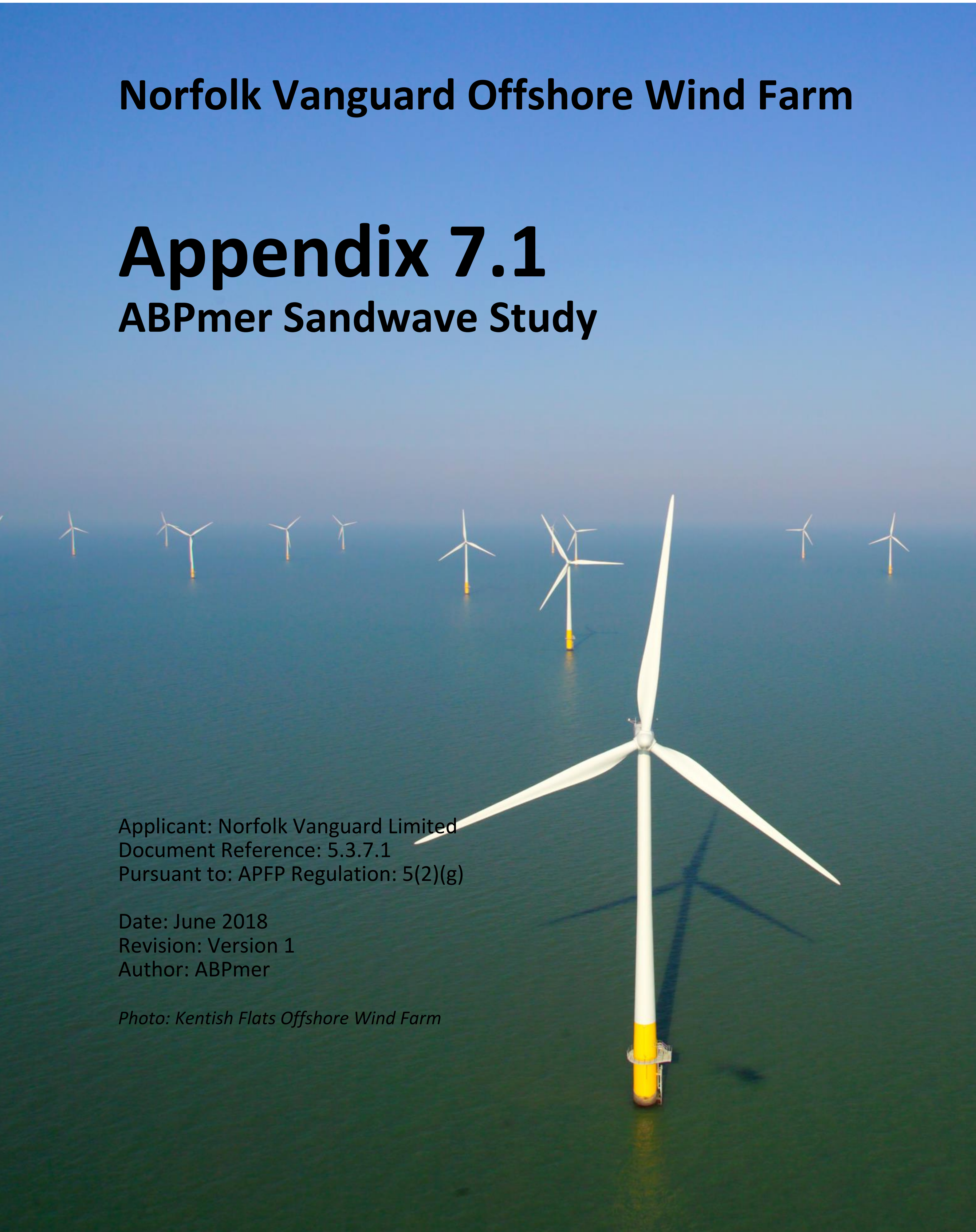
Norfolk Vanguard Offshore Wind Farm

Appendix 7.1
ABPmer Sandwave Study



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June 2018

For and on behalf of Norfolk Vanguard Limited

Approved by: Ruari Lean and Rebecca Sherwood

Signed: [redacted]

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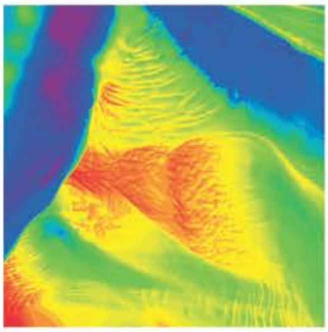
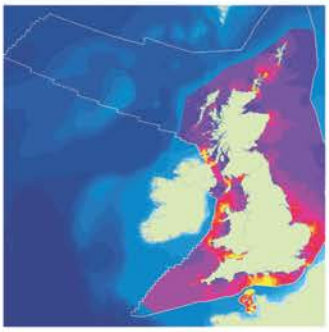
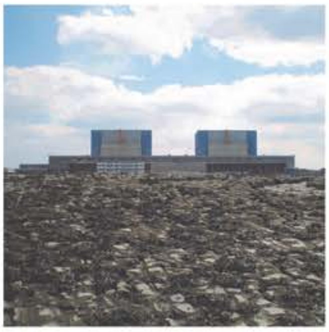
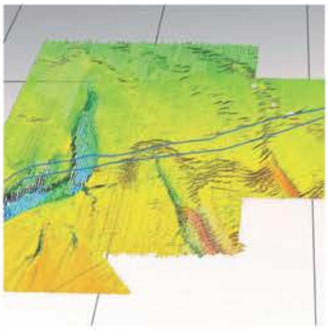
Royal HaskoningDHV

Norfolk Vanguard and Norfolk Boreas Export Cable Route

Sandwave bed levelling

April 2018

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Norfolk Vanguard and Norfolk Boreas Export Cable Route

Sandwave bed levelling

April 2018

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Summary

Vattenfall proposes to undertake cable installation activities in the offshore cable corridor for the Norfolk Vanguard and Norfolk Boreas Offshore Wind Farms and these works may entail seabed levelling through a number of sandwaves. Natural England has raised concerns about the proposed bed levelling works and is seeking reassurance that any future operations will not adversely affect the sandbank systems within the Haisborough, Hammond and Winterton Special Area of Conservation (SAC).

In order to address the concerns raised, ABPmer has completed a study assessing the potential for any impacts on the seabed and sandwave morphology within the study area and any onward effects on the form and function of the systems within the Haisborough, Hammond and Winterton SAC (hereafter referred to as the Haisborough SAC). This included investigating the sandwave properties (height, wavelength, asymmetry, mobility and migration characteristics) and the sediment transport potential present within the study area.

Results highlight the study area is in an active and highly dynamic environment, governed by flow speeds, water depth and sediment supply; conditions conducive for the development and ongoing maintenance of sandwave bedforms. Assessed sandwave migration rates varied between 5 and 30 m/year, with both northerly and southerly migrating sandwaves present along the cable corridor. The different migration directions relate to localised sediment re-circulation patterns around sandbanks or the influence of the bedload parting zone that crosses this part of the study area and Southern North Sea.

The estimated time for the cable trenches and the seabed levelling to be naturally infilled (and sandwave recovery) in relation to the transport regime is in the order of a few days to a year. This is based on the representative forcing conditions at a single water depth, with storm effects having the potential to accelerate the process to days or weeks. Due to the sandwave migration characteristics and prevalent sediment transport, it is likely that any affected sandwaves would have migrated away from the levelled area before being reformed.

The governing sediment transport processes within the Haisborough, Hammond and Winterton SAC study area, occurs at a much larger scale than the proposed bed levelling works. Therefore, these processes will not be disrupted by the localised bed levelling. In addition, the volume and area being affected is small in comparison to the volume of material within the local sandbank systems (i.e. Newarp Banks system) and the Haisborough SAC, as a whole.

Finally, the proposed sandwave levelling methodology is to dispose of sediment locally so there is no net loss of sediment to the SAC. It is therefore likely that neither the form nor function of the sandbank systems locally or within the wider Haisborough SAC will be disrupted as a result of the proposed levelling through the sandwave crest or sediment disposal within the indicative spoil zone.

The following can also be concluded from the study:

- Due to the ongoing migration characteristics of the sandwaves, in the time it takes the levelled area to reform, the sandwave, including the originally levelled area, would have moved and reshaped. Therefore, the levelled sandwaves are unlikely to fully return to their original shape, but this will not disrupt the onward migration of the sandwaves or the form and function of the sandwave field;
- The absolute width, length, shape and thickness of sediment deposition as a result of disposal cannot be predicted with certainty and is likely to vary due to the nature of the dredged

material, the local water depth and the ambient environmental conditions during disposal. However, there is not expected to be any significant difference in the thickness or extent of spoil deposits associated with either a surface release or disposal at the seabed via a downpipe. Following disposal, the material will most likely remain within the Haisborough SAC on the same time frame it would take surficial sediment to move through the Haisborough SAC as currently occurs; and

- The cable installation scenario would be the phased levelling at adjacent locations, with a short separation distance, aligned in an approximately south-north direction, with the works progressing in the same direction as sandwave migration (from south to north). In this scenario the adjacent or nearby areas of a sandwave could be repeatedly levelled up to four times. However, the area and volume of sandwave to clear per phase would be proportionally reduced. The likelihood of this altering the form and function of the sandwave field and the wider sandbank system is considered to be minimal. This is because all evidence suggests the study area is in a dynamic environment conducive to the development and maintenance of sandwaves. Sandwave bedforms are continually being modified, converging and bifurcating, also with new bedforms being created and migrating through the cable corridor.

Contents

Appendix

Tables

Figures

1 Introduction

Vattenfall proposes to undertake bed levelling activities through a number of sandwaves as part of cable installation activities in the export cable route for the Norfolk Vanguard and Norfolk Boreas Offshore Wind Farms. Part of the proposed bed levelling works is to occur on the sandwaves within the Haisborough, Hammond and Winterton Special Area of Conservation (SAC), referenced as the Haisborough SAC in the remainder of the report. The Haisborough SAC is designated as an Annex I habitat, on the basis of the sandbanks and biogenic reefs that occur within the area. This study mainly assesses the effects of works on the sandwave bedforms which are the smaller features that overly the more static and larger sandbank bedforms. Therefore in relation to the designated features, this study only focusses on the sandbank characteristics, for which the area is designated on the basis of the following descriptive criteria:

> *Sand banks which are slightly covered by sea water all the time. These features consist of sandy sediments that are permanently covered by shallow sea water, typically at depths of less than 20 m below chart datum (but sometimes including channels or other areas greater than 20 m deep (JNCC, 2010; 2017)).*

Natural England has raised concerns about the proposed bed levelling works, which are described further in Section 1.2. It is seeking reassurance that any future operations will not adversely affect the sandbank systems within the Haisborough SAC and therefore pose a risk to the conservation objectives of the site. The conservation objectives (JNCC and Natural England, 2013; JNCC, 2016; Natural England, 2017) are to ensure that subject to natural change, the integrity of the site is maintained or restored as appropriate, and that the site contributes to achieving the Favourable Conservation Status of its qualifying features, by maintaining or restoring:

- The extent and distribution of qualifying natural habitats and habitats of the qualifying species;
- The structure and function (including typical species) of qualifying natural habitats;
- The structure and function of the habitats of the qualifying species;
- The supporting processes on which qualifying natural habitats and the habitats of qualifying species rely;
- The populations of qualifying species; and
- The distribution of qualifying species within the site.

ABPmer has been commissioned to undertake an assessment of the potential nature, magnitude, extent and duration of effects of the proposed bed levelling activities on the physical environment. This is in relation to the structure and function of the qualifying natural habitat, which are the sandbanks (and overlying sandwaves, although not explicitly mentioned within the designation documents (JNCC and Natural England, 2013; JNCC, 2016)). No assessment has been undertaken for the qualifying species within the site, which is considered in a separate study (i.e. Envision Sabellaria reef mapping, Appendix 7.2 of the Norfolk Vanguard Information to support HRA report (Vattenfall, unpublished). This study assesses the effect of the proposed bed levelling with regards to:

- Potential effects on the local sandwave morphology and evolution;
- Potential effects on the seabed morphology and sediment transport regime; and
- Potential effects or onward effects on the structure and function of the sandwaves and sandbanks within the Haisborough SAC, in relation to the conservation objectives.

This study provides a summary of the relevant baseline environmental conditions and an estimated rate of recovery (including recovery of sediment volume and shape) for the sedimentary features which may be affected by the proposed bed levelling activities. In addition to understanding the general effects of bed levelling the following questions are considered in the concluding section:

- Will sandwaves within the Haisborough SAC reform following dredging of the crest?
- If the sediment is disposed of within an adjacent disposal site where will that sediment be transported to?
- Are there any onward effects on the form and functioning of the sandwaves and sandbanks within the Haisborough SAC?

