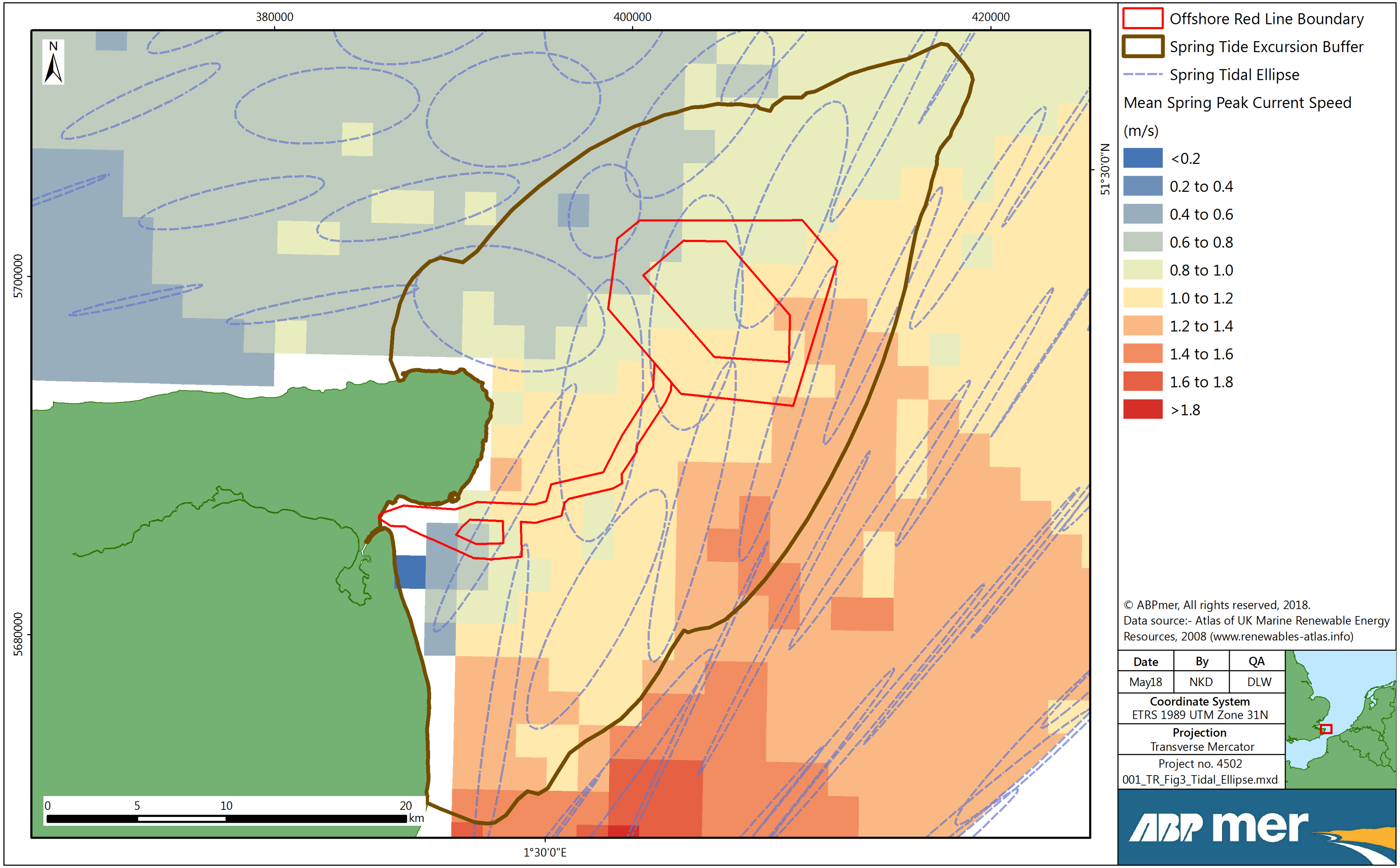


Figure 3. Spatial extent of spring tidal excursion ellipse buffer around the Thanet Extension array area and export cable corridor

If drilling occurs simultaneously with other construction activities (e.g. installation of inter-array cables) and these activities are aligned in relation to the ambient tidal streams, then there is potential for overlap between the areas of effect on SSC and sediment deposition. The effect on SSC in areas of overlap will be additive if the downstream activity occurs within the area of effect from upstream (i.e. sediment is disturbed within the sediment plume from the upstream location). The effect on SSC will not be additive (i.e. the effects will be as described for single occurrences only) if the areas of effect only meet or overlap downstream following advection or dispersion of the effects. Effects on sediment deposition will be additive if and where the footprints of the deposits overlap. Given that the minimum spacing between foundations is 480 m, it is unlikely that coarse sands or gravels put into suspension will be dispersed far enough (i.e. between adjacent foundation locations) to cause any overlapping effects before being redeposited to the seabed. Only relatively fine sediment is likely to be advected far enough to potentially cause overlapping effects on SSC.

3.3.3 Seabed preparation by dredging prior to foundation installation

Summary

To provide a stable footing for the quadropod suction caisson foundations, standard dredging techniques may be used to remove or lower the level of the mobile seabed sediment veneer within a footprint slightly larger than the foundation base. Dredging has the potential to cause elevated SSC by, sediment over-spill at the water surface during dredging and by the subsequent release of the dredged material from the dredger during spoil disposal at a nearby location. The subsequent settlement of the sediment disturbed by dredging will lead to sediment accumulation of varying thickness and extent on the seabed. These changes are quantitatively characterised in this section using spreadsheet based numerical models.

Evidence base

The evidence-base with regards to dredging and elevated levels of SSC is broad and well established through a variety of monitoring and numerical modelling studies. The following text from the UK Marine SAC Project (www.ukmarinesac.org.uk) is representative of the wider evidence base.

> *"Dredging activities often generate no more increased suspended sediments than commercial shipping operations, bottom fishing or generated during severe storms (Parr et al., 1998). Furthermore, natural events such as storms, floods and large tides can increase suspended sediments over much larger areas, for longer periods than dredging operations (Environment Canada, 1994). It is therefore often very difficult to distinguish the environmental effects of dredging from those resulting from natural processes or normal navigation activities (Pennekamp et al., 1996).*
>
> *…In general, the effects of suspended sediments and turbidity are generally short term (<1 week after activity) and near-field (<1 km from activity). There generally only needs to be concern if sensitive species are located in the vicinity of the maintained channel."*

Dredging for construction aggregates is a common marine activity in the Thames Estuary Region. The total mass of aggregate recovered from each region is reported annually by the British Marine Aggregate Producers Association (http://www.bmapa.org). It is reported that, in 2015, *c.* 1.50 million tonnes (~0.94 million m^3) of construction aggregate were dredged from a permitted licensed tonnage of 2.70 million (~1.70 million m^3). In addition, 1.16 million tonnes (~0.73 million m^3) were dredged for beach nourishment.

In comparison, the total volume of sediment that could potentially be dredged in the Thanet Extension array area is 453,895 m^3 (28 x 12 MW quadropod suction caisson foundations plus one OSS) over the whole duration of the construction period, which is expected to span up to 28 months. (This is equivalent to approximately 50% of the annual volume of aggregate material extracted from licenced areas in the Outer Thames.) It is also noted that sediment dredged as part of construction activities for Thanet Extension will all be returned to the seabed nearby to the dredging location, whereas sediment dredged as part of aggregate extraction is removed permanently from the seabed.

Assessment of change

The greatest SSC and thickness of sediment deposition as a result of bed preparation by dredging for a single turbine foundation is assessed for the largest diameter (12 MW) quadropod suction caisson foundation (5 x diameter of each suction caisson can which measure 20 m diameter, 3 m depth); up to 28 such turbine foundations might be installed within the Thanet Extension array area with a minimum spacing of 480 m.

The distribution of grain/clast sizes in the dredging over-spill and spoil release plumes is not known in advance, so results are provided separately for scenarios where 100% of the material is assumed to be either fines, (medium) sand or (coarse) gravel sized. In practice, depending on the actual ground conditions and dredging vessel used, the distribution of grain/clast size in the over-spill and spoil will be some variable mixture of these with a corresponding intermediate duration, extent and magnitude of change.

The maximum adverse scenario for sediment release by ground preparation dredging for a single large quadropod suction caisson foundation is characterised in Table 10.

Table 10. Maximum adverse scenario for sediment release by ground preparation dredging for one large (12 MW) quadropod suction caisson foundation

Parameter	Maximum Adverse Scenario	Working and Other Assumptions
Number of large 12 MW turbine quadropod suction caisson foundations to be dredged	1 (28)	The largest volume of sediment disturbed by ground preparation dredging for a single turbine quadropod suction caisson foundation is associated with the largest turbine quadropod suction caisson foundation. Up to 28 large quadropod suction caisson foundations may be installed: this represents the maximum adverse scenario for the array area as a whole.
Dredged area	3,200 m^2	
Depth of dredged area	3 m	
Total volume of sediment to dredge for one large quadropod suction caisson foundation	9,600 m^3	3,200 m^2 x 3 m depth
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).

Parameter	Maximum Adverse Scenario	Working and Other Assumptions
Total mass of sediment to dredge for one large (12 MW) quadropod suction caisson foundation	15,264,000 kg	9,600 m^3 x 2,650 kg/m^3 x 0.6 Only a fraction of this material will be released as dredge over-spill. The remainder will be deposited to the seabed nearby, within the Thanet Extension array area
Dredger hopper capacity	11,000 m^3	The dredging will be undertaken by a trailing suction hopper dredger (TSHD) with an assumed representative hopper capacity of 11,000 m^3
Equivalent number of dredging cycles to dredge one large quadropod suction caisson foundation	1 (0.87) cycle	9,600 m^3 divided by 11,000 m^3
Dredger sediment over-spill release rate	30 kg/s	Assumed value
Time to fill dredger	4 hours	Assumed value
Total mass of over-spilled sediment from dredging one large (12 MW) quadropod suction caisson foundation	377,018 kg	30 kg/s x 0.87 cycles x 4 hours x 60 min/hour x 60 s/min
Total (consolidated) volume of over-spilled sediment from dredging one large (12 MW) quadropod suction caisson foundation	237 m^3	377,018 kg divided by 2,650 kg/m^3 divided by 0.6
Area over which sediment is released at the water surface	100 m^2	Assumed value – sediment over-spill is released at the water surface in an area approximately 10 m x 10 m = 100 m^2. Using a larger value will increase initial dispersion, decrease SSC and reduce the thickness of subsequent deposits and *vice versa*.

The maximum adverse scenario for sediment spoil disposal by the dredger is characterised as:

- Dredge spoil will be returned to the seabed by the dredger at a nearby location within the Thanet Extension array area;
- The dredging will be undertaken by a TSHD with a split bottom release (allowing the fastest possible release of all sediment in the hopper). It is assumed that the full representative hopper capacity of 11,000 m^3 is released;
- The majority of the sediment load (up to 90% based on monitoring evidence from the aggregate industry) will descend to the seabed as a single unit, behaving as a density flow. This downward movement of material is termed the 'dynamic phase' of the plume. The rate of descent of the dynamic phase through the water column is rapid (in the order of several metres per second) relative to the normal settling rate for the individual grains that comprise it. The remaining 10% of the sediment volume released will form a more dispersed plume

throughout the water column, termed the 'passive phase', that will settle at approximately the rate of the individual grains.

- The rate of sediment release by over-spill during dredging is determined by the performance of the dredging vessel but is conservatively estimated to be 30 kg/s; and
- Spoil will be disposed of at the end of each dredging cycle from the base of the dredging vessel at a nearby location within the Thanet Extension array area. During disposal, up to 11,000 m^3 of material will be released from the bottom of the vessel in a sudden event; 90% of the material will be deposited directly to the bed as a single mass, and 10% of the material will be re-suspended as a plume of elevated SSC.

Levels of SSC resulting from dredging overspill (assuming 100% of the overspill comprises fines) are shown in Table 11 for the range of dispersion scenarios listed below. The approximate timeframe and distance downstream from the point of release for each dispersion scenario is indicated, based on the representative rates of lateral dispersion and current speeds previously described in Section 3.3.1:

- Source concentration at the point of release (total mass evenly dispersed in a volume of water 10 m wide, 10 m length, 1 m depth);
- Vertical diffusion to 5 m, 20 m lateral spread in footprint dimensions (30 seconds to one minute after release, 15 to 30 m downstream);
- Vertical diffusion to 15 m (from surface to approximately half water depth), 50 m lateral spread in footprint dimensions (five to ten minutes after release, 150 to 300 m downstream); and
- Vertical diffusion to 25 m (so affecting the seabed), 100 m lateral spread in footprint dimensions (30 minutes after release, 900 m downstream).

Table 11. Suspended sediment concentration as a result of over-spill during dredging for any size quadropod suction caisson foundation (100% of over-spill as fines)

Plume Width (m)	Plume Depth (m)	Plume Section Length (m)	Resulting SSC (mg/1)
10	1	10	6,000
20	5		600
50	15		80
100	25		24

* Rate of sediment release 30 kg/s; total mass released into receiving water 600 kg; representative current speed 0.5 m/s.

Levels of SSC as a result of overspill during dredging for any foundation size assuming 100% of the overspill are sands or gravels is shown in Table 12. The estimated area and average thickness of sediment deposition thickness assuming 100% of the overspill are sands or gravels is shown in Table 13.

Levels of SSC in the passive phase of the plume created during dredge spoil disposal for any foundation size assuming 100% of the material is fines is shown in Table 14. Levels of SSC in the passive phase of the plume created during dredge spoil disposal for any size foundation assuming 100% of the material is sands or gravels is shown in Table 15; the resulting estimated area and average thickness of sediment deposition thickness is also provided.

Table 12. Suspended sediment concentration as a result of over-spill during dredging for any size quadropod suction caisson foundation (100% over-spill as sands or gravels)

Sediment Type	Water Depth (m)	Settling Rate (m/s)	Duration of Settlement (s)	Distance Plume Advected by Peak Current (m)	Maximum Mass in Suspension (kg)
100% Sand	14	0.05	280	140	8,400
	25		500	250	15,000
	36		720	360	21,600
	47		940	470	28,200
100% Gravel	14	0.5	28	14	840
	25		50	25	1,500
	36		72	36	2,160
	47		94	47	2,820

Sediment Type	Water Depth (m)	Diameter of Midwater SSC Influence (m)	Area of Midwater SSC Influence (m^2)	Midwater Average SSC (mg/l)*	Diameter of Near-Bed SSC Influence (m)	Area of Near-Bed SSC Influence (m^2)	Near-Bed Average SSC (mg/l)*
100% Sand	14	8	54	TnTh	12	105	Th
	25	14	165	Th	20	322	Th
	36	21	334	Th	29	659	Hn
	47	27	563	Th	38	1,113	Hn
100% Gravel	14	3	7	Th	4	13	Th
	25	5	19	Th	7	36	Th
	36	7	37	Th	9	71	Hn
	47	9	61	Hn	12	118	Hn

* U- units(single digit); Hn – hundreds; Th – thousands; TnTh – tens of thousands;

Table 13. Sediment deposition as a result of over-spill during dredging for a large (12 MW) quadropod suction caisson foundation (100% over-spill as sands or gravels)

Sediment Type	Water Depth (m)	Area of Seabed Deposition (m^2)	Average Thickness of Seabed Deposition (m)
100% Sand	14	8,691	0.03
	25	16,604	0.01
	36	25,471	0.01
	47	35,294	0.01
100% Gravel	14	816	0.29
	25	1,492	0.16
	36	2,198	0.11
	47	2,934	0.08

Table 14. Suspended sediment concentration as a result of dredge spoil disposal (passive phase only) for any size quadropod suction caisson foundation (100% over-spill as fines)

Plume Width (m)	Plume Depth (m)	Plume Section Length (m)	Resulting SSC (mg/l)*
10	25	10	699,600
100	25	100	6,996
1000	25	1000	70
5000	25	5000	3

* Total mass fine sediment released into passive phase 1,749,000 kg (10% x 11,000 m^3 x 2,650 kg/m^3 x 0.6 solidity); sediment released uniformly by the active phase during descent from surface to seabed; water depth 25 m.

Table 15. Suspended sediment concentration and sediment deposition as a result of dredge spoil disposal (passive phase only) for any size quadropod suction caisson foundation (100% as sands or gravels)

Sediment Type	Water depth (m)	Settling rate (m/s)	Duration of settlement (s)	Distance plume advected by peak current (m)	Maximum mass in suspension (kg)	Area of seabed deposition (m^2)	Average thickness of seabed deposition (m)
100% Sand	14	0.05	280	140	1,749,000	2,870	0.38
	25		500	250	1,749,000	8,978	0.12
	36		720	360	1,749,000	18,477	0.06
	47		940	470	1,749,000	31,366	0.04
100% Gravel	14	0.5	28	14	1,749,000	99	11.08
	25		50	25	1,749,000	299	3.68
	36		72	36	1,749,000	606	1.81
	47		94	47	1,749,000	1,020	1.08
Sediment Type	**Water depth (m)**	**Diameter of midwater SSC influence (m)**	**Area of midwater SSC influence (m^2)**	**Midwater average SSC (mg/l)***	**Diameter of near-bed SSC influence (m)**	**Area of near-bed SSC influence (m^2)**	**Near-bed average SSC (mg/l)***
100% Sand	14	8	54	Mn	12	105	Mn
	25	14	165	HnTh	20	322	HnTh
	36	21	334	HnTh	29	659	TnTh
	47	27	563	TnTh	38	1,113	TnTh
100% Gravel	14	3	7	Mn	4	13	Mn
	25	5	19	Mn	7	36	Mn
	36	7	37	Mn	9	71	HnTh
	47	9	61	HnTh	12	118	HnTh

* U- units(single digit); TnTh – tens of thousands; HnTh – hundreds of thousands; Mn – low millions.

Estimates of the area and average thickness of sediment deposition are provided in the preceding tables based on the approximate footprint of the plume and tidal advection factors. The extent, thickness and shape of sediment deposits on the seabed will be highly variable in practice. However, given the total volume of sediment, a range of potential alternative combinations can be calculated. A range of alternative possible value combinations are provided in Table 16 for dredging overspill and in Table 17 for the active and passive phases of the dredge spoil disposal plume. For more details about the basis of these tables, see the previous assessment for drilling (Section 3.3.2).

Table 16. Alternative potential extents and thicknesses of sediment deposition as a result of over-spill during dredging

Foundation Type / Operation	Deposition Scenario	Nominal Diameter of Influence (m) as a Result of Dredging Overspill for One Foundation (and the area of influence of all foundations as a proportion of the Thanet Extension array area, 72.8 km^2)	Thickness of Deposit (m)[a]
Dredging overspill for 28 larger (12 MW) quadropod suction caisson foundations, 1 x OSS and 1 x met mast (237 m^3 overspill per foundation).	Uniform thickness	25 (0.02%)	0.5
		35 (0.04%)	0.25
		78 (0.20%)	0.05

[a] Average uniform thickness. All value pairs are part of a continuous scale of possible outcomes.

Table 17. Alternative potential extents and thicknesses of sediment deposition as a result of dredging spoil disposal (active and passive phases)

Foundation Type / Operation	Deposition Scenario	Nominal Diameter of Influence (m) as a Result of One Spoil Disposal Event (and the area of influence of all events as a proportion of the Thanet Extension array area, 72.8 km^2)	Thickness of Deposit (m)*
Spoil disposal from the dredger, 26.5 events for all foundations (9,900 m^3 in active phase, 90% of 11,000 m^3).	Cone	49 (0.07% - steepest) 99 (0.28%) 148 (0.63%)	15.5 3.9 1.7
	Uniform thickness	159 (0.72%) 225 (1.44%) 502 (7.20%)	0.5 0.25 0.05
Spoil disposal from the dredger, 26.5 events for all foundations (1,100 m^3 in passive phase, 10% of 11,000 m^3).	Uniform thickness	53 (0.08%) 75 (0.16%) 167 (0.80%)	0.5 0.25 0.05

* Height of peak for cones and average uniform thickness. The dimensions of the steepest cone are provided here to indicate the smallest possible area that could be impacted. It is not realistically expected that cone deposits of greater thicknesses (e.g. >5 to 10 m) will be allowed to accumulate in practice. All value pairs are part of a continuous scale of possible outcomes.

In summary, the influence of dredging overspill and spoil disposal on increasing SSC above ambient levels is characterised as follows:

- SSC levels will be highest (potentially tens to hundreds of thousands of mg/l) at the point of sediment release, which is at or near the water surface during dredging overspill and distributed through the whole water column during dredge spoil disposal. This feature will only be present during (the relatively longer) periods of active dredging or during (the relatively short) dredge spoil disposal events;

- For fine material in dredging overspill, SSC levels will decrease rapidly through vertical and horizontal dispersion to low tens of mg/l within the order of hundreds of metres from the point of release;

- For fine material released into the passive plume phase during dredge spoil disposal, SSC levels will be initially higher than for overspill (due to the sudden nature of the sediment release). SSC levels will decrease through horizontal dispersion to a few thousand mg/l within the order of low hundreds of metres and a few tens of mg/l within the order of one thousand metres distance from the source;

- For sand and gravel material in dredging overspill, local SSC levels will decrease to low thousands or hundreds of mg/l locally (low tens of mg/l in a depth mean sense) through horizontal dispersion whilst settling to the seabed;

- For sand and gravel material released into the passive plume phase during dredge spoil disposal, local SSC levels will decrease from hundreds to tens of thousands of mg/l due to horizontal dispersion whilst settling to the seabed;

- Sands will deposit to the seabed within the order of hundreds of metres from the source (taking in the order of 5 to 15 minutes to settle from surface to seabed), and gravels likewise within tens of metres (0.5 to 1.5 minutes). The horizontal diameter of the main sand or gravel plume footprint within the water column and on the seabed is likely to be in the order of only tens of metres;

- Following cessation of dredging or spoil release, the influence of sands or gravels on SSC levels will reduce rapidly as described above and will end when the sediment is redeposited to the seabed (in the order of 0.5 to 15 minutes, depending on the grain size and water depth); and

- Once redeposited to the seabed, the locally dredged overspill and spoil material are essentially the same as the local sediment type. The dredged material will therefore immediately re-join the natural sedimentary environment and will not contribute further to elevated SSC above naturally occurring levels.

In summary, sediment deposition as a result of dredging for foundation installation is characterised as follows:

- Deposits of mainly gravel sized dredge overspill will be concentrated within a relatively small area in the order of tens of metres from the site of dredging, with an average thickness in the order of less than ten centimetres;

- Deposits of mainly sand sized dredge overspill sediment will be concentrated within an area in the order of 150 to 500 m downstream/upstream and approximately tens of metres to one hundred metres wide from individual foundations, with an average thickness in the order of less than a few centimetres;

- Spoil disposal will form more concentrated sediment deposits on the seabed. The main mass of sediment (90% of the total volume, falling as the active phase of the plume) will initially result in discrete mounds of sediment in the order of tens to hundreds of metres in diameter (depending on the pattern of settlement) and tens of centimetres to a few metres in local thickness. An area equivalent to a circle of 502 m in diameter might be covered to an average depth of 0.05 m. Any larger area of change would correspond to a smaller average thickness. It is possible that consecutive disposal events may overlap on the seabed, resulting in a greater local thickness of sediment but a smaller overall area of influence;

- The smaller mass of material (10% of the total volume) falling as the passive phase of the spoil disposal plume will result in a narrow deposit downstream either hundreds of metres in length and a few centimetres or less thick (for sands), or, tens of metres in length and up to tens of centimetres to a few metres thick (for gravels);

- Fine grained material released as overspill or as the passive phase of spoil disposal will be dispersed widely within the surrounding region and will not settle locally with measurable thickness. Fine grained material in the active phase of spoil disposal will remain bound in the main sediment mass and will not be differently dispersed to that described above;

- The assessments undertaken and the summaries above describe the influence of conservatively marginal scenarios where the material being dredged or disposed is entirely fines, sands or gravels. Based on these marginal cases, the following summary describes the overall influence of the same activities assuming that a mixture of sediment grain sizes is present;

- SSC of low tens of mg/l will be present in a narrow plume (tens to a few hundreds of metres wide, up to one tidal excursion in length (up to ~13 km on spring tides and 7 km on neap tides) aligned to the tidal stream downstream from the source;
- If dredging occurs over more than one flood or ebb tidal period, the plume feature may be present in both downstream and upstream directions;
- Outside of the area up to one tidal excursion upstream and downstream of the foundation location, SSC less than 10 mg/l may occur more widely due to ongoing dispersion and dilution of material;
- The majority of gravel and sand sized sediment will be deposited to the seabed within tens to hundreds of metres from the source, respectively. A larger proportion of such material in the plume may result in SSC reducing more rapidly in this region and reducing the length or extent of the plume feature overall; and
- Sufficiently fine sediment may persist in suspension for hours to days or longer, but will become diluted to very low concentrations (indistinguishable from natural background levels and variability) within timescales of around one day.

If dredging, or any other activity causing sediment disturbance, is undertaken simultaneously at two or more locations that are aligned in relation to the ambient tidal streams, then there is potential for overlap between the areas of effect on SSC and sediment deposition. The potential for in-combination effects on SSC has previously been discussed in Section 3.3.2.

3.3.4 Sandwave clearance

Summary

Within certain sections of the array area and export cable corridor, relatively large mobile bedforms are present and these may be associated with a considerable thickness (up to 8 m) of coarse grained (primarily sandy) sediment. To ensure effective burial below the level of the stable bed, it may (in places) be necessary to first remove sections of sandwaves using jetting techniques, before trenching into the underlying bed. In addition to short term elevations in SSC and associated sediment deposition, sandwave clearance will necessarily result in localised changes to the sandwave and seabed topography. This section therefore also gives consideration to the potential for sandwave and seabed recovery and for longer term changes to sediment transport.

Evidence base

A discussion of available evidence regarding the impacts of dredging is provided within Section 3.3.3. Sandwave clearance has previously been undertaken along the Race Bank export cable corridor, using TSHD. An assessment of potential changes associated with these activities has previously been undertaken, using desk based analysis techniques (DONG Energy, 2016). Key findings are summarised below:

- Dredging activities for sandwave clearance will result in sediment plumes (due to overspill and spoil disposal), causing increases in SSC above background levels and deposition of sediment onto the seabed. The magnitude, extent and duration of any particular type of influence (assessed using spreadsheet based numerical models) will be variable depending on the operational characteristics of the dredger being used, and the local water depth, sediment type and representative current speed;

- As would also logically be expected, for a given rate of dredging, a greater current speed and/or water depth typically leads to a greater extent, but progressively lower magnitude of influence on SSC due to dispersion. Coarser sediment will tend to settle to the seabed more rapidly than finer sediment, leading to a smaller extent and duration but greater magnitude of influence on SSC, and a smaller extent but greater thickness of sediment deposition. Fine sediments that take longer than a few tides to settle out of suspension will be dispersed to very low concentrations and are therefore unlikely to settle in measurable thicknesses;
- Bedform recovery will likely occur in relation to the migration and sediment transport processes across the system. Estimated recovery rates for sandwaves were in the order of several years, based on representative forcing conditions at a single water depth; and
- The proposed bed levelling is not likely to pose any barrier to ongoing sediment transport within or to locations beyond the sandbank system.

Assessment of change

The volume of material to be cleared from individual sandwaves will vary according to the local dimensions of the sandwave (height, length and shape) and the level to which the sandwave must be reduced (also accounting for stable sediment slope angles and the capabilities and requirements of the cable burial tool being used). Based on the available geophysical data, it is anticipated that the bedforms requiring clearance are likely to be in the range 1 to 8 m in height. Presently available details of the maximum adverse scenario for sediment disturbance by sandwave clearance for cable installation are set out in Table 18.

Table 18. Maximum adverse scenario for sediment release by sandwave clearance for cable installation

Parameter	Maximum Adverse Scenario	Working and Other Assumptions
Clearance method	Dredging	-
Volume of sediment in sandwaves to be cleared	1,440,000 m^3	-
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).
Pre-sweeping width of dredging corridor [m]	20 m	-
Volume of sediment disturbed per metre of sand wave clearance	60 m^3	Assumption based on preliminary appraisal of available geophysical evidence. See Volume 2, Chapter 1: Project Description - Offshore (Document Ref: 6.2.1) for further details.

Changes in SSC associated with sandwave clearance by dredging will be the same as described in section 3.3.3 for quadropod suction caisson foundation bed preparation. The sediments in the sandwave feature will be predominantly sand, although potentially with some small proportion of fines (<5 to 10%). Individual sandwaves typically require less than one dredging cycle per sandwave (dredge volumes *circa* a few hundred to few thousand m^3) but between one and two dredging cycles per sandwave in the case of a few larger sandwaves (order of several thousand m^3). Dredge spoil will be returned to the seabed in the vicinity of the dredged area and so may be less than one full hopper in volume per release. In this case, the volume of sediment entering into suspension from the disposal plume (and so the resulting SSC level), and the volume of sediment deposited to the seabed (and so the resulting extent and thickness of any deposits) is expected to be proportionally smaller.

Recovery of sandwave features

The rate of recovery will vary in relation to the rate of sediment transport processes, faster infill and recovery rates will be associated with higher local flow speeds and more frequent wave influence. The shape of the bedform following recovery might recover to its original condition (e.g. rebuilding a single crest feature, although likely displaced in the direction of natural migration) or it might change (e.g. a single crest feature might bifurcate or merge with another nearby bedform). All such possible outcomes are consistent with the natural processes and bedform configurations that are already present in the study area and would not adversely affect the onward form and function of the individual bedform features.

The levelled areas are not considered likely to create a barrier to sediment movement. Evidence drawn from aggregate dredging activities indicate that if any changes occur to the flow conditions or wave regime, these are localised in close proximity to the dredge pocket. However, the aggregate dredge pockets concerned had widths and lengths of several kilometres. The proposed works will be at a much smaller scale and footprint, with trench widths expected to be in the order of a few tens of metres. This means there is likely to be little to no influence on the flow or wave regime, which in turn means no change to the regional scale sediment transport processes across the array area and export cable corridor.