Following an Evidence Plan Process meeting with the benthic ecology expert topic group[1] on 31 January 2018, a number of points for clarification were raised by Natural England which are also included in the report, namely:

- Further consideration of the sandwave recovery potential, providing evidence from existing examples or case studies where available;
- Assess the impacts of sediment disposal, including the deposition extent and thickness, also considering where the dredged and disposed sediment will go, and if will it remain within the Haisborough SAC. What are the different impacts with the sediment disposed at the sea surface or close to the seabed? and
- Reassess the effects on the local sandwave morphology and evolution, seabed morphology, sediment transport and onward effects on the form and function of the Haisborough SAC in relation to a phased cable installation methodology and redefined indicative spoil zone.

1.1 Study area

The study covers the area of the Haisborough SAC, focussing on the Newarp Banks sandbank system and cable corridor that transects the Haisborough SAC. The other sandbank systems present within the Haisborough SAC (i.e. further north of the cable corridor) are also discussed, as applicable, as is consideration of the larger region covered by the Southern North Sea.

The study area is located in an active and dynamic sediment environment that is conducive to the development and ongoing maintenance of sandwave bedforms. This is in relation to the governing tidal processes, seabed depths and abundant sediment availability. Depths within the study area generally range between -13 and -50 m Lowest Astronomical Tide (mLAT), with depths of between -23 to -28 mLAT typifying it. The study area along with the sandbanks which occur within the Haisborough SAC are illustrated in Figure 1.

Within the Haisborough SAC are a number of distinct sandbank systems. The Haisborough Sand sandbank system comprises of Haisborough Sand, Haisborough Tail, Hammond Knoll, Winterton Ridge and Hearty Knoll. These sandbanks in addition to Hewett Ridges, Smiths Knoll, Newarp Banks and Cross Sands make up the Haisborough, Hammond and Winterton SAC (Figure 1), which is classified for their Annex I habitat “Sandbanks slightly covered by sea water all the time".

The Haisborough Sand system is composed of alternating ridge headland associated sandbanks (Haisborough Sand) and open shelf sinusoidal sandbanks which have evolved over the last 5,000 years. The sandbanks would have originally been associated with the coastal alignment at the time the Holocene marine transgression occurred (Dyer and Huntley, 1999; Cooper *et al.*, 2008; JNCC, 2016).

1 MMO, Cefas, Natural England and Eastern Inshore Fisheries and Conservation Authority (EIFCA).

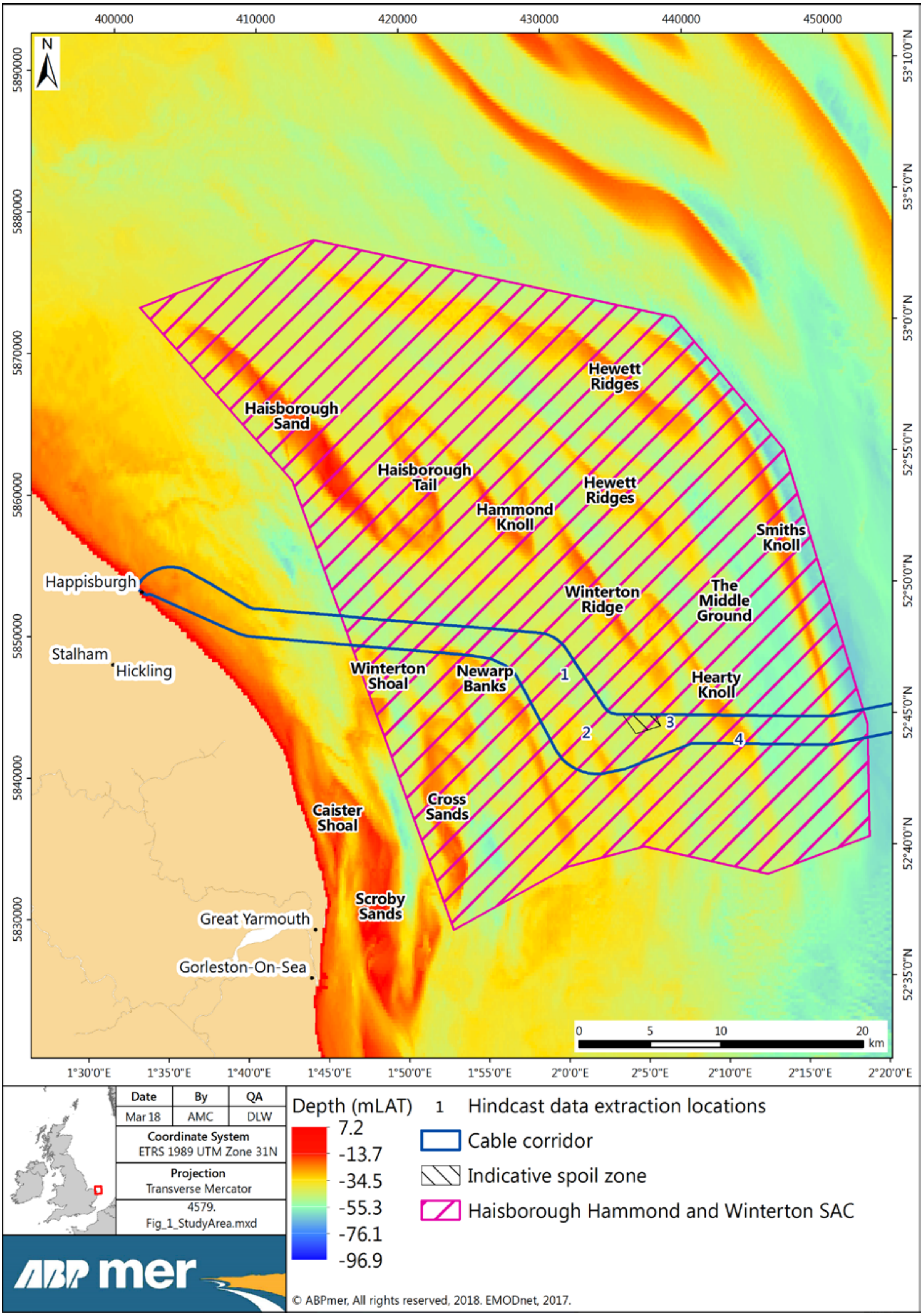

Figure 1. **Study area**

A recent study suggests this system comprises of one complex sinusoidal feature, with ongoing sediment linkages between the sandbanks from Haisborough Sand through to Hearty Knoll (Burningham and French, 2016).

Further offshore of the Haisborough system are Hewett Ridge and Smiths Knoll, which form an older sequence of sandbanks located along the outer boundary of the Haisborough SAC (Figure 1). The origin of these sandbanks is considered to be similar to the Haisborough sandbank system, which would have initially formed as alternating ridge headland associated sandbanks, but are geologically older (JNCC, 2016). These features are still actively evolving most likely due to the relatively shallow depths of their crests, which are likely to experience wave influence. Bed level differences estimated by Burningham and French (2016) provide evidence for migration of the sandbanks over the last 150 years, with the rate of change slowing more recently.

Inshore and to the southeast of the Haisborough system are Winterton Shoal, Newarp Banks and North and Middle Cross Sands (Figure 1). The origin of the inshore features is considered to be geologically recent (JNCC, 2016) and again originated as alternating ridge headland associated sandbanks. This sandbank system is of most interest to this study as the cable corridor passes through it.

1.2 Proposed bed levelling works

1.2.1 Introduction

Information on the proposed bed levelling is taken from the "Norfolk Vanguard Offshore Windfarm - Export Cable Installation Study (221_NVOWF_Installation_Study_002)" (CWind, 2017).

The export cable route and corridor cross a number of sandwaves and sandbanks. Were cables to be installed in the present day superficial sediments in the mobile parts of these features, they would be at risk of exposure, requiring regular monitoring and likely reburial. Localised bed levelling to remove the crests of mobile sandwaves and burying the cable into the underlying immobile seabed is therefore a proposed option. The majority of the sandwaves requiring levelling occur along the cable route within the Haisborough SAC.

Two methods are considered for carrying out the bed levelling work in CWind (2017), namely, a trailer suction hopper dredger (TSHD) or a mass flow excavator (MFE). Both of these techniques will displace sediment material to create a corridor through the sand wave crest in which the cable burial tool can then be used.

1.2.2 Assessment scenario

The cable installation scenario assessed in this report is the phased installation and associated bed levelling events across the Haisborough SAC, with a hiatus between phases. The following realistic worst case scenario for phasing of the export cable installation is as follows:

i. Bed levelling associated with the installation of Norfolk Vanguard cable pair 1;
ii. Gap of 6 to 24 months;
iii. Bed levelling associated with the installation of Norfolk Vanguard cable pair 2;
iv. Gap of 6 to 24 months;
v. Bed levelling associated with the installation of Norfolk Boreas cable pair 1;
vi. Gap of 6 to 24 months; and
vii. Bed levelling associated with the installation of Norfolk Boreas cable pair 2.

For the locations that require levelling, a dredge corridor for each cable with a nominal width of 7 m, allowing for 1:3 side slopes is applied. Based on the information presented in CWind (2017) and the associated supporting spatial data for the High Voltage Direct Current (HVDC) cables, the following applies:

- There will be two cable pairs for each offshore wind farm project and within each project there will be:
  - A 75 m separation between the cables pairs for each project, with around 68 m between the dredge corridor margins; and
  - Each cable pair will be laid in the same trench.
- There will be 250 m separation between the cables for each project.

1.2.3 Volumes for assessment

Initial estimations by CWind (2017) indicate that most sandwaves would be levelled by 0.5 to 4 m below the seabed surface, with isolated locations being levelled by as much as 6 m (associated with the crests of steep sandwaves generally in depths greater than -20 mLAT).

Vattenfall estimate a worst case dredge volume of 250,000 m^3 per cable pair (which also relates to per phase of installation). This results in a total volume of 500,000 m^3 per wind farm and a cumulative total of 1,000,000 m^3 for the Norfolk Vanguard and Norfolk Boreas Offshore Wind Farms within the SAC.

Based on the above phasing information and bed levelling volumes, an assessment of the impacts on sandwave recovery from the cable installation for Norfolk Vanguard and Norfolk Boreas individually and the cumulative impacts on sandwave recovery from both together is provided in Section 4.2.

Vattenfall aims to keep all the dredged sediment within the Haisborough SAC's boundaries during bed levelling activities. This is in order to keep the dredged sediment volume within the sandbank system, also enabling the material to be re-worked by natural processes and encouraging the re-establishment of bedform features (CWind, 2017). The exact disposal location and extent is still to be finalised, it is however, anticipated that material will be deposited within a suitable spoil disposal zone such as that shown indicatively in Figure 1. At present, based on the regional net sediment transport direction, the indicative spoil zone is located down-drift of where the proposed levelling is to occur, although there are likely to be spatial and temporal variations in the sediment transport characteristics (see Section 2.6.2.

2 Baseline Environmental Conditions

2.1 Previous studies

The study first completes a literature review from previous studies, summarising the baseline environmental conditions within the Haisborough SAC and the Southern North Sea where applicable. The following studies and data sources have been reviewed in order to inform the relevant environmental characteristics:

- Zonal Environmental Assessment (ZEA) Physical Processes Baseline (East Anglia Offshore Wind (EAOW), 2012 and the references therein);
- A synthesis of current knowledge on the genesis of the Great Yarmouth and Norfolk Bank Systems' (ABPmer, 2007; Cooper *et al*., 2008);
- Southern North Sea Sediment Transport Study Phase II (SNSSTS) (HR Wallingford *et al*., 2002);
- Sandbanks, sand transport and offshore wind farms (Kenyon and Cooper, 2005);
- Strategic Environmental Assessments Area 2– SEA 2 (Balson *et al*., 2001);
- SAC Selection Assessment Haisborough, Hammond and Winterton (JNCC, 2010);
- Historical morphodynamics of the Haisborough Sand bank system (Burningham and French, 2016);
- ABPmer SEASTATES Wave Hindcast Database (ABPmer, 2013); and
- ABPmer SEASTATES Tide and Surge Hindcast Database (ABPmer, 2017).

The ZEA physical processes baseline document (EAOW, 2012) is particularly useful due to the close proximity of the study area and the nature of the primary data collected to inform it.

2.2 Seabed depths

All depths specified within this report are referenced to depths below Lowest Astronomical Tide (LAT). Water depths within the Haisborough SAC approximately range between -2 and -55 mLAT. A number of the sandbanks within the SAC have fairly steep slopes with the sandbanks generally having heights of over 10 m above the surrounding seabed. The seabed between the sandbanks has depths of around -30 mLAT, with the deeper troughs between sandbanks being up to -50 mLAT in depth. These features fall within the JNCC description for the Annex I habitats defined in Section 1.

In the local vicinity of the cable corridor the seabed is characterised by relatively shallow water depths, with sandbank and sandwave bedforms present. In this area, water depths approximately range between -13 and -50 mLAT. The depths on the sandbank crests are at about -13 to -18 mLAT. Away from the crests and along the sandbank flanks, depths are typically between -23 and -28 mLAT, increasing to depths of up to -50 mLAT in the sandbank troughs. The shallowest areas (less than -15 mLAT) occur over the northern extent of the Newarp Bank and on the sinuous banks east of the main sandbank body, which are still classed as part of the Newarp Banks (Figure 1). The deepest areas occur at the eastern margin of the study area in a trough between Hearty Knoll and Smiths Knoll, and another trough running parallel to the eastern flank of Smiths Knoll. Figure 1 illustrates the depths within the study area and to the wider morphology within the Haisborough SAC, where similar depths occur.

A representative seabed depth of -28 mLAT is applied in the analyses completed as part of this study as it is the median depth that occurs locally in relation to the cable corridor and is considered a characteristic depth around the sandbank flanks.

2.3 Seabed morphology

The sandbanks which are present within the study area have developed and evolved during the Holocene period (Caston, 1972; Belderson *et al.*, 1982; Dyer and Huntley, 1999; Balson; 1999; HR Wallingford *et al.*, 2002.; Cooper *et al.*, 2008). These extend from 8 to 40 km offshore of the Norfolk coast and are subject to a range of current flow speeds, which are strongest around the inshore banks and reduce offshore (JNCC, 2010). Present understanding of the formation and morphology of the sandbanks can be summarised as follows:

- The sandbanks are formed on a relatively flat seabed comprising Pleistocene sediments (Cooper *et al,* 2008; Stride, 1988; Caston, 1972; Houbolt, 1968), with no underlying bedrock control (Burningham and French, 2016);
- The sandbanks have a northwest to southeast orientation and are asymmetric with a steeper flank facing the northeast (Stride, 1988; Caston, 1972; Houbolt, 1968);
- The summits of the sandbanks are in water shallower than -20 mLAT and the flanks of the banks extend into waters that are up to -40 mLAT deep;
- The internal structure of the sandbanks comprise layered sands interspersed by clay layers; this has been interpreted as sand laid down by tidal currents overlain by sand deposited after storm events with a higher content of fines (Stride, 1988); and
- The internal structure of the sandbanks indicates that they are migrating in a north-westerly direction at a rate of 1 to 16 m/year (Stride, 1988; Caston, 1972; Houbolt, 1968).

BGS maps and regional studies within the Southern North Sea identify that sandwaves are abundant across the study area and the wider region (BGS, 1984; 1988; Cameron *et al.*, 1992; McCave, 1971). Sandwaves commonly occur on the flanks of the large tidal sandbanks, but also occur on areas of seabed where sandbanks are absent but there is a sufficient supply of sand (Belderson, *et al.*, 1982; HR Wallingford *et al.*, 2002; Cooper *et al.*, 2008). Sandwaves within the Southern North Sea mainly occur in water depths between 18 and 60 m; their absence in depths shallower than 18 m is attributed to the effects of storm waves (Cameron *et al.,* 1992; Limpenny *et al.*, 2011).

Superimposed on the sandbanks in proximity to the cable corridor and along the flanks are a number of tidally aligned sandwaves, which also partially extend into the troughs between the larger sandbank bedforms. The overlying sandwaves range between from 50 to 200 m in wavelength and 3 to 7 m in height. The presence of these sandwaves generally coincides with locations where the superficial sediments are greater than 1 m in thickness.

The current speeds assessed for the site are also of sufficient strength to form sandwaves (Belderson *et al.*, 1982), which are still actively evolving. Across the cable corridor there is up to a ±9 m change in seabed level in the period between 2014 and 2016, with the largest change occurring in relation the migrating sandwave crests. The largest range, also associated with the larger migration distance is mostly observed for the sandwave bedforms overlying Newarp Banks which are at the shallowest water depths of about -13 mLAT. Away from the Newarp Banks sandwaves, the variation in seabed levels are much lower at about ±2 m for even larger sandwave bedforms.

Migration direction based on the sandwave asymmetry showed a circulation pattern around individual sandbanks within the Southern North Sea (McCave and Langhorne; 1982; HR Wallingford *et al.*, 2002; Collins, *et al.,* 1995). In this study, closer examination of the sandwaves in proximity to the cable corridor showed both southerly and northerly sandwave movement at different locations. This was also confirmed by asymmetry estimates for several sandwaves across the same area. A northerly migration was observed on the sandwaves in the eastern part, whereas a southerly movement was observed on the sandwaves on the western flank of the Newarp Banks. The behaviour is likely to be even more complex as there as also instances that along a single transect there is movement towards the sandbank crest from either direction. Migration properties of the sandwaves along the cable corridor are assessed and discussed further in Section 3.3.4 and 4.2.

Stride (1963) deduced a migration direction for the sandwaves from their asymmetry within the Southern North Sea and related this with the direction of the strongest tidal current. In these instances, the asymmetry followed the net bed load sediment transport direction, which was towards the north. Sandwave migration rates of approximately 15 m/year and above are not uncommon in parts of the Southern North Sea (McCave, 1971; Belderson *et al*., 1982; HR Wallingford *et al*., 2002). However, along the cable corridor, a comparison of the limited available historical data, showing the position of individual sandwave crests at different times, suggests that net migration rates for the sandwave features vary across this area and the sandbank system.

The general understanding on the migration direction of bedforms in this part of the Southern North Sea is that although there is a dominant northerly migration of bedforms (both sandwave and sandbanks) (Belderson *et al*., 1982; HR Wallingford *et al*., 2002; Cooper *et al*., 2008), there are also instances of localised re-circulation around the sandbanks which modify the dominant pattern (HR Wallingford *et al*., 2002; Collins, *et al.,* 1995). Such re-circulations were identified for the sandbanks within the Haisborough Sand sandbank system, north of the study are but still within the Haisborough SAC (McCave & Langhorne, 1982; JNCC, 2010). There is therefore the potential for similar patterns on the sandbanks that intersect the cable corridor, particularly the Newarp Banks.

2.4 Water levels and currents

2.4.1 Tidal water levels

Water levels vary due to semi-diurnal tidal influences by up to 3 m over the water depth described in Section 2.1, based on the difference between the highest and lowest astronomical tides. The mean spring and neap tidal range is approximately 2 and 1 m respectively. The regional tidal regime is influenced by the position and interaction of two tidal amphidromes in the Southern North Sea (positions of near-zero tidal range, about which the tidal wave rotates). The tidal range therefore tends to increase from east to west through the through the Haisborough SAC.

Over the cable operational lifetime, there may be some small influence of sea level rise on total water levels. Data extracted from UK Climate Projections (UKCP09; Lowe *et al*., 2009), for locations along the adjacent UK coastline, indicate that over the operational lifetime of the export cable route, mean sea level (MSL) is likely to increase by between 0.03 and 0.1 m (and based on a range of uncertainties for a high emission greenhouse gas scenario). The scale of any change in mean sea level is very small in proportion to the total water depth and natural variability in local water level (e.g. due to tides, surges and waves) and so is unlikely to have any effect on the conclusions of this study.

2.4.2 Tidal currents

Currents within the Southern North Sea are mainly tidal in nature, especially in areas of deeper water. The tidal currents in the region are broadly to the south on the flood tide and to the north on the ebb tide. Tidal current direction through the study area is rectilinear (with minimal variance of direction during the periods of flood and ebb tide). The orientation of the tidal axis is relatively uniform through the study area, with slight localised variations due to flow around the sandbank bedforms (McCave and Langhorne, 1982; Dyer and Huntley, 1999 HR Wallingford *et al*., 2002; Burningham & French, 2016).

A broad indication of the regional current speeds within the study area, as provided by the Atlas of UK Marine Renewable Energy Resources (ABPmer *et al*., 2008), is around 1.3 and 0.7 m/s for the peak mean spring and neap tides, respectively. Information from the ZEA confirms peak mean spring and neap current speeds of approximately 1.29 and 0.72 m/s, respectively (EAOW, 2012, based on a United Kingdom Hydrographic Office (UKHO) tidal diamond within the study area). This is again consistent with metocean observations of around 1.34 m/s further east of the study area. Therefore, due to its proximity, current speeds from the tidal diamond within the study area are used as the representative tidal conditions. Relatively faster current speeds were typically observed to occur during the ebb tide across the ZEA and this is thought to also occur within the study area (EAOW, 2012).

2.4.3 Storm surges

Total water levels and currents within the study area are a combination of a predictable "astronomical" tidal component (described in the preceding sections), and an episodic "residual" (surge) component. Surges are formed by rapid changes in atmospheric pressure, with low atmospheric pressure raising the water surface (positive surge) and high atmospheric pressure depressing the water surface (negative surge). Regional scale patterns of stronger winds also contribute to storm surge effects. Larger surges are typically associated with larger storms and so are more likely to occur in winter months.

When they occur, surges will modify the normal tidal current speed (i.e. a greater or lesser than expected speed for the expected tidal range depending on the relative orientation of the tidal and surge current contributions) and the surge effect might persist for more than one normal tidal cycle. When a surge is in phase with the tidal flow, its effects can be considered to be additive, but when it is opposite, its effects are reduced.

The magnitude, direction and duration of surge events are variable, however the SNSSTS considered the surge tide to be of major relevance to sediment transport in the region (HR Wallingford *et al*., 2002). Representative surge water levels (above the normal astronomical levels) for 1-year and 50-year return period surge events are 1.6 m and 2.3 m, respectively (EAOW, 2012). A maximum surge current of 0.4 m/s (potentially in addition to the expected tidal value) is predicted to be associated with an (approximately 50-year return period) surge event of 2.5 m (EAOW, 2012).

2.4.4 Other non-tidal currents

Within the study area, (in addition to surges, described above) additional currents can be generated as a result of wind stress over the sea surface and by waves. The depth to which wind and wave driven currents act is relatively limited but could still influence the seabed in relatively shallow water, e.g. over larger seabed bedforms in shallow water within the study area.

Local wind driven surface currents are typically confined to the upper part of the water column and do not contribute to near bed current speeds. Maximum wind driven current speeds (up to 3% of the wind speed) occur at the water surface and decrease rapidly with depth. Wind driven currents are orientated in approximately the same direction as the local wind.

Near-bed wave induced orbital currents are more likely to occur with a greater frequency and magnitude in relation to larger waves, with a longer period, in relatively shallower water depths. The ZEA (EAOW, 2012) estimated that peak orbital current speeds may exceed 0.8 m/s during a 1-year return period wave event, increasing to over to 1.1 m/s during a 50-year return period wave event. These are estimated at a water depth of around -23 mLAT. In shallower water, it is likely that the effects would be greater and the reverse for deeper water depths. The wave characteristics associated with these speeds are discussed in Section 2.5.

2.5 Waves

The local wave regime comprises both locally generated wind waves (smaller height, shorter period and length waves), and swell (longer waves generated by distant storm events). The longest fetches (distances of open water) for wave development to the study area are to the north and northeast (>600 km). Across much of the proposed cable route, water depths are likely to be sufficiently deep to limit the effect of wave stirring on local seabed sediments, apart from over shallower seabed areas and during events when wave periods are at their maximum.

A broad indication of the regional scale spatial variation of annual mean significant wave height is provided by the Atlas of UK Marine Renewable Energy Resources (ABPmer *et al*., 2008). Within the study area, the annual mean significant wave height reported by the Atlas is approximately 1.5 m, associated with a wave period of approximately 5 s.

Wave observations are also available from field surveys and secondary information collected for the ZEA (EAOW, 2012), with a wave buoy deployed towards the eastern boundary of the study area, between January and July 2011. The key wave characteristics in proximity to the study area include:

- Significant wave height (Hs) is most frequently in the range 0.5 to 1.0 m, accounting for approximately 34% of all records;
- Wave period is most frequently in the range 3.5 s to 4 seconds, accounting for approximately 25% of all records;
- The dominant wave directions are from the south-southwest and north-northeast, with very similar occurrence percentages. These approach directions each account for 17% of all records, as there is no clear geographical trends in relation to the relative dominance; and
- The largest waves are over 4 m in height and come from directions between north and northeast.

The annual mean significant wave height generally increases with distance offshore. Estimates of the annual representative significant wave height for the period between 2010 and 2016 from the SEASTATES wave hindcast database for a location at -28 mLAT is 1.7 m. Similar representative value of the peak wave period is 7 s, these values are used as the representative annual averages in ongoing analyses.