The proposed jetting activities only locally displace the disturbed sediment volume, which will remain the same sediment type as the surrounding seabed. No sediment volume will be removed from the sedimentary system.

3.3.5 Cable burial

Summary

The impact of cable burial operations mainly relates to a localised and temporary re-suspension and subsequent settling of sediments (BERR, 2008). The exact nature of this disturbance will be determined by the soil conditions within the Thanet Extension array area and offshore cable corridor, the length of installed cable, the burial depth and burial method. These changes are quantitatively characterised in this section for export, array and substation interconnector cables using spreadsheet based numerical models.

Evidence base

The evidence base with respect to 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). 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 9 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 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 (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 at the Burbo offshore wind farm in Liverpool Bay, 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 regulatory authorities 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).*

Assessment of change

Export and array cables may be installed by burial into the seabed. The Thanet Extension export cable corridor runs from the southwestern margin of the array area to a landfall position in Pegwell Bay.

For Thanet Extension, the maximum adverse scenario for sediment release caused by cable burial is characterised in Table 19. The potential effects of sediment release due to cable burial are typically localised to the cable route or the active cable burial location. As such, the maximum adverse scenario information mainly considers local trench dimensions and rates of sediment disturbance. The total volume of sediment disturbance is not relevant to the assessment and so is not presented here.

Table 19. Maximum adverse scenario for sediment release by cable installation

Parameter	Maximum Adverse Scenario	Working and Other Assumptions
Number of export cables	4	-
Minimum spacing between pairs of export cables	120 m	-
Length of individual export cables	30 km	-
Total length of all export cables	120 km	30 km x 4 cables
Maximum rate of cable burial	450 m/hr	Same for all cable types.
Total length of all inter-array cables	64 km	The total length of inter-array cables will be installed as multiple shorter lengths (number, length and routes to be determined as part of the cable burial design plan)
Methods of cable burial	Jetting	Jetting 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 (Volume 2, Chapter 1: Project Description - Offshore (Document Ref: 6.2.1)) are expected to re-suspend a smaller amount of material into the water column. Due to spatial

Parameter	Maximum Adverse Scenario	Working and Other Assumptions
		variation in the geotechnical properties of the underlying geology within this region, it is possible that a combination of techniques may be used.
Dimensions of cable trench using jetting	Up to 10 m wide and 3 m deep with a 'V' 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* 3 m. Assume up to 50% of material is actually ejected from the trench. The rest is retained as sediment cover within the trench.
Volume of sediment disturbed per metre progress using vertical injection	7.5 m^3	10 m x 3 m x 0.5 x 50% (0.5 to account for 'V' shape of trench) Assumes up to 50% of material is actually ejected from the trench. The rest is retained as sediment cover within the trench.

The jetting process 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). For the purposes of this investigation, it is conservatively assumed that 50% 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 3.3.1. 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 offshore cable corridor is heterogeneous. In most locations, the majority of disturbed material will be sand and gravels. However, muddy sands are also present whilst disturbance of the underlying sub-soils (e.g. chalk and sediments belonging to the Thanet and Southern Bight Formations) may also include some proportion of fine grained (i.e. <63 µm) sediments, depending on 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 maximum adverse scenario 'end-member' scenarios. These are:

- Jetting through 100% (coarse) gravel (15,000 µm);
- Jetting through 100% (medium) sand (375 µm); and
- Jetting through 100% (fine) silt (10 µm).

These three scenarios represent the full potential range of change both in terms of the duration, spatial extent of changes to SSC, and maximum thicknesses of sediment deposition. In practice, a release comprising entirely fines 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 which, given the density of the sub seabed sediment units along parts of the export cable corridor, are more realistically expected to be used in these areas (DNV, 2014) (Figure 4). Also, even when fully disaggregated, the Thanet and Southern Bight Formations do not comprise 100% fine grained material. Ploughing will result in a much lower rate of sediment re-suspension, hence this method has not been explicitly assessed.

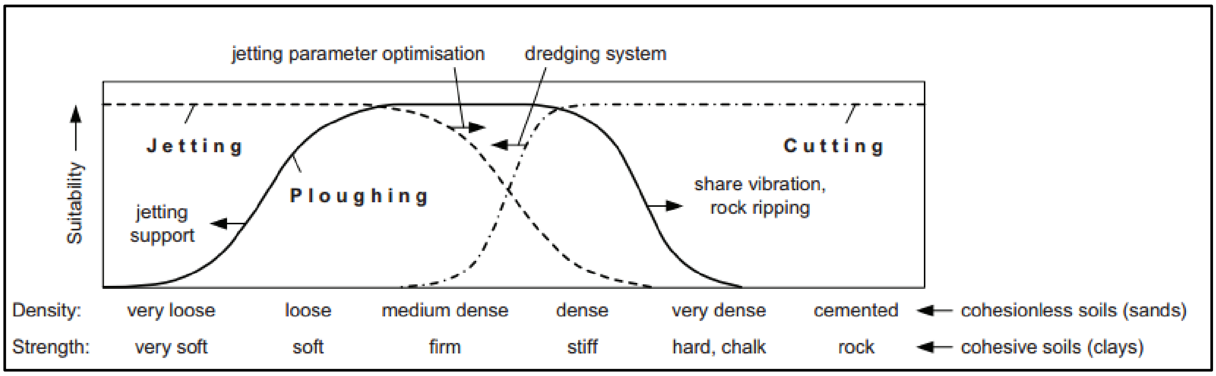


Figure 4. Indicative burial tool suitability in different ground conditions (DNV, 2014)

Results from the assessment scenarios outlined above are presented in Table 20 (for the gravel release scenario) and Table 21 (for the sand release scenario).

Table 20. 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)
0.25	1	2	0.5	0.5	2.0	Mn	15.00
0.5	1	2	1.0	1.0	2.0	Mn	7.50
1	1	2	2.0	2.0	2.0	Mn	3.75
1.25	1	2	2.5	2.5	2.0	Mn	3.00
0.25	5	10	2.5	2.0	8.0	HnTh	3.00
0.5	5	10	5.0	4.0	8.0	HnTh	1.50
1	5	10	10.0	8.0	8.0	HnTh	0.75
1.25	5	10	12.5	10.0	8.0	HnTh	0.60
0.25	10	20	5.0	2.0	8.0	HnTh	1.50
0.5	10	20	10.0	4.0	8.0	HnTh	0.75
1	10	20	20.0	8.0	8.0	HnTh	0.38
1.25	10	20	25.0	10.0	8.0	HnTh	0.30

* U- units(single digit); 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.

Results are presented for a range of representative current speeds, noting that cable burial will continue through all states of the tide, including current speeds 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 moves relatively quickly (up to 450 m/hr), any influence of the plume experienced downstream will be similarly limited in duration to approximately 8 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.

Following the same principles, changes associated with cable burial into 100% fine grained sediment will be similar to that described for sand in Table 21 for the predicated actual plume length in a downstream direction (2 to 8 m), the duration of change to SSC locally (8 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) but the plume will be subject to significant dispersion in that time, reducing any change to SSC to tens of mg/l or less in the same timeframe. As a result of dispersion, no measurable thickness of accumulation of fine sediment is expected.

Table 21. Suspended sediment concentration and thickness of sediment deposition as a result of cable burial in 100% sand (settling rate 0.05 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)
0.25	1	20	5.0	2.0	8.0	Mn	1.50
0.5	1	20	10.0	4.0	8.0	Mn	0.75
1	1	20	20.0	8.0	8.0	Mn	0.38
1.25	1	20	25.0	10.0	8.0	Mn	0.30
0.25	5	100	25.0	2.0	8.0	HnTh	0.30
0.5	5	100	50.0	4.0	8.0	HnTh	0.15
1	5	100	100.0	8.0	8.0	HnTh	0.08
1.25	5	100	125.0	10.0	8.0	HnTh	0.06
0.25	10	200	50.0	2.0	8.0	HnTh	0.15
0.5	10	200	100.0	4.0	8.0	HnTh	0.08
1	10	200	200.0	8.0	8.0	HnTh	0.04
1.25	10	200	250.0	10.0	8.0	HnTh	0.03

* U- units(single digit); 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.

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

- Medium to coarse sand and gravels 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 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 sands;

- Finer material 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, 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; and

- Irrespective of sediment type, the volumes of sediment being displaced and deposited locally are relatively limited (up to 7.5 m^3 per metre of cable burial) which also limits the combinations of sediment deposition thickness and extent that might realistically occur. Fundamentally, the maximum distance from each metre of cable trench over which 7.5 m^3 of sediment can be spread to an average thickness of (for example) 0.05 m is 150 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.

If cable burial, or any other activity causing sediment disturbance, is undertaken simultaneously at two or more locations that are aligned in relation to the ambient tidal streams, then there is potential for overlap between the areas of effect on SSC and sediment deposition. The potential for in-combination effects on SSC and sediment deposition are discussed in Section 3.3.2.

3.4 Cumulative changes

A Cumulative Effects Assessment (CEA) has been undertaken to consider the impact associated with Thanet Extension together with other projects and plans. Each project on the CEA long list (see Volume 1, Annex 3-1: CEA Annex (Document Ref: 6.1.3.1)) has been considered on a case by case basis for scoping in or out of the marine processes chapter, based upon data confidence, effect-receptor pathways and the spatial/temporal scales involved.

In terms of the potential for cumulative changes to SSC, bed Levels and sediment type, the screening approach described above was informed using modelled spring tidal excursion ellipses. This is because meaningful sediment plume interaction generally only has the potential to occur if the activities generating the sediment plumes are located within one spring tidal excursion ellipse from one another and occur at the same time.

Given the length and orientation of tidal excursion ellipses in the vicinity of Thanet Extension, it is the case that the potential for sediment plume interaction would be limited to instances in which Thanet Extension construction activities occur simultaneously with:

- Dredge disposal activities; and
- Aggregation extraction operations

The potential for cumulative change is discussed in this section.

It is noted here that the existing TOWF export cables have developed faults necessitating the installation of replacement cables in due course. However, there is presently insufficient information regarding the nature and timing of the works to undertake an assessment of potential changes.

3.4.1 Thanet Extension and dredge disposal activities

The Thanet Extension export cable corridor is approximately 120 m from the Pegwell Bay (TH140) disposal site and overlaps with the Nemo Link Interconnector (TH152) disposal site. Should export cable installation be occurring at the same time as dredge disposal activities at these sites, there could be the potential for cumulative changes in SSC and bed levels.

The disposal site TH140 is situated 1.8 km offshore, southeast of the entrance to Ramsgate Harbour. The site is considered suitable only for the disposal of dispersive maintenance dredging material and is largely used for the disposal of sandy muds dredged from Ramsgate Harbour (Cefas, 2001). Between 1986 to 2012, average disposal of (maintenance) dredged material of *circa* 80,000 (wet) tonnes/year (Cefas, 2014).

Disposal site TH152 is only to be used for the dredge arisings from sandbanks excavated during installation of the Nemo Link Interconnector.

The interaction between sediment plumes generated by Thanet Extension export cable installation activities and those from nearby dredge disposal operations could occur in two ways:

- Where plumes generated from the two different activities meet and coalesce to form one larger plume; or

- Where a vessel or barge is disposing of material within the plume generated by Thanet Extension construction activities (or *vice versa*).

Given the very close proximity of the two activities, it is considered that both types of plume interaction could occur. However, it is noted that in line with UNCLOS, (The United Nations Convention on the Law of the Sea), cable installation vessels typically request a 1 nautical mile (*circa* 1.85 km) vessel safety zone when installing or handling cables. Accordingly, whilst plume interaction may still occur, the potential for much higher concentration and more persistent plumes than that previously described in the project-alone assessments of SSC (Section 1.1) is considered to be small.

Cumulative increases in bed level could also occur. However, it is noted that this location has been chosen for the disposal of dispersive dredged material and therefore disposed material is expected to be regularly re-worked. It is anticipated that in the long-term material will be transported away from the area in a north-easterly direction (Cefas, 2001).

3.4.2 Thanet Extension and aggregate dredging activities

The Thanet Extension export cable corridor is within a distance of one spring tidal excursion ellipse from the Goodwin Sands aggregate option area. Accordingly, it is necessary to consider the potential for cumulative changes in SSC and bed levels.

Dover Harbour Board is proposing to dredge up to 2.5 million m^3 of aggregate (generally comprising fine to coarse sand) from South Goodwin Sands, located approximately 10 km to the south of the Thanet Extension export cable corridor. Dredging will be undertaken using one or two TSHDs. The proposed dredge area covers an area of 3.9 km^2 and dredging would be carried out over an approximate 2-year period, between 2017 and 2019 (DHB, 2016).

On the basis of the spreadsheet based modelling considering potential changes in SSC associated with export cable installation (Section 3.3.5), it is found that any fine grained sediment plume will be subject to rapid dispersion, 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. Similarly, on the basis of the numerical plume modelling undertaken for the Goodwin Sands Aggregate Dredging Environmental Statement, it is found that peak increases of suspended fine sand in excess of 10 mg/l are restricted to within a distance of approximately 1.5 to 2 km to the north of the proposed dredge area (DHB, 2016).

Given the above information and that the two sediment disturbance activities are located approximately 10 km apart, any cumulative increase in either the spatial footprint or peak concentration of sediment plumes will be indistinguishable from background levels. Any associated changes in bed level will also not be measurable in practice.

4 Assessment of Turbid Wakes Associated with Foundation Structures

4.1 Overview

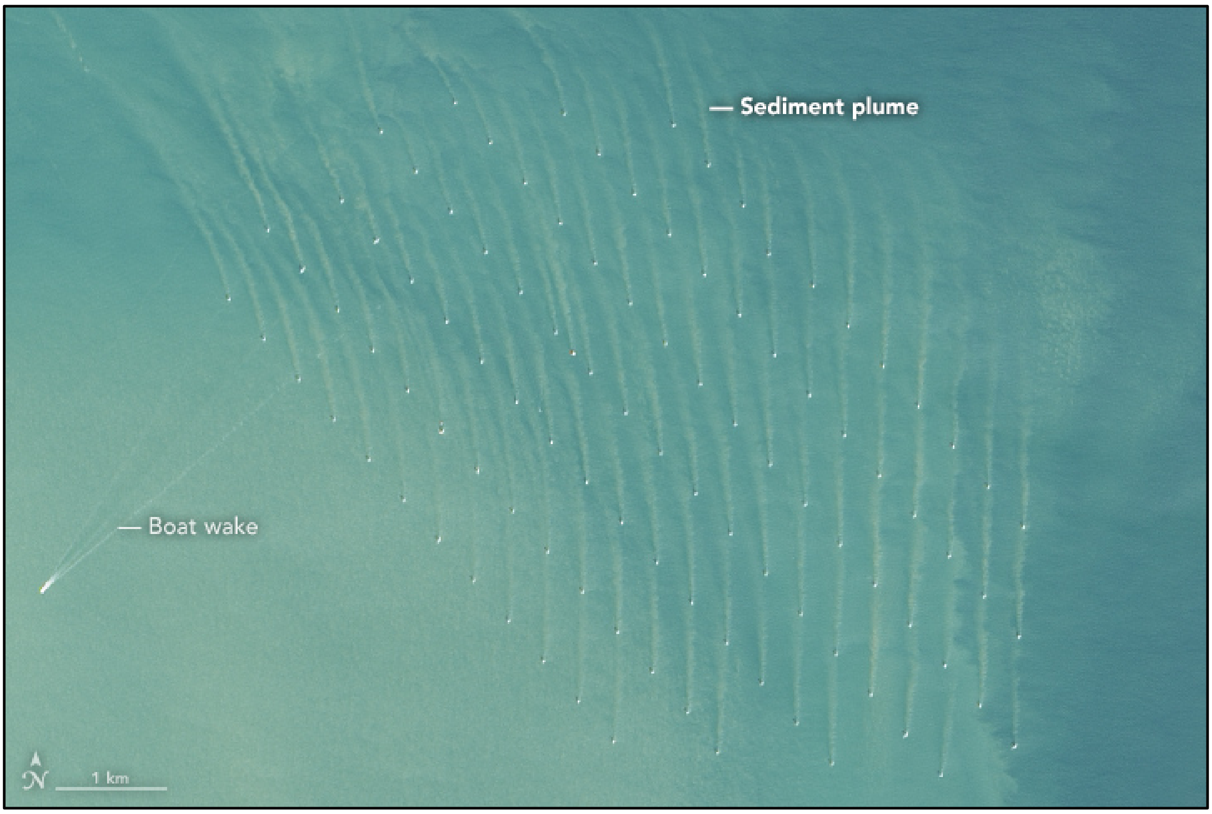
Turbidity is a measure of the degree to which the water loses its transparency due to the presence of sediment and other organic material in suspension. Suspended sediment concentration (SSC) refers specifically to the inorganic (mineral) fraction of suspended solids whilst SPM includes contributions from both inorganic and organic matter.

The natural flow of water through the site due to tidal currents will interact with the foundations of the wind farm infrastructure, resulting in an area of water downstream of the foundation termed 'the wake' (see Section 6.4.1). The wake is characterised by both a reduced time-mean current speed and elevated local turbulence intensity. Differences are greatest very close to the foundation (within a few foundation diameters distance) but will recover rapidly to ambient conditions with distance downstream.

Turbid wakes (wakes additionally characterised by an elevated level of turbidity relative to water immediately outside of the feature) have been observed at the Thanet, London Array and Greater Gabbard OWFs in the outer Thames estuary in aerial (e.g. Vattenfall, 2017) (Figure 5) and satellite imagery (e.g. Vanhellemont and Ruddick, 2014; NASA, 2016a) (Figure 6), as well as directly via field measurements (Forster, 2017). Similar features have also been noted for other OWFs in the waters of Germany, The Netherlands and Belgium, suggesting that this is a general phenomenon associated with the placement of these structures in the sea (Forster, 2017).

Source: Vattenfall, 2017

Figure 5. Aerial image of turbid wakes in TOWF



Source: NASA, 2016a

Figure 6. Landsat 8 satellite imagery of TOWF, acquired 30/06/2015

This section assesses the potential for turbid wakes to develop in association with the operational presence of the Thanet Extension array and characterises their likely:

- Cause;
- Spatial extent (horizontal and vertical);
- Magnitude of changes in SSC (relative to naturally present background levels and ranges);
- Duration, frequency and/or persistence; and
- Effect on seabed sediment texture.

The presence of turbid wake features could theoretically impact a range of environmental characteristics and receptors, including (for example):

- Sediment re-deposition, affecting seabed sediment texture;
- SSC, affecting sensitive benthic and/or pelagic species;
- Water column visibility, affecting light penetration and foraging behaviour;
- General effects on water quality and/or rates of primary production, etc.

Significance of effect assessments associated with the presence of the turbid wake features characterised in this section are carried out and presented in the following PEIR topic chapters:

- Volume 2, Chapter 3: Marine Water and Sediment Quality (Document Ref: 6.2.3);
- Volume 2, Chapter 4: Marine Ornithology (Document Ref: 6.2.4);
- Volume 2, Chapter 5: Benthic Ecology (Document Ref: 6.2.5);
- Volume 2, Chapter 6: Fish and Shellfish (Document Ref: 6.2.6); and
- Volume 2, Chapter 7: Marine Mammals (Document Ref: 6.2.7).

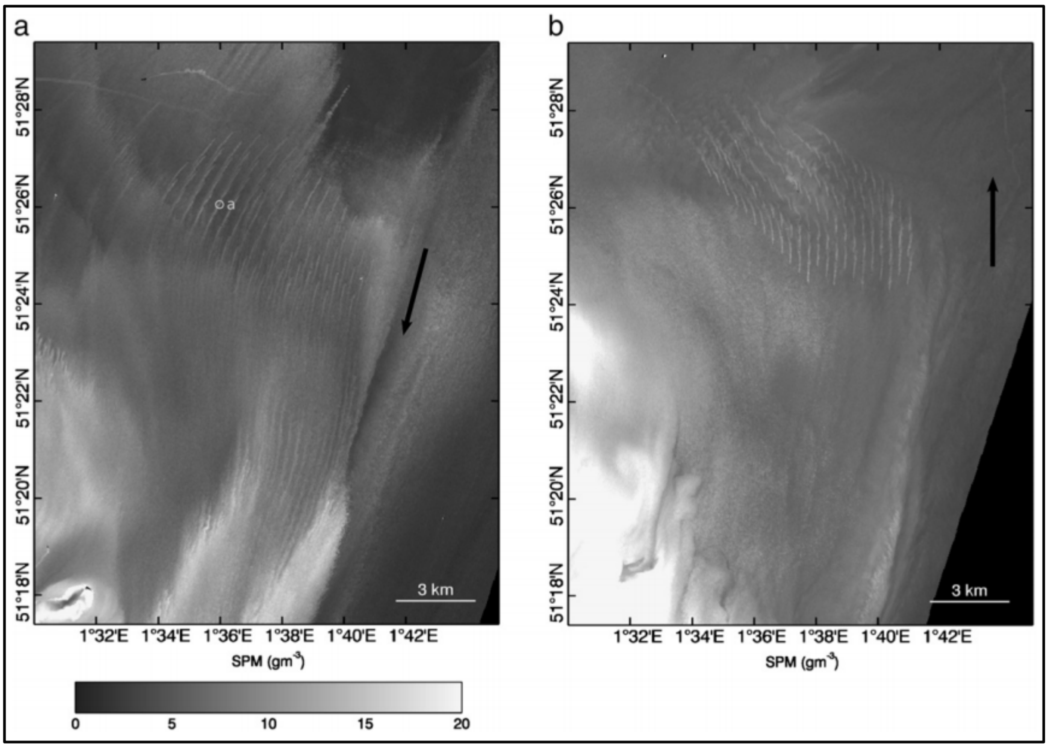
4.2 Baseline conditions

A summary of the baseline characteristics within and nearby to the Thanet Extension array area is provided below, based on existing publicly available information.

- Both the Thanet Extension and the existing operational TOWF are located in an area already characterised by naturally high levels of turbidity, primarily in response to the input of fine grained sediments from fluvial sources, erosion of soft cliff coasts and the frequent re-suspension of mobile material from shallow seabed settings (Cefas, 2016);
- Seabed sediments within and nearby to the Thanet Extension array area are typically characterised by the presence of fine to coarse sands, with smaller areas of muddy sand and sandy gravel (Fugro, 2016a; Thanet Offshore Wind Limited, 2005); and
- The seabed sediments present within and nearby to the Thanet Extension array area will be regularly mobilised by normal tidal currents, which exceed 1 m/s during mean spring tides.

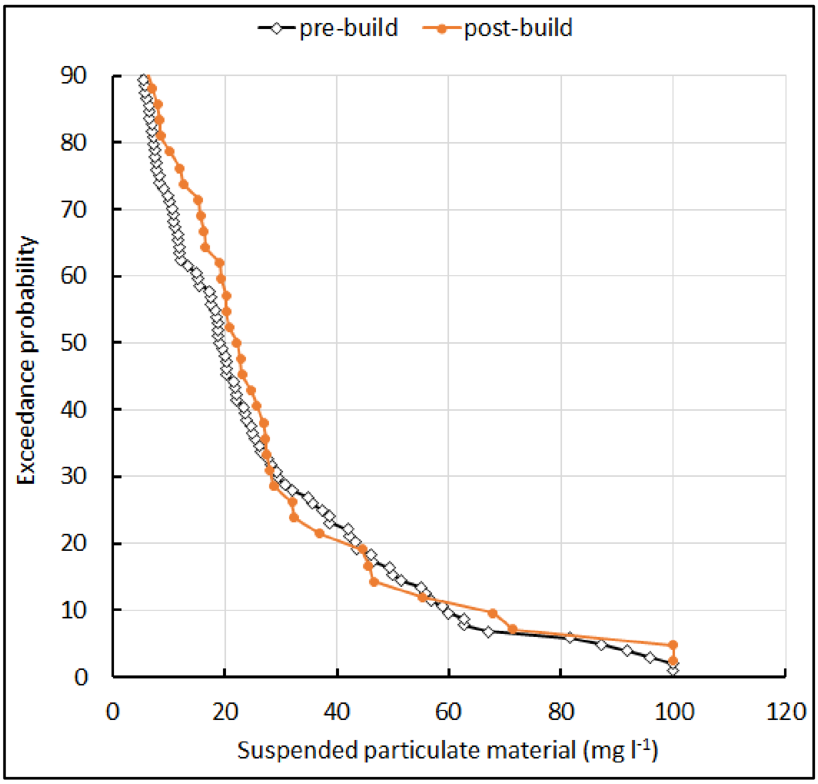
4.3 Evidence base

As noted in Section 4.1, there is now a wide range of evidence regarding turbid wakes at operational wind farm sites. The evidence includes remote sensing data (e.g. Vanhellemont and Ruddick, 2014; NASA, 2016a) and local field studies (Forster, 2017). Analysis of satellite observed (sea surface) SPM concentrations potentially suggests that these features have resulted in a net increase in average surface SPM within and nearby to the TOWF array area, with a notable increase in the frequency with which SPM in the range 10 to 20 mg/l is encountered (Figure 7 and Figure 8). Annual mean SPM has risen from 26.7 to 30.1 mg/l, whilst the 50% exceedance has increased from 19.2 to 22.2 mg/l. It should be noted, however, that inter- and intra-annual variability in SPM is high.



Source: Vanhellemont and Ruddick, 2014

Figure 7. Satellite image of TOWF on (a) 28/04/2013 (10:54 UTC) and (b) 03/09/2013 (10:54 UTC)



From: Forster, 2017

Figure 8. Exceedance curves for satellite-derived surface suspended particulate material within the zone of the TOWF. Curves were produced from monthly-mean SPM data for the periods before and after construction at the site

The particular turbid wake features observed at the TOWF have been described in detail by Vanhellemont and Ruddick (2014) and Forster (2017), with key spatial characteristics summarised below:

- The features are reported by Vanhellemont and Ruddick (2014) as being typically 30 to 150 m wide and extending 'one or more' kilometres downstream from each turbine; in one case the plumes can be seen to extend for 'more than 10 km' at the TOWF;
- On the basis of available satellite imagery, plumes are visible throughout most of the tidal cycle with the direction and length of the plumes directly influenced by tidal state;
- At low water, the tidal flow is from north to south and plumes across the TOWF array area are strongly aligned in this direction. Clockwise rotation occurs during the rising flood tide so that by mid-flood, plumes run from northeast to southwest (Forster, 2017);
- Close to the peak of high tide there is a reversal in flow direction and plumes become aligned with the south-north current (Forster, 2017);
- A period of 'no plume' observation is observed in images acquired between 1 and 2 hours into the ebb tide (although further evidence is required to confirm this) (Forster, 2017); and
- During the peak ebb flow, plumes are aligned with the current leaving the Thames estuary from west to east (Forster, 2017).

The direct observational evidence presented in Forster (2017) from the TOWF array area included optical and acoustic profiling of the water column from surface to seabed at locations both inside and outside of individual turbid wake features. The evidence collected shows that plumes are caused by re-distribution of suspended sediment in the water column due to increased vertical mixing in the monopile wake. Not only are suspended sediment concentrations higher at the surface, but the evidence shows that the near-bed concentration of sediment is actually lower within the plume. This indicates that a re-distribution of suspended material from the near-bed to the surface is caused by the increased turbulence within the wake.

Discrete water sampling was also undertaken for laboratory analysis of optically-active components (sediment quantity and composition, plankton, dissolved organic/inorganic material). Forster (2017) found that the data supports the hypothesis that the turbid wake features are associated with suspended sediment: other optically-active constituents such as plankton (chlorophyll) or chromophoric[2] dissolved organic matter do not show significant enrichment within the plumes.

A previously considered hypothesis was that turbid wakes might be the result of ongoing local scouring of seabed sediments. This hypothesis was considered and discounted by Forster (2017), on the basis of a range of field survey evidence. Calculations of the mass/volume of sediment required to create the observed turbid wakes (see paragraph below) also show that extensive scouring would be required; however, the post-construction monitoring of scour at TOWF does not indicate that excessive scouring is happening at this location (Titan, 2012 a, b; 2013).

The SSC in the surface waters of the turbid wakes (estimated from the satellite data images) is between 10 and 30 g/m^3 (10 and 30 mg/l) (Vanhellemont and Ruddick, 2014). Using a representative water depth of 20 m for the sites, the volume of water in the wake from one foundation can be estimated as 1 million m^3 (20 m deep x 50 m wide x 1,000 m long). The total mass of sediment in suspension (assuming a representative concentration throughout the wake of 20 g/m^3) is 20,000 kg. Assuming a sediment density of 2,650 kg/m^3 and a porosity factor for seabed sediments of 0.6, this total mass equates to approximately 13 m^3 of seabed sediment. If 13 m^3 of seabed was being eroded from around each foundation every half tide (every 6 hours), this would cumulatively result in serious erosion in a short time scale (approximately 18,000 m^3 per year around each foundation). However, the scour monitoring from TOWF shows that in 2013, scour pits typically had a diameter of approximately 20 to 25 m and a depth of 3.7 to 4.4 m, equating to a total locally scoured sediment volume in the approximate range 700 to 1,300 m^3 for individual foundations. It is noted here that the estimate of 13 m^3 per foundation is conservatively small as the turbid wake features may extend considerably more than 1,000 m from each foundation (see Vanhellemont and Ruddick (2014) which describes wakes of over 10 km in length). At this time, the volume of sediment may be closer to 130 m^3 (i.e. an order of magnitude higher), making the suggestion that scour is the source of suspended sediment even less plausible.

Finally, it is noted here that another distinctive turbid wake feature is observed on Figure 9, to the north of the Thanet Extension array area, which is not associated with TOWF infrastructure or vessel movements. The feature extends a distance of several kilometres to the south-southwest and is more laterally extensive than those turbid wakes associated with monopiles in the TOWF array area. It is suggested that this feature could be associated with a wreck which is shown on UKHO Admiralty Charts to be in this location. The assertion that shipwrecks may give rise to sediment plumes detectable in satellite imagery is supported by several recent studies (e.g. Baeye *et al*., 2016; NASA, 2016b). Unfortunately, the coverage of the 2016 Thanet Extension geophysical survey does not extend this far north from the array boundary and therefore the dimensions of the wreck (in terms of its spatial footprint and elevation off the seabed) are unknown. Accordingly, its value as an analogue

2 A chemical group capable of selective light absorption resulting in coloration of certain organic compounds

for determining the anticipated characteristics of turbid wakes within the Thanet Extension array area is limited.