Results of extreme wave analysis completed by Noble Denton (2010) estimated the significant wave height and associated wave period to be 5.2 m and 8 s for the 1-year return period wave event, and 6.2 m and 8.8 s for the 50-year return period wave event, respectively. The largest waves originate from the north, which is associated with the largest fetch distance. There is however a reasonable level of uncertainty associated with these values mainly in relation assumptions applied and measurement errors in the input data.

2.6 Seabed sediment and sediment transport

2.6.1 Seabed sediments

The seabed within the Haisborough SAC is broadly characterised as coarse Holocene sediments, predominantly sand, with pockets of slightly gravelly sand and gravelly sand (BGS, 1984; 1988; 2002; Cameron *et al*., 1992).

Locally, along the cable corridor, benthic grab samples indicate the sediment mainly consists of slightly gravelly sand (Fugro, 2017); with localised areas of more gravelly sand, gravelly sandy mud and sandy gravel (Figure 2).

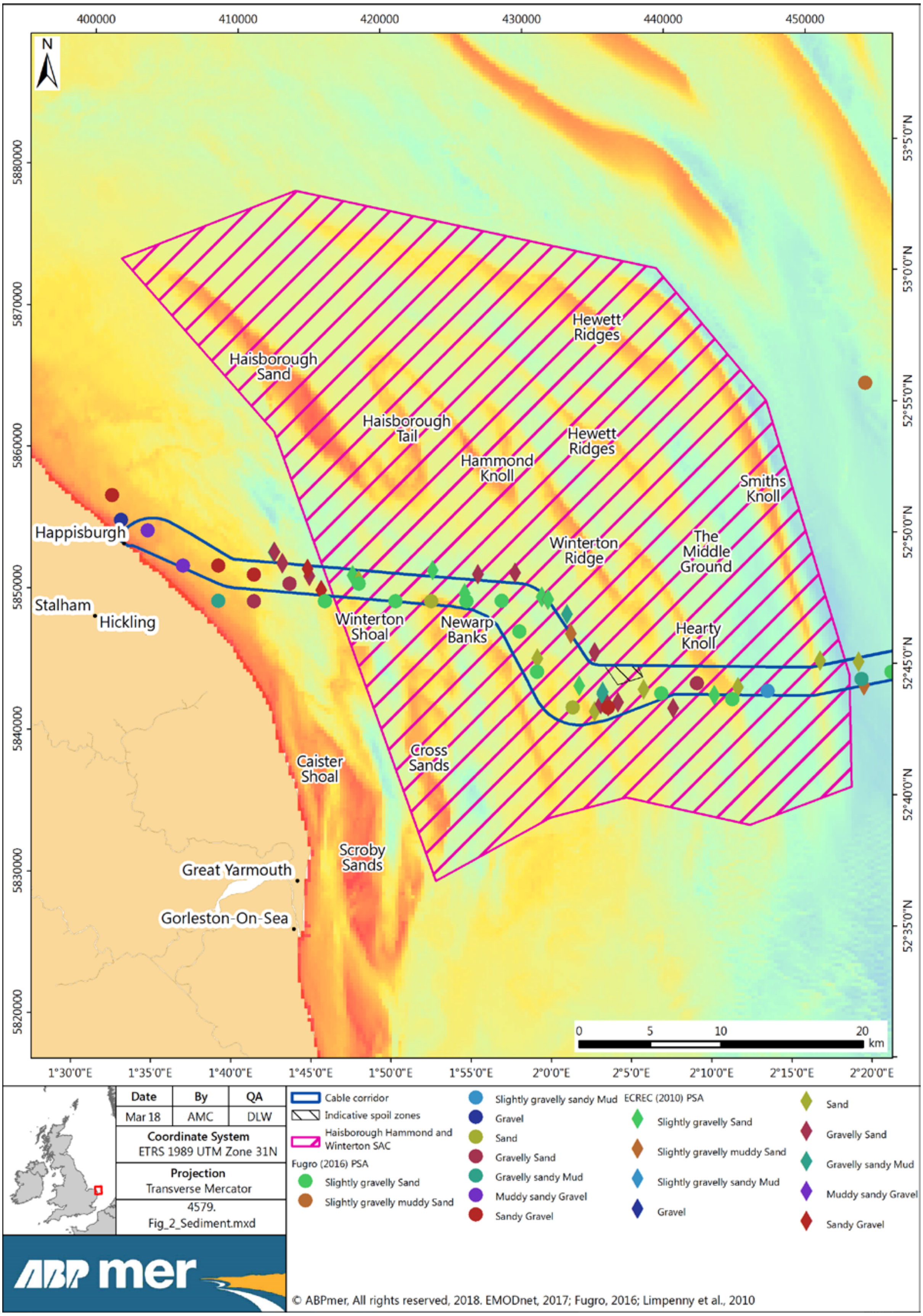

Figure 2. Seabed sediment across the study area

The available sediment samples are characterised as predominantly well-sorted, with limited occurrences of poorly sorted sediment (Fugro, 2017). Typically, up to 90% (by mass) of the sediment is sand, with a median grain size in the range 250 to 500 µm, corresponding to medium sand. Benthic grab samples along the cable route outside of the Haisborough SAC (Fugro, 2017) and the ZEA (MESL, 2011 in EAOW, 2012), indicate there are localised areas of very fine to coarse gravel sized material; however, these are less common along the cable corridor.

2.6.2 Sediment transport

Sediment transport is driven by the combined action of tidal currents, surge, swell and wind-wave currents, the dominance of which are geographically variable across the Southern North Sea (Kenyon, 1970; Chang and Evans, 1992; Barne *et al.*, 1995; 1998; Kenyon and Cooper, 2005). Studies of sediment transport potential and analyses of bedform indicators demonstrate that tidal currents, in particular the residual current magnitude and direction are the dominant process controlling net sand transport in the Southern North Sea (Terwidnt, 1971; Kenyon *et al.*, 1981; McCave and Langhorne, 1982; Stride, 1988; HR Wallingford *et al.*, 2002; Kenyon and Cooper, 2005; Limpenny *et al.*, 2011). Waves may also have an influence on sediment transport in shallower water depths. The relative magnitude of wave effects on local sediment transport is dependent on the combination of local water depth and wave climate.

A conceptual understanding of the sediment transport pathways through the study area are illustrated in Figure 3. These are based on information from modelling studies and identification of transport characteristics from bedform features (HR Wallingford *et al.*, 2002; Kenyon and Cooper, 2005; Cooper *et al.*, 2008). These studies suggest the net sediment transport direction through the study area is towards the north to north-northwest, which is consistent with the migration direction for the sandbank bedforms present (HR Wallingford *et al.*, 2002; Kenyon and Cooper, 2005; Cooper *et al.*, 2008). In addition, the studies also highlight the presence of a bedload parting zone which crosses the study area (Figure 3). The presence of the bedload parting means there is a dominant southerly sediment transport direction to the west and closer to the coast, whereas on the eastern side there is a northerly transport trend. Further influences on the transport regime are from the sandbank bedforms, as these are considered to introduce localised variations and re-circulation patterns (McCave and Langhorne, 1982; HR Wallingford *et al.*, 2002; Collins, *et al.*, 1995). Therefore, the general picture for the study area is of a complex sediment transport regime, determined and influenced by a number of large scale and regional processes. Over longer time scales, it is these properties and the resulting net sediment transport characteristics that controls the morphological evolution of sedimentary features present.

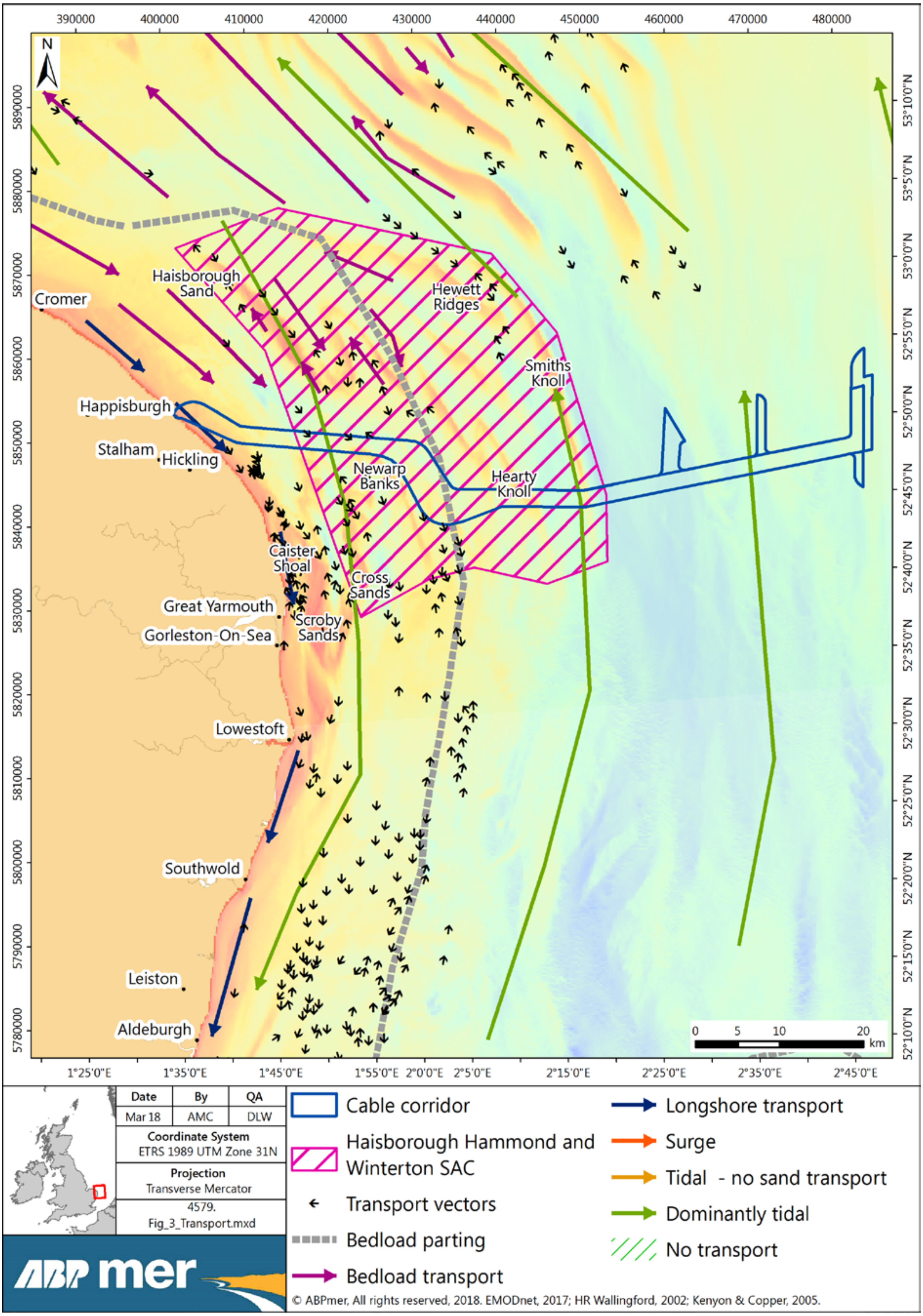

Figure 3. Conceptual sediment transport regime

3 Methodology

3.1 Data sources

In addition to the more general environmental baseline information and data sources described Section 2.1; the following key datasets are used to inform the assessment on potential environmental changes from the proposed bed levelling works:

- High-resolution multibeam bathymetry along the cable route (Fugro, 2016);
- High-resolution multibeam bathymetry (HI1428) from the UKHO obtained from the Inspire bathymetry data centre;
- High-resolution multibeam bathymetry from the East Coast Regional Environmental Characterisation (ECREC) survey in 2010;
- Geotechnical data collected by the East Anglia ZEA (EAOW, 2012);
- Particle Size Analysis (PSA) data from benthic grabs along the cable route (Fugro, 2016) and East Anglia ZEA (EAOW, 2012); and
- BODC observational flow data collected as part of the East Anglia ZEA (EAOW, 2012).

Also, the following regional-scale process investigations are used:

- East Coast Regional Environmental Characterisations (Limpenny *et al*., 2011)
- 'A synthesis of current knowledge on the genesis of the Great Yarmouth and Norfolk Bank Systems' (Cooper *et al*., 2008); and
- Southern North Sea Sediment Transport Study (http://www.sns2.org/index.html)

The methods of analysis applied in this study aim to improve the understanding of the localised seabed and bedform mobility, particularly through:

- Investigation of seabed mobility, bedform evolution and migration properties; and
- Consideration of the potential sediment transport regime throughout the area.

Assessing the potential impacts of the bed levelling activities on the morphology considers the total area and volume of sediment disturbance in relation to the proposed levelling works. Information on the total area and volume of disturbance are summarised in Section 1.2.3. The applied methods of analysis are described in further detail below. They are principally completed for sandwaves that intersect the export cable route. Where necessary, consideration is also given to the sandbanks adjacent to but not directly intersected by the routes.

3.2 Previous monitoring of levelled sandwave recovery at Race Bank Wind Farm

Monitoring data is available on the sandwave recovery pre and post bed levelling from ten locations along the Race Bank export cable route (DONG Energy, 2017). The bathymetric images have been interpreted by ABPmer to provide information on the potential for recovery of dredged sandwaves for cable installation. The interpretations of the bathymetry images are summarised as follows:

- The images illustrate evidence of partial sandwave recovery in the 5-months after levelling, whereby the levelling was mostly transverse to the sandwave alignment.

- At most of the sites, the images indicate the sandwaves were reforming *in situ*. Although the crest height were not at the same point prior to levelling within the 5-month period, the shape and form of the sandwaves were reforming within the levelled area without any significant migration or decay of the adjacent unaffected crest areas.
- The images also suggest movement of smaller bedform features (i.e. interpreted to be ripples and mega-ripples) and potential sediment mobility, but do not demonstrate any sandwave migration. However this may simply relate to the time frame of the monitoring data and the potential migrations characteristics of the sandwaves (i.e. episodic rather than continuous).
- The observed partial recovery is interpreted to relate to the natural infill of the levelled area, potentially through a combination of the contribution from the sediment transport regime and from smaller ripple and mega-ripple bedforms.
- However, at two of the sites, the levelled sandwaves did not appear to have reformed as described above, but instead had developed into separate distinct features, with indications of potential convergence in the future.

ABPmer interpretation of the bathymetry monitoring images indicates sandwave recovery which is consistent with the Race Bank site being in an active and dynamic environment that is conducive to the development and maintenance of sandwave bedforms.

3.3 Analysis methods

A set of analysis methods are applied in order to assess the potential effects of the bed levelling works on the local sandwave and seabed morphology, the sediment transport regime and any potential onward effects on the form and function of the bedforms in the Haisborough SAC. The purpose of each method and its application within this study is described in the sections below.

3.3.1 Analysis of sediment transport potential and seabed mobility

Mobilisation of sediments occurs when the shear stress imposed by the forcing exceeds a critical threshold, which leads to the erosion and transportation of sediments. The bed shear stress required to initiate sediment transport can be estimated using standard approaches and relationships (e.g. as described in Soulsby, 1997). A summary of the sediment types within the cable corridor, along with the respective grain size description and critical bed shear stress for the initiation of sediment transport, are provided in Table 1. Typically, up to 90% (by mass) of the sediment within the cable corridor is sand, with a median grain size in the range 250 to 650 µm, corresponding to medium sand (EAOW, 2012). Therefore, a representative sediment size of 350 µm is used for the analyses of sediment transport potential and direction. Further descriptions of the sediment properties within the study area are in Section 1.

Table 1. Sediment characteristics and the associated bed shear stress threshold

Representative Size (µm)	Size Class (Wentworth)	Bed Shear Stress Threshold (N/m^2)
250	Fine Sand	0.19
350	Medium Sand	0.21
650	Coarse Sand	0.31
2,000	Coarse Sand	1.15
2,500	Very Fine Gravel	1.58
7,000	Fine Gravel	5.89
25,000	Coarse Gravel	21.82

The sediment transport potential, which is an estimate of the amount of material available for transport is used to assess the rate of movement of material across the cable corridor and the Haisborough SAC and therefore the amount of sediment available for reworking. This includes assessing if the dredged or disposal areas pose a potential impact on the sediment transport and resulting seabed morphology within the cable corridor and across the Haisborough SAC. The transport direction is used as a basis to inform where sediment would likely move to and the extent of movement. It is important to note that the analysed transport direction is a representation, with high degrees of variability in relation to the temporally and spatially varying hydrodynamic forcing conditions.

The sediment transport potential across the study area was calculated in response to typical and peak flow speeds under mean spring and neap tidal current conditions, determined from UKHO tidal diamonds in the study area (Section 2.4.2). Consideration was also given to the enhancement of the sediment transport potential by both typical and more extreme wave action that is likely to occur over the operational lifetime of the export cable route, as defined for the nearby ZEA (EAOW, 2012) and described in Sections 2.4.4 and 2.5. The relationships used to estimate the resulting sediment transport rates are the total load transport equations as a result of combined currents and waves, as described in Soulsby (1997).

To further explore the transport potential over a longer time frame, a time series of current and wave characteristics were obtained from the SEASTATES hindcast databases (ABPmer. 2013; 2017) for the period between 01/01/2006 and 31/12/2016 (i.e. 11-year period). The associated bed shear stress was calculated for the current and wave only instances, in addition to the combined case, to account for varying forcing mechanisms. The results were used to assess the transport potential over the time frame and the proportion of time the characteristic site seabed sediment (350 µm) would be mobile. Other sediment sizes, including fine sand and very fine gravel (Table 1) were also assessed at different depths to inform how the transport potential varied. The current speeds and wave parameters used to assess transport potential are described for the study area in Section 2.4 and 2.5.

The sediment transport direction was calculated using the time series of current and wave properties for four locations within the proposed cable corridor (Figure 1). This was carried out for the period between 2006 and 2016 (11 years, inclusive), using data obtained from the SEASTATES hindcast database. To inform this, a progressive vector analysis method was applied to demonstrate the relative sediment transport magnitude and direction across the locations. A description of the method is provided further below.

Transport potential due to tidal currents

Within the study area, the behaviour of the sediment regime is primarily determined by the response of sediments to the applied hydrodynamic forces. Tidal currents are the most frequently occurring and persistent process controlling sediment transport through the study area. However, there can also be contributions from storm events, which can result in short but sharp influences on the transport, after which the tides then control the transport again.

The bed shear stress and sediment mobility potential for the study area are estimated in Table 2. These use relationships contained in Soulsby (1997) and described in Appendix A, for the peak mean spring and neap current speeds of approximately 1.29 and 0.72 m/s (Section 2.4.2) and assuming a representative water depth of -28 mLAT, based on site properties described in Section 2.2.

For the purpose of providing a representative 'everyday' condition, a nominal typical current speed of 0.5 m/s is also considered, as this current speed will be met or exceeded on almost every tide (i.e. several times every day). The estimated bed shear stress and resulting sediment transport rate is sensitive to the 'roughness' of the seabed, with a coarse grained and/or undulating seabed inducing greater flow turbulence and bed shear stress than otherwise encountered with a smooth, flat seabed. For these calculations, the seabed is assumed to consist of medium sand with a D_{50} value of 350 µm. The bed shear stress as a result of the forcing (Table 2) is compared against the mobility threshold for different sediment sizes (Table 1) to infer which material would be moved because of the forcing (Table 2).

Table 2. Summary of sediment mobility due to tidal currents

Tidal Condition	Peak Current Speed (m/s)	Resultant Bed Shear Stress (N/m^2)	Mobility Statement (Based on Thresholds in Table 1)
Typical	0.50	0.21	Mobility up to medium sand (~350 µm)
Peak mean spring	1.29	1.39	Mobility up to coarse sand (~650 µm)
Peak mean neap	0.72	0.43	Mobility up to coarse sand (~650 µm)

As shown in Table 2, coarse sand size and smaller material are potentially mobile during peak flow conditions on both mean spring and neap tides. Based on the mobility thresholds for different grain sizes (Table 1), the mean neap tidal currents with a shear stress of 0.43 N/m^2 are only sufficient to mobilise coarse sands up to 650 µm (i.e. threshold of 0.31 N/m^2). Spring currents with a shear stress of up to 1.39 N/m^2 would mobilise coarse sands up to 2000 µm (i.e. threshold of 1.15 N/m^2).

Higher peak current speeds tend to occur during the ebb tide (EAOW, 2012), which will generally promote the north-north-westerly transport of material. This transport direction is consistent with the available historical studies in terms of the directions of both net sediment transport (medium sand) and bedform migration in the area.

Transport potential due to waves

Waves in relatively shallow water produce an oscillatory movement of water at the seabed which can help to mobilise sediments. The magnitude of the wave induced flow is a function of the wavelength (related to the wave period), the wave height and the water depth. Relatively longer wavelengths associated with swell conditions influence the movement of water to a greater depth and so can contribute to sediment mobility in relatively deeper water. The wave induced motion is largely symmetrical in deeper water (relative to the wave length) and so actual net transport of sediment as a result of wave action alone is expected to be typically limited in the study area.

The bed shear stress and sediment mobility potential in the study area are estimated in Table 3. These use relationships contained in Soulsby (1997) and described in Appendix A, for wave properties (in the absence of currents) summarised in Section 2.5 and assuming a representative water depth of -28 mLAT, based on site properties described in Section 2.2.

The wavelengths and periods of waves required to initiate sediment transport within the study area will vary with depth. In this way, material in shallower water will become mobile under relatively smaller wave conditions, whilst in deeper water, larger wave events would be required to mobilise an equivalent class of sediment.

Table 3 shows that annual average wave conditions (alone) would be insufficient to mobilise the characteristic sediment types in the study area (such as medium sand at 350 µm). Less frequently, the 1-year extreme return period wave event has the potential to mobilise up to coarse sand, while a 50-year wave event has the potential to mobilise up to very fine gravel (~2,500 µm). Although wave events can theoretically mobilise larger sediment sizes, this occurs infrequently and only for a very short period of time.

Table 3. Extreme and typical wave conditions and resulting sediment mobility

Wave Event	Significant Wave Height (m)	Wave Peak Period (s)	Resultant Bed Shear Stress (N/m²)	Comment
Representative annual average	1.7	6.7	0.14	Not sufficient to mobilise sand
Representative 1-year	5.2	8.0	1.52	Mobility up to coarse sand (~650 μm)
Representative 10-year	5.8	8.5	2.08	Mobility up to very fine gravel (~2,500 μm)
Representative 50-year	6.2	8.8	2.47	Mobility up to very fine gravel (~2,500 μm)

Transport potential due to combined tidal currents and waves

The bed shear stress and sediment mobility potential in the study area are estimated in Table 4. These use relationships contained in Soulsby (1997) and described in Appendix A, for a combination of current and wave forcing summarised in Sections 2.4.2 and 2.5 and assuming a representative water depth of -28 mLAT, based on site properties described in Section 2.2.

Table 4. Summary of sediment mobility due to combined tidal currents and waves

Wave Event	Significant Wave Height (m)	Wave Peak Period (s)	Current Speed (m/s)	Resultant Peak Bed Shear Stress (N/m²)	Comment
Representative annual average	1.7	6.7	Typical: 0.5	0.34	Mobility up to coarse sand (~650 μm)
			Spring: 1.29	1.90	Mobility up to very fine gravel (~2,500 μm)
			Neap: 0.72	0.65	Mobility up to coarse sand (~650 μm)
Representative 1-year	5.2	8.0	Typical: 0.5	0.63	Mobility up to coarse sand (~650 μm)
			Spring: 1.29	2.76	Mobility up to very fine gravel (~2,500 μm)
			Neap: 0.72	1.10	Mobility up to coarse sand (~650 μm)
Representative 10-year	5.8	8.5	Typical: 0.5	0.72	Mobility up to coarse sand (~650 μm)
			Spring: 1.29	3.00	Mobility up to very fine gravel (~2,250 μm)
			Neap: 0.72	1.22	Mobility up to coarse sand (~2,000 μm)
Representative 50-year	6.2	8.8	Typical: 0.5	0.77	Mobility up to coarse sand (~650 μm)
			Spring: 1.29	3.15	Mobility up to very fine gravel (~2,500 μm)
			Neap: 0.72	1.31	Mobility up to coarse sand (~2,000 μm)

A nominal typical current speed of 0.5 m/s is again used as a representative 'everyday' condition. Under more 'typical' wave conditions (annual average), there is potential for the mobility of gravel and coarse sand under peak spring and neap tidal conditions, respectively, which would mean the transport of medium sand (350 µm) characteristics to the cable corridor. With suitable water depths and sediment availability, sandwaves begin to develop with flow speeds of 0.5 m/s and above (Belderson *et al.*, 1982), as typically experienced within the study area. When larger extreme wave events are coupled with peak spring and neap tidal currents, sediments up to very fine gravel (~2,500 µm) size can theoretically be mobilised. However, it is noted that this higher level of mobility will only take place for a limited time during peak flow conditions and under infrequent extreme events.

A comparison of the bed shear stresses generated by tidal currents (Table 2) and waves alone (Table 3) would indicate that under 'typical' wave conditions (i.e. annual average), tidal currents predominantly control the potential for sediment mobility as waves are insufficient to mobilise sediment. However, the combined influence of tides and waves would increase the mobility potential over that from tides alone and the occurrence of extreme events has the potential to increase sediment mobility.