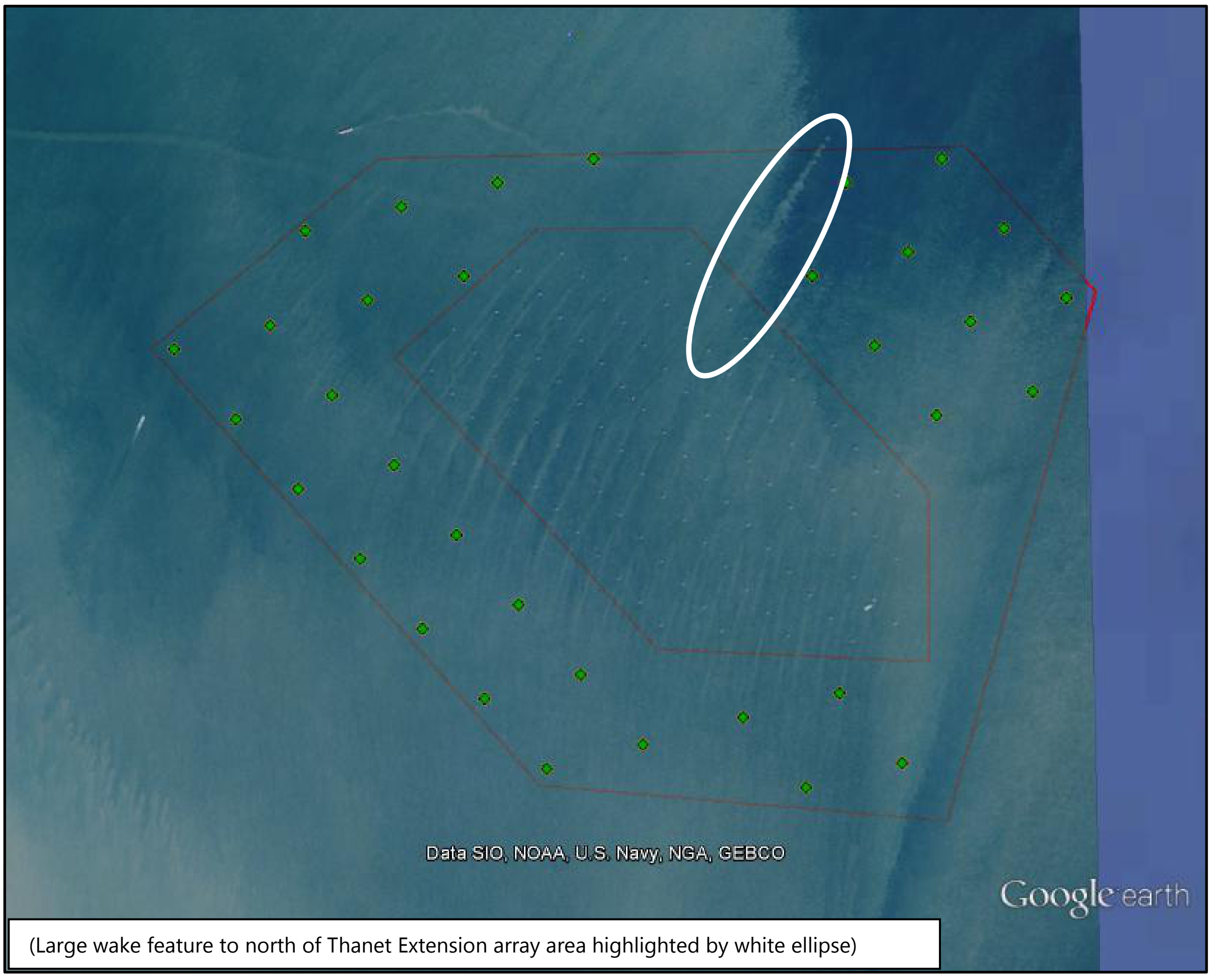


Figure 9. Operational Land Imager (OLI) satellite image of the Thanet Extension array area on 28/04/2013 (10:54 Universal Coordinated Time (UTC))

4.4 Assessment

4.4.1 Overview

It is reasonable to assume that the naturally occurring near-bed layer of relatively higher SSC that is present across the TOWF site will also be similarly present across the Thanet Extension array area. As such, turbid wake features are also similarly likely to develop in this area. Turbid wake features can be expected to develop regardless of the foundation type (monopiles or quadropods) as both will realistically result in a turbulent wake. However, the physical characteristics of the feature might be different, depending on the relative dimensions of the foundations and the resulting wake.

To enable robust assessment of the potential ecological impacts of the turbid wakes, it is necessary for key attributes of the features to be described, in particular, the likely:

- Spatial extent (horizontal and vertical);
- Magnitude of increase in SSC (relative to naturally present background levels and ranges);
- Duration, frequency and persistency; and
- Effect on seabed sediments.

These attributes are quantitatively defined in the following section.

4.4.2 Spatial extent of turbid wakes

The spatial footprint of the turbid wakes will primarily be dependent upon:

- The ambient tidal conditions;
- The characteristics of the sediment within the near bed turbid layer; and
- The dimensions/ characteristics of the foundation structures.

Accordingly, the extent of the turbid wakes will fluctuate over tidal cycles (ebb/ flood, spring/ neap) and also possibly in response to seasonal influences (e.g. input of finer grained sediment from fluvial discharge).

On the basis of the satellite imagery covering the TOWF array area, turbid wakes are typically 30 to 150 m wide, extending downstream for a distance of over 10 km during spring tides (Vanhellemont and Ruddick, 2014). The widest plumes in this range appear to be the result of two or more individual wakes intersecting and combining to produce a single wider feature. It is noted here that the largest monopiles proposed for the Thanet Extension array area are 10 m in diameter which is over twice the diameter of the largest monopile within the TOWF array area (4.9 m in diameter). Larger monopiles are likely to be associated with more extensive (both in the x and y axis) turbulent wake field (e.g. Rogan *et al.*, 2016). As a worst case scenario, the length and width of turbid wakes in the Thanet Extension array area may be larger in proportion to the difference in foundation diameter (i.e. double that of the TOWF); as a minimum, turbid wakes in the Thanet Extension array area will have at least the same dimensions as those presently observed in the TOWF. The dimensions of individual turbid wakes in the Thanet Extension array area are most likely to be larger than those presently observed in the TOWF, but less than the worst case scenario, for the following reasons.

Factors limiting turbid wake length: limited length of the enhanced turbulence effect

Levels of elevated turbulence in the wake behind monopiles are highest immediately behind the structure and recover at an exponential rate towards ambient conditions. Turbulence levels reduce from a peak of approximately 17 times the ambient value at the foundation, to 2 times the ambient value by a distance 40 D downstream (D= monopile diameters), and to 1.1 times the ambient value by 400 D downstream (Rogan *et al.*, 2016). As an indirect proxy measure, surface waves have been observed to no longer be affected by turbulence in the wake of monopile foundations by a distance approximately 80 D downstream (Li *et al.*, 2014).

Where levels of turbulence are sufficiently elevated in the wake, sediment will be actively resuspended and maintained in suspension throughout the height of the water column. However, where levels of turbulence have sufficiently decreased (which may be within the wake footprint depending on the threshold used to define elevated turbulence), sediment initially resuspended higher into the water column will start to settle back towards the bed at a rate determined by the characteristics of the sediment in suspension and in equilibrium with the levels of turbulence still present.

For coarser sediment, resettlement will start at relatively higher levels of turbulence (at a smaller distance from the foundation) and the response will be more rapid (a shorter time/distance is required from the point that sediment begins to settle out, to the point that turbidity actually decreases). For finer sediment, a lower level of turbulence is required to maintain suspension and, even when the turbulent effect ceases, the concentration of sediment in surface waters may take a longer time to reduce due to slow rates of settlement. Accordingly, the effect of doubling the foundation diameter (from approximately 5 m to 10 m) may only partially increase the extent of the area where turbulence is elevated (e.g. from approximately 400 m to 800 m for an elevation of two or more times the ambient value), while the distance for recovery through settlement would remain the same or similar.

Factors limiting turbid wake length: tidal excursion distance

As described in Section 4.3, turbid wakes are tidally aligned features that are advected by the ambient tidal currents. As such, the maximum length to which the turbid wake features could theoretically extend is also limited by the tidal excursion distance. This distance can be conservatively but generally characterised for a range of normal tidal conditions by the spring tidal excursion ellipse buffer around the Thanet Extension array area (shown in Figure 3). The maximum distance the mean spring tidal excursion buffer extends outside of the Thanet Extension array area is ~13 km (Figure 3), which is consistent with the maximum observed extent of turbid wake features from the TOWF array (over 10 km, as described by Vanhellemont and Ruddick (2014)).

Whilst the spring tidal excursion ellipse buffer estimates the maximum extent or area within which the turbid wakes may be encountered, it is not the case that the entire area of the buffer footprint will experience an increase in surface SPM concentration. Assuming that turbid wake features extend an average distance of ~13 km downstream from each of the 34 turbine foundations in the Thanet Extension array area, and are up to 150 m wide, the maximum footprint of influence would be ~66,300,000 m^2 at any given time. This equates to approximately 11% of the whole spring tidal excursion ellipse buffer area. It is more likely that individual turbid wake features will normally be shorter than the tidal excursion distance and that the footprint of at least some individual features will overlap, reducing the total footprint area.

Interaction between turbid wakes affecting their extent

The maximum observed width and length (and hence estimated maximum spatial footprint) of the turbid wakes for Thanet Extension may vary also due to interaction between individual wake features. Vanhellemont and Ruddick (2014) note that turbid wakes at TOWF may be up to 150 m wide, but this appears to relate to overlapping plumes from multiple individual foundations that are nearly aligned to the ambient tidal currents.

Given the proximity of the Thanet Extension array area to the operational TOWF site, it is very likely that, where foundations are tidally aligned, turbid wake features from the two wind farms may overlap or coalesce. The resulting combined turbid wake(s) may appear wider and/or longer than individual non-overlapping turbid wake features, but (based on the underlying processes) there is no reason why the overall extent should be wider or longer than a superimposition of the individual contributing features. This is consistent with the satellite derived images of overlapping turbid wakes at the TOWF (Vanhellemont and Ruddick, 2014).

4.4.3 Magnitude of increase in SSC within turbid wakes

As a logical conclusion of the processes likely controlling turbid wakes (described in Section 4.3) and the field evidence provided by Forster (2017), *depth averaged* SSC (i.e. the total mass of sediment in suspension throughout the water column as a whole) within the Thanet Extension array area will not change either locally or regionally as a result of turbid wakes, as no additional sediment is being eroded from the seabed as part of the process. However, the vertical distribution of sediment in suspension will be affected, becoming more uniformly distributed throughout the water column. Therefore, within the turbid wake features, *surface* SSC is expected to increase relative to the baseline distribution, with a corresponding decrease in nearbed SSC.

According to the *in situ* measurements from Forster (2017) as well as the satellite data presented in Vanhellemont and Ruddick (2014) the SSC/ SPM in the surface waters of the turbid wakes at TOWF is typically between about 10 and 30 mg/l above background levels. The relative contrast in SSC between inside and outside of the turbulent wakes is likely to vary, in response to natural variability in the naturally present magnitude and vertical distribution of SSC both nearbed and elsewhere in the water column.

Because the naturally present distribution of SSC is expected to be broadly similar between the Thanet Extension and TOWF array areas, it is reasonable to assume that the magnitude of elevated SSC in turbid wakes at Thanet Extension will be broadly similar to those observed at TOWF at any given time.

The magnitude of SSC/SPM elevation within turbid wakes in the Thanet Extension has been estimated from a limited number of observations but in practice both ambient and turbid wake SSC may vary over a wider range. The uncertainty is related to:

- Natural variability in the grainsize distribution and concentration of sediments naturally present in suspension;
- Variation in current speed (and so patterns of turbulence intensity elevation and recovery in the wake) due to tidal and non-tidal processes over a range of timescales; and
- The complex relationship between these two (sedimentary and hydrodynamic) conditions at any given time. Because the processes are directly related, any uncertainty is likely to be within the range of natural variability in nearbed SSC.

Given the proximity of the Thanet Extension array area to the operational TOWF site, it is very likely that, where foundations are tidally aligned, turbid wake features from the two wind farms may overlap or coalesce. However, based on the underlying processes there is no reason why SSC should be locally higher than that of the contributing features considered individually (i.e. a non-additive effect). This is consistent with the satellite derived images of overlapping turbid wakes at the TOWF (Vanhellemont and Ruddick, 2014).

4.4.4 Duration, frequency and persistence of turbid wakes

The development and persistence of turbid wake features will be dependent upon a range of factors including:

- The particle size distribution of material in suspension;
- The ambient flow conditions; and
- The extent to which material in suspension is mixed throughout water column, before entering the Thanet Extension array area.

In order to accurately quantify the anticipated frequency and duration of the turbid wake features, it would be necessary to have access to a relatively detailed record of satellite derived SPM maps from the TOWF, covering a range of conditions. Such interpreted satellite records are not available and therefore the worst case scenario is assumed to be that turbid wake features are always present. Areas inside of the Thanet Extension array area that are downstream of foundations on both ebb and flood tides *might* therefore be affected up to 100% of the time. Other parts of the array area and areas outside of the Thanet Extension array area that are downstream of foundations on either ebb or flood tides might only be affected by turbid wake features for up to 50% of the time due to current direction reversal.

In practice, it is unlikely that the turbid wakes will be continually present. A period of 'no plume present' is apparent in satellite images acquired between 1 and 2 hours into the ebb tide (i.e.

following tidal reversal and at relatively low current speeds) although further evidence is required to confirm this (Forster, 2017). Similarly, it is likely that during the stormier winter months, turbid wake features will be either less pronounced or absent due to naturally enhanced mixing of sediment through the water column in the ambient environment.

4.4.5 Potential for change in seabed sediments by turbid wakes

The patterns of turbulence elevation and recovery, and the associated patterns of sediment resuspension and resettlement, may result in selective transport and deposition patterns for sediment of different grain sizes. Within the turbid wake, coarser sediments are more likely to start resettlement sooner and so closer to the foundation, whilst finer grained material may persist in suspension for longer and so may only be redeposited at greater distances downstream. All of the material in suspension within the turbid wake was naturally maintained in suspension before entering the wind farm, and has the potential to continue to be transported in suspension following resettlement into the lower water column, when conditions are suitable.

The effect on relatively coarse grained (e.g. sand sized) material is likely to be limited as the additional distance (proportional to the time needed for grains to settle through the water column) is relatively small; as such, coarser sediment will be present at normal ambient concentrations near bed and will be redeposited in normal quantities when conditions are suitable (e.g. around slack water). Potential effects on fine grained material may have a greater extent due to the relatively slower settling rate; as such, the nearbed concentration of finer sediments may be relatively lower than ambient levels in parts of the wake, especially closer to the foundation, and so would be deposited in smaller quantities when conditions are suitable. This may cause net winnowing of finer material from the seabed in the footprint of turbid wakes, due to a slightly reduced rate of supply or deposition over long time periods.

Field evidence from particle size distribution analysis of 12 discrete grab samples, from within and outside of the TOWF in 2005, 2007 and 2012 (MESL, 2013) does not show any clear evidence of such fine sediment winnowing. The proportion of silt to sand both increases and decreases at different locations within the site. The number and distribution of grab samples are, however, limited and does not provide sufficient resolution for a definitive assessment of this potential effect.

Separately, the elevated turbulence in the wake causes locally increased bed shear stress which may also cause winnowing of finer material not related to the turbid wake feature or effects on sediment supply. If this effect is locally persistent due to strongly rectilinear tidal currents (e.g. at Scroby Sands OWF) this process can cause elongated scour pits to form, due to the additional net erosion potential over time.

4.5 Cumulative changes

Interaction between turbid wakes created by separate wind farms only has the potential to occur if the extent of the turbid wake features from one location overlaps with that from the other. Wind farms not aligned in relation to the ambient tidal streams, or located more than one spring tidal excursion distance from one another, are very unlikely to cause cumulative turbid wake effects. In practice, the length of the turbid wake features is observed to be typically less than the full tidal excursion distance.

The closest wind farm to Thanet Extension (other than the TOWF) is London Array, which is located approximately 11 km to the north (nominally slightly less than one full spring tidal excursion distance within the Thanet Extension array area). However, the two wind farms are not aligned in relation to the ambient tidal streams and so, therefore, there is no realistic potential for interaction of turbid wakes between these two wind farms.

5 Assessment of Change at the Landfall

5.1 Overview

The export cable will make landfall in the southwest of Pegwell Bay, just to the west of the mouth of the River Stour (Figure 1). The location is characterised by the presence of saltmarsh across the upper intertidal, with muddy/ sandy sediments present in the lower intertidal/ shallow subtidal.

The cable will be installed via trenching across the intertidal/ shallow subtidal. This could be achieved using several techniques including ploughing and jetting or HDD under the seawall adjacent to the Country Park. Cables would be buried via trenching to a depth of approximately 3 m below the seabed (which is located within the Sandwich Bay SAC) although appropriate consideration will be given to anticipated future variability in coastal morphology.

Where the cable crosses into the Pegwell Bay Country Park, it may be necessary to re-align a small section of the existing sea wall. The re-aligned sea wall would involve the use of rock armour along an approximate 155 m stretch of (north-south orientated) frontage, with the new position of the defence up to approximately 18.5 m seaward of the existing defence. The temporary use of cofferdams may also be required, depending on the preferred cable installation option.

A more detailed descriptions of the three landfall options is provided in the project design statement (Volume 2, Chapter 1: Project Description - Offshore (Document Ref: 6.2.1)

There are several source/pathways via which morphological receptors at the landfall could potentially be impacted:

- Disturbance of sediments from cabling activities, resulting in localised elevations in SSC and associated changes to bed levels (construction);
- Changes to the nearshore wave regime/ longshore sediment transport due to the presence of cable protection measures and/or any ancillary structures associated with cable installation (construction/ operation);
- Re-alignment of the sea wall (construction/ operation);
- Temporary use of cofferdams (construction);
- Excavation of HDD exit pits (construction)
- Exposure of cables leading to morphological change (operation); and
- Coastal recession/ instability, leading to exposure of cable infrastructure within the intertidal (operation).

The various impact sources set out above are considered in turn, within the following section. In this assessment, the landward limit of the 'landfall' is defined as the HAT mark whilst the seaward limit is defined by the -5 mLAT contour.

5.2 Baseline conditions

A summary of the baseline characteristics at the landfall are provided below, based on existing publicly available information.

- The south-western corner of Pegwell Bay is predominantly low-lying intertidal saltmarsh flanked by mud/sand flats (which are designated features within the Sandwich Bay SAC). A key feature is the River Stour which meanders and exits into the Bay to the north of Shell Ness;

- Shell Ness at the mouth of the River Stour on the western margin of Pegwell Bay is an important feature as it partially controls the position of the channel of the River Stour, which has historically meandered both behind the spit and also across the intertidal areas. Future evolution of the spit (including ongoing northward progradation or a significant erosion or breach event) could alter the course of the river channel across the intertidal area;

- In the vicinity of the cable landfall, an embankment of height 4.5-5.5 mODN (7.38 to 8.38 m above LAT) runs from the central Bay in a southerly direction for approximately 1 km. This protects parts of the frontage which are exposed to wave action and inundation during extreme events. No defences are present to the east of the landfall, around Shell Ness (SMP policy unit 4b21).

- The proposed landfall at Pegwell Bay lies within SMP unit 4b20: 'Ramsgate Harbour (west) to north of the River Stour' (SECG, 2010). The current strategy throughout all three management epochs (i.e. the next 100 years) is to Hold the Line (HTL), with No Active Intervention (NAI) throughout undefended sections;

- Sediments in Pegwell Bay comprise medium to silty sands overlying chalk (Rees Jones ,1998; Dussart and Rodgers, 2002; Thanet Offshore Wind Limited, 2005); and

- During winter months average SPM concentrations at the surface of the water column are relatively high (typically >30 mg/l) whilst during summer months, values are typically much less (Cefas, 2016). However, owing to the presence of fine sands and shallow water depths within the Bay, sediment will be regularly re-suspended and SSC may be in the order of hundreds to thousands of mg/l, especially during storm events.

5.3 Evidence base

Open trenching and ploughing through the intertidal zone are also commonly used techniques for cable installation in a range of intertidal environments. A wide range of different burial tools and techniques are described in BERR (2008): by design, a tool that is suitable for the intertidal material will achieve the required burial depth with a minimal footprint of disruption (to minimise the force required to cut the trench) and the majority of sediment will be retained in the trench (to maximise protection of the cable). When used above the water line, trenching techniques do not mix sediment with water and so result in minimal sediment resuspension impacts.

Open cut trenching methods were used to install the TOWF export cables at a location just to the northeast of the petrol station located at the west of Pegwell Bay on the A256. Comparison of aerial photography from before (2008) and after (2013 + 2016) installation shows that changes to the intertidal associated with cable installation were localised and predominantly of short-term duration. Morphological change is restricted to the area of the trench itself and by 2016 the location of the trench is barely discernible.

5.4 Assessment

5.4.1 Disturbance of sediments, resulting in localised elevations in SSC and changes to bed levels (construction)

Cable installation by open cut trenching is considered to represent the realistic worst case in terms of the potential to cause elevated levels of SSC and localised changes in bed level during the construction phase. A detailed cable installation plan is not yet available although it is reasonable to assume that an open cut channel may be created by either jetting, trenching by use of a tracked excavator or similar, or ploughing.

5.4.2 Changes in SSC

If cable installation is carried out in a sub-aerial setting, there will be very limited potential for the disturbed material to enter into suspension. However, where cable installation is carried out below the water line, jetting has the potential to cause the greatest volume of material to enter into suspension. Accordingly, this technique represents the maximum adverse scenario in terms of sediment dispersion.

Potential changes associated with jetting activities at the landward end of the export cable route have previously been considered in Section 3.3.5. Given the high concentration of finer grained (sands and silt) material, it is reasonable to expect that some of the disturbed material will enter into suspension.

The type of sediment most susceptible to mixing with water during ploughing is silt, because silt possesses no internal cohesion and the particles are small enough to be eroded by gentle water turbulence. Silt may remain in suspension for days giving the current chance to transport the sediment some distance away from the trench (BERR, 2008).

However, it is important to emphasize that Pegwell Bay is a naturally quite turbid environment, owing to the combined influence of the River Stour, wide spread presence of fine sediments at the bed, shallow water depths and relatively energetic tidal/ wave conditions. Furthermore, the absolute volumes of material entering into suspension will be small, especially in relation to the ambient total suspended load during spring tides/ storm conditions.

5.4.3 Changes in bed levels

Cable installation via trenching across the intertidal (landfall options 2 and 3) will result in the displacement of some sediment out of the trench. As previously stated, some of this material will be released into suspension although the majority of the displaced material is expected to remain in or immediately adjacent to the trench. It is anticipated this material would then be used as backfill once the cables had been laid, thereby minimising the risk of future erosion and promoting recovery within the intertidal zone.

The dimensions of the temporary changes in intertidal elevation adjacent to the cable trench will depend upon several factors including the cable installation method, trench width, cable burial depth and the nature of the excavated material. However, taking a 3 m burial depth as the probable maximum case, the width resulting for a ploughed trench of 30° would be 10 m. Should the subsequent spoil berms be taken into account, the whole width would be 31 m whilst the spoil berm height would be approximately 2.1 m. Importantly, trenches (and associated spoil berms) of this dimension would only be present in shallow sub-tidal/ lower inter-tidal areas. Higher up the inter-tidal, the spacing between the four trenches would narrow and the width of individual trenches would also reduce, to approximately 1 m. Accordingly, the overall amount of disturbance would be limited (4,703 m^2).

Given that the mounds would only be present for a very short period of time (period of a few weeks), any associated morphological changes resulting from local modification of the tidal and wave regime would be highly localised and of very limited extent. Accordingly, there would be no potential for long term change to intertidal morphology. This assessment is supported by the observed recovery of the intertidal in the subsequent years following installation of the TOWF export cable in Pegwell Bay.

5.4.4 Changes to the nearshore wave regime/ longshore sediment transport due to the presence of cable protection measures and/or ancillary structures (construction/ operation)

At the time of writing, it is unclear as to whether cable protection measures may be required at the landfall. In theory, the installation of cable protection measures could cause a morphological response via (for instance) modification of the local nearshore wave regime and associated patterns of sediment transport. However, it is assumed that if cable protection was installed at the landfall it would be installed with a sufficiently low profile relative to the surrounding bed to present minimal barrier to the passage of waves and so cause no change to long term patterns of sediment transport.

5.4.5 Re-alignment of the sea wall (construction/ operation)

Where the Offshore Export Cable Corridor makes landfall in Pegwell Bay, it may be necessary to re-align (extend) a small section of the sea wall, if Option 2 is selected, which is currently in place at the seaward limit of Pegwell Bay Country Park. The re-aligned sea wall would involve the use of rock armour along an approximately 155 m long stretch of (north-south orientated) frontage, with the new position of the defence up to 18.5 m seaward of the existing defence. Whilst this modification of the existing defence will result in a small loss of saltmarsh habitat (1,398.9 m^2 - which is independently assessed in Volume 2, Chapter 5: Benthic Ecology (Document Ref: 6.2.5)), the potential for wider changes in marine physical processes is considered to be very small. The reasons for this are set out below:

- The toe of the existing sea wall is located at approximately the HAT mark (*circa* 3.1 m ODN) and the toe of the new defence is located at approximately the MHWS mark (*circa* 2.6 m ODN). Accordingly, the amount of time that water levels are high enough that currents or waves will have the potential to interact directly with the new structure is and will remain very limited (estimated to be approximately 1.3% of time, based on an analysis of 18 years of hindcast tide and residual surge water levels from Pegwell for the period 1980 to 1997).

- Flows within Pegwell Bay are generally weak and this will especially be the case in an upper salt marsh setting where flows are further reduced by the presence of vegetation. Accordingly, the potential for measurable changes to flows in the vicinity of the new defence will be very limited.

- Because the toe of the defence may be slightly lower in the tidal frame than the existing sea wall, it is possible that waves may interact with the structure slightly more frequently than is currently the case. This may result in some additional turbulence from wave breaking or localised scour in the immediate vicinity of the armour units at the toe of the structure (order of a few metres extent). However, it is important to note that this could only occur infrequently for limited periods of time (only around high water during larger spring tides and when waves are present).

5.4.6 Temporary use of cofferdams (construction) (Options 2 and 3)

Prior to works commencing, a temporary cofferdam would be installed at the seaward interface of the landfall works to act as a barrier to tidal inundation and waves, and as a preventative barrier to contain any already present contaminants released from the landfill area. The cofferdam will be installed in such a way as to permit open trenching from the intertidal to the sea wall extension, allowing a dry working area below the high water mark on the saltmarsh in the area east of the Country Park. This cofferdam would extend a maximum of 25 m in a seaward direction, along up to 165 m of the frontage, and would be constructed of sheet piles.

Given the similarities in scale and location within the inter-tidal zone, the cofferdam will interact with marine physical processes in a similar manner to the re-aligned sea wall. It follows from this that the potential for modification to inter-tidal morphology will be similarly limited. In fact, any changes are expected to be even less than for the re-aligned sea wall as the cofferdam will be a temporary structure that is in place for only a few weeks.

5.4.7 Excavation of HDD exit pits (construction) (Option 1)

If HDD is used to install the export cables at the landfall, up to four HDD exit pits may be excavated on the mud/ sand flat in the inter-tidal, at least 100 m seaward of the sea wall. The dimensions of the HDD exit pits, one per cable, will be up to 20 m x 20 m, with a depth of a few metres. This corresponds to a maximum total volume of excavated material of a few thousand cubic metres for all four pits (estimated volume of *circa* 5,000 m^3, based on an average excavation depth of 3 m).

It is anticipated that, if possible, the excavated material would be stored nearby as temporary spoil mounds. Depending upon the position of the pits and mounds in the inter-tidal (and hence the water depth in which they are situated), they may have the potential to modify the nearshore wave regime and therefore seabed/ inter-tidal morphology. In particular, localised changes in water depth over the pits and mounds could in theory allow greater or differently distributed transmission of wave energy to the coast resulting in a localised morphological response.

It is noted here that the individual morphological elements within Pegwell Bay may have differing sensitivities and responses to any small-scale and localised changes to the wave regime. For instance, wave driven sediment transport is a key process at Shell Ness whereas tidal processes (including the settling of fine grained sediments) will be particularly influential in the salt marsh setting at the landfall. However, the HDD exit pits (and any associated spoil mounds) would be temporary features and it is anticipated that they would only be present for a short period (up to a few weeks) before the excavated material was used to back fill the pits. Accordingly, the potential for longer term morphological change arising from changes to the hydrodynamic and/or wave regime is considered to be very small. Moreover, if the pits were located relatively high up the inter-tidal, they would only be inundated infrequently and as such, there would be very limited potential for interaction with waves.

5.4.8 Exposure of cables leading to morphological change (operation)

Following burial, the only way in which the cables could influence hydrodynamics and seabed/ intertidal morphology during operation would be if they became exposed as a consequence of natural morphological change. Detailed understanding of the likely temporal variability in intertidal and shallow subtidal elevation throughout the lifetime of the Project is therefore critical for the appropriate siting of cables as well as determination of appropriate target burial depths.

Arguably the most robust means by which to understand the potential for future variability at the landfall is through detailed consideration of the observed longer term morphological behaviour which has taken place. This assessment approach is followed here and has been described below.

Historical morphological analysis of Pegwell Bay has been undertaken using:

- Google Earth historical satellite and aerial imagery,
- Environment Agency LiDAR topographic surveys;
- Coastal Channel Observatory bathymetric surveys; and
- Bathymetric analyses previously presented in the TOWF ES (Thanet Offshore Wind Limited, 2005).