The potential volumetric sediment transport rate (i.e. the rate that would occur with an unlimited supply of sediment present for transport) for the range of sand grain sizes found in the study area are estimated in Table 5. These use relationships contained in Soulsby (1997) and described in Appendix A, for a combination of current and wave forcing summarised in Sections 2.4.2 and 2.5. They assume a representative water depth of -28 mLAT based on site properties described in Section 2.2. The estimates are representative of the typical and higher rates at which sands might be transported over the seabed to contribute to the processes considered in this study, such as bedform migration, including dispersion of dredged sediment and infill of the levelled sandwave crests.

Table 5. Summary of potential sediment transport rates for sand in the study area due to combined tidal currents and waves

Wave Event	Current Speed (m/s)	Potential Sediment Transport Rate for Fine Sand at 250 µm (m^3/m/hour)	Potential Sediment Transport Rate for Medium Sand at 350 µm (m^3/m/hour)	Potential Sediment Transport Rate for Coarse Sand at 500 µm (m^3/m/hour)
Representative annual average waves	Typical: 0.5	0.02	0.02	0.01
	Spring: 1.29	3.35	2.71	2.04
	Neap: 0.72	0.18	0.17	0.11
Representative 1-year storm	Typical: 0.5	2.98	2.36	2.29
	Spring: 1.29	15.47	11.30	10.34
	Neap: 0.72	5.89	3.87	3.62
Representative 10-year storm	Typical: 0.5	7.28	4.80	3.96
	Spring: 1.29	27.68	12.21	14.04
	Neap: 0.72	11.88	8.30	5.39
Representative 50-year storm	Typical: 0.5	10.70	7.94	4.94
	Spring: 1.29	34.54	27.70	18.11
	Neap: 0.72	13.93	12.39	8.02

It is noted that these estimates of sediment transport potential are empirical in nature (i.e. based on a limited range of observed conditions) and the absolute rates are therefore subject to uncertainty (a discussion is provided in Soulsby, 1997). However, by using a consistent approach (as used in the present study), greater confidence can be placed in any relative comparisons of predicted rates than placing reliance on a single value.

Sediment transport direction

Initial investigations presented the sediment transport magnitude and described this in relation to the recognised sediment transport pathways across the study area. A request for further information was raised by Natural England regarding the direction of sediment transport, particularly in relation to sediment disposal. To inform the answer, progressive vector analysis (PVA) has been applied to investigate the relative net magnitude and direction of potential sand transport in four areas of the study area within the cable corridor (Figure 1). Due to the varying depths that occur across the study area, three depths are assessed using PVA. These are carried out at -16 mLAT as a representation of the depths over the sandbanks, at -31 mLAT, which is the representative depth within the indicative spoil zone and at -50 mLAT, which relates to the deepest depths within the cable corridor.

The long-term net sediment transport pathways within the study area and the wider Southern North Sea occur mainly as a result of the tidal asymmetry (HR Wallingford *et al*., 2002), with the potential for local variations and re-circulation in relation to the larger scale bedforms which are present (Section 2.6.2). PVA is carried out to investigate the effect of the tidal asymmetry and the contribution of occasional storm surge and wave events, more locally within the study area on the net sediment transport. Tide and surge water levels, currents, wave heights and wave period time series data from the ABPmer SEASTATES hindcast database (ABPmer, 2017) have been used to support the PVA.

When using PVA results the following should be taken into consideration:

- PVA provides an estimate of the long term (net) magnitude and direction of potential sediment transport relative to a fixed location (i.e. a Eularian analysis). It therefore provides an indication of the general magnitude and direction of residual sediment displacement through that location over the assessed period of time. Due to inherent uncertainties in the accuracy of the estimates of sediment transport at any given point in time, only relative differences in the magnitude and direction of the PVA results should be compared between the different locations.
- PVA for an individual site or area alone does not provide a reliable description of the long-term path taken by sediment in transport through it (i.e. a Lagrangian analysis). This is because, as the sediment is transported away from the location being assessed, it will be subject to different water depths, flow and wave conditions, etc. However, spatial patterns in the magnitude and direction of PVA results for multiple locations can provide a more reliable basis for the estimation of likely net sediment transport paths through a region.
- When considering the long-term transport direction of a particular grain or body of sediment it is also likely that, in practice, sediment grains will only be transported short distances before becoming buried at a lower level in or even below the active part of the seabed surface, or incorporated into larger bedforms, and may not be transported further until exposed again at some point in the future.

3.3.2 Analysis of sediment deposition extent and thickness

Analysis of the potential deposition extent and resulting sediment thickness or change in bed levels that could arise as a result of the disposal of dredged material was undertaken in order to address the request for further details from Natural England.

The study has used a worst case disposal scenario. This scenario assumes all of the dredged material is deposited within a single indicative spoil zone within the export cable corridor (Figure 1), where water depths range between -26 and -37 mLAT. The analysis completed for the sediment deposition extent and thickness is based on the disposal scenarios only (i.e. released at the surface or at the seabed) into the single indicative spoil zone (Figure 1). It does not include material overspill during the dredging, although this would be minor in proportion.

Sediment released into the water column during disposal of the dredged material will settle downwards at a rate depending upon its grain size. On initial release from the hopper, it is assumed around 90% of the material released will fall directly to the seabed as a single mass in the 'dynamic phase'. The remaining 10% of material would then be shed from the dynamic phase during its descent to the seabed and enters suspension, termed the 'passive phase' of the plume. In the passive phase, the sediment plume will be advected away from the point of release by any currents that are present and will also 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 resulting sediment thickness will be a combination of the deposition during the dynamic and passive phases.

Once deposited to the seabed, the previously dredged sediment will be of a similar type and similarly mobile to the surrounding seabed material. Any subsequent transport of the deposited or surrounding sediment will be generally at the same rate and in the same direction as would happen naturally, irrespective of the dredging and disposal activity.

To assess the potential impact from disposal, two disposal sediment release mechanisms are considered for their deposition extent and thickness, namely the release of dredged material from the hopper at the sea surface and discharged through a downpipe at approximately 5 m above the seabed.

The exact pattern of sediment deposition at the seabed will depend on the disposal method (i.e. at the surface using a split bottom barge or at the seabed via a downpipe), sediment type and the ambient environmental conditions at the time of the event, which may all be variable. However, given the total volume of sediment, a range of potential alternative combinations of extent, thickness and shape can be calculated. For example, for a given sediment volume, 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. For the proposed disposal, a range of deposition scenarios are assessed, which include:

- The maximum possible thickness, associated with the smallest footprint or extent of impact;
- The different thicknesses and footprints associated with varying spoil deposition 'cones';
- The maximum thickness from a single disposal from the hopper compared with the cumulative thickness associated with multiple disposal events; and
- The most extensive accumulation over the entire indicative spoil zone and the resulting thickness.

More concentrated and localised deposits of coarse sediments are assumed to deposit naturally into a cone shape where the maximum thickness is in the centre of the deposit and thickness decreases gradually from the centre towards the edges. Operationally, very thick deposits in shallow water 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 diameter of the steepest cone is provided for comparison. The largest possible areas impacted by uniformly distributed thicknesses of 0.5, 0.25 and 0.05 m are also provided (making no assumptions regarding the shape of the area) along with the deposition thickness associated with a uniform disposal within the indicative spoil zone (Figure 1).

The above methods are used to consider the main mass of spoil in the active phase (90% of the material volume in the hopper), which will descend rapidly to the seabed as a single unit irrespective of the detail of sediment properties. The remaining sediment volume (10%) in the passive phase will settle according to the properties of the individual sediment grains. Coarser grained (e.g. sand/ gravel) sediments, will settle out of suspension quickly (e.g. in the order of seconds to minutes) over a smaller area. Finer grained (e.g. silt/ clay) sediments would remain in suspension for a longer period of time (in the order of hours to days), potentially affecting a larger area, but at a progressively reducing concentration due to ongoing advection and dispersion.

To estimate the potentially greater extent but limited thickness of deposit associated with settlement of the passive phase, the representative water depth and current speed are used to determine the horizontal plume footprint at the seabed (accounting for horizontal advection and dispersion during settling). The maximum average deposition thickness is then estimated as the total volume of sediment in the passive phase, divided by the deposition footprint area on the seabed. The likelihood of a combined effect on seabed levels through overlap of the active and passive phases is greater when the passive phase contains mainly coarser material.

The above methods are used to estimate the dimensions of spoil mounds resulting from individual disposal events, however, multiple dredging cycles will be required.

To analyse the potential changes to the bed levels and deposition extent based on the total proposed disposal volumes, a number of spreadsheet based numerical models have been developed. Such models are used regularly to inform the EIA for both dredging and disposal activities and apply the following information, assumptions and principles:

- A hopper volume of 14,000 m^3 is used as the representative maximum sediment volume to be disposed during any one event. The hopper capacity is less than the proposed dredge volumes, as a result, several dredge and disposal events will be needed;
- A representative current speed of 0.5 m/s is used as an indication of the typical everyday condition for the site (Section 3.3.1), in order to inform the deposition extent. Assuming a higher value will increase dispersion of the passive phase as it descends through the water column and reduce the thickness of subsequent deposits and *vice versa*; and
- For the purpose is estimating the settling rate and deposition extent, it is assumed that the sediments released will comprise of medium sands with a representative grain size of 350 μm and settling rate of 0.5 m/s. Also, the material would be released into the indicative spoil zone with a representative mean depth of 31 m.

Results of this analysis are presented and discussed further in Section 4.3.

3.3.3 Analysis of sandwave orientation, wavelength and asymmetry

To inform the sandwave properties, bathymetry transects were extracted from a subset of representative sandwave features within the cable corridor, using the Fugro (2016) bathymetric survey data. The bathymetry transects were orientated perpendicular to the dominant crest alignment (crests are aligned approximately east to west) (Figure 4). The key dimensions (height, wavelength, slope steepness and asymmetry) of individual sandwave features were characterised (Figure 4).

Using the transect data the sandwave height was determined as the elevation of the crest relative to the level of the adjacent troughs. The wavelength was determined as the distance between sandwave crests. The steepness of the bedform slopes was calculated based on the local bed level gradients. The sandwave asymmetry (an indicator of the sandwave migration direction) was calculated as the ratio of the length of the slopes (measured from crest to trough) either side of the crest.

3.3.4 Analysis of sandwave migration rate

The sandwave migration rate was calculated to investigate the rate at which the bedforms are moving and the likelihood of a new morphology baseline forming, from which future change occurs. To estimate the migration rate, directly comparable bathymetry transects were extracted from the site specific Fugro (2016), UKHO (2014) and ECREC (2010) bathymetries. Both the UKHO and ECREC bathymetries had previously been corrected to the same spatial and vertical datums (i.e. ETRS89 31N and LAT respectively) as the Fugro bathymetry. The position and character of key bathymetric features (e.g. the position and elevation of individual sandwave crests) were noted and compared. The movement of the sandwave crests along a transect chainage between the surveys was used to indicate the direction and rate of bedform migration (Figure 4).

The migration rates varied within each bedform field and more broadly across the study area. An average rate of about 16 m/year was calculated with an associated standard deviation of ±10 m/year, for the period between 2014 and 2016 for the assessed sandwaves across the analysis transects. The minimum and maximum rates within the same period were 4 and 34 m/year respectively. Faster rates generally occurred in relation to the sandwaves located on Newarp Banks (Transects 1 and 2, Figure 4, while slower rates occurred with the sandwave field east of Newarp Banks (Transect 3, Figure 4).

3.3.5 Analysis of sandwave sediment volumes

The approximate volume of material associated with the sandwave bedform field was calculated as a proxy estimate of the sediment volume available for transport by natural processes. Three sandwave fields, as illustrated in Figure 5 were assessed for their potential sediment volumes. The estimation of available volume was based on a plane depth at the base of the sandwaves, on the main body of the sandbank, rather than the base of the sandbanks or Holocene sediment unit. The volume was calculated as the total volume of the three-dimensional shape formed between the applied plane depth and the seabed surface. In doing so, it is the case that part of the main body of the underlying sandbank was also included in the volume and smaller sandwaves on the flanks of the sandbank were potentially under-represented. Calculations were made using the ESRI ArcGIS spatial analysis software based on the UKHO (2014) bathymetry due to it wider coverage over the bedforms. The estimated sediment volumes in relation to each sandwave field is summarised in Table 6 below.