The following review aims to characterise the level, extent and character of the intertidal and nearshore areas within and nearby to the export cable corridor.

A number of historical satellite and aerial images covering the period 1940 to 2017 are available from Google Earth (shown in Figure 10). The images show that:

- Historically, the area in the vicinity of the landfall has experienced notable change throughout the period 1940 to present, associated with anthropogenic modification of the coast, movement in the position of the River Stour channel and migration of Shell Ness;

- Whilst overall the saltmarsh and adjacent mud/sand flat has been relatively stable over the past decade or so, the eastern margin has been greatly eroded by westerly migration of the Stour river channel; and

- Shell Ness is experiencing consistent progradation towards the north. From the 1940's to present, the spit has prograded north at an average rate of approximately 4 m per year. This indicates a surplus of sediment supply to the spit from marine or fluvial sources and a net northerly transport of sediment along the western margin of the bay.

A number of aerial LiDAR topographic surveys of the intertidal above a relatively low water level at 1 to 2 year intervals between 2007 and 2013 were obtained from the Environment Agency (Figure 11). Maps of differences in intertidal elevation between survey intervals are compared in Figure 12 whilst changes in topography along selected profiles are shown in Figure 13. It is noted here that the analysed LiDAR data includes both Digital Terrain Models (DTM) (which describe the earth surface without any surface objects (including vegetation)) and Digital Surface Models (DSM) (which include objects). The differences between these two models are potentially relevant when considering morphological change in areas containing inter-tidal vegetation, such as is found in parts of Pegwell Bay. However, it is noted here that the inter-annual topographic comparisons undertaken here are aimed at described broad, macro-scale trends and therefore the combined analysis of both DTMs and DSMs is considered appropriate.

Together, the data show that in the period 2007 to 2013 (6 years):

- Elevation changes across the main mid to upper intertidal areas are typically small (< ~0.3 m) during the analysis period;

- Shell Ness at the mouth of the River Stour has migrated north-westwards; and

- The River Stour channel bends have migrated across the intertidal, with channel migration of several tens of metres having occurred in places. The relative depth of the channel below the surrounding intertidal level in this area varies from approximately 3.5 to 0.7 m.

A number of bathymetric surveys of the seabed/ intertidal area below approximately mean water level between 2003 and 2016 were obtained from the Channel Coastal Observatory (CCO) (Figure 14). Maps of differences in bathymetry between survey intervals are compared in Figure 15. Together, the data show that in the period 2003 to 2016 (13 years):

- Elevation changes across the mid to lower intertidal and shallow subtidal areas are typically in the range (< ±1 m) during the analysis period;

- The River Stour channel exhibits significant migration across the intertidal. This is particularly notable between 2010 and 2016 where the channel has migrated several hundred metres to the north. The relative depth of the channel below the surrounding seabed level at this location is approximately 0.3 to 1.0 m, but is deeper (up to 1.6 m) higher up the intertidal and closer to the spit where the channel is above the tidal water level for more of the time;

- There has been notable erosion in the northeast of the bay, between 2010 and 2016, with erosion in excess of 1 m in places. This erosion is clear between the 2010 and 2016 surveys but is less apparent between 2003 and 2010; and

- Throughout the analysis period there is ongoing accumulation of material at/ just below the LAT mark, with approximately 1 m of material deposited during the 13 year analysis period. These sediments may be associated with deposition from the River Stour channel although could also reflect seasonal variations in wave conditions and the associated build-up (and removal) of offshore bars.

Finally, a comparison between water depths recorded in the 1955 UKHO Admiralty Chart for Pegwell Bay and those recorded during the TOWF export cable corridor survey (carried out in 2005) was presented in the TOWF ES (Figure 16). In the TOWF ES, it was reported that the bathymetry had changed between the +1 m CD (1.3 m above LAT) and -1.5 m CD (-1.2 mLAT) contours in the Bay and in the area of the Port of Ramsgate extension. It was noted that the major areas of change, with accretion levels of up to 1.5 m, appeared to be associated with a southerly migration of the River Stour channel across the Bay (which is just about visible in the 1955 dataset – see Map 1; Figure 16). The channel is known to have shifted historically in response to changes to the Goodwin Sands, Brake Bank and Shell Ness and may also have been influenced by port extension at Ramsgate (Thanet Offshore Wind Limited, 2005). The observation from the bathymetric evidence that the River Stour channel is highly dynamic is entirely consistent with the available historic aerial imagery and more recent LiDAR data described above.

Figure 10. Satellite and aerial images of Pegwell Bay covering the period 1940 to 2017

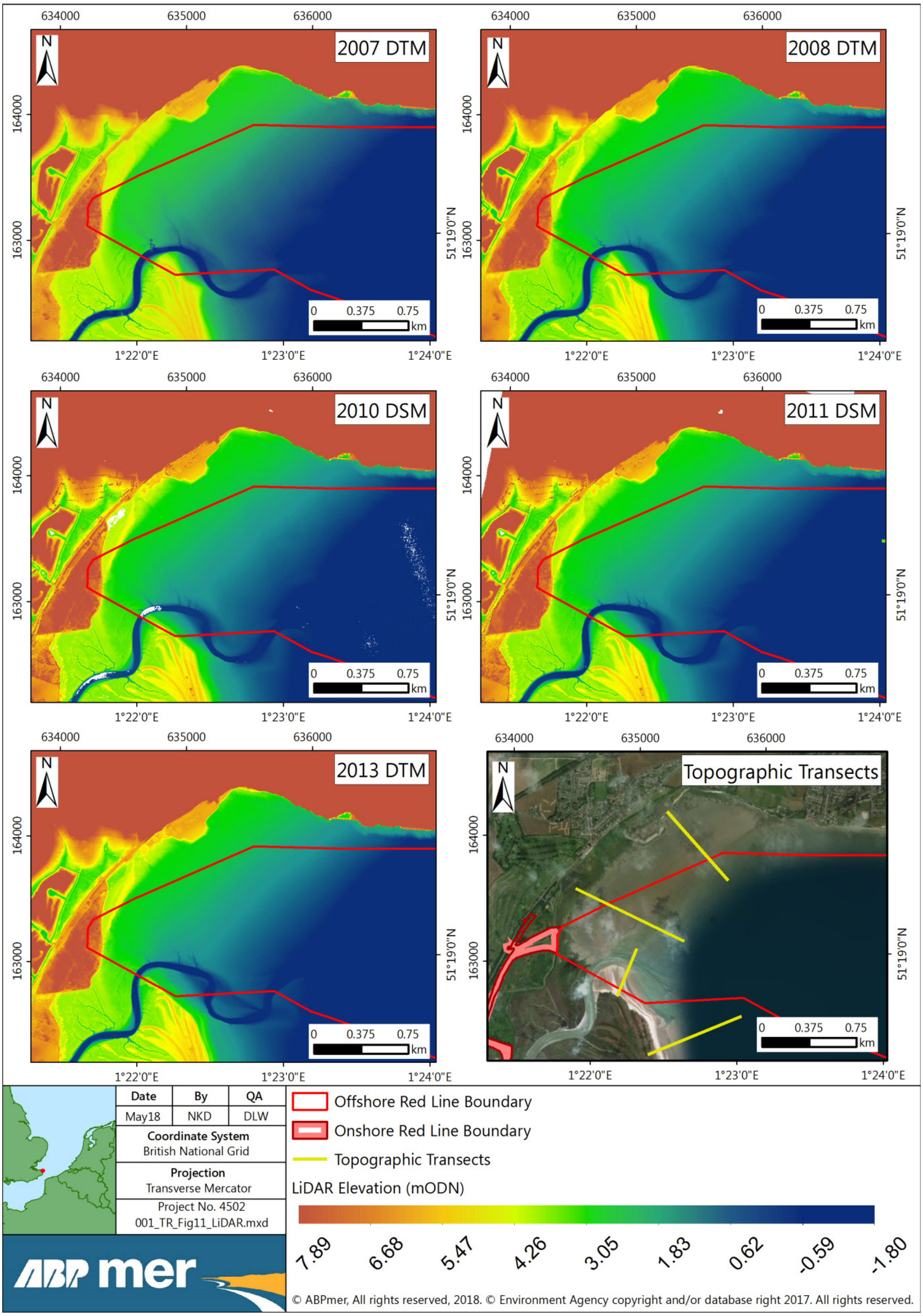


Figure 11. **LiDAR survey topography of Pegwell Bay**

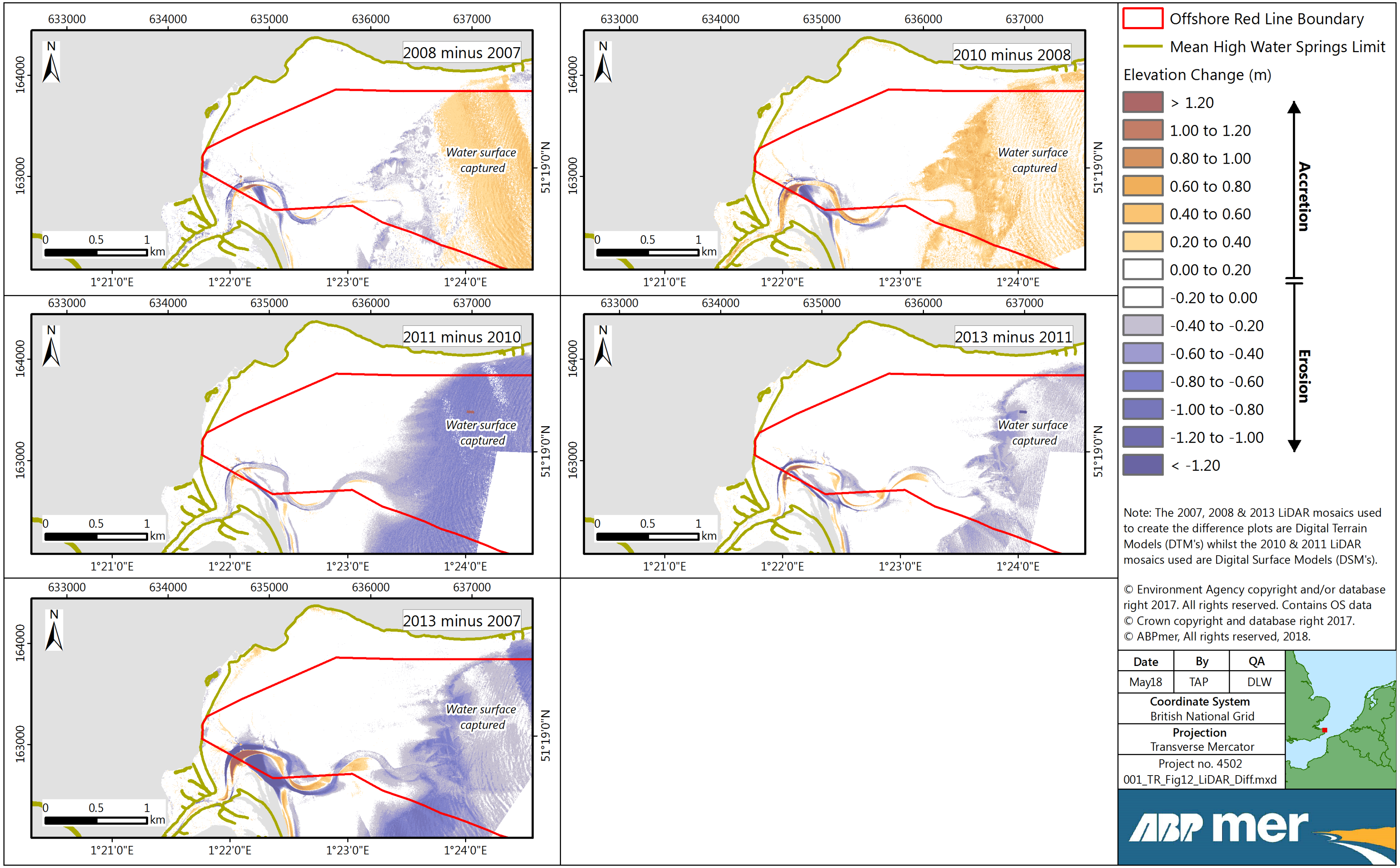


Figure 12. Difference in LiDAR survey topography in Pegwell Bay

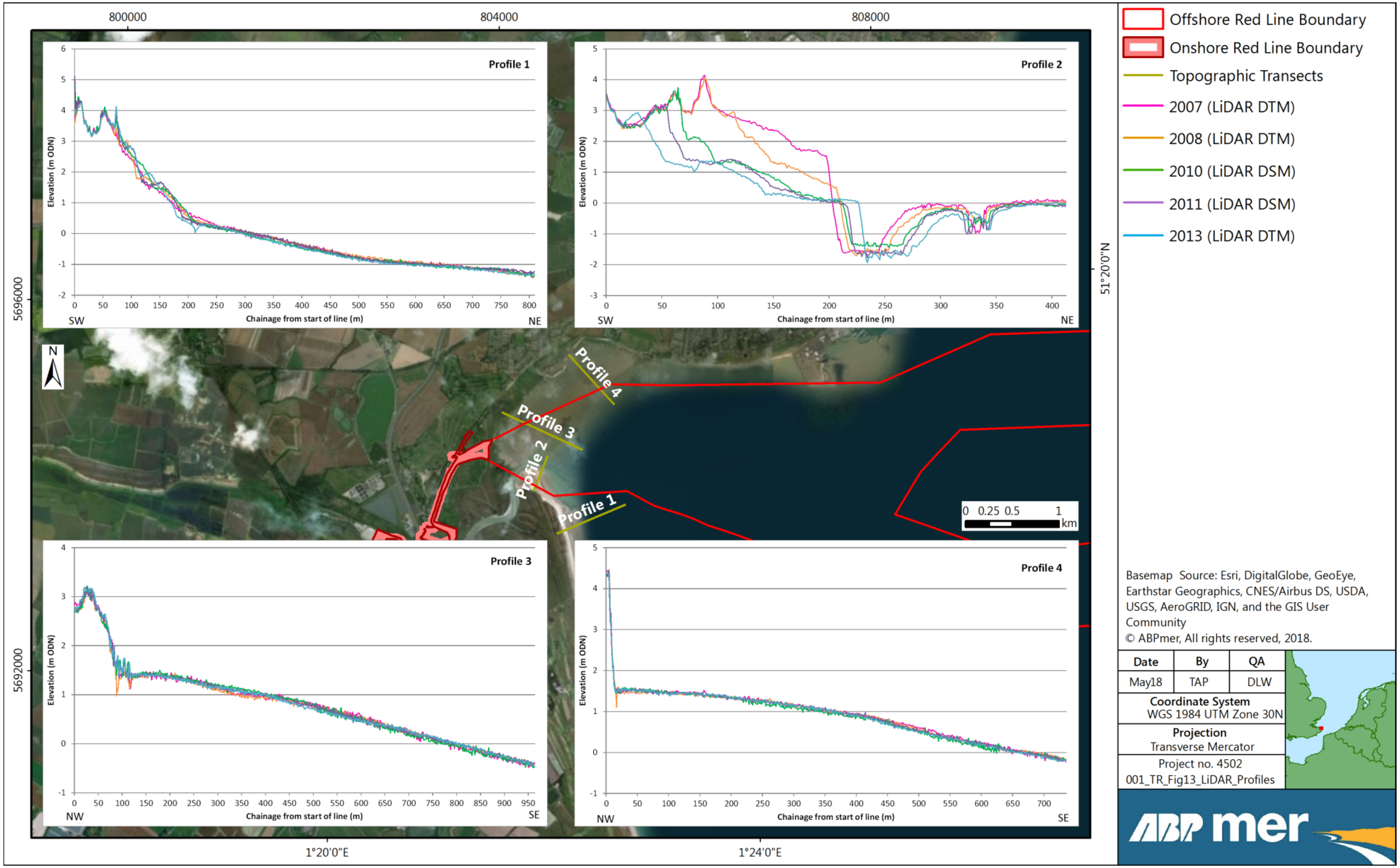


Figure 13. Topography (m ODN) along profile transects 1 to 4 during the period 2007 to 2013, based on LiDAR and CCO beach topography data

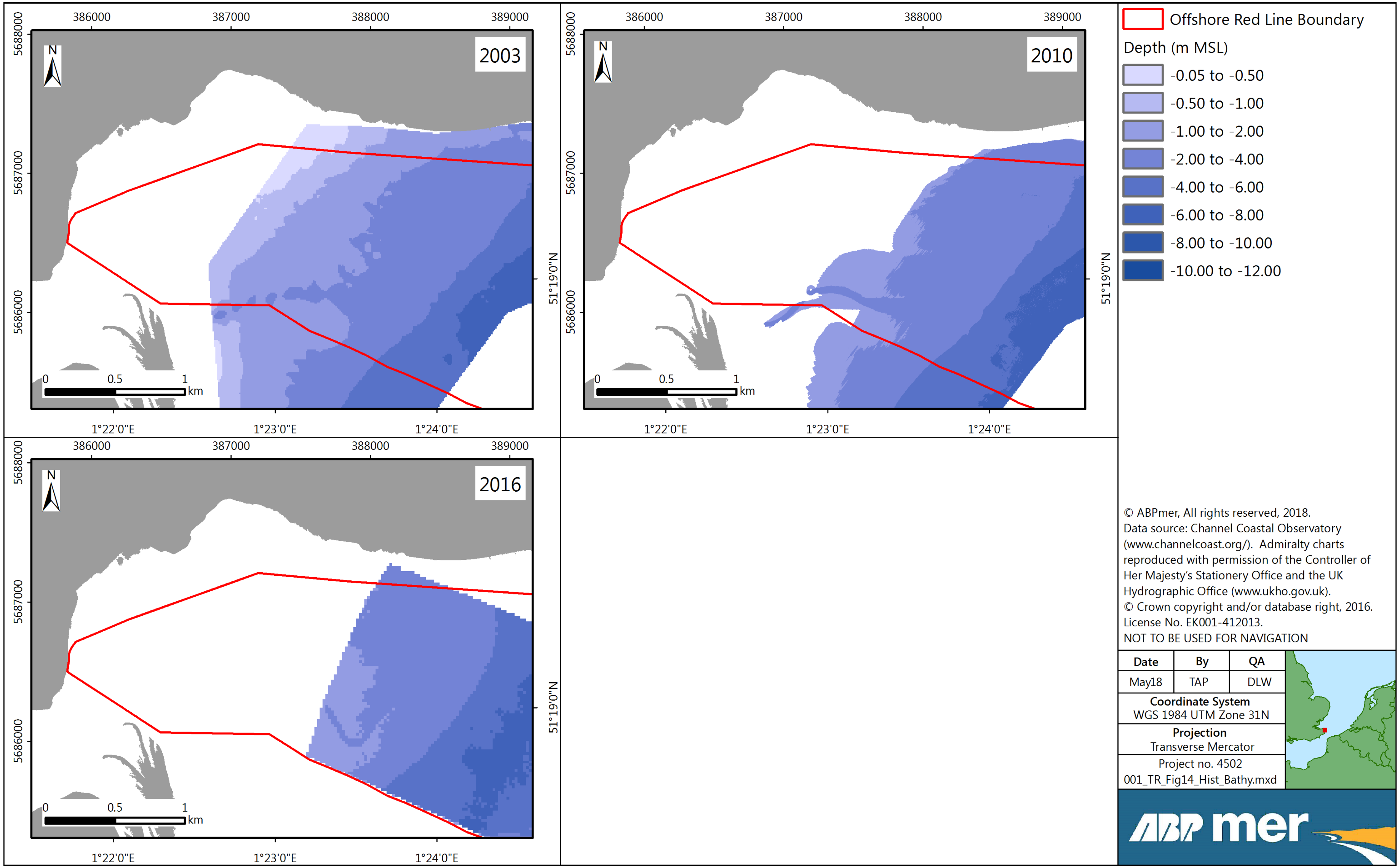


Figure 14. Historical bathymetry in Pegwell Bay

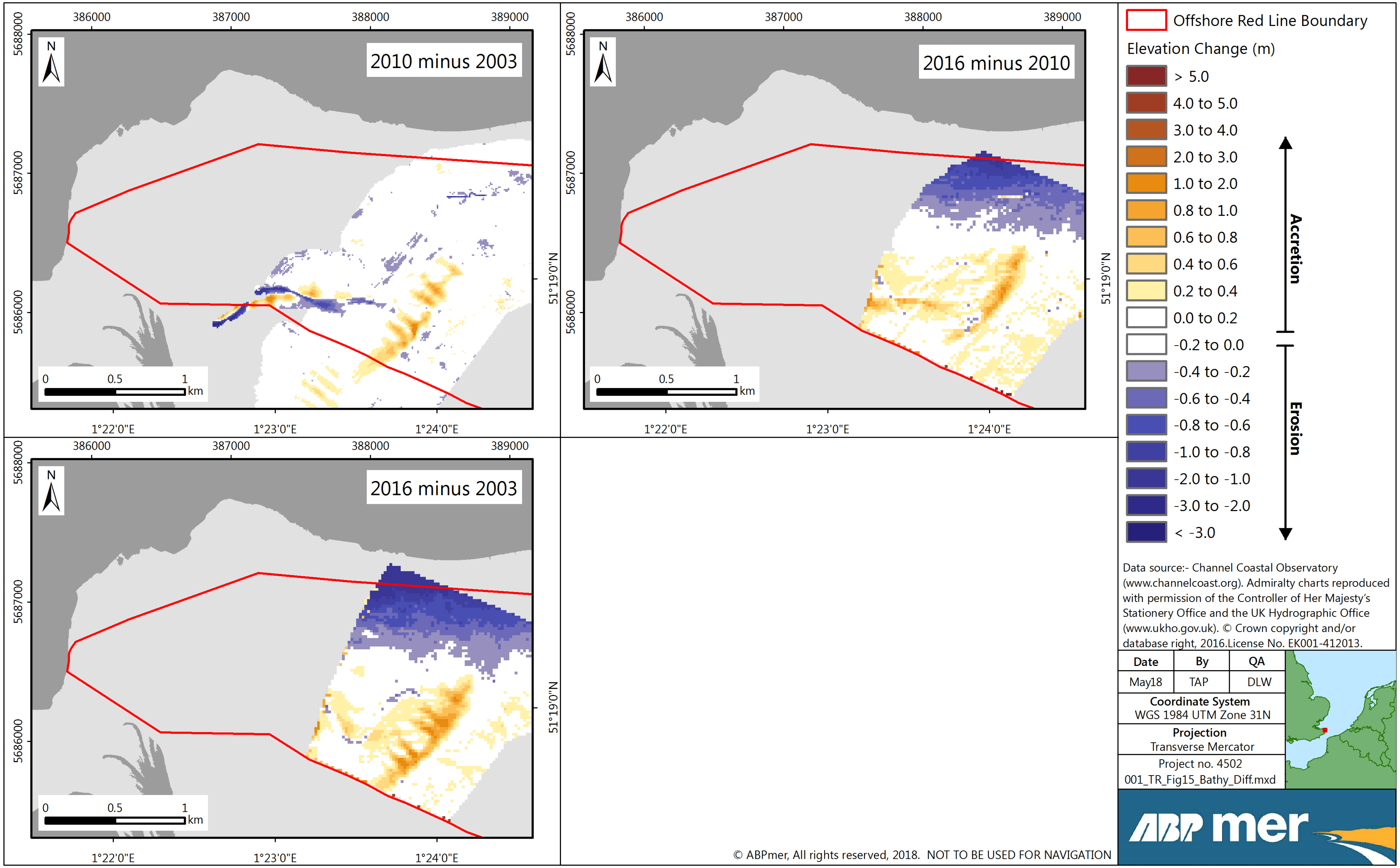
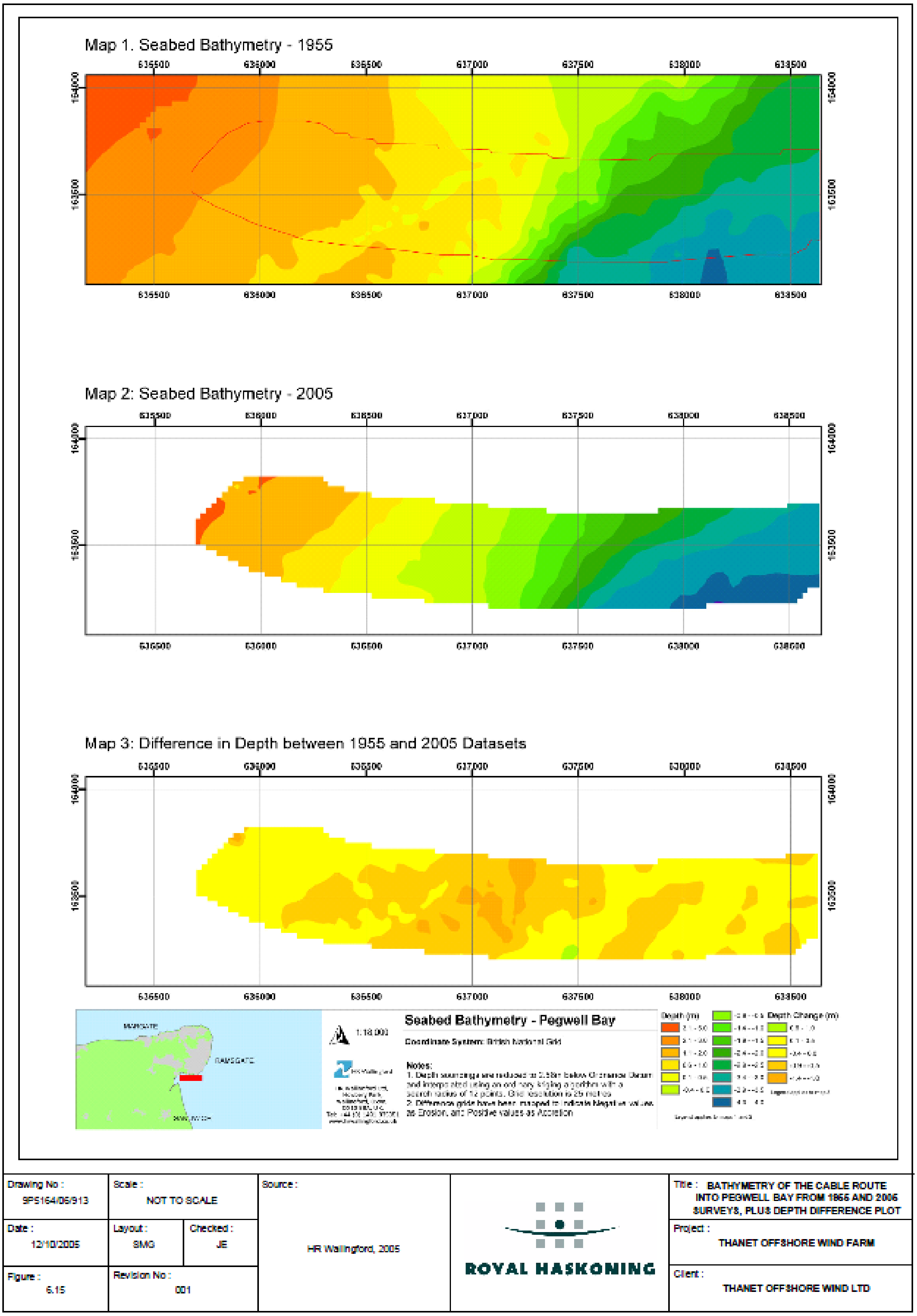


Figure 15. Difference in historical bathymetry in Pegwell Bay



Source: Thanet Offshore Wind Limited (2005)

Figure 16. Seabed bathymetry in Pegwell Bay 1955 to 2005

The natural processes controlling morphological variability at the landfall described above will continue to act in the same way following installation of the cables and irrespective of any temporary local disturbance caused.

It is anticipated that the information on morphological variability will feed into a detailed engineering assessment of cable burial depth which will minimise the risk of exposure. Managing the risk of exposure relating to the ongoing migration of the River Stour channel will be particularly important here. Appropriate consideration will also need to be given to the potential effects of climate change which is expected to lead to mean sea level rise and potentially increased rates of erosion and shoreline retreat.

If the export cables are buried at a sufficient depth below the base of the mobile seabed material, the cables will have no potential to influence either hydrodynamics or seabed/ intertidal morphology. If a section of a cable does become exposed, it might locally influence coastal processes and morphology at a scale proportional to the diameter of the cable (order of a few tens of centimetres) and the length of the exposed section.

If the cable were to become exposed at any point during the operational lifetime of the Project, the exposed cable section may need to be reburied. This would be achieved using similar methods to that used for the initial installation, with similar potential impacts.

5.4.9 Coastal recession, leading to exposure of cable infrastructure within the intertidal (operation)

At the landfall, the potential for future coastal retreat should be limited due to the presence of coastal defences (embankment) and the (planned) 'Hold the Line' management policy. Following consent, a full cable landfall assessment will be undertaken to inform engineering design. This will take into consideration (*inter alia*), elevation, soil conditions and the latest available information regarding the future management policy at the exact location of the landfall. Due consideration will also be given to the potential influence of climate change (especially sea level rise) on coastal morphology.

5.5 Cumulative changes

Provided the Thanet Extension cables remain buried, there is no potential for them to influence hydrodynamics or seabed/ intertidal morphology and therefore there is no potential for cumulative impacts. In the unlikely event that a section of cable became exposed, the potential impacts will be highly localised (order of tens of metres). Other projects with which cumulative changes could potentially occur are situated at too great a distance for any interaction to occur.

6 Assessment of Change to the Tidal Regime

6.1 Overview

The interaction between the tidal regime and the foundations of the wind farm infrastructure will result in a general reduction in current speed and an increase in levels of turbulence locally due to frictional drag and the shape of the structure. Resistance posed by the array (due to the sum of all foundation drag) to the passage of water at a large scale may distort the progression of the tidal wave, also potentially affecting the phase and height of tidal water levels.