Table 6. Estimated sediment volume from sandwave fields

Location	Estimated Sediment Volume (million m^3)
Main body of Newarp Bank	76
Newarp Bank "Tail"	40
Sandwave field east of Newarp Bank	112

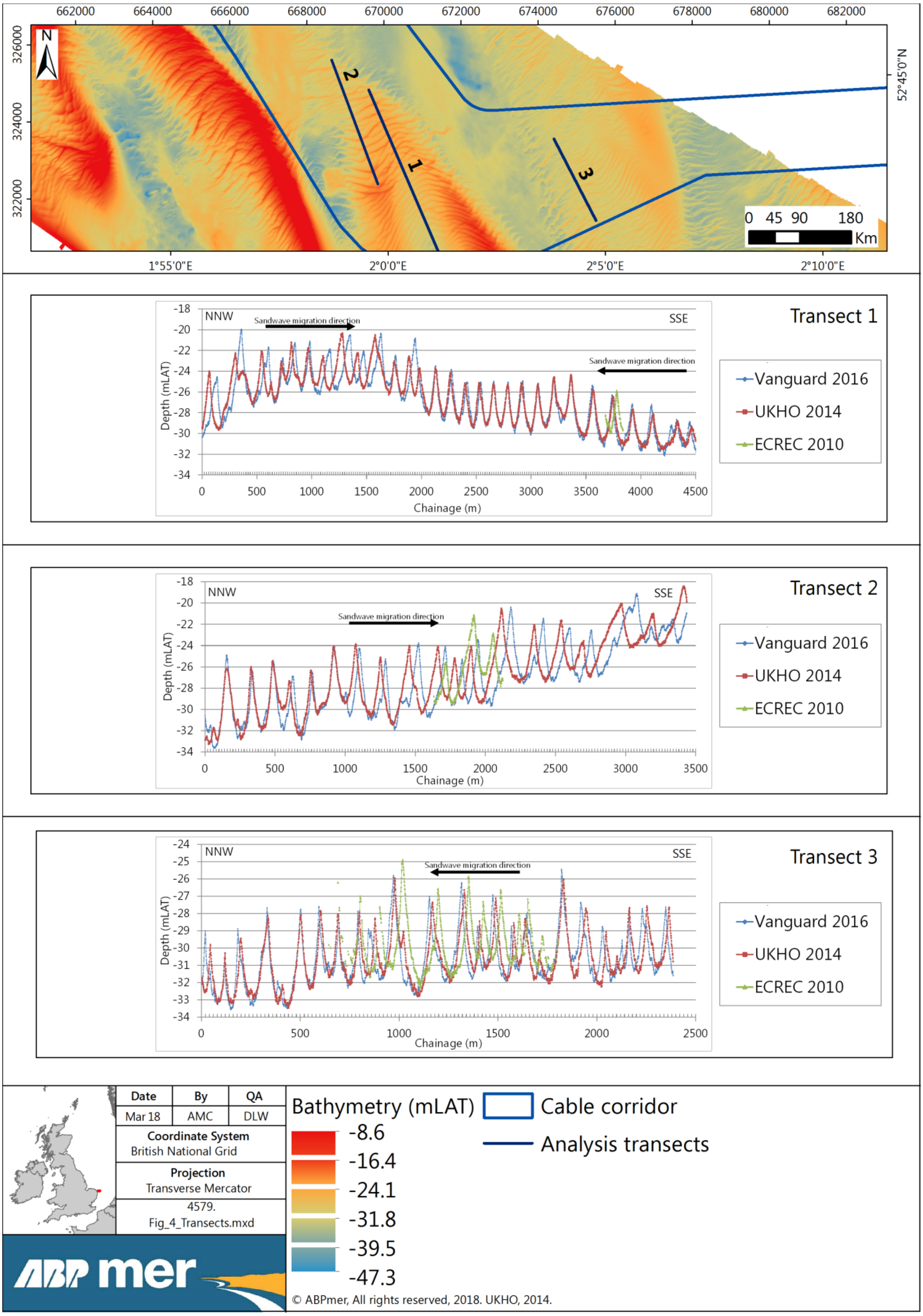

Figure 4. Analysis transects and assessed migration directions

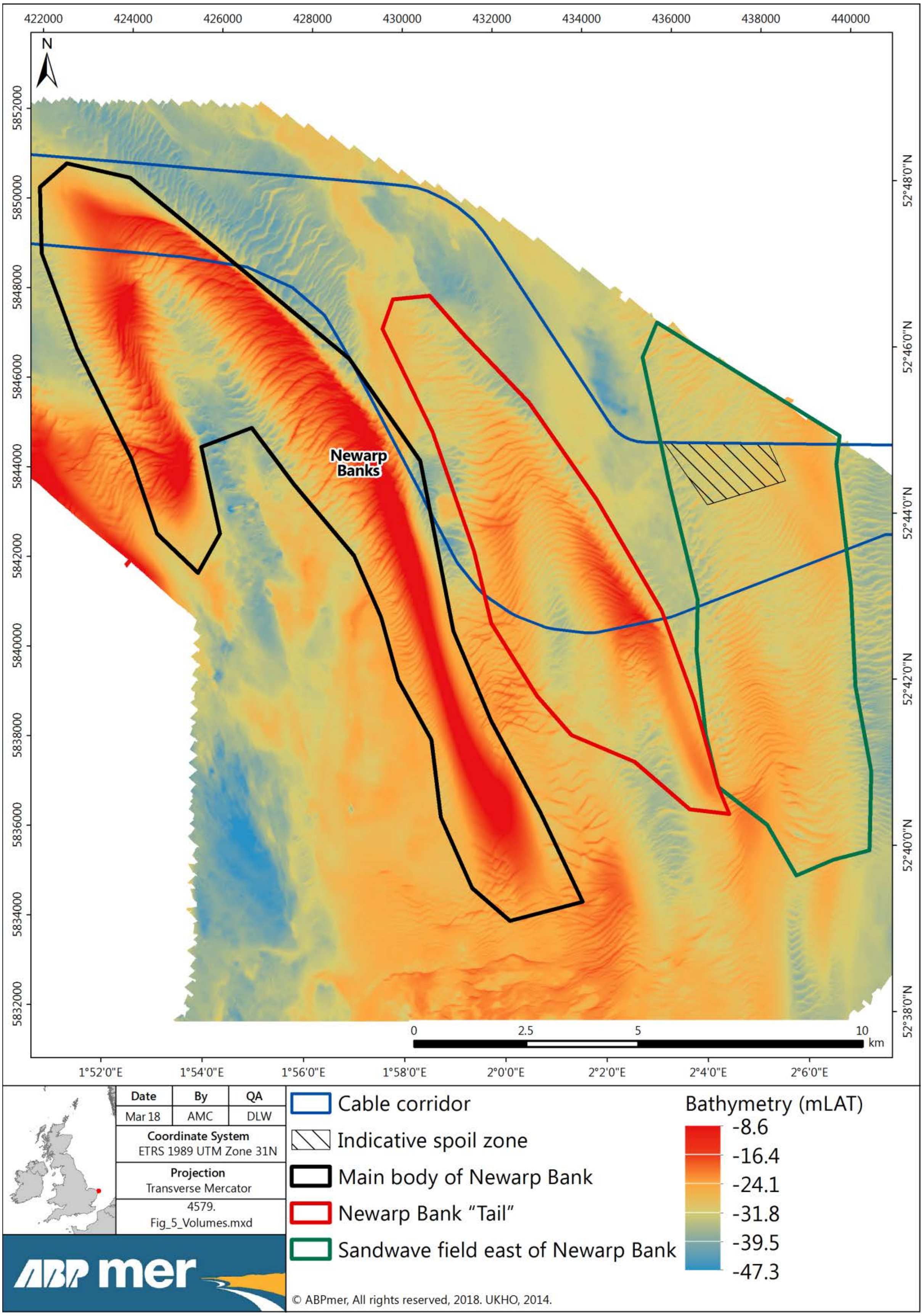

Figure 5. **Assessed sandwave fields**

4 Assessment

4.1 Potential effects on seabed morphology

Sediment re-circulation patterns were identified around the sandbanks within the Haisborough SAC (Section 2.3). The potential for such re-circulations have also been identified more locally on the Newarp Banks along the cable corridor, with both northerly and southerly movement at different locations, which may also relate to the presences of a bedload parting zone. Therefore, any potential changes to sediment thickness caused by dredging and disposal of material will in the short term only affecting very local areas to the south-southeast or north-northwest. Due to the presence of the parting zone, these patterns could potentially continue in the long term, so that to the east of the zone, areas to the north-northwest would potentially be affected over greater distances. To the west of the zone, areas to the south-southeast would then be affected. Any deposited material can be considered to move in the same net directions.

The analysis of potential sediment transport results for a time series of tide and wave conditions for the period between 01/012006 and 31/12/2016 (i.e. 11-years), obtained from the SEASTATES hindcast database (ABPmer, 2013; 2017) is included in (Table 7). This information was used to assess the proportion of time different sediment is above the threshold for transport at different depths within the study area. The results highlight the dynamic properties of the study area and the contribution from the sediment transport processes into the seabed morphology across the Haisborough SAC.

Table 7. Proportion of time sediment is mobile, based on SEASTATES data for 2006-2016

Scenarios	Tidal Currents Only	Waves Only	Combined Tides and Waves
Fine sand, sandbank and sandwave crests	75%	55%	92%
Fine sand, sandbank and sandwave flanks	71%	5%	87%
Fine sand, sandbank and sandwave troughs	69%	<1%	86%
Medium sand, sandbank and sandwave crests	74%	52%	91%
Medium sand, sandbank and sandwave flanks	71%	5%	86%
Medium sand, sandbank and sandwave troughs	69%	<1%	85%
Very fine gravel, sandbank and sandwave crests	35%	20%	67%
Very fine gravel, sandbank and sandwave flanks	25%	<1%	55%
Very fine gravel, sandbank and sandwave troughs	20%	<1%	51%
Fine sand is 250 µm; Medium sand is 350 µm; Very fine gravel is 2500 µm. Sandwave crests at -13 mLAT; flanks at -28 mLAT and troughs at -40 mLAT.			

The SEASTATES time series data for the study area, suggests the mobility of material under the combined influence of tides and waves is a more realistic estimate of the conditions that can be expected within the Haisborough SAC. On the occasions when the seabed is mobilised, sand and to a lesser degree gravel, will be locally redistributed, at the instantaneous transport rate, to infill dredge trenches or level out deposition mounds. Any transported sediment would move in the broad directions described above.

For the bed levelled areas, it may be that the dredged trenches act as localised and temporary sediment sinks for a period of time, however, the wider sediment transport processes will still continue uninterrupted. The maximum rate of sediment accumulation will be at the ambient rate of transport although the net rate of infill may be lower due to simultaneous transport out of the area. An assessment of effect of seabed lowering from aggregate dredging indicates that dredge pockets can result in small decreases in flow speeds within the dredge pocket and its immediate area (ABPmer, 2014). However, the effect on the flow speeds from the proposed levelled area will be much smaller. This is mainly due to the difference in scales between the aggregate dredge pocket and the bed levelling trenches. The proposed bed levelling approach states that the levelling area will have a nominal width of 7 m (plus side slopes) for each cable (CWind, 2017 unpublished). This is small compared with the aggregate dredge pocket with widths of several kilometres (ABPmer, 2014). Therefore, any effect from the trenches on the flow will be minimal and localised to the levelled area. Due to the localised variations in flow speeds and the re-circulations present, it is most likely that any changes in the flow properties as a result of the levelled area will be undiscernible from the background variations.

Similar variations are observed in the wave regime for the aggregate sites, for the same reasons as described for the flow properties. Therefore, the proposed levelling area is again likely to have no effect on the wave regime. As the proposed levelling area will not disrupt the wave regime across this part of the Southern North Sea, any contributions to the sediment transport from waves should then continue undisrupted across the study area.

Results of the PVA provide an illustration of the long term general direction and magnitude of the residual sediment movement through the assessed locations (Figure 6). This is based on a representative grain size of 350 µm) over the 11 year period. The results highlight dominant northerly transport direction, although there is a slight variation (towards the north-northeast) with increasing depth. The exception to the above is Location 3, whereby the trend is more to the northeast, which is due to variances in the flow and wave fields represented within the SEASTATES data. The described variations are considered to relate to difference in the flow field as represented within the hindcast datasets. Also represented within the graphs are infrequent but significant changes to the sediment transport direction (Figure 6). During these events, the transport is more towards the west and northwest and is represented at all four locations. The events occur a number of times within the assessed time period (i.e. 2006 to 2016) (Figure 6) and relate to larger storm events, with sustained significant wave heights of over 3 m.

In terms of the transport magnitude, the progressive vector results illustrate the largest magnitudes occur at the shallower assessed depth (i.e. -16 mLAT which occurs on the sandbank crests), with cumulative transport rates of up to 12,000 m^3/m over the 11-year period. Based on the tide and wave properties at the same location, but for deeper depths, the cumulative rates are less than half. This would mean that within the study area, shallower areas would have larger transport rates, more than double that would occur at deeper locations. In relation to the proposed works, these are likely to occur at varying depths as the cable routes transect the sandbank features, which are the bedforms that contribute to the largest depth changes. Therefore, varying transport magnitudes can be expected at the different locations where levelling and disposal are to occur.