Changes to the tidal regime may potentially influence seabed morphology in a number of ways. In particular, a causal relationship between flow speed and bedform type can be expected (Belderson *et al*., 1982) and thus any changes to flows have the potential to alter seabed morphology over the lifetime of the project. More generally, changes in flow may alter the balance between sediment erosion and deposition as well as the rate and direction of sediment transport. These potential changes to the sediment transport regime are discussed separately, in Section 8.4.

A review of the foundation options presented in the Project Design Statement (Volume 2, Chapter 1: Project Description - Offshore (Document Ref: 6.2.1)) has established that the 28 four-legged quadropod foundations, required for the 12 MW turbine option, are likely to lead to the most blockage on the free passage of tidal flows moving through the array area. Of the two methods under consideration for securing this foundation to the seabed, the suction caisson option is also likely to have the most influence on blockage should there be any remaining parts of the caisson proud of the seabed. Appendix B provides the justification behind the determination of the worst-case foundation option for tides in relation to blockage effects.

6.2 Baseline conditions

A summary of the baseline water level and flow characteristics within and nearby to the array area are provided below, based on the project-specific oceanographic survey data (Partrac, 2017) and existing publically available information, including the Atlas of UK Marine Renewable Energy resources (ABPmer *et al*., 2008):

- At all sites, the largest tidal range and spring tidal range can be described as macro-tidal (> 4 m) conditions, whereas the neap tidal range can be described as meso-tidal (2 to 4 m);
- Depth averaged mean spring currents within the Thanet Extension array area vary from approximately 0.7 m/s to 1.2 m/s depth averaged mean neap currents vary from approximately 0.4 m/s to 0.7 m/s;
- Flows are slightly stronger at the southern metocean survey location, as might be expected due to the slightly higher tidal range. This site is also under the influence of the Dover Straits where current speeds are also increased by the narrowing channel width;
- The axis of tidal flows in the southern part of the array area is aligned approximately south (flood) to north (ebb), and is approximately parallel to the adjacent coastlines. The northern part of the array area is under the influence of the tidal exchange with the Outer Thames. This

influence leads to a re-orientation of the flood tide to the south-southwest and the ebb set to north-north-east; and

- Surge related influences are a frequent occurrence and may provide both positive and negative variations to the normal tidal elevation. The project-specific oceanographic data (16/12/2016 to 14/03/2017) also demonstrates that flow speed may be modified by meteorological forcing. Maximum surface flows speeds of 1.3 m/s and 1.7 m/s were recorded at Site A2 (northern section of the array area) and A3 (southern section of the array area), respectively – see Figure 1. These observed flows represent approximately a 1:1 year return period event (Vattenfall, 2017).

6.3 Evidence base

On the basis of: (i) post construction monitoring of wake fields (e.g. from Burbo and Lincs offshore wind farms (ABPmer *et al*., 2010); and (ii) numerical modelling results available from other offshore wind farm project Environmental Statements, it is apparent that changes to flow speeds as a result of flow blockage are greatest in the immediate vicinity of the foundation structures, reducing quickly in magnitude with increased distance from the foundations. As such, the largest changes in flow speed are anticipated to occur within the Thanet Extension array area itself. Outside of the array area, changes in flow speed are typically confined to within the order of hundreds of metres of individual wind turbines and therefore also within the site boundary.

6.4 Assessment

6.4.1 Changes to flows

The presence of foundations in the sea will interfere with passage of tidal flows as a consequence of blockage type effects which leads to some reduction in flow speed behind the structure and lead to the development of a wake. For slender structures, the scale of these effects can be related to the surface area presented to the oncoming flow and the drag coefficient of the structure (American Petroleum Institute, 2014). For very large structures (i.e. where the ratio of diameter to water depth exceeds 0.5), flows will also diverge further and become separated to move around the obstacle, leading to eddy formation and further shielding effects in their lee. Whilst all these effects can be scaled for the steady flow condition, the further consequence of structures is to induce additional turbulence into the flow (i.e. increase turbulence intensity), a process which is more challenging to quantify.

In an array of multiple structures, the effect can be considered as the sum of all individual effects unless there are measurable interactions between adjacent structures, however, due to the requirements of relatively large separations based on rotor diameters to achieve optimal wind energy yield, and the relatively small structures under consideration, these types of interactions do not occur, nor have they ever been observed in an offshore wind farm.

The worst-case foundation option for Thanet Extension has been determined as the larger quadropod (four-legged jacket structure) required for the 12 MW turbine (Appendix B). The quadropod also has the option of either being pin-piled to the seabed or will use suction caissons. No further consideration of these securing options is offered for tidal flows as they are expected to be present in the seabed rather than the water column.

For the 12 MW turbine, there will only be 28 quadropod structures required across the 72.8 km^2 project area and their spacing will be relatively large to account for the biggest rotor diameters. The minimum turbine spacing will be 716 m x 480 m, however it is likely that turbines will, in general, be spaced considerably further apart..

The maximum leg spacing for each larger quadropod is 40 m, narrowing to 20 m at MSL. The estimated solidity ratio (A/Af) is 0.56, meaning that 56% of the total frontal area (Af) is solid structure (A, comprising the individual legs and cross-members).

In contrast, TOWF uses 100 monopile foundations with diameters of 4.1 to 4.9 m which are spread across 35 km^2 with in row separation of 0.5 km and between row separation of 0.8 km.

Each of these foundations has a local scale effect on the local tidal flow through drag forces and wake formation, the immediate consequence of which is the development of vortices around the structure which can lead to scouring of the local seabed (Section 9).

The wider effects of TOWF on the tidal regime are partly revealed by the presence of turbid wakes which have been observed at certain times (Section 4). Importantly, the length (and width) of the observed sediment plumes is not an indication to the extent of effect on tidal flows, rather the observed plume extent is a function of visible fine sediments in transport after being entrained into suspension by the local disturbance in the tidal stream around a foundation. The slow fall velocity of the fine sediment maintains the material in suspension over a relatively long distance and without further disturbances along their extents they maintain their narrow linear form. The width of the plumes is a function of dispersion caused by ambient turbulent mixing. The plume extents provide an indication of the overall Lagrangian flow pathway occurring at the time, noting individual pathways seem to be maintained as they transit across the wind farm array which is further evidence that the array is not disrupting the overall flows passing across the array and each disturbance remains as an individual local effect.

Direct flow measurements undertaken at Burbo Bank (ABPmer, 2011) in the lee of a 4.7 m diameter monopile indicated that the mean current speed within the wake recovers to within 10% of the ambient value approximately 200 m downstream of the origin (i.e. ambient flows are effectively recovered at 40 diameters). This evidence helped validate the earlier assertions of effects which were modelled for the corresponding EIA.

Wake features have also been assessed at the Donghai Bridge offshore wind farm in the East China Sea using sea surface backscatter from TerraSAR-X (TS-X) Synthetic Aperture Radar (SAR) (Li *et al.*, 2014). This wind farm comprises of 34 monopile foundations which have a 15 m diameter concrete cap at the water surface (to mitigate ice loads). The tidal current interacts with these cylindrical piles and induces water turbulence, which dampens the surface Bragg waves, and therefore modulates the sea surface roughness and consequently is imaged by TS-X as wakes downstream. Approximately 1.2 km away from the pile, the backscatter signal became comparable to the mean upstream value, indicating that the wake length in this case was approximately 80 diameters in length.

For Thanet Extension, similar tidal and sediment plume type effects are anticipated on the tidal regime as those observed at TOWF, but with some notable contrasts;

- Depending on the final design option, there will only be up to a maximum of 34 foundations (or 28 foundations for the 12 MW case) in Thanet Extension compared to 100 foundations already present within TOWF;
- The worst-case foundation option under consideration is a quadropod structure rather than a monopile as this has been assessed to result in the greatest amount of local blockage to the tidal flows. The immediate consequence of this structure is to create a more disturbed local

flow across the larger incident width. This disturbed flow can be expected to lead to local scour at sites without appropriate seabed protection, and the encouragement of similar, but proportionally wider, sediment plumes for areas with active seabed transport of fine sediments. These plumes are more likely to be visible at the shallower sites, noting the suspected wreck located in the northern section of the site is at around 25 m (below LAT) and already creates a similar sediment plume;

- The lateral extents of modification to tidal flows in the wake are likely to be proportionally larger due to increased widths of the structure. Conservatively, using a mid-depth leg spacing of 30 m for the 12 MW quadropod foundation, and estimating the wake length as 80 diameters, then a likely extent of a measurable / detectable wake is estimated to be in the order of 2.4 km (at times of peak flow) (see Figure 3) and along the axis of flows as measured in the metocean deployments; and

- The individual turbines in Thanet Extension will be spaced further apart than those within TOWF, so the potential of interaction between foundations in Thanet Extension is much reduced, further limiting any potential for array scale effects.

If these effects described above occurred from the outer limits of the proposed development area then they also remain too short to reach:

- The adjacent coastlines;
- Any other windfarm in the area along the same axis of flow; or
- Any adjacent sandbank features with designated nature conservation areas.

On the flood tide, only the foundations located in the northern sector of Thanet Extension will create wake effects that have the potential to move into TOWF and in a similar manner as the effects of the sediment plume from the probably wreck site in this area (Figure 9). For an indicative layout in which turbines are distributed evenly throughout the array area, there are estimated to be around six locations close enough to TOWF where this might occur.

On the ebb tide, only the foundations located in the southern sector of Thanet Extension will create wake effects that have the potential to move into TOWF. There are estimated to be around seven locations close enough to TOWF where this might occur.

Ebb and flood flows through the east and western sectors are unlikely to transit through TOWF.

As currents move water past the individual offshore wind farm foundations, a turbulent wake is formed (see Section 4.3). Within the turbulent wake, vertical mixing can be enhanced above ambient levels. This increase in turbulence intensity might potentially contribute to a local reduction in the strength of vertical stratification (e.g. Cazenave *et al.*, 2016; Carpenter *et al.*, 2016). On the basis of available long term (1958 to 2008) field evidence on the spatial variation in water column stratification within the southern North Sea, the Thanet Extension array area is located within an area characterised in terms of stratification as 'permanently mixed' (van Leeuwen *et al.*, 2015). The wind farm will therefore have no influence on the natural degree of stratification. Areas which may be characterised as intermittently stratified are found approximately 15 to 20 km to the east of the array area. However, given that changes to the tidal regime are not anticipated to extend more than approximately 2.4 km outside of the array boundary, it is considered that there is no potential to influence water column stratification in these areas.

6.4.2 Changes to water levels

Offshore wind turbine foundations can be considered too small and widely dispersed to affect flows at the array scale and therefore will have limited to no measurable effect on water levels (tidal or residual surge) at either the local or regional scale. There is no evidence from other operational OWF to suggest a measurable array scale effect on water levels.

This assertion is entirely consistent with numerical modelling undertaken to inform the (much larger) Round 3 developments (e.g. East Anglia Offshore Wind, 2012; Moray Offshore Renewables Ltd, 2012, Navitus Bay Development Ltd, 2014).

6.5 Cumulative changes

Interaction between separate wind farms only has the potential to occur if the extent of the turbulent wake features from one location overlaps with that from the other. Wind farms not aligned in relation to the ambient tidal streams, or located more than one spring tidal excursion distance from one another, are very unlikely to cause cumulative changes.

The closest wind farm to Thanet Extension (other than the TOWF) is London Array. London Array is located approximately 11 km to the north (nominally slightly less than one full spring tidal excursion distance but considerably more than the approximate 2.4 km distance of effect estimated to be associated with the largest 12 MW quadropod suction caisson foundation within the Thanet extension array area). However, the two wind farms are not aligned in relation to the ambient tidal streams and so, therefore, there is no realistic potential for interaction of the wakes between these two wind farms.

7 Assessment of Change to the Wave Regime

7.1 Overview

The interaction between waves and foundation infrastructure may result in a local reduction in wave energy potentially extending into the far-field. The influence of a single structure on individual waves is not easily measurable in practice but the cumulative change of many structures is generally accepted to be a slight reduction of wave energy (height and period).

Where the wave climate is persistently modified, these changes may potentially alter the frequency of sediment mobilisation and rates of transport and deposition.

A review of the foundation options presented in the Project Design Statement (Volume 2, Chapter 1: Project Description - Offshore (Document Ref: 6.2.1)) has established that the 28 four-legged quadropod foundations, required for the 12 MW turbine option, are likely to lead to the most blockage on the free passage of waves moving through the array area. Of the two methods under consideration for securing this foundation to the seabed, the suction caisson option is also likely to have the most influence on blockage should there be any remaining parts of the caisson proud of the seabed. Appendix B provides the justification behind the determination of the worst-case foundation option for waves in relation to blockage effects.

7.2 Baseline conditions

Baseline characteristics of the wave regime are briefly summarised below:

- The layout and scale of Thanet Extension is such that wave conditions will vary across the array area relative to differences in water depths and exposure to different fetches;

- The dominant wave directions within the Thanet Extension array area are from the north east and south west. This is mainly due to a large fetch length within the North Sea and wave propagation northwards within the English Channel;

- Wave heights are generally smaller throughout the western side of the Thanet Extension array area due to sheltering from both North and South Foreland. Across the Thanet Extension array area, significant wave heights (Hs) are found to be in the range 0 to 1 m for between approximately 65% and 80% of the time whilst waves between 1 and 2 m in height occur for approximately 20% to 30% of the time. The 1:1 year return period wave height across the array area is 3.0 and 3.4 m, with the largest waves occurring in the south of the array area; and

- Mean wave periods (Tm) are typically in the range 3 to 6 seconds and are indicative of a setting in which wind waves generally dominate. However, longer period (> approximately 8 seconds) swell waves are also encountered which are associated with waves propagating down the North Sea and from the English Channel.

7.3 Evidence base

Modelling analysis of the impact of an array of different foundation types on waves at Gwynt y Môr (Npower Renewables Ltd, 2005) show no effect on wave height greater than 0.1 m as a result of 250 x 6 m diameter monopile foundation type (a maximum reduction of approximately 2% of the baseline wave condition).

A generic study investigating the effects of large Round 2 offshore wind farm developments utilising monopiles (ABPmer, 2005) also confirm that wave effects will be limited, concluding that *'the scale of the installation will be too small to grossly modify the wave regime'*. Here the arrays were composed of 100 structures with 1 km spacing. The turbines used in this study had a 6 m diameter, in comparison to the maximum 10 m diameter proposed for Thanet Extension. (The minimum turbine spacing for Thanet Extension is 716 m x 480 m, however, it is likely that turbines will, in general, be spaced considerably further apart).

The only presently available field evidence with respect to the effect of wind farm infrastructure on the wave regime is provided in Cefas (2005). The study considers Scroby Sands, a Round 1 development located at closer proximity (2.3 km) to the shoreline. The array consists of 30 monopiles of 4 m diameter, supporting turbines rated at 2 MW. Field measurements of waves using radar concluded that the *'wave diffraction caused by monopiles in an [offshore wind farm] is not significant compared with variations due to other mechanisms'* and *'Cumulative effect of wind turbine structures upon wave conditions can be considered negligible'*. It was also shown that concerns regarding impacts upon the sediment transport regime, through changes in the wave climate, should be eliminated.

7.4 Assessment

The presence of foundations in the sea, plus the swept radius of turbine blades in the air, can collectively modify the wave and wind wave regime passing through an offshore wind farm. As summarised by (Christensen, *et al*., 2013) the primary effects on waves are caused by:

- Drag forces against passing waves in contact with the foundation;
- Reflection (and scattering) of wave energy off the face of the foundation; and
- Diffraction of wave energy around the structure.

For any offshore wind farm, the scale of effect on waves is further related to local water depths, wave period (wave length) and the dimension (foundation scale) and layout of structures (array scale). Further to this, the effect on an adjacent receptor, such as a coastline, will relate to the distance from the offshore wind warm over which the effects may dissipate.

At the foundation scale, the diameter (or width) (D) of the structure relative to the incident wavelength (L) are the relevant dimensions. When D/L > 0.2 then interactions between a structure and the incident wave become relevant.

Taking the full width of the 12 MW quadropod at mean depth as D = 30 m (ignoring the solidity ratio A/Af), and using the values of wavelengths from Table 22 at various representative depths, suggests D/L exceeds 0.2 for each case and with the largest values attributed to the shorter period "typical" wave conditions (0.39 to 0.47). The equivalent values for the longer period "large" waves are 0.27 to 0.36.

Table 22. Summary of wave induced near bed orbital velocity and surface wavelengths for 'typical' and 'large' wave conditions observed during oceanographic survey (Partrac, 2017)

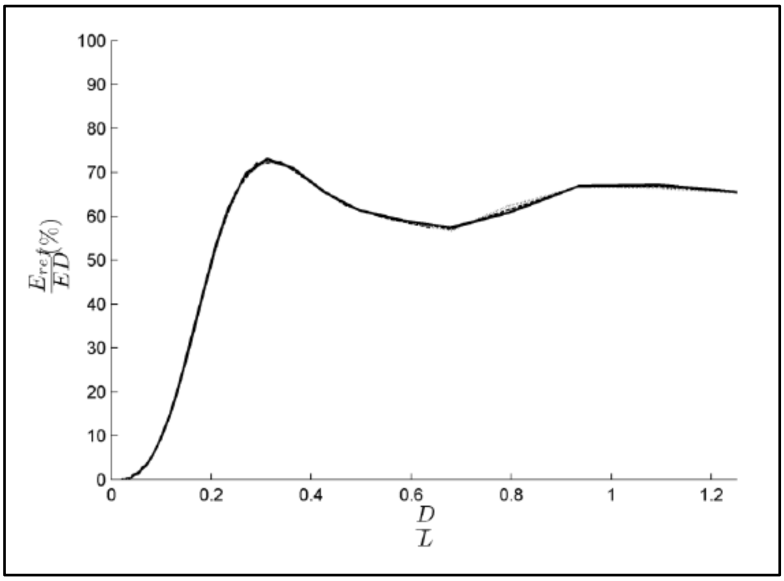
Wave Condition		Typical Wave		Large Wave	
		Significant wave height (Hs)= 1.5 m	Peak Wave Period (Tp) = 7s	Hs = 2.5 m	Tp = 8.5 s
Parameter		Bed Velocity, U_{bot} (m/s)	Wavelength, L (m)	Bed Velocity, U_{bot} (m/s)	Wavelength, L (m)
Depth (m)	12.5	0.40	64.30	0.78	83.20
	20	0.23	72.00	0.50	97.10
	30	0.11	75.50	0.30	106.50
	40	0.05	76.30	0.19	110.50

In relation to TOWF, D/L for the largest diameter monopile of 4.9 m produces results for D/L up to 0.13 at most. Wave interactions with the smaller monopiles are therefore expected to be negligible at each foundation and therefore negligible for the whole array for both typical and large waves. The effective diameter would need to be greater than 7.5 m to interfere with the transmission of waves.

In relation to the influence of drag forces on waves, the maximum dissipation of wave energy is likely to remain the smallest influence and is estimated to be less than a 10% reduction in wave energy at each foundation (Christensen *et al.*, 2013).

In relation to the capacity of a foundation structure to reflect wave energy, Figure 17 shows a relationship as a function of diameter (D, equivalent to the width of the obstacle), and the wave length (L). Using values of D/L for the "large" wave suggests that around 70% of incident wave energy would be reflected. For "typical" waves, D/L in the range 0.39 to 0.47 suggests slightly less wave energy would be reflected, in the order of 65%.

For 4.9 m monopiles used in TOWF D/L would equate to values of 0.04 to 0.08 which would have minimal size to reflect wave energy, in the order of less than 10%.



Source: Christensen, *et al.*, 2013

Figure 17. Sensitivity of reflected wave energy (y axis, %) to the ration of foundation width (D) and wavelength (L) (x axis)

The summation of the array effects of the Thanet Extension on waves from the north-east is estimated as:

- Drag; 10% energy reduction per turbine, summed for each row through which waves travel and weighted by relative blockage per row;
- Reflections and scattering; energy 65% reduction per turbine for "typical" waves and 70% for "large" waves, summed for each row and weighted by relative blockage per row; and
- Diffraction; no measurable contribution is expected for the proposed foundation types.

On the basis of the above, the maximum reduction in wave energy attributed to waves passing through multiple rows in Thanet Extension (and TOWF) is around 10%, averaged across the leeward side.

As wave energy is proportional to the square of wave height, these reductions translate to a reduction of the incident 1.5 m "typical" wave to 1.46 m (i.e. a reduction of ~2.7 %), and the incident "large" wave from 2.5 m to 2.44 m (i.e. a reduction of ~2.4 %) along the downwind margin of the Thanet Extension array area. These effects will also dissipate over distance towards the coast (which is approximately 8 km away) and therefore there are not expected to be any detectable changes or impacts on the coastline due the Thanet Extension interacting with waves.

Only slight influences are expected to spectral wave period where the structures have relatively greater influence on short period waves than longer period waves.

No other effects are expected as the "typical" waves propagate over the adjacent seabed as their wave periods are too short to stir the seabed. For the "large" wave there may be an associated slight reduction in wave orbital influence on the adjacent seabed. As an illustration, as these waves pass over shallow water in the order of 12.5 m depth, the adjusted seabed orbital velocity would change from 1.19 m/s for the 4 m wave to 1.17 m/s for the 3.92 m wave.

7.5 Cumulative changes

The assessment of waves shows that the largest waves are from the north-east and waves from this direction would reach the adjacent coastline but with very little moderation due to the Thanet Extension. Upwind, the north-east fetch includes Greater Gabbard and Galloper wind farms, however, these sites are more than 34 km away and in deeper water so any local effects on waves from these sites are unlikely to reach Thanet Extension.

Waves at Thanet Extension may also come from the south and south-southwest, but are also typically smaller in wave height and period than the waves from the north-east. The downwind path for southerly waves propagating through the western side of Thanet Extension could theoretically extend to London Array (over 12 km to north-north-west) and have a similar level of reduction in wave energy for the "typical" wave from the north east. As noted above, the nature of short period waves means they are expected to have minimal influence on the seabed.

8 Assessment of Change to the Sediment Transport Regime

8.1 Overview

Potential changes to the sediment transport regime could occur in response to the presence of:

- Turbine foundations and sub-stations; and
- Cable protection measures.

Infrastructure installations may present a direct blockage to the transport of sediment. Interaction between the naturally present oceanographic regime (currents and waves) and the wind turbine foundations may also result in a reduction in current speed and wave energy, and locally an increase in levels of turbulence. Elevated turbulence may result in local scour (considered in Section 11) and will also enhance the carrying capacity of the flow (e.g. Butt *et al*., 2004, Gyr and Hoyer, 2006). Persistent changes to wave and currents over larger areas may cause changes, over time, to patterns of net sediment transport (rates and directions) (considered in Section 8).

The sensitivity of morphological features to these patterns of change would depend upon the relative importance of currents and/or waves, the magnitude and extent of any change to them and the degree to which the system is presently in balance. The potential for such changes to occur is assessed in this section, with the influence of foundation infrastructure and cable protection measures considered separately.

8.2 Baseline conditions

Baseline characteristics of the sediment transport regime are briefly summarised below:

- On the basis of the existing regional scale mapping of sediment transport presented in Kenyon and Cooper (2005), it is suggested that the net (bedload) sediment transport is to the southwest across the Thanet Extension array area, with more complex patterns of sediment transport just to the east of the Thanet Extension array area associated with the South Falls sandbank. The suggestion of a general southerly movement of sediment across the array area is supported by several independent lines of evidence, including analysis of bedform migration (determined through comparison of recently collected project-specific bathymetry with that previously collected from TOWF).

- Notwithstanding the above, in the northwest of the array area the asymmetry of the mapped sandwaves is clearly indicative of a north-westerly direction of transport, towards the Thames Estuary;

- The observational evidence (in the form of bedform asymmetry analysis) from the export cable route corridor geophysical survey (Fugro, 2016b) is limited although tentative evidence for a general northerly migration of bedforms is present just to the north of Goodwin Sands, approximately 3 km offshore in the outer reaches of Pegwell Bay;

- Within the approaches to Pegwell Bay, mapped sandwaves immediately to the north of Cross Ledge suggest a general easterly migration of bedforms. However, it should be noted that the effects of wave shoaling and wave breaking during extreme conditions can further influence the sediment transport processes in shallow inshore/nearshore areas, leading to a highly dynamic environment; and

- The southwestern part of Pegwell Bay where the cable makes landfall is predominantly low-lying intertidal saltmarsh and mud/sand flats located adjacent to the River Stour which meanders and exits into the Bay. Large sections of the neighbouring coastline to Pegwell Bay have been historically developed, with coastal defence schemes preventing cliff and/or beach erosion. This has resulted in a low supply of sediment within the nearshore, limiting rates of beach accretion (SECG, 2010).

8.3 Evidence base

Very limited observational evidence is available with regard to the impacts of wind farm foundations on potential regional scale patterns of bedload sediment transport and associated changes to bathymetry. However, it is noted here that comparisons of data recorded before (2005 & 2007) and after (2012) construction of TOWF indicate that seabed sediment composition has remained broadly similar. Comparable monitoring stations remain largely unchanged and continue to be dominated by sandy deposits with varying proportions of silts and gravels (MESL, 2013). This evidence provides some support to the assertion that TOWF is not causing widespread change to patterns of sediment transport within/ nearby to the array area.

Cefas (2005) describe the results of post construction monitoring at Scroby Sands offshore wind farm which was undertaken to investigate the impacts of monopiles on coastal processes. It was found that at Scroby Sands, the impacts on sediment transport are probably limited to local scour pits and scour wakes. Any ensuing bathymetric impacts are probably limited to the order of 100 m around each monopile. It was further noted that, given the spacing between monopiles is greater than 300 m, such bathymetric/ sediment transport impacts are unlikely to be cumulative between monopiles and across the turbine array.

8.4 Assessment

8.4.1 Turbine and OSS foundations

8.4.2 Transport at the coast

On the basis of the quantitative analysis of potential changes to the wave regime (Section 7.4), it is found that there will be no measurable reduction in wave height at adjacent coastlines in response to the presence of the turbine foundations since reductions in wave height along the downwind margin of the array area will be no greater than ~2.7%. Changes in wave height of this magnitude are small in both relative and absolute terms. Such small differences are not measurable in practice and would be indistinguishable from normal short term natural variability in wave height (both for individual wave heights and in terms of the overall seastate). Accordingly, these changes are not predicted to have any measurable influence on longshore sediment transport.

8.4.3 Bed load transport

Across the Thanet Extension array area and offshore sections of the offshore cable corridor, sediment transport is dominated by the action and asymmetry of tidal currents. Potential changes to currents have previously been described in Section 6.4.1. In brief, current speed will be reduced in a narrow wake extending downstream from each foundation and potentially also increased (by a lesser magnitude but in a slightly wider corridor than the area experiencing decreased flow) between the rows of foundations. This results in limited net difference in the total flow rate of water through the array area, with measurable changes largely restricted to the footprint of the array area.

The extent to which these long term, but localised changes, in flow speed could influence rates of bedload transport within and nearby to the array area will depend upon the magnitude of change relative to sediment mobilisation thresholds. In places, it is probable that localised flow reductions will lessen the frequency with which sediment particles are mobilised and therefore rates of transport may also be similarly reduced. Conversely, marginally greater rates of sediment transport may be experienced where localised flow accelerations are found. The overall result of these slight changes in flow speed could potentially be a very small reduction in the net volume of material transported as bedload through the array area. The reduction would likely not be measurable in practice and would be within the range of natural variability in sediment transport rates.

8.4.4 Suspended sediment transport

As discussed in Section 6.4.1, changes to tidal currents (which primarily control the rate and direction in which suspended sediment is transported) due to the operational presence of the array area are assessed to be very limited in absolute magnitude and spatially restricted to the array area plus a small distance downstream in the main flood and ebb directions.

During large storm events, waves may stir the seabed within shallower parts of the array area, naturally causing an additional short-term contribution to SSC levels locally. The maximum adverse scenario layout will potentially cause a small reduction in wave heights within and nearby to the array area and it is therefore possible that there will be a corresponding small reduction in the rate at which sediment is locally re-suspended from the seabed.

The change described above would only be apparent during larger storm events (if at all) and would potentially slightly reduce SSC from that which would have occurred in the baseline condition. However, levels of SSC will remain dominated by regional scale inputs that are not affected by the presence of the wind farm. No measurable changes to SSC outside the range of natural variability are expected to occur within or nearby to the array area.

8.4.5 Cable protection measures

Installation of cable protection could result in a locally raised obstacle up to 0.5 m above the present-day seabed level (Volume 2, Chapter 1: Project Description - Offshore (Document Ref: 6.2.1)). Cable protection would be placed onto the seabed surface above the cable and could therefore directly trap or block sediment in transport, locally impacting down-drift locations. The spatial extent and location of the cable protection is to be confirmed.

Following installation and under favourable conditions, an initial period of sediment accumulation would be expected to occur, creating a smooth slope against the cable protection. The process of wedge formation may take place over a period of a few weeks to months, depending on rates of sediment transport.

The presence of cable protection could potential influence sandy sediments which are being transported as bedload. Bedload transport occurs via ‘saltation’, ‘rolling’ and ‘sliding’:

- ***Saltation*** is the process by which sands are moved up into the water column. These suspended sands would be expected to move relatively freely over the top of the armour although to begin with would regularly be deposited upon it, filling void spaces. Once any void spaces have been infilled, saltation is expected to be largely unaffected by the presence of the cable protection such that existing transport process (including bed form migration) will remain unaffected.

The process of void infilling is expected to occur relatively quickly (in the order of a few months). This is due to saltation as well as the anticipated high rates of transport in areas of mobile seabed (which is where much of the cable protection is anticipated).

- ***Rolling and sliding*** is the process by which sands move while still in contact with the seabed. Transport via these mechanisms will be temporarily affected up until such time that the armour is covered by sand and the slope gradient either side has been reduced in response to the accumulation of a sediment wedge with stable slope angles (approximately 30 degrees). Following this, bedload will continue because the slope angle presented by sections of protected cable would be within the natural range of bed slope angles associated with bed forms mapped within the corridor.

Accordingly, for all areas in which cable protection is used (including where sandwaves are present), it is not expected that the presence of the cable protection devices will continuously affect patterns of sediment transport following the initial period of accumulation. It follows that any changes on seabed morphology away from the cable protection will also be very small. The extent of the cable protection measures does not constitute a continuous blockage along the cable route corridor.

8.5 Cumulative changes

The primary process mechanisms driving sediment transport within the study area are currents and waves. It has been demonstrated in Section 6.4 and 7.4 that the footprint of measurable change to these parameters is too small in both extent (and magnitude) to cumulatively interact with similar changes associated with other developments. It follows that any associated changes to sediment transport will also be similarly limited in extent and as such, no cumulative changes are expected.

9 Assessment of Scour and Seabed Alteration

9.1 Overview

The purpose of this section is to conservatively and quantifiably estimate the area of seabed that might potentially be altered during the operational phase of the wind farm as a result of sediment scour developing adjacent to turbine foundations (in the absence of any scour protection).

The term scour refers here to the development of pits, troughs or other depressions in the seabed sediments around the base of turbine foundations. Scour is the result of net sediment removal over time due to the complex three-dimensional interaction between the foundation and ambient flows (currents and/or waves). Such interactions result in locally accelerated time-mean flow and locally elevated turbulence levels that enhance sediment transport potential in the area of influence. The resulting dimensions of the scour features and their rate of development are, generally, dependent upon the characteristics of the:

- Obstacle (dimensions, shape and orientation);
- Ambient flow (depth, magnitude, orientation and variation including tidal currents, waves, or combined conditions); and
- Seabed sediment (geotextural and geotechnical properties).

Based on the existing literature and evidence base, an equilibrium depth and pattern of scour can be empirically approximated for given combinations of these parameters. Natural variability in the above parameters means that the predicted equilibrium scour condition may also vary over time on, for example, spring-neap, seasonal or annual time-scales. The time required for the equilibrium scour condition to initially develop is also dependant on these parameters and may vary from hours to years.

Scour assessment for EIA purposes is considered here for two foundation types: monopiles and piled quadropod foundations (a four legged version). Each foundation type may produce different scour patterns therefore both monopiles and quadropod foundations have been considered. Suction caisson foundations (for quadropods) have not been considered in the assessment below because these will fall within the envelope of change associated with the other two foundation types. Indeed, local scour around each suction bucket will be limited (largely owing to the fact that they will only have limited protrusion above the seabed), with the total spatial extent of local scour expected to be less than the extent of group scour for quadropod foundations.

The concerns under consideration include the seabed area that may become modified from its natural state (potentially impacting sensitive receptors through habitat alteration) and the volume and rate of additional sediment resuspension, as a result of scour. The seabed area directly affected by scour may be modified from the baseline (pre-development) or ambient state in several ways, including:

- A different (coarser) surface sediment grain size distribution may develop due to winnowing of finer material by the more energetic flow within the scour pit;
- A different surface character will be present if scour protection (e.g. rock protection) is used;
- Seabed slopes may be locally steeper in the scour pit; and
- Flow speed and turbulence may be locally elevated.

The magnitude of any change will vary depending upon the foundation type, the local baseline oceanographic and sedimentary environments and the type of scour protection implemented (if needed). In some cases, the modified sediment character within a scour pit may not be so different from the surrounding seabed; however, changes relating to bed slope and elevated flow speed and turbulence close to the foundation are still likely to apply. No direct assessment is offered within this document as to the potential impact on sensitive ecological receptors.

The assessment presented here is not intended for use in detailed engineering design. However, methodologies similar to those recommended for the design of offshore wind foundations (DNV, 2016) have been used in some cases where they are applicable. The methods applied to assess scour are set out in Appendix C.

9.2 Baseline conditions

Where obstacles are not present on the seabed, normal sediment transport processes can cause spatial and temporal variations in seabed level and sediment character in the baseline environment. Scour is a similar but localised change resulting from particular local patterns of sediment transport. Scour may also occur in the baseline environment in response to natural obstacles such as rocky outcrops or boulders. Key features of the baseline environment pertinent to the assessment of scour due to the presence of wind farm infrastructure are summarised below:

- Seabed sediments within and nearby to the Thanet Extension array area are typically characterised by the presence of fine to coarse sands, with smaller areas of muddy sand and sandy gravel (Fugro, 2016a; Thanet Offshore Wind Limited, 2005). These sediments will be regularly mobilised by the relatively strong tidal currents.

- In several places within the Thanet Extension array area the surficial sediment units are either very thin or absent, with the underlying geology exposed at the bed. Conversely, where bedforms are present the surficial sediment layer may (locally) be several metres thick (Fugro, 2016a); and

- Locally, the seabed level is expected to vary naturally on hourly timescales in the order of centimetres to decimetres, due to the migration of small scale bedforms due to the action of tidal currents and waves. Larger natural variation in bed level over longer timescales might be associated with regional scale bed level change and the migration of larger sandwave features which are present within the Thanet Extension array area.

9.3 Evidence base

The most relevant evidence available to inform understanding of the potential for scour development within the Thanet Extension array area is the post construction survey monitoring from the operational TOWF (Titan, 2012a,b, 2013; MES Ltd, 2013). Wind turbines within the TOWF site are supported by monopile foundations with diameters of between 4.1 and 4.9 m and no scour protection is present. TOWF was constructed between 2008 and 2010 and repeat high-resolution bathymetric surveys as well as sediment sampling was carried out at four turbine locations between 03/04/2012 and 21/04/2013. The width, depth and gradient of scour around each turbine are set out in Table 23, with key observations summarised below. Seabed scour at Turbine E01 is shown in Figure 18.

- At turbines E01, E02, F01 and F02, scour depth ranged between 3.5 m and 4.7 m in a circular shape around the base of the monopile. Scour depth has mostly stayed consistent throughout the analysis period, though a slight increase has been detected at turbines E01 and F02;

- Erosion has caused scour width to slightly increase around the turbine monopile at all locations over the analysis period; and

- Within the assessed scour pits, substrates were found to comprise a mixture of coarse sediments ranging from muddy sandy gravels to cobbles. On average these sediments were coarser than those recorded from samples throughout the TOWF site.

The post construction monitoring evidence therefore generally suggests that the vast majority of scour had been accomplished by the start of the monitoring campaign (in spring 2012).

Table 23. Turbine scour summary with the TOWF site

Date Surveyed	Turbine Number	Width (m)	Scour Depth (m)	Max Gradient (deg)
E01	03/04/2012	22	4.1	49.5
	13/10/2012	24	4.7	38.1
	21/04/2013	25	4.4	43.2
E02	03/04/2012	18	3.7	47.5
	13/10/2012	19	3.7	30.0
	21/04/2013	20	3.7	31.7
F01	03/04/2012	22	3.5	51.0
	13/10/2012	25	3.5	38.0
	21/04/2013	27	3.7	37.5
F02	03/04/2012	20	3.2	44.0
	13/10/2012	21	3.6	30.4
	21/04/2013	21	3.8	30.5

Source: Titan (2012 a, b, 2013)

Whitehouse (1998) provides a synthesis of a range of research papers, industry reports, monitoring studies and other evidence available at that time, describing the patterns and dimensions of scour that result from a variety of obstacle shapes, sizes and environmental conditions. Building upon a theoretical understanding of the processes involved, the accepted methods for the prediction of scour mainly rely on stochastic relationships and approaches (i.e. relationships that are based on and describe the available evidence). As such, scour analysis is an evidence based science where suitable analogues provide the most robust basis for prediction.

Since the publication of Whitehouse (1998), evidence continues to be collected and other predictive relationships have been developed and reported by the research community. In general, more recent observations have confirmed the approaches (and associated ranges of uncertainty) presented in Whitehouse (1998). As the evidence base has grown, additional approaches and relationships have been developed to better predict scour for a wider range of more specific obstacle shapes, sizes and environmental conditions.

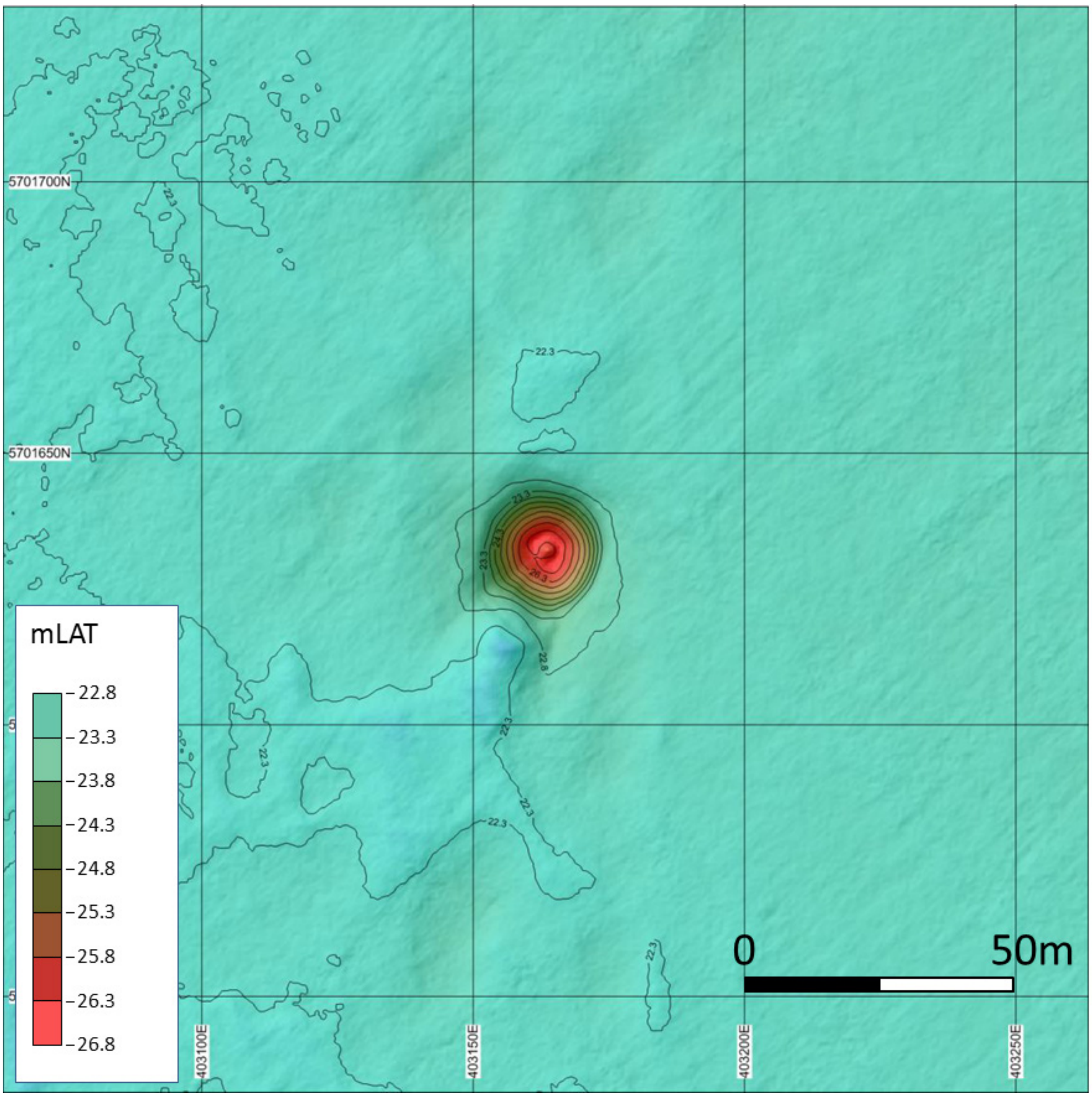


Figure 18. Turbine E01 with circular scouring

In addition to the monitoring evidence from the TOWF array, monitoring evidence regarding scour development around unprotected wind farm monopile installations is provided by HR Wallingford *et al*. (2007) and ABPmer *et al*. (2010) in a series of monitoring data synthesis reports for the Department for Trade and Industry (DTI) and the Collaborative Offshore Wind Research into the Environment (COWRIE). HR Wallingford *et al*. (2007) note that the available data support the view that scour is a progressive process that can occur where the seabed sediment is potentially erodible and there is an adequate thickness of that sediment for scouring to occur. Where the seabed comprises consolidated pre-Holocene sedimentary units (such as that encountered within many areas of the Thanet Extension array area), the scour will be slower to develop and limited in depth. For instance, geotechnical surveys at Kentish Flats offshore wind farm (Outer Thames) show that the seabed consists of non-cohesive sands over more resistant London Clay. The post construction monitoring evidence generally indicates that maximum scour rates around the monopiles (of diameter 4.3 m) occurred during the first year from installation and then rapidly slowed with near stability occurring by the third anniversary of the works. Scour depths ranged from 1.5 to 1.9 m at the monitoring locations and the results indicate that the scour depth is restricted by the cohesive underlying clay formation.

9.4 Assessment

9.4.1 Outline of structures considered in assessment

The following foundation structures have been considered within the assessment presented in this section:

- Monopile foundations:
  - 10 m diameter (largest) and 9.0 m diameter (mid-size)[3];
- Quadropod foundations: and
  - 40 m x 40 m base with four 3.5 m diameter leg piles (largest) and 30 m x 30 m base with four 3.0 m diameter leg piles (smallest).

For each foundation type, both the largest and smallest structures have been considered. This is because the former has the potential to cause the greatest extent of scour at the scale of individual foundations whereas the latter may potentially be associated with the greatest extent of scour at the array scale, owing to the larger number of structures.

9.4.2 Factors affecting equilibrium scour depth

As summarised in Whitehouse (1998), a number of factors are known to influence equilibrium scour depth for monopiles, contributing to the range of observed equilibrium scour depths. These factors include the:

- Frequency and magnitude of ambient sediment transport;
- Ratio of monopile diameter to water depth;
- Ratio of monopile diameter to peak flow speed;
- Ratio of monopile diameter to sediment grain size; and
- Sediment grain size, gradation and geotechnical soil properties.

The influence of these factors where they do apply is to generally reduce the depth, extent and volume of the predicted scour, hence providing a less conservative estimate. For example, a greater frequency and magnitude of sediment transport can actually reduce the equilibrium scour depth, as the scour hole is also simultaneously being (partially) in-filled by ambient sediment transport.

The above factors have been considered in the context of the Thanet Extension array area and were not found to significantly or consistently reduce the predicted values for the purposes of EIA.

The greatest influence on local scour depth would arise from the installation of scour protection. If correctly designed and installed, scour protection will essentially prevent the development of local primary scour as described in this section. The dimensions and nature of scour protection may vary between designs but, given its purpose, would likely cover an area of seabed approximately similar to the predicted extent of the scour.

Interaction between ambient currents and the scour protection may lead to the development of secondary scour at its edges. The local dimensions of secondary scour are highly dependent upon the specific shape, design and placement of the protection. These parameters are highly variable and so there is no clear quantitative method or evidence base for accurately predicting the dimensions of

[3] The mid-size (10 MW) option is considered here as there may potentially be 34 turbines of this size i.e. the same number as the smallest (8 MW) option.

secondary scour. However, as for foundations, the approximate scale of the scour depth and extent is likely to be proportional to the much smaller size of the individual elements comprising the protection.

9.4.3 Time for scour to develop around the foundation options

Scour depth can vary significantly under combined current and wave conditions through time (Harris *et al*., 2010). Monitoring of scour development around monopile foundations in UK offshore wind sites suggest that the time-scale to achieve equilibrium conditions can be of the order of 60 days in environments with a potentially mobile seabed (Harris *et al*., 2010). However, as previously stated in Section 9.3, equilibrium scour depths may not be reached for a period of several months or even a few years where erosion resistant sediments/ geology are present. This assertion is supported by the post construction monitoring from the TOWF, described in Section 9.3. These values account for tidal variations as well as the influence of waves. (Near) symmetrical scour will only develop following exposure to both flood and ebb tidal directions.

Under waves or combined waves and currents an equilibrium scour depth for the conditions existing at that time may be achieved over a period of minutes, whilst typically under tidal flows alone equilibrium scour conditions may take several months to develop.

9.4.4 Spatial extent of scour

At the Scroby Sands offshore wind farm, narrow, elongated scour features have been observed to extend over tens or hundreds of metres from individual foundations, leading to a more extensive impact than would normally be predicted. The development of elongate scour features at Scroby Sands is considered to have occurred due to the strongly rectilinear nature of the tidal currents (a very well defined tidal current axis with minimal deviation during each half tidal cycle) which allows the narrow turbulent wake behind each foundation to persist over the same areas of seabed for a greater proportion of the time, leading to net erosion in these areas. Due to a relatively higher rate of tidal rotation, the development of elongate scour features is not considered likely to occur within the Thanet Extension array area. This assertion is supported by the field evidence from TOWF (Titan, 2012 a, b, 2013).

9.4.5 Results

Table 24 and Table 25 summarise the key results of the first-order scour assessment undertaken using the methodological approach set out in Appendix C. Results conservatively assume maximum equilibrium scour depths are symmetrically present around the perimeter of the structure in a uniform and frequently mobile sedimentary environment with unlimited seabed thickness. Local scour extent is measured from the edge of the monopile or quadropod pin pile; 'global scour' extent is measured from the centroid of the quadropod foundation location. Global scour refers to a region of shallower but potentially more extensive scour associated with a multi-member foundation resulting from the change in flow velocity through the gaps between members of the structure and turbulence shed by the entire structure. Global scour does not imply scour at the scale of the wind farm array.

Scour footprints exclude the footprint of the structure. Scour pit volumes for monopiles and quadropod foundation structures are calculated as the volume of an inverted truncated cone, minus the structure volume; scour pit volume for the quadropod foundations are similarly calculated but as the sum of that predicted for each the corner piles.

Table 24. Summary of predicted maximum scour dimensions for largest individual turbine foundation structures

Parameter		Foundation Type	
		Monopile (10 m Diameter)	4 legged Quadropod (40 m x 40 m x 4 m Legs)
Equilibrium Scour Depth (m)	Steady current	13.0	5.2
	Waves	Insufficient for scour	Insufficient for scour
	Waves and current	13.0	5.2
	Global scour	N/A	1.6
Extent from foundation* (m)	Local scour	20.8	8.3
	Global scour	N/A	40.0
Footprint [a] (m^2)	Structure alone	78.5	50.3
	Local scour (exc. structure)	2,013.3	1,288.5
	Global scour (exc. structure)	N/A	4,976.3
Volume [a] (m^3)	Local scour (exc. structure)	10,141.6	2,596.0
	Global scour (exc. local scour and structure)	N/A	7,962.1
	Drill arisings or bed preparation	1,325.4	1,400.0

[a] Based upon the scour depth for steady currents. Footprint and volume values are per foundation.

Table 25. Total seabed footprint of the different turbine foundation types with and without scour

Parameter	Monopiles		4 Legged Quadropod	
	(9.0 m Diameter)	(10 m Diameter)	(30 m Base)	(40 m Base)
Maximum number of foundations	34 (+1 OSS & 1 met mast)	28 (+1 OSS & 1 met mast)	34 (+1 OSS & 1 met mast)	28 (+1 OSS & 1 met mast)
Seabed footprint of all foundations (m^2)	2,305	2,356	1,018	1,486
Proportion of Thanet Extension array area [a] (%)	< 0.1%	< 0.1%	< 0.1%	< 0.1%
Seabed footprint of all local scour (m^2)	59,091	60,400	26,093	38,092
Proportion of Thanet Extension array area [a] (%)	< 0.1%	< 0.1%	< 0.1%	< 0.1%
Seabed footprint of all foundations + local scour (m^2)	61,397	62,756	27,111	39,578
Proportion of Thanet Extension array area [a] (%)	< 0.1%	< 0.1%	< 0.1%	< 0.1%
Seabed footprint of all global scour (m^2)	N/A	N/A	100,770	147,111
Proportion of Thanet Extension array area [a] (%)	N/A	N/A	0.14	0.20

All scour dimensions are based upon the scour depth for steady currents.
[a] Corresponding proportion of the Thanet Extension array area (72.8 km^2).

Key findings are summarised below:

- Scour development within the Thanet Extension array area is expected to be dominated by the action of tidal currents;
- The greatest area of local scour effect (per foundation) is associated with the largest (12 MW) monopiles (10 m diameter), with an area of 2,013 m^2 susceptible to scour development;
- The greatest potential volume of scoured material from a single foundation is associated with the largest monopile (10 m diameter), with a scoured volume of 10,141 m^3 per foundation;
- For the Thanet Extension array as a whole, the greatest extent of local scour would be associated with an array comprising 28 large sized (12 MW) monopile foundations (and 1 OSS and 1 met mast). The potential spatial extent of this scour (excluding the footprint of the foundations) is 60,400 m^2: this would represent approximately 0.08% of the total Thanet Extension array area;
- For the Thanet Extension array as a whole, the greatest extent of global scour would be associated with an array comprising 28 large quadropod foundations (and 1 OSS and 1 met mast). The potential spatial extent of this scour (147,111 m^2) would represent approximately 0.2% of the total Thanet Extension array area; and
- Erosion resistant (pre-Holocene) material is present at or close to the seabed in several areas of the Thanet Extension array area and this is likely to lead to a natural limitation of scour depth and a related reduction in the footprint and volume of seabed affected by scour, both for individual foundations and for the array as a whole.

9.5 Cumulative changes

Scour around all structures will be confined to the Thanet Extension array area. Accordingly, there is no potential for cumulative changes arising from interactions with other projects.

10 Decommissioning

The following decommissioning activities could potentially give rise to increases in SSC and associated deposition of material with in the Thanet Extension array area and the export cable corridor:

- Removal of foundation structures;
- Cutting off of monopiles and quadropod foundation legs;
- Cutting off sub-sea cables and leaving *in-situ*; and/or
- (Possible) removal of cables from the intertidal zone.

However, any changes will be comparable (or subordinate) to those already identified and described for the construction phase (see Section 3 and Section 5). Any changes to the tidal (Section 6), wave (Section 7) and sediment transport (Section 8) regimes as a consequence of the decommissioning phase will also be less than for the construction and operation phases.

Post-decommissioning, the Thanet extension array area and export cable corridor is expected to return to the baseline conditions, allowing for some measure of climate change and within the range of natural variability.

11 Summary

This technical Annex provides an assessment of the potential for change to marine physical processes as a consequence of the construction, operation & maintenance and decommissioning of the Thanet Extension (array area and export cable corridor), both on its own and in conjunction with other built and consented projects. These findings have subsequently been used to underpin the significance of effect assessments for physical processes receptors, presented in Volume 2, Chapter 2: Marine Geology, Oceanography and Physical Processes (Document Ref: 6.2.2). The results have also been used to inform assessments for other EIA receptor groups which may potentially be sensitive to changes in physical processes.

In order to assess the potential changes relative to the baseline (existing) coastal and marine environment, a combination of complementary approaches have been adopted for the Thanet Extension physical processes assessment. These include:

- The 'evidence base' containing monitoring data collected during the construction and operation of other OWF developments, in particular the operational TOWF. The evidence base also includes results from numerical modelling and desk based analyses undertaken to support other OWF EIAs;
- Analytical assessments of project-specific data, including the use of rule based numerical models; and
- Standard empirical equations describing the relationship between (for example) hydrodynamic forcing and sediment transport or settling and mobilisation characteristics of sediment particles released during construction activities (e.g. Soulsby, 1997).

A wide range of potential changes to physical processes have been considered. These can broadly be summarised as follows:

- Construction and decommissioning phase: short-term sediment disturbance due to mechanical interaction with the seabed during foundation and cable laying activities, with material being transported in the water column and deposited at locations away from the source;
- Operational phase: persistent blockage of the passage of waves and tides due the physical presence of structures on the seabed and through the water column during the lifetime of the Project (30 years, but may increase by the time the project nears decommissioning as technology/maintenance improves), with the potential for localised interactions leading to the probable development of turbid wakes and possible scouring around the base of individual foundations; and
- Potential cumulative modifications of marine processes associated with overlapping "array scale" changes between Thanet Extension and other nearby projects that are of a concern to an environmental receptor.

All assessments have been made with due consideration of naturally occurring variability in, or long-term changes to, marine processes during the proposed developments' lifetime. This encompasses both seasonal change as well as climate change. This is important as it enables a reference level to be established against which the potentially modified marine processes can be compared, throughout the proposed developments' lifecycle.

Key findings from the assessments presented in this technical Annex are summarised below:

- Construction related activities within the Thanet Extension array area and along the export cable corridor will result in sediment plumes and associated changes in bed levels due to settling. The concentration and persistence of sediment plumes will depend upon the prevailing hydrodynamic conditions and nature of the disturbed sediment. Short term and localised elevations in SSC of several hundred mg/l can be expected within close proximity to the location of sediment disturbance although elevations in SSC of this magnitude will be very short lived;

- Measurable sediment plumes arising from construction related activities will be restricted to the distance of one spring tidal excursion ellipse from the source of sediment disturbance;

- Owing to the presence of sandwaves within the array area and along the export cable corridor, sandwave clearance operations may be required. However, the proposed activities are not expected to adversely alter wider sediment transport pathways;

- The exact method for cable installation at the landfall has not yet been determined although may involve trenching across the intertidal. However, cable trenches would only be open for a very short period of time and therefore the potential for interference with coastal processes will be very limited. Accordingly, there would be no potential for long term morphological change;

- Provided the export cables at the landfall are buried at a sufficient depth below the bed, the cables will have no potential to influence hydrodynamics or coastal morphology throughout the lifetime of the Project. However, managing the risk of exposure related to the ongoing northward migration of the River Stour Channel will be important. This will require detailed consideration within the engineering design of the landfall, in particular with regards to the exact location, installation method and burial depth for cables;

- It is reasonable to assume that turbid wake features are likely to develop as a consequence of wind turbine foundation installation within the Thanet Extension array area. These features can be expected to extend outside of the array area and develop regardless of the foundation type (monopiles or quadropods) as both will realistically result in the development of turbulent wakes. However, whilst surface SSC may be higher than baseline levels in areas where turbid wakes are present, depth averaged SSC will remain unaltered as no additional material is being added;

- The Kent coast is potentially sensitive to modification of the wave regime, through changes to the net rate and direction of longshore sediment transport. However, it is found that any changes to the wave regime at the coast would be very small (not measurable in practice and within the range of natural variability) and as such, the potential for morphological change to the shoreline would be extremely limited;

- A number of sandbanks are located within relatively close proximity to the Thanet Extension array area, including South Falls (approximately 6 km to the east). Sandbanks are potentially sensitive to changes in tidal current and waves; however, the extent of change to both of these parameters as a result of the operational presence of Thanet Extension will be insufficient to cause widespread morphological impacts;

- A number of designated chalk features are located within the study area including cliffs, platforms and reefs. However, because changes to the wave and tide will be of very small magnitude, there will be no measurable increase in erosion of the chalk features; and

- Scour development around wind turbine foundations within the Thanet Extension array area is expected to be dominated by the action of tidal currents. However, erosion resistant (pre-Holocene) material is present at or close to the seabed in several areas of the Thanet Extension array area. This is likely to lead to a natural limitation of scour depth and a related reduction in the footprint and volume of seabed affected by scour, both for individual foundations and for the array as a whole.

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13 Abbreviations/Acronyms

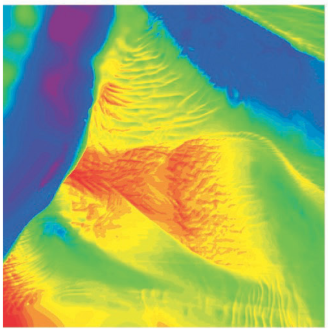
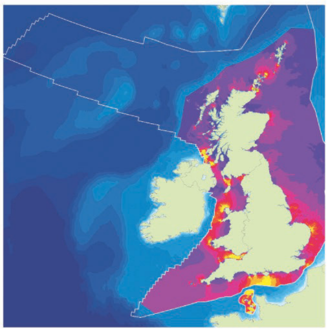
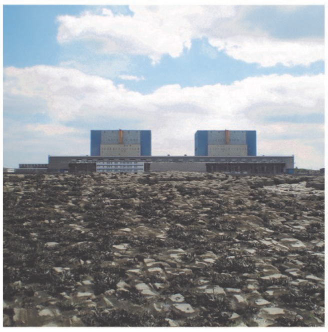
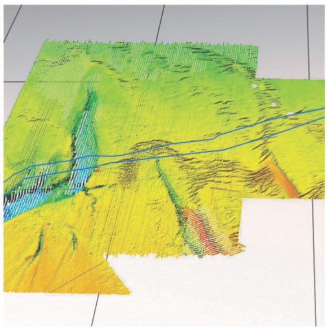
AWAC	Acoustic Wave and Current meter
BERR	Department for Business Enterprise and Regulatory Reform
BGS	British Geological Survey
BODC	British Oceanographic Data Centre
BSB	Base of Sea Bed
CCO	Channel Coastal Observatory
CD	Chart Datum
CEA	Cumulative Effects Assessment
Cefas	Centre for Environment, Fisheries and Aquaculture Science
COWRIE	Collaborative Offshore Wind Research into the Environment
CPT	Seabed Cone Penetration Test
CREL	Centrica Renewable Energy Ltd
deg	Degree(s)
DHB	Dover Harbour Board
DNV	Det Norske Veritas
DONG	Dong Energy
DSM	Digital Surface Model
DTI	Department for Trade and Industry
DTM	Digital Terrain Model
EA	Environment Agency
EIA	Environmental Impact Assessment
ES	Environmental Statement
GFS	Global Forecast System
GIS	Geographic Information System
GoBe	GoBe Consultants Ltd
HAT	Highest Astronomical Tide
HDD	Horizontal Directional Drilling
Hs	Significant Wave Height
HSE	Health and Safety Executive
HTL	Hold The Line
JNCC	Joint Nature Conservation Committee
KC	Keulegan-Carpenter
LAT	Lowest Astronomical Tide
LiDAR	Light Detection and Ranging
MAG	Magnetometer
MALSF	Marine Aggregate Levy Sustainability Fund
MAREA	Marine Aggregate Regional Environmental Assessment
MBES	Multibeam Echo Sounder
MESL	Marine Ecological Surveys Ltd
MHWS	Mean High Water Springs
MSL	Mean Sea Level
MW	Megawatt
NA	Not Applicable
NAI	No Active Intervention
NASA	North America Space Agency
NCEP	National Centres for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
NOC	National Oceanography Centre

NTSLF	National Tide and Sea Level Facility
OBS	Optical Backscatter Point Sensor
ODN	Ordnance Datum Newlyn
OECC	Offshore Export Cable Corridor
OLI	Operational Land Imager
OSS	Offshore substation
OWF	Offshore Wind Farm
PDS	Project Design Statement
PEI	Preliminary Environmental Information
PEIR	Preliminary Environmental Information Report
PINS	Planning Inspectorate
POL	Proudman Oceanographic Laboratory
PSA	Particle Size Analysis
REC	Regional Environmental Characterisation
SAC	Special Areas of Conservation
SAR	Synthetic Aperture Radar
SBES	Single Beam Echo Sounder
SBP	Pinger
SECG	South East Coastal Group
SMP	Shoreline Management Plan
SNSSTS	Southern North Sea Sediment Transport Study
SOLAS	Safety of Life At Sea
SPM	Suspended particulate matter
SSC	Suspended Sediment Concentration
SSS	Sidescan sonar
TEDA	Thames Estuary Dredging Associated
Tm	Mean wave period
TOWF	Thanet Offshore Wind Farm
Tp	Peak Period
TSHD	Trailer Suction Hopper Dredger
TS-X	TerraSAR-X
UHR	Ultra-High Resolution
UK	United Kingdom
UKCIP	UK Climate Impacts Programme
UKCP09	UK Climate Projections 2009
UKHO	United Kingdom Hydrographic Office
UKMO	Met Office European Wave Model
UNCLOS	The United Nations Convention on the Law of the Sea
USA	United States of America
UTC	Universal Coordinated Time
VOS	Voluntary Observing Ships
WTG	Wind Turbine Generator

Cardinal points/directions are used unless otherwise stated.

SI units are used unless otherwise stated.

Appendices

Innovative Thinking - Sustainable Solutions

A Supporting Data

A.1 Approach

The evidence base provided in the main report is supported by a data and literature search for Marine Geology, Oceanography and Physical Processes and is presented in this Appendix. This has been undertaken through reference to (i) primary, secondary and tertiary datasets; (ii) published and grey literature; and (iii) data archives/ online repositories. The review was carried out in 2016 and covers the following parameters:

- Water levels (tidal and residual surge);
- Currents (tidal and non-tidal);
- Wind;
- Waves;
- Sediments (including concentrations, fluxes, transport pathways); and
- Seabed morphology.

The output from this activity is principally a list of the available literature and data sources and where possible a summary of findings associated with the study area. These are expressed in high-level terms and based on the present understanding to identify the main physical processes and highlight likely spatial variations across the study area. In addition, the list includes high-level details of suitable models that have been developed for the area.

A desk-based data and information review has identified a large number of potentially useful metocean records. The metadata associated with these various sources has been presented within this section. Key technical and administrative information for each entry has been documented, including location (latitude and longitude), source and deployment period. Broad differentiation is made between 'near' and 'far' field records. Near-field records are located within the Thanet Extension array area and/or export cable corridor. Far-field records lie within the far-field boundary defined in Figure 1 of this Annex.

A.2 Water Levels

Marine water level measurements typically contain both a predictable astronomical tidal signal (that is caused by the sun and moon), as well as a more random non-tidal signal caused primarily by meteorological influences. In particular, regional scale patterns of atmospheric pressure and wind speed can depress/raise the water surface from the predictable tidal level, generating negative/positive residual surges, respectively. These surges are formed by rapid changes in atmospheric pressure with an inverse relationship, i.e. low atmospheric pressure raises the water surface (positive surge) and high atmospheric pressure depresses the water surface (negative surge). Available water level records from the study area are summarised in Table A1.

A.2.1.1 Tidal water levels

The best available data for characterising tidal heights within the study area, which are ordered in relation to quality, extent, resolution and relevance to inform the EIA are:

- The National Tide and Sea Level Facility (NTSLF);
- United Kingdom Hydrographic Office (UKHO) Co-tidal charts;
- Metocean modelling results (HR Wallingford, 2007);
- HSE (2002); and
- The Marine Renewables Atlas (ABPmer *et al.*, 2008).

The best quality water level information is available from the NTSLF which comprises the UK National Tide Gauge Network (as well as geodetic networks for monitoring vertical land movements). This source provides long-term quality assured information from a network of 44 maintained coastal gauges which have been levelled in to Ordnance Datum. The closest standard port to the study area is located at Dover, with a secondary port at Sheerness. Data is available from 1924 for Dover and is available under licence from http://www.pol.ac.uk/ntslf/.

Water level information is also available from a series of models which have been calibrated against permanent (shore-based) tide gauges located within the region and then subsequently used to extrapolate values for offshore areas. This includes the results of the metocean study completed for the TOWF by HR Wallingford (2007).

Maps of mean spring tidal range are available from HSE (2002). Whilst this data source does not provide a time-series of continuous data, it can be used to further validate the regional scale performance of other numerical models or previously published results.

Further synoptic data is available from the Marine Renewables Atlas and is available to download from http://www.renewables-atlas.info/, including information on the co-tidal and co-range characteristics across the study area.

A.2.1.2 Non-tidal water levels

Non-tidal water level data is available from several sources, which are ordered and presented in relation to quality, extent, resolution and relevance to inform the EIA:

- The National Tide and Sea Level Facility (NTSLF);
- Environment Agency (EA, 2011a);
- Metocean modelling results (HR Wallingford, 2007);
- UKCIP (2009); and
- HSE (2002).

Data from tide gauges provided by the NTSLF provides typically robust long term time series data for total water levels (including tidal and non-tidal effects) and thereby also providing non-tidal information at coastal locations.

Information on extreme water level return periods (up to 1:10,000 years) for coastal locations is available from the Environment Agency (EA, 2011a). In this Annex, statistical analysis (skew surge joint probability method) has been applied to data from the POL continental shelf tide-surge (CSX3) model (12 km resolution) to provide return-period predictions for locations around the coast. Further information on the extreme sea level conditions was also provided in the TOWF metocean study (HR Wallingford, 2007). The extreme levels were in turn determined from previous assessments completed using tidal data from Margate and Ramsgate (Jeremy Benn Associates, 2004, as referenced in HR Wallingford, 2007).

Information on the rate and magnitude of anticipated relative sea level change in this region during the 21st Century is available from UKCP09 (http://ukclimateprojections.metoffice.gov.uk/). It is predicted in UKCP09 that by 2050, relative sea level will have risen by approximately 0.35 m above 1990 levels (medium emissions scenario) at the landfall with rates of change increasing over time.

Maps of the extreme 50-year return period positive storm surge elevation are available from the Health and Safety Executive (HSE) (HSE, 2002). Given the intended use of this data source for engineering design, the information is considered to be conservatively realistic and robust, although the spatial resolution is relatively low within the study area.

Table A1 Water level records

Technical							Administrative
Record	**Water Level Parameter**	**Record Type**	**Latitude (°N)**	**Longitude (°E)**	**Deployment Duration**	**Near/Far Field**	**Supporting Information (Availability and Licensing)**
National Tide and Sea Level Facility (NOC)	Tidal water levels Storm surges	Observational time-series	Sheerness		1952-present	Far	Data available to download: http://www.ntslf.org/networks
			Dover		1924-present		
Admiralty co-tidal and co-range charts (UKHO)	Tidal water levels	Prediction	(UK seas)		(Not applicable)	Near and Far	Digital versions available to order from SeaZone Solutions as part of the HydroSpatial product: http://www.seazone.com/marine-maps/products
TotalTide (UKHO)	Tidal water levels	Model Prediction	(UK seas)		(Not applicable)	Near and Far	http://www.ukho.gov.uk/PRODUCTSANDSERVICES/Pages/Home.aspx
TOWF Metocean report (HR Wallingford, 2007)	Tidal water levels Extreme sea level	Model Prediction	Thames Estuary		(Not applicable)	Near and Far	Results presented in report
Marine Renewables Atlas (ABPmer *et al*., 2008)	Tidal water levels	Synoptic data	(UK seas)		(Not applicable)	Near and Far	Data available to download: http://www.renewables-atlas.info/
HSE (2002) Extremes Report	Storm surges	Prediction	(UK seas)		(Not applicable)	Near and Far	
Environment Agency Extremes Report (2011a)	Extreme sea level Storm surges	Prediction			(Not applicable)	Near and Far	Report available to download: http://publications.environment-agency.gov.uk/
UKCP09 (Lowe *et al*., 2009)	Long-term Future MSL	Model Prediction	(UK coastal locations)		(Not applicable)	Near and Far	Data available to download: http://ukclimateprojections-ui.defra.gov.uk/ui/admin/login.php

A.3 Currents

The current regime within the study area comprises (i) astronomically driven tidal currents; and (ii) non-tidal currents associated with meteorological forcing. In this region, residual storm surge currents are the most significant non-tidal currents and may cause an increase in the locally observed current speed, additional to that expected from astronomical forcing alone.

Available current records from the study area are summarised in Table A2.

A.3.1 Tidal currents

Tidal current data for the study area are available from several sources. These are ordered and presented in relation to quality, extent, resolution and relevance to inform the EIA:

- British Oceanographic Data Centre (BODC);
- Metocean modelling results (HR Wallingford, 2007);
- Southern North Sea Sediment Transport Study (HR Wallingford *et al*., 2002);
- English Channel/ Southern North Sea tidal model (ABPmer, 2008); and
- UKHO TotalTide;
- HSE (2002); and
- Marine Renewables Atlas (ABPmer *et al*., 2008).

The observed data from the BODC data archives are likely to be the most robust and accurate datasets but are typically limited in spatial and temporal resolution and coverage. There are approximately 60 BODC data sets in the greater Thames area. The BODC data sets are typically 1-6 weeks in duration and were mostly collected in the period 1970 to 1975, with a few more recent datasets in 1995. The type of measurement device used is typically an impellor vane meters measuring at a single height in the water column. There are no data sets available from within the Thanet Extension array area or export cable corridor; the closest data points are about 7 km away from the Project. Nonetheless information on the tidal currents will still be relevant in proximity to the extension area.

The metocean study for the TOWF EIA provides information on the current regime in and around the study area. This was based on a regional flow model for the Southern North Sea, updated for the properties local to the TOWF. The model was used to predict the influence of strong winds on tidal currents at the site for different return periods and outputs were assessed against Admiralty Tidal Diamond data for calibration and validation.

Mapped numerical model estimates of peak mean spring range tidal current speed and direction are available from HSE (2002). Whilst this data source does not provide a time-series of continuous data, it can be used to further validate the regional scale performance of other numerical models or previously published results.

The Admiralty 'TotalTide' software provides local time series information based on a high-level extrapolation of a small amount of historical measured data. TotalTide is therefore generally considered to be less accurate than many other primary and secondary data sources, but is still potentially useful for context in the absence of locally measured data. Data from the TotalTide software is broadly equivalent to the generalised tidal stream information quoted on UKHO Admiralty Charts.

A synoptic description of the tidal current regime within the study area is available from the Marine Renewables Atlas (ABPmer *et al.*, 2008). This provides a spatial and temporal description of astronomical tidal processes, to the level of accuracy achieved by model calibration and quantified by model validation. The dataset is considered to be less accurate than many other primary and secondary datasets as the tidal model has a coarse resolution of 1/60° latitude by 1/40° longitude, equating to approximately 1 nautical mile.

A.3.1.1 Non-tidal currents

Non-tidal current data for the study area are available from several sources and are ordered and presented in relation to quality, extent, resolution and relevance to inform the EIA for Thanet Extension:

- British Oceanographic Data Centre (BODC);
- Metocean modelling results (HR Wallingford, 2007);
- HSE (2002).

Non-tidal current information can be obtained from the available BODC current meter data sets using harmonic analysis. It is noted that observed data alone are normally of insufficient duration and spatial coverage to inform extreme return period analysis and so observed data will only ever normally be used to provide a sample of typical, non-extreme non-tidal currents.

To inform extreme value analysis, numerical models are normally used to simulate non-tidal process or a range of significant non-tidal events over much longer periods of time (decades). Using such model data, estimates of the 50-year return depth-averaged hourly-mean storm surge currents are available from HSE (2002).

Patterns of surge currents in and around the Project study area were also previously modelled by HR Wallingford (2007) using a selection of historical severe storms; some uncertainty was noted in relation to this study due to the wider possible range of actual conditions.

Table A2 Current records

Technical							Administrative
Record	Current Parameter	Record Type	Latitude (°N)	Longitude (°E)	Deployment Duration (days)	Near/ Far Field	Supporting Information
British Oceanographic Data Centre (BODC) current database	Tidal currents	Observational time-series	51.569 51.465 51.403	1.413 1.397 1.449	40 56 56	Far	Data holdings catalogue available: https://www.bodc.ac.uk/data/online_delivery/nodb/
TOWF Metocean report (HR Wallingford, 2007)	Tidal currents	Model Prediction	Thames Estuary		(Not applicable)	Near and Far	Results presented in report
English Channel and Southern North Sea model (ABPmer, 2008)	Tidal currents	Model Prediction	English Channel and Southern North Sea		(Not applicable)	Near and Far	NA
Southern North Sea Sediment Transport Study tide model (HR Wallingford, 2002)	Tidal currents Surge currents	Model Prediction	Southern North Sea		(Not applicable)	Near and Far	Report and associated project outputs available to download: http://www.sns2.org/project-outputs.html
Thames Estuary Dredging Association MAREA tide levels HR Wallingford, 2010)	Tidal currents	Model Prediction	Thames Estuary		(Not applicable)	Near and Far	Report available to download: http://www.marine-aggregate-rea.info/documents
Marine Renewables Atlas (ABPmer *et al.*, 2008)	Tidal currents	Synoptic data	(UK seas)		(Not applicable)	Near and Far	Data available to download: http://www.renewables-atlas.info/
UKHO tidal diamonds	Tidal currents	Model Prediction	(UK seas)		(Not applicable)	Near and Far	Information available through TotalTide. Annual subscription to the Admiralty Total Tide is £49.00. http://www.ukho.gov.uk/PRODUCTSANDSERVICES/Pages/Home.aspx
HSE (2002) Extremes Report	Surge currents	Prediction	(UK seas)		(Not applicable)	Near and Far	

A.4 Wind

Wind data for the study area are available from several sources and are ordered and presented in relation to quality, extent, resolution and relevance to inform the EIA:

- Thanet meteorological buoy;
- Met Office hindcast data reported in HR Wallingford (2007);
- Other hindcast model data sources; (e.g. National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP) wind data)
- HSE (2002); and
- Marine Renewables Atlas (ABPmer *et al*., 2008).

The main primary wind data source within the study area is from the Thanet meteorological buoy, located within the existing TOWF. The buoy provides information on the wind speed and direction at 10-minute intervals for the period between 20/07/2005 and 19/06/2006. Additional information is available from the wave radar deployment between January 2011 and May 2014. This dataset provides information on the wind speed and direction at hourly intervals. Together these datasets provide local validation information regarding the wind characteristics within the Thanet Extension array area.

The metocean study associated with the TOWF (HR Wallingford, 2007) used the Met Office European Wave Model (UKMO), to provide long term hindcast wind data for a point located at 51.50°N, 1.53°E, near the TOWF, for the period between the October 1986 and March 2005. The wind information was taken from the UKMO data from a layer at 19.5 m above sea level in the atmospheric model. The hindcast model data was calibrated and validated against coincident measured data. The long time series of data was used to characterise the wind climate in various ways for the Thanet Extension array area.

Wind data are also available from other data providers, e.g. the ABPmer SEASTATES service, or the Met Office. The data would need to be validated against the nearest available measured data (i.e. the Thanet meteorological buoy) prior to use.

To inform extreme value analysis, numerical models are again normally used to simulate winds over much longer periods of time (decades). Using such model data, estimates of the extreme 50-year return period wind speed are available from HSE (2002).

Other synoptic wind data is presented in the Marine Renewables Atlas (ABPmer *et al*., 2008). This data source does not provide the same level of detail about wind climate as the site specific metocean study and hindcast time series described above, but does provide some additional regional context regarding any potential spatial gradients in wind climate. The Marine Renewables Atlas draws upon seven years of detailed wind information sourced from the Met Office UK Wavewatch III model. Monthly, seasonal and annual wind data is available from the study area (at a spatial resolution of approximately 8 km and at a height from the ground of 80 and 100 m) and can be accessed from http://www.renewables-atlas.info. Using the Atlas, it might be reasonably demonstrated/assumed that wind speed and direction (and so the wind climate) does not vary significantly over the Thanet Extension array area and export cable corridor, indicating the geographical area of validity when using certain data sources.

Available wind records from the study area are summarised in Table A3.

Table A3 Wind records

Technical							Administrative
Record	Parameter	Record Type	Latitude (°N)	Longitude (°E)	Deployment Period	Near/ Far Field	Supporting Information
TOWF meteorological buoy	10 minute mean wind speed and direction	Observational time-series			20/07/2005 – 19/06/2006	Near	Data associated with the post monitoring of the TOWF.
TOWF meteorological and wave radar	Hourly-mean values/	Observational time-series			01/01/2011 - 01/05/2014	Near	Data associated with the post monitoring of the TOWF
Met Office UK Waters Model/ Wave Watch III Model	(Hourly-mean values/ Extreme wave statistics)	Hindcast model data	51.51	1.53	(UK Waters model based on period Mar 2000 - Nov 2008; Wave Watch III 2008 -present)	Near	Model defined on 8 km grid
Visual observations from ships	Visibility measurements	Observational records	(Sea area covering the study area		1971 to 2010	Near and Far	The Met Office maintains a fleet of around 350 Voluntary Observing Ships (VOS) on which the crew make weather observations. These observations are made in support of the International Maritime Organization's SOLAS (Safety of Life At Sea) Convention.
Visibility data	Visibility measurements	Model	(European coverage)		(Unknown)	Near and Far	GFS (Global Forecast System) Global Model from the "*National Centres for Environmental Prediction*" (NCEP) Archive data available on request http://www.weatheronline.co.uk/cgi-bin/expertcharts=
Marine Renewables Atlas (ABPmer *et al.*, 2008)		Synoptic data	(UK Seas)		(Derived from 7 years of archive data spanning June 2000 – May 2007)	Near and Far	Data available to download: http://www.renewables-atlas.info/

A.4.1 Waves

The wave regime is defined as the combination of swell waves moving into and propagating through the study area and more locally generated wind-waves. Swell waves are long-crested, uniformly symmetrical waves which are generated remotely from the study area whilst wind-waves result from the transfer of wind energy to the water surface. In this region, the study area would be mainly exposed to waves from the north and east, originating in the North Sea.

Available wave records from the study area are summarised in Table A4.

Wave data for the study area are available from several sources and are ordered and presented in relation to quality, extent, resolution and relevance to inform the EIA:

- TOWF wave radar;
- South Knock (active) and Kentish Knock (historic) WaveNet sites;
- Goodwin Sands Channel Coastal Observatory Wave Rider buoy;
- Met Office hindcast data reported in HR Wallingford (2007);
- Other hindcast model data sources;
- HSE (2002; 2005); and
- Marine Renewables Atlas (ABPmer *et al*., 2008).

The only primary wave data source within the study area is from the wave radar deployed within the existing TOWF. This dataset provides hourly-averaged significant wave height and direction for the period between January 2011 and May 2014. It however does not provide information on the wave period for the observed wave conditions.

Additional wave datasets are available from the area surrounding the proposed development. It is important to note that individual data sources are of varying quality and duration. The highest quality datasets are the observational wave records available from WaveNet, for the South Knock (active) and Kentish Knock (historic) sites. Wave data are available from the Channel Coastal Observatory (CCO), from the Goodwin Sands Wave Rider buoy, south of the study area. It is noted that the CCO buoys are typically located in shallow (<10 m below Chart Datum, CD) water, where larger wave are more likely to be influenced by the local water depth. Measured wave data are also available from the Drill Stone Buoy location between February and December 2004, adjacent to the TOWF, mainly to inform the EIA for the London Array Round 2 OWF development.

The inherently limited duration and spatial coverage of the available observed data can be supplemented by numerical model outputs that can be used to characterise the wave regime across both the study area. HR Wallingford (2007) completed the modelling of the wave regime as part of the EIA for the TOWF. The model was developed using information from the Met Office UK Waters Wave model and validated against nearby observational time series.

If the originally used model data are no longer available, long term hindcast wave data are also available from other data providers, e.g. the ABPmer SEASTATES service, or the Met Office. The data would need to be validated against the nearest available measured data (i.e. the TOWF wave radar) prior to use.

Table A4 Wave records

Technical							Administrative
Record	**Wave Parameter**	**Record Type**	**Latitude (°N)**	**Longitude (°E)**	**Deployment Period**	**Near/Far Field**	**Supporting Information**
TOWF wave radar	(hourly wave statistics)	Observational time-series			01/01/2011 – 01/05/2014	Near	Data associated with the post monitoring of the TOWF
South Knock WaveNet Site (Cefas)	(hourly wave statistics)	Observational time-series	50.633	-1.717	15/01/2010 – present	Far	(Directional Waverider MkIII); 26 m water depth. http://cefas maps.defra.gov.uk/wavenetmapping/login.asp
Kentish Knock WaveNet Site (Cefas)					Historic deployment		
Goodwin Sands Wave Rider Buoy (Dover District Council) (CCO)	(hourly wave statistics)	Observational time-series	51.251	1.483	2008- present	Near	Datawell Directional Waverider Buoy Mk III (since June 2008) in around 20 m water depth. Data available to download: http://www.channelcoast.org/
Drill Stone Buoy	(hourly wave statistics)	Observational time-series			February to December 2004	Near	Dataset collected and used for the TOWF EIA
Met Office UK Waters Model/ Wave Watch III Model	(Hourly-mean values/ Extreme wave statistics)	Hindcast model data	(UK Seas)		(UK Waters model based on period Mar 2000 - Nov 2008; Wave Watch III 2008 -present)	Near and Far	Model defined on 8 km grid
TOWF Metocean report (HR Wallingford, 2007)	(Monthly/ annual wave statistics)	Model Prediction	Thames Estuary			Near and Far	Results presented in report
Southern North Sea Sediment Transport Study tide model (HR Wallingford, 2002)	(Monthly/ annual wave statistics)	Model Prediction	Southern North Sea		(Not applicable)	Near and Far	Report and associated project outputs available to download: http://www.sns2.org/project-outputs.html
Marine Renewables Atlas (ABPmer *et al.*, 2008)	(Monthly/ annual wave statistics)	Synoptic data	(UK Seas)		(Derived from 7 years of archive data)	Near and Far	Data available to download: http://www.renewables-atlas.info/
HSE (2001) extremes	(Extreme wave statistics)	Prediction	(UK Seas)			Near and Far	
Thames Estuary Dredging Association MAREA tide levels (HR Wallingford, 2010)	(Extreme wave statistics)	Model Prediction	Thames Estuary			Near and Far	Report available to download: http://www.marine-aggregate-rea.info/documents
Environment Agency (2011b) Design Swell Waves Report	(Extreme wave statistics)	Prediction	(UK Seas)			Far	Based on Met Office model and validated using WaveNet records. Report available to download: http://publications.environment-agency.gov.uk/

To inform extreme value analysis, numerical models are again normally used to simulate waves over much longer periods of time (decades). Using such model data, estimates of the extreme 50-year return period wave height are available from HSE (2002). Given the intended use of this data source for engineering design, the information is considered to be conservatively realistic and robust, although the spatial resolution is somewhat poor in the study area.

The Marine Renewables Atlas (ABPmer *et al.*, 2008) is a synoptic scale mapped data source providing a high level summary of seven years of modelled wave data sourced from the Met Office UK Waters Wave model. Monthly, seasonal and annual wave data are available from the study area (at a spatial resolution of approximately 8 km) and can be freely accessed from http://www.renewables-atlas.info. Due to the model resolution and validation, this information should only be used to provide regional context and is not appropriate to characterise the metocean conditions at the project level.

A.4.2 Seabed morphology and sediments

Extensive data are available on the sedimentological and morphological regime within the study area and in the far-field area. In this section, the sedimentological and morphological regimes have been considered under five separate headings. These are:

- Morphology;
- Seabed sediments;
- Sub-strata;
- Suspended sediments; and
- Sediment transport.

Available seabed morphology and sedimentary records from the study area are summarised in Table A5.

A.4.2.1 Morphology

Information used to inform the TOWF EIA provides the best available coverage and data quality for the Thanet Extension array area and export cable corridor. This includes seabed bathymetry data from multibeam echo sounder (MBES) survey carried out in 2005, in addition to historical bathymetry from 1960, 1970, 1973, 1980 and 1997, which were all used to inform the TOWF EIA. The historical datasets identified in the EIA report are not presently obviously available in the public domain and may require additional work to find and/or possibly digitise the original data.

Further MBES survey data is also available from the Outer Thames Estuary Coast REC, the footprint of which overlapped the northern part of the Thanet Extension array area. Notably, the surveys were completed along selected tracks, so the dataset only provides coverage along the narrow bands.

In this region, seabed morphology is largely related to the bedrock lithology, the availability of mobile sediment and wave and tidal action. On geological timescales, these parameters have been influenced by fluctuations in sea level over the Pleistocene period (last ~2.6 million years). The morphological elements encountered within the study area can be broadly separated into 'relict' and 'active features' and have been described in a number of publications including BGS (1989; 1990) and Cameron *et al.* (1992).

A.4.2.2 Seabed sediment

Information on the seabed sediments within the study area is available from samples, bathymetric and geophysical surveys completed for the TOWF EIA in 2005. These data provide the highest quality information regarding the spatial distribution of seabed sediments within the study area, as the completed survey encapsulated much of the Thanet Extension array area and export cable corridor.

The SNSSTS (HR Wallingford *et al*., 2002) provides distribution maps of seabed sediment, which was principally derived from British Geological Survey (BGS) sediment distribution maps (e.g. BGS, 1990), which are in turn based on the Folk (1954) sediment classification scheme. It should be noted though, that the resolution of the available PSA data is highly variable.

A further resource although beyond the extent of the study area is the spatial distribution of seabed sediments presented in the Outer Thames Estuary Regional Environmental Characterisation (REC) (Selby *et al*., 2009). These datasets provide data immediately north of the Thanet Extension array area and would provide information for the far-field area. Although this information is also based on existing BGS data, holdings, it has been augmented by Particle Size Analysis (PSA) data collected during the REC survey. The REC seabed sediment maps are freely available for download from the Marine Aggregate Levy Sustainability Fund (MALSF) (http://www.marinealsf.org.uk/data/) along with additional maps revealing (*inter alia*) median grain size and the percentage contributions of gravel, sand and mud in the seabed sediments.

Seabed sediment maps for the wider region have been compiled by the BGS. This information is available as a series of 1:250,000 hard copy maps (BGS 1989, 1990) whilst digital versions of these same publications are available for purchase through SeaZone solutions (http://www.seazone.com/index.php).

A.4.2.3 Sub-strata

Information on the near-surface geology is also available from geophysical surveys completed for the TOWF EIA in 2005 as indicated within the Environment Statement (Warwick Energy, 2005). This data is limited to the extent of the near-field study area.

Information on the geology across the study area is principally available from BGS compiled data. This includes the Solid Geology map (BGS, 1989) and '*Geology of the Southern North Sea*' publication (Cameron *et al*., 1992). This information was used as part of the SNSSTS (HR Wallingford *et al*., 2002). Detailed information on the boreholes records which were used to compile the solid geology information can be identified through the BGS GeoRecords Plus browser (http://shop.bgs.ac.uk/GeoRecords/).

A.4.2.4 Suspended sediments

Suspended sediment concentrations maps for the Southern North Sea were developed as part of the SNSSTS (HR Wallingford *et al*., 2002), which was in turn used to inform the EIA for TOWF.

More up to date data is available as a series of monthly/ seasonal/ annual turbidity maps from Dolphin *et al*. (2011) and Cefas (2016), based on satellite derived measurements of SPM. These satellite derived maps provide a very useful overview of spatial and temporal trends in suspended sediment concentrations at the regional scale. However, sources of uncertainty exist in the relationship between satellite-derived reflectance and ground-based SSC or turbidity data. These uncertainties result from differences in sediment colour, grain size, and mineralogy within a study region reducing accuracy and hence applicability at the local scale.

A.4.2.5 Sediment transport

Sediment movement occurs in the two following ways:

- Bedload transport of sand and gravel; and
- Suspended sediment transport of muds and fine sands.

The peak offshore tidal currents are the main control on sediment movement, rather than wave action, although during high energy storm events, sediment entrainment may occur as a combination of tidal and wave induced currents (Draper, 1967). However, these events are considered to be insignificant in terms of regional sediment transport due to their low frequency.

The most comprehensive repository of information on the direction of offshore and littoral (beach) sediment transport in this region is available from the bibliographic database compiled for the SNSSTS (http://www.sns2.org/). This includes information on the transport characteristics compiled from asymmetry observations in bedforms and modelled sediment transport regime. The study provide numerical model outputs quantifying the magnitude and direction of sediment transport for sediments of a given grain size. However, information of this type is of considerably less value than direct observational evidence provided by the analysis of bedforms. This is because the modelled sediment transport maps only provide information on the *theoretical* potential for sediment transport and typically do not account for those areas of the seabed where sediment is either absent or of a size that renders it immobile.

Assessment of the sediment transport characteristics was completed for the TOWF EIA under varying tide and wave conditions. The sediment transport characteristics were informed by the results obtained from the metocean study. It particularly considered the net sediment flux magnitude and rate of fine material over a tidal cycle associated with the transport of fine sand in suspension. Further data on the sediment transport potential within the study area and far-field region is available from the JNCC Coast and Seas of the United Kingdom, Region 7 report (Barne *et al.*, 1998).

Table A5 Seabed morphology and sedimentary records

Technical							Administrative
Record	Sediment Parameter	Authors/ Data Owner	Latitude (°N)	Longitude (°E)	Date of Publication/ Record	Near/ Far Field	Supporting Information
BGS grab sample data holdings	Seabed sediments Seabed morphology	(BGS)	(UK Seas)		(various)	Near and Far	Grab sample PSA data available from BGS. http://www.bgs.ac.uk/data/boreholes.html
BGS Thames Estuary 1:250,000 (i) Seabed Sediment and Quaternary	Seabed sediments Seabed morphology	BGS (1990)	51	0	1990	Near and Far	Digital seabed sediment tiles available from SeaZone Solutions. http://www.seazone.com/howtobuyLicencefees.php
(ii) Solid Geology map	Solid geology	BGS (1989)	51	0	1989		
The Geology of the Southern North Sea	Seabed sediments Seabed morphology Solid geology	Cameron *et al.*, (1992)	Southern North Sea		1992	Near and far	(Hard copy report)
Inshore seabed characterisation of the sector from Dungeness to the Deben Estuary	Seabed sediments Seabed morphology Solid geology	Evans and Slater (2000)	Thames Estuary		2000	Near and far	(Hard copy report)
Southern North Sea Sediment Transport Study tide model (HR Wallingford, 2002)	Seabed sediments Seabed morphology Sediment transport	HR Wallingford (2002)	Southern North Sea		2002	Near and far	Data derived from observational evidence and model predictions. Report and appendices available to download: http://www.sns2.org/project-outputs.html
The Outer Thames Estuary Regional Environmental Characterisation (Selby and Thomas, 2009)	Seabed sediments Seabed morphology Sediment transport	Selby, I. and Thomas N.	Outer Thames Estuary		2009	Near and far	Seabed sediment data (updated from BGS map). Hard copy report and GIS layers. Data available to download: http://www.thamesrecgis.org.uk/
Coasts and seas of the United Kingdom. Region 7 South-east England: Lowestoft to Dungeness	Seabed sediments Seabed morphology Sediment transport	JNCC/BGS Barne *et al.*, 1998	Coast between Lowestoft and Dungeness		1998	Near and far	(Hard copy report)
UKHO Admiralty Charts	Bathymetry	UKHO	(UK Seas)		(various)	Near and far	Digital Admiralty Chart tiles available from SeaZone Solutions. (http://www.seazone.com/howtobuyLicencefees.php)

Technical							Administrative
Record	Sediment Parameter	Authors/ Data Owner	Latitude (°N)	Longitude (°E)	Date of Publication/ Record	Near/ Far Field	Supporting Information
Aggregate Area Surveys	Bathymetry Seabed sediments	(Aggregate industry)	Thames Estuary		(various)	Near	Various single/ multi beam and sidescan sonar records from licence areas.
Thames Estuary Dredging Association MAREA Sediment Transport Study	Sediment transport)		Thames Estuary			Near and far	Data derived from observational evidence and model predictions. Report available to download: http://www.marine-aggregate-rea.info/documents
North Kent Coast - Isle of Grain to Dover Harbour, Subcell 4a & 4b - Shoreline Management Plan	Coastal morphology and type Sediment transport		North Kent coast		2009	Near	Report Available to download:
Sandbanks, sand transport and offshore wind farms	Sediment transport	Kenyon & Cooper (2005)	(UK Seas)		2005	Near and far	(Broads-scale, high level report useful for regional-scale characterisation)
Sand ribbons of the European tidal seas	Sediment transport	Kenyon (1970)	(UK Seas)		1970	Near and far	Marine Geology 9: 25–39. (Broads-scale, high level report useful for regional-scale characterisation)
UKSeaMap 2006/2010	Bed shear stress	Conner *et al.*, (2006).	(UK Seas)		2006	Near and far	Data derived from model predictions Wed based GIS and accompanying report: http://jncc.defra.gov.uk/page-5534
FutureCoast Project	Coastal morphology and type Sediment transport	Halcrow Group (for Defra)	(Not applicable)		2002	Near and far	Overview available: http://www.halcrow.com/Our-projects/Project-details/Futurecoast-England/
MALSF turbidity report	Suspended sediments	Dolphin *et al.*, (2011)	(Not applicable)		2011	Near and far	Data derived from satellite observations. Data available to download: http://www.marinealsf.org.uk/catalogue/

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B Determination of the Maximum Adverse Scenario for Wave and Current Blockage

B.1 Overview

This appendix sets out the justification of the realistic and likely 'worst case' of the various development options for local wave and tidal conditions. The identification of a worst case scenario for waves and tides represents the first stage of the assessment process, with the confirmed outcomes being used to support the development of the PEI and ES reports. Importantly, the considerations presented within this appendix are limited to the project design option(s) which are deemed to lead to the greatest degree of blockage effects on the passage of the tide and waves moving across the Thanet Extension array area and towards adjacent receptors, such as the neighbouring coastline.

B.1.1 Basis for worst case

The Scoping Opinion (PINS, 2017) states that where flexibility is sought in design of the Proposed Development at the time of application, the Applicant should consider a worst case approach with regard to the assessment on a topic specific basis.

In line with accepted practice, the worst case is established with reference to stated variations of key parameters that exist within the current detailed design (Volume 2, Chapter 1: Project Description - Offshore (Document Ref: 6.2.1)) but not beyond these.

B.1.2 Blockage effects

Blockage effects are a familiar consideration for solitary offshore oil and gas installations, and is generally determined from simple actuator disc theory where the effect can be considered directly proportional to the total 'projected' cross-sectional area of all structural members within the water column (HSE, 1997).

In their application to offshore wind farms, blockage effects on the free passage of waves and tidal flows can be related to the scale and type of foundation units being proposed (foundation scale) and further in relation to their multiple deployment across the scale of the development area to form an array (array scale).

The identification of a worst case scenario for waves and tides is based on the relative magnitude of blockage effects at both the foundation and array scale. This process is supported by detailed calculations and comparison of various measures of blockage, based on the proposed design envelope.

B.2 Summary Details for Thanet Extension Array Area

The following information for the Thanet Extension has been used in the assessment of blockage effects.

B.2.1 Variation in water depth

Throughout the array area water depths range between -11.5 m relative to Lowest Astronomical Tide (mLAT) and -45 mLAT (Fugro 2016). Eastern and north eastern areas of the array area are generally deeper, with the greatest water depths encountered along the southeast margin of the array. A major reef structure (Drill Stone Reef) exists in the north-east of the Thanet Extension array area. The reef stretches over approximately 3.5 km in west-north-west to east-south-east direction with a maximum width of approximately 1.3 km including a slightly detached part in the south-east.

B.2.2 Variation in water levels

B.2.2.1 Tidal water levels

By definition, the minimum tidal level is 0 mLAT, which is also close to local Chart Datum (CD). The Highest Astronomical Tide level (HAT) is at least 5.0 m CD, however, the tide only approaches these minimum and maximum levels infrequently, during vernal and autumnal equinoxes. Tidal water levels vary on a semi-diurnal basis (two high and low waters per day). The overall tidal range will vary predictably on spring-neap and other cycles.

As the development area extends over a distance of 14 km east to west and over 10 km north to south, then some measurable spatial variation in tidal range (and phase) is also expected.

A preliminary assessment of metocean design criteria (Vattenfall, 2015) compiled tidal levels at three locations around the perimeter of Thanet Extension, based on available hindcast information. This data suggested a minimal east to west variation in tidal range for mean spring tides of 4.36 to 4.38 m, but a more prominent north to south variation with a mean spring tidal range of up to 4.74 m, and a LAT to HAT range of up to 5.9 m.

B.2.2.2 Surge water levels

As well as a predictable tidal variation in water levels, the site is also exposed to residual surge related variations. These variations are generally expressed as a statistical extreme event with an amplitude that re-occurs on a return period basis. The available metocean study to inform preliminary design criteria (Vattenfall, 2015) suggests a positive and negative surge related influences of more than 1 m for a 1 in 1 return period event.

For the determination of the worst case for blockage related effects, only tidal variation in water depth has been considered, without surge influence.

B.2.3 Distance to the coastline

The inshore boundary for Thanet Extension array area is around 8 km from the adjacent shoreline at Broadstairs, compared to around 11 km for the existing operational TOWF.

B.2.4 Approaching waves

Waves approaching from seaward directions of 33 to 94°N would have the opportunity to pass through the Thanet Extension array area to reach the Kent shoreline. Within this arc, waves from 50 to 86°N would also be passing through the operational TOWF. Based on present understanding of long term wave behaviour, these directions also represent the most active and longest fetches from the southern North Sea.

B.2.5 Current directions

Flood tide currents are orientated in an approximate south-southwesterly direction and ebb currents are approximately to the north-northeast.

B.3 Estimating Blockage

B.3.1 Foundation scale

The worst case option for foundation scale blockage is determined from a comparison of the relative size of each foundation unit in the water column, quantified by the cross-sectional area of all structural members presented normal to tidal flows and waves.

B.3.1.1 Foundation types

Three foundation types remain under consideration in the Project Design Statement (Revision 6); (i) monopile, (ii) tripod (piled or suction caisson), and (iii) quadropod (piled or suction caisson). Since the tripod leg/ cross brace dimensions are no greater than for quadropods, they are not considered further in this assessment as this necessarily means they will provide lesser blockage. Gravity bases are not under consideration for Thanet Extension.

In addition to turbine foundations there is also a single offshore sub-station with foundation options of monopile, tripod or quadropod. The tripod and quadropod options may utilise pin piles or suction caissons.

B.3.1.2 Foundation (turbine) size

Each variant of foundation type is also scaled to accommodate three possible turbine rating options; 8, 10 or 12 MW, with the highest rated turbine requiring the largest sized foundation of each type. The variation in turbine rating also leads to a variation in the number of turbines and so the number of foundations required in the Thanet Extension array area.

It is noted here that subject to final design it is possible that an alternative, larger capacity, turbine (i.e. >12 MW) type may be selected. In this scenario the overall project capacity will remain at 340 MW and the physical parameters such as maximum blade tip height, rotor diameter, and height of nacelle will remain within the maximum envelope described in this chapter and subsequent technical assessment chapters.

B.3.1.3 Results

On the basis of typical water depths (including tidal variation) and foundation geometries offered in the Project Design Statement (PDS) a set of blockage estimations has been made based on the 'projected' cross-sectional area of each structure to the incident flow and wave conditions. For the quadropod structures, the PDS also states the maximum number of structural levels through the vertical, up to HAT (affecting the distribution of the secondary members). For the purposes of a worst case estimation, the number of levels is not varied across the site to any specific water depth. The PDS also assumes scour to be active around each caisson which also suggests that the caisson must remain proud of the seabed to some extent. In addition, pin piles are installed through sleeves which will have a slightly larger diameter and will also remain proud of the seabed by a nominal amount. Sensitivity in blockage estimates is examined by varying the water depth, tidal influence and likely heights of any protrusions.

Table B1 summarises normalised 'projected' cross-sectional values for each foundation type and scale to illustrate the case with the largest blockage effect (excluding the sub-station). Whilst the absolute values may vary to some degree for different water depths the ranking of largest blockage effect always remains as the suction caisson quadropod for the 12 MW turbine case.

Table B1 Normalised 'projected' cross-sectional area for each foundation (for typical depth of 25 m)

Foundation Type	Turbine Size (MW)		
	8	10	12
Monopile	0.29	0.32	0.45
Quadropod (piled)	0.66	0.66	0.99
Quadropod (suction caisson)	0.67	0.67	**1.00**

For comparison, the normalised 'projected' cross-section value for TOWF is 0.12, based on a 4.9 m diameter monopile.

B.3.2 Blockage: array scale

The worst case option for array scale blockage is determined by the multiple of individual foundation units, their relative spacing and the proximity to the related receptors based on a consideration of layout options. The key assumption at this stage is there are no mixed foundation types or turbine ratings requiring a mixture of foundation sizes.

B.3.2.1 Dimensions of development area

The Thanet extension array area surrounds the operational TOWF site and measures up to approximately 14.5 km along the east to west axis and up to approximately 10.5 km along the north to south axis. The total footprint of the Thanet Extension array area is 72.8 km^2 in comparison to 35 km^2 for TOWF.

B.3.2.2 Number of foundation units

There may be up to 34x8 or 10 MW rated turbines or up to 28x12 MW turbines, equivalent to a total installed capacity of 272, 340 or 226 MW, respectively. This equates to a density of (approximately) 0.4 to 0.5 turbines per km^2. In addition, there is also a single offshore substation. For TOWF, there are 100 turbines rated at 3 MW (300 MW of installed capacity) with a corresponding density of 2.9 turbines per km^2.

B.3.2.3 Results

The implications of the different number of foundation units of different dimensions forming the Thanet Extension array provides a further moderation to the 'projected' cross-sectional area at the array scale (Table B2). The suction caisson quadropod remains as the worst case option determined for blockage at the array scale despite there being only 28 installations compared to 34 for the other two cases.

For comparison, the normalised 'projected' cross-section value for the TOWF array, based on 100 units over 35 km^2 is 0.86. This normalised value is much larger than for the monopile cases being considered for Thanet Extension, as might be expected due to the greater density of turbines per km^2. The value is also very similar to the array blockage from 8 and 10 MW quadropod foundations;

however, the largest array scale blockage value is the 12 MW quadropod case (using either pin piles or suction caissons).

Table B2 Normalised 'projected' cross-sectional area for the array scale (for typical depth of 25 m)

Foundation Type	Turbine Size (MW)		
	8	10	12
Monopile	0.19	0.20	0.24
Quadropod (piled)	0.81	0.81	0.99
Quadropod (suction caisson)	0.82	0.82	**1.00**

Various indicative layouts remain under consideration and the final layout will only be confirmed in conjunction with detailed post-consent site investigation work.

The minimum turbine spacing is 716 m x 480 m although the final layout may well have greater spacing between turbines. For comparative purposes, TOWF has separations of 500 m within rows and 800 m between rows.

The effect of placing turbines closer together would be to increase the relative blockage effect for these portion of the Thanet Extension array area. The worst case option will also occur where more of the sites are placed closer to the receptor of interest (e.g. the coast or offshore sandbanks).

Given that the separation between foundations is large relative to the size of the individual foundations, interaction between foundation units is expected to be very limited and the array scale affect is likely to remain as the sum of individual foundation effects.

B.4 Summary of Worst Case Option for Thanet Extension

From a consideration of the information presented in the PDS, the worst case option for waves and tidal flows is considered to be the 12 MW quadropod suction caisson foundation. This conclusion is based on an assessment of relative 'projected' cross-sectional blockage effects determined from the summation of all structural members comprising each foundation comprising the full array.

The relative array blockage effect for all monopile cases would remain less than TOWF. The 8 and 10 MW quadropod cases would be of similar magnitude to TOWF, with the 12 MW case being the highest relative blockage. The suction caisson option would appear to be the worst case for blockage, assuming that each caisson unit remains proud of the seabed by a nominal amount.

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C Scour

C.1 Overview

In order to quantify the area of seabed that might be affected by scour (either the footprint of scour or scour protection), estimates of the theoretical maximum depth and extent of scour are provided below. Estimates are made of the primary scour, i.e. the scour pit directly associated with the presence of the main obstacle. The equilibrium primary scour depth for each foundation type has been conservatively calculated assuming the absence of any scour protection, using empirical relationships described in Whitehouse (1998). This analysis considers scour resulting from the characteristic wave and current regime, both alone and in combination.

The project description (Volume 2, Chapter 1: Project Description - Offshore (Document Ref: 6.2.1)) provides maximum adverse scenario extents of scour protection for each foundation type. Scour protection might be applied around the base of some or all foundations depending upon the seabed conditions and other engineering requirements. By design, scour protection will largely prevent the development of primary scour, but may itself cause smaller scale secondary scour due to turbulence at the edges of the scour protection area.

C.2 Assumptions

The following scour assessment for Thanet Extension reports the estimated equilibrium scour depth, which assumes that there are no limits to the depth or extent of scour development by time or the nature of the sedimentary or metocean environments. As such, the results of this study are considered to be conservative and provide an (over-) estimation of the maximum potential scour depth, footprint and volume. Several factors may naturally reduce or restrict the equilibrium scour depth locally, with a corresponding reduction in the area and volume of change.

This study makes the basic assumption that the seabed comprises an unlimited thickness of uniform non-cohesive and easily eroded sediment. The Thanet Extension specific surveys indicate that whilst unconsolidated surficial sediment is present in many areas, this unit is typically thin (generally less than ~1 m thick) or absent across much of the array area. In practice, once exposed by initial scouring, the more erosion resistant subsoils are expected to either reduce or prevent further scour, limiting the depth, extent and volume of scour accordingly.

The foundation types, dimensions and numbers used in the assessment are consistent with the project design information provided in Volume 2, Chapter 1: Project Description - Offshore (Document Ref: 6.2.1).

Reported observations of scour under steady current conditions (e.g. in rivers) generally show that the upstream slope of the depression is typically equal to the angle of internal friction for the exposed sediment (typically 32° in loose medium sand; Hoffmans and Verheil, 1997) but the downstream slope is typically less steep. In reversing (tidal) current conditions, both slopes will develop under alternating upstream and downstream forcing and so will tend towards the less steep or an intermediate condition. For the purposes of the present study a representative angle of internal friction (32°) will be used as the characteristic slope angle for scour development.

C.3 Equilibrium Scour Depth

The maximum equilibrium scour depth (S_e) is defined as the depth of the scour pit adjacent to the structure, below the mean ambient or original seabed level. The value of Se is typically proportional to the diameter of the structure and so is commonly expressed in units of structure diameter (D).

Scour depth decreases with distance from the edge of the foundation. The scour extent (S_{extent}) is defined as the radial distance from the edge of the structure (and the point of maximum scour depth) to the edge of the scour pit (where the bed level is again equal to the mean ambient or original seabed level). This is calculated on the basis of a linear slope at the angle of internal friction for the sediment, i.e.:

$$S_{extent} = \frac{S_e}{tan32°} \approx S_e \times 1.6$$

(Eq. 1)

The scour footprint ($S_{footprint}$) is defined as the seabed area affected by scour, excluding the foundation's footprint, i.e.:

$$S_{footprint} = \pi\ S_{extent} + \frac{D^2}{2}\ \ \pi \frac{D^2}{2}$$

(Eq. 2)

The scour pit volume is calculated as the volume of an inverted truncated cone described by Equations 1 and 2 above, accounting for the presence of the foundation but excluding its volume.

C.4 Scour Assessment Method: Monopiles

The outline design of the proposed monopile structure is shown in Figure C1 Compared to other more complex foundation types, scour around upright slender monopile structures in steady currents is relatively well-understood in the literature and is supported by a relatively large empirical evidence base from the laboratory and from the field. The maximum equilibrium scour depth, adjacent to the structure, below the mean seabed level (S_c), is typically proportional to the diameter of the monopile and is therefore expressed in units of monopile diameter (D).

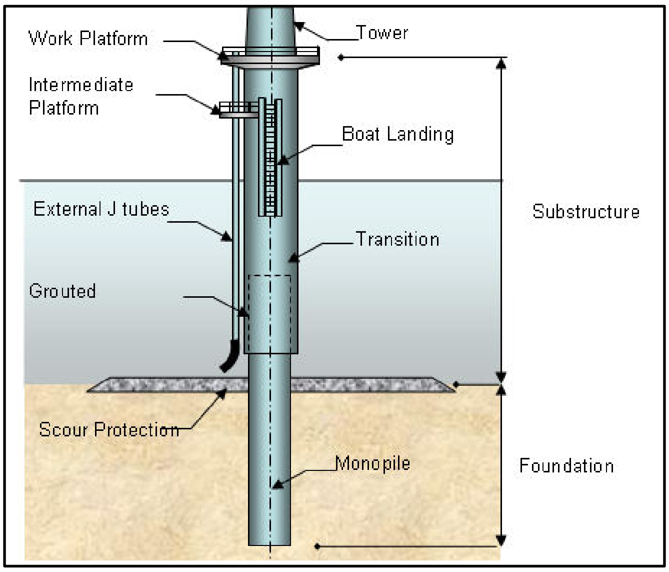

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Figure C1. Outline design of a typical steel monopile foundation (with scour protection)

C.4.1 Under steady currents

Breusers *et al.* (1977) presented a simple expression for scour depth under live-bed scour (i.e. scour occurring in a dynamic sediment environment) which was extended by Sumer *et al.* (1992) who assessed the statistics of the original data to show that:

$$\frac{S_c}{D} = 1.3 \pm \sigma_{S_c/D}$$

(Eq. 3)

Where $\sigma_{Sc/D}$ is the standard deviation of observed ratio S_c /D. Based on the experimental data, $\sigma_{Sc/D}$ is approximately 0.7, hence, 95 % of observed scour falls within two standard deviations, i.e. in the range $0 < S_c/D < 2.7$. Based on the central value $S_c = 1.3$ D (as also recommended in DNV, 2016), the maximum equilibrium depth of scour for the largest diameter monopile (10 m) is estimated to be 13.0 m. The equivalent value for the smallest diameter monopile (8.5 m) is 11.1 m.

C.4.1.1 Under waves and combined wave-current forcing

The mechanisms of scour associated with wave action are limited when the oscillatory displacement of water at the seabed is less than the length or size of the structure around which it is flowing. This ratio is typically parameterised using the Keulegan-Carpenter (KC) number:

$$KC = \frac{U_{0m} T}{D}$$

(Eq. 4)

Where U_{0m} is the peak orbital velocity at the seabed (e.g. using methods presented in Soulsby, 1997) and T is the corresponding wave period. Sumer and Fredsøe (2001) found that for KC < 6, wave action is insufficient to cause significant scour in both wave alone and combined wave-current scenarios.

Values of KC are < 6 for monopiles in the Thanet Extension array area, for a range of extreme wave conditions (see Table C1) and for the full expected range of tidally affected water depths across the site (approximately -11.5 mLAT to -45 mLAT). Therefore, it is predicted that waves do not have the potential to contribute to scour development around monopiles in the Thanet Extension array area.

Table C1 Extreme omni-directional wave conditions considered.

Return Period (years)	Significant Wave Height, Hs (m)	Zero crossing Period, Tz[1] (s)
1:1	3.9	5.8
1:10	4.9	6.4
1:100	5.7	6.9
[1] Defined as the portion of a wave record between two successive zero up crossings		

Source: Thanet Offshore Wind Limited (2005); ABPmer SEASTATES

The value of U_{0m} for given (offshore or deep water) wave conditions depends upon the local water depth, which varies between approximately -11.5 mLAT to -45 mLAT within the array due to variations in absolute bathymetry and relative water level; the influence of shoaling and wave breaking have been ignored in the present study (a conservative assumption).

C.5 Scour Assessment Method: Quadropod Foundations

The outline design of the proposed four legged quadropod foundation for turbines is shown in Figure C2 Above the seabed quadropod foundations comprise a lattice of vertical primary members and diagonal cross-member bracing, up to 3.5 m and 2.5 m in diameter, respectably. Near-bed horizontal cross-member bracing will be approximately 3 m above the bed which is sufficiently high into the water column not induce significant local scour. The four legged quadropod foundation will have a nominally square plan view cross-section with base edge dimensions of between 30 m and 40 m (Volume 2, Chapter 1: Project Description - Offshore (Document Ref: 6.2.1)).

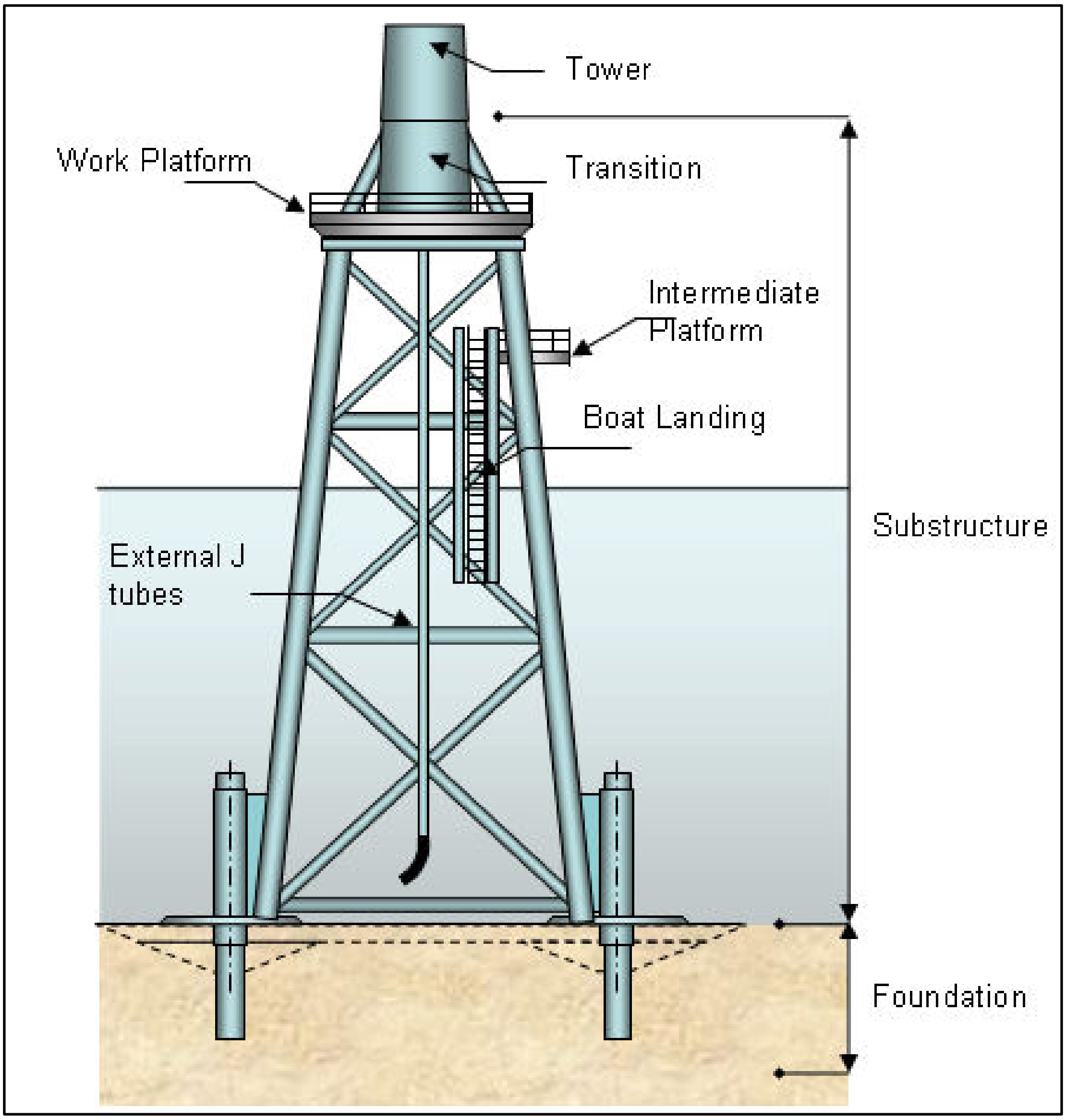

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Figure C2. Outline design of a typical quadropod foundation

The quadropod foundation is anchored to the seabed at each corner by a pile driven into the seabed, between 3 and 4 m in diameter. A quadropod foundation structure may result in the occurrence of both local and group or global scour. The local scour is the local response to individual structure members.

C.5.1 Under steady currents

Under steady currents alone, the equilibrium scour depth around the vertical members of the structure base can be assessed using the same methods as for monopiles, unless significant interaction between individual members occurs. The potential for such interaction is discussed below. The main scour development will be in proportion to the size of the largest exposed member near to the seabed. In this case, the largest exposed member will be the leg pile: for the largest quadropod foundation this will have a diameter of 4 m. Using Equation 3, the scour depth for the largest quadropod foundation is therefore estimated as 5.2 m. The equivalent value for the smallest quadropod foundation (leg pile diameter of 3 m) is 3.9 m.

In the case of currents, inter-member interaction has been shown to be a factor when the gap to pile diameter ratio (G/D) is less than 3. In this case limited experiments by Gormsen and Larson (1984) have shown that the scour depth might increase by between 5% and 15%. However, in the case of the present study the gap ratio for members at the base of the quadropod foundation structure is much greater than 3, and so no significant in-combination change is expected.

Empirical relationships also presented in Sumer and Fredsøe (2002) indicate that the depth of group scour (measured from the initial sediment surface to the new sediment surface surrounding local scour holes) for an array of piles similar to a quadropod foundation (2x2) can be approximated as 0.4 D (i.e. approximately 1.6 m based on 4 m diameter quadropod leg pile). On the basis of visual descriptions of group scour pits, their extent from the edge of the structure is estimated as half the width of the structure and following a broadly similar plan shape to that of the quadropod foundation (i.e. square).

Together, the predicted maximum scour depth at the corner piles (5.2 m) and the group scour (1.6 m) is conservatively consistent with evidence from the field reported in Whitehouse (1998), summarising another report that scour depths of between 0.6 m and 3.6 m were observed below quadropod structures in the Gulf of Mexico (although these could potentially be constrained from the maximum possible equilibrium scour depth by environmental factors and could also be subject to uncertainties in the seabed reference datum against which to measure the scour).

On the basis of the proposed quadropod design, the diagonal bracing members are not predicted to induce seabed scouring due to the distance of separation from the seabed.

C.5.2 Under waves and combined wave-current forcing

Values of the KC parameter (Eq. 4) were calculated for a 4 m diameter quadropod leg pile from the extreme wave conditions found at the site (Table C1). Values of KC are less than 6 over the full expected range of tidally affected water depths across the site (approximately -11.5 mLAT to -45 mLAT) and so it is predicted that waves do not have the potential to contribute to scour development around the base of the quadropod foundations.

The diagonal bracing members will have a smaller diameter and so a larger KC value. However, they are again not predicted to induce seabed scouring due to the distance of separation from the seabed. For moderate KC numbers a sufficient distance to avoid scour is approximately one diameter for a horizontal member, increasing to approximately three diameters under increasing KC numbers. As such, little or no significant additional scour is predicted to result from waves, either alone or in combination with currents.

C.6 References

ABPmer SEASTATES: http://www.seastates.net/

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Contact Us

ABPmer

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

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

www.abpmer.co.uk