Natural England questioned whether any of the disturbed sediment (through dredging and subsequent disposal) would be lost from within the SAC. The likelihood of any disturbed material being lost from the Haisborough SAC is considered to be minimal. Previous studies (HR Wallingford *et al*., 2002; Kenyon and Cooper, 2005; Cooper *et al*., 2008), as well as the PVA results, demonstrate a distinctive northerly net transport pathway and the boundary in this direction is many kilometres away. Also, when considering the long-term transport direction of a body of sediment, sediment grains will only be transported short distances before becoming buried at a lower level in or even below the active part of the seabed surface, or incorporated into larger bedforms, and may not be transported further until exposed again at some point in the future.

The Haisborough SAC is not a closed system and it presently has sediment both entering and leaving it around the boundaries. The proposed works are some distance from the boundaries (over 6 km from the southern boundary) and are unlikely to bring about any disruption to the transport regime discussed above. Therefore, the movement in and out of the Haisborough SAC as occurs at present will continue, irrespective of the proposed dredging or disposal activities.

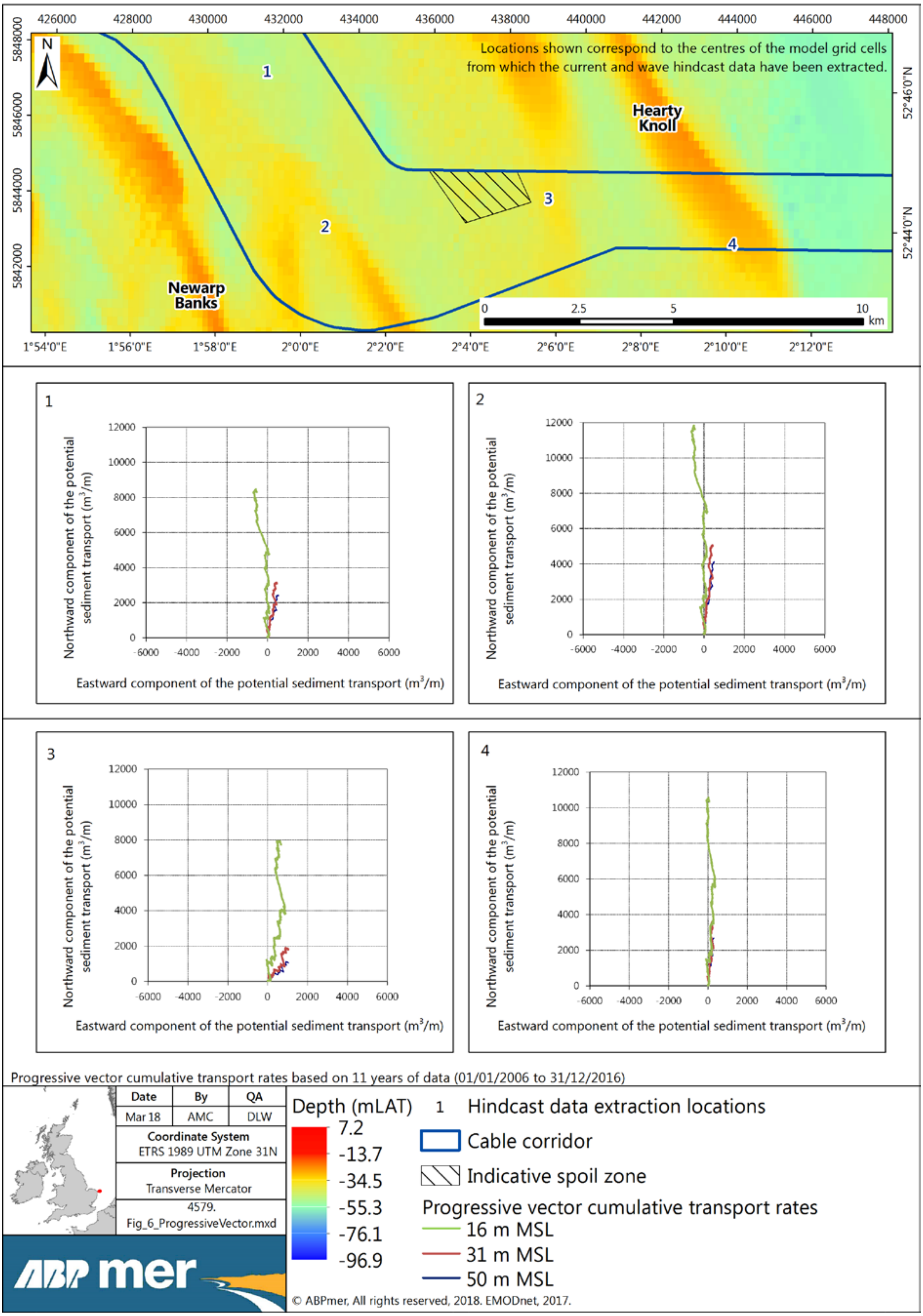

Figure 6. Progressive vector analysis

4.2 Potential effects on sandwave morphology

4.2.1 Introduction

The present study area is also an active and dynamic sediment environment that is conducive to the development and maintenance of sandwave bedforms. This is in relation to the flow speeds, water depths and sediment availability. Evidence of sandwave migration, along with bifurcating and converging sandwaves means the sandwaves are continually evolving with the formation of new bedforms. The availability of sand to form the bedforms as a result of the sediment transport processes and its continuation means there is ongoing potential for new bedforms to be established within the study area, a process which will not be disrupted by the proposed bed levelling works.

The cable orientation in relation to the sandwaves requiring levelling within the study area is mostly transverse to the bedform alignment and migration direction. This is particularly the case for the sandwaves overlying the Newarp Banks. In these instances, only a section of each sandwave is being levelled.

There can be varying asymmetry and migration properties along the length of a single sandwave, which does not necessarily disrupt the overall functioning of that particular sandwave or the system as a whole. The same can be implied for the proposed levelling works, in that the works affect a limited area of each sandwave, but the sandwave can continue to evolve and migrate along the remainder of its length. This is because, the processes that determine or influence the sandwave properties are not affected by the bed levelling works, therefore the form and function of the system (inclusive of the sandwaves and sandbanks) should continue unaffected. This is a process that is also evident from the sandwave response at the assessed sites along the Race Bank export cable route (DONG Energy, 2017).

In the sandwave field east of the Newarp Banks, the cable corridor is orientated roughly parallel to the bedform alignment, in these instances broader sections of the sandwave would be levelled. This has the potential to affect a number of sandwaves, potentially levelling a larger proportion of each sandwave than elsewhere along the corridor. In these cases, the area and volume of material being affected would be large in respect to each sandwave. It would however be minimal in the context of the sandwave field and sandbank as a whole which comprises of a large number of sandwaves. Furthermore, the current speeds, sediment availability and water depth are all conducive to the formation of new sandwaves. Therefore, despite the levelling of the sandwaves that intersect the cable corridor, the overall form and function of this sandwave field will remain undisturbed, with potentially new sandwaves being formed in time. Furthermore, the effects are limited to the overlying sandwaves, the form and function of the sandbanks within the Haisborough SAC would not be disrupted.

The sediment transport regime through the study area is governed by tidal processes, with notable influence from storm events, which can alter the transport direction and magnitude (Section 4.1 and Figure 6). Both of these processes occur at a larger scale to the proposed bed levelling works. As the works are not considered to disrupt these characteristics, the sediment transport is also not likely to be disrupted. The sediment transport potential based on predicted tide and wave conditions that occur within the study area is summarised in Table 5 and Table 7.

4.2.2 Norfolk Vanguard cable route

Section 1.2 summarises the proposed phased cable installation approach, whereby there is a gap of 6 to 24 months between the installation of each of the two cable pairs, for each windfarm. The proposed cable routes cross a number of sandwaves, for which a nominal volume of 35 m^3 per metre width was estimated as a representative sandwave cross section area requiring dredging. The potential dredge volumes from individual sandwaves (35 m^3/m) divided by the prevailing sediment transport rates ($m^3/m/hr$) described in Table 5 suggests that a volume of sediment equivalent to the dredged volume could be naturally transported back into each dredged area within the order of few months to years, depending on the frequency and magnitude of larger storms. This is due to the prevailing transport rates (Table 5) and sediment will be simultaneously moving into, through, and out of the dredged area.

In addition, due to the (mostly) northerly sandwave migration, with rates of 4 to over 30 m/year, it is again likely that in the time it takes the levelled area to reform (as a result of sediment infill, re-emergence of bedforms or up drift sandwaves migrating through), the sandwave, including the originally levelled area, would have moved and have been reshaped due to mobility, migration properties and the environment they are located. This means that the sandwaves are unlikely to return to their original shape and position, but their onward migration would continue uninterrupted. At the same time, as established sandwaves migrate out of an area, new sandwaves would continue to be naturally formed and migrate through. It is also possible that in the time it takes the levelled area to reform, or for the sandwaves to migrate onwards, the governing processes will act to bifurcate or converge the sandwave features.

The described sandwave response post-dredge would expect to start immediately after bed levelling. The length of time between each phase will then determine how much migration or reshaping the levelled sandwave will undergo. In terms of both HVDC cable pairs, there is an expected separation of 75 m. Based on the assessed migration rate for the sandwaves, there is the potential that any levelled sandwaves could undergo reshaping and migrate into the location of the next planned sandwave clearance area within the interval between phases of installation. This is most likely to occur with the fastest moving sandwaves (i.e. over 30 m/year) with the longest construction hiatus (i.e. 24 months).

In these instances, it is possible that the form of the affected sandwaves could be altered to a greater extent locally, affecting the timescale and nature of the recovery for that sandwave section. It is also possible, however, that a partially recovered section of sandwave that migrates closer to another location requiring levelling at a later date could then present a smaller local cross-section or volume requiring levelling. This could reduce the overall area and volume of levelling/dredging required and could even reduce the overall timescale for recovery as the effect is limited to a single smaller area. With the implementation of a shorter time gap between each phase (e.g. 6 to 12 months), there will not be enough time for the affected sandwaves to migrate into the area to level for the next cable pair.

It is not considered that spatially closer or overlapping levelling activities would be any more likely to alter the overall form and function of the sandwave field (and sandbank system) as very similar behaviour is evident in the natural environment, e.g. bifurcation of sandwaves. The largest impacts would occur for the sandwaves that are orientated parallel to the cable routes, while the least impacts would occur for the sandwaves orientated perpendicular, of which the majority are. Although the sandwaves are also unlikely to return to their original shape with a phased approach, their onward migration would continue in relation to the governing processes. At the same time, as established sandwaves migrate out of an area, new sandwaves would continue to be naturally formed and migrate through.

The bathymetry monitoring images from (DONG Energy, 2017) would suggest that the sandwave migration rate along the Race Bank export cable route is slower than what has been assessed within the present study area, which is more likely due to the different environmental conditions and sandwave migration characteristics (Section 3.2). The images also suggest that the levelled sandwaves are undergoing partial recovery mainly through natural infill, rather than from the migration of the sandwave bedforms (DONG Energy, 2017 and see Section 3.2). Due to the environmental conditions and assessed migration properties within the study area, recovery of the levelled sandwaves is more likely to occur in relation to both the natural infill of the levelled area and through migration of the sandwave features within the time frames discussed above (i.e. months to years).

In addition, there is evidence of bifurcating and converging sandwaves on and between the existing sandbanks within the study area, indicating this process is active within the Newarp Banks sandbank system. Therefore, localised changes on the seabed may result in the ongoing development of new bedforms within the study area, thereby also contributing the sandwave recovery. The Race Bank images illustrate this process, with indications of converging bedforms approximately 5-months after levelling (DONG Energy, 2017). This further supports the potential for such recovery of the sandwaves within the study area as these processes are presently active and are known to occur after levelling, as indicated at Race Bank.

Overall, the partial recovery and the associated recovery rate of the sandwaves along the Race Bank export cable route provides some support and justification for similar responses within the study area. Active bedform development requires the conditions which prevail across the Haisborough SAC and which contribute to the maintenance of the features present. The conditions include the flow speeds, water depth and supply of sediment (Belderson, *et al*., 1982). These conditions will continue after the bed levelling and are expected to lead to the recovery of the sandwaves. There is, also, the potential that further bedforms may be established, which would be consistent with the dynamic properties of the system. In this case, the form and function of the sandbank system will not be disrupted. The bedforms outside the levelled area and within the wider bedform field and sandbank system would continue to migrate and evolve with respect to the natural governing processes, as will the affected bedforms. This interpretation is supported by the evidence from the assessed Race Bank bed levelling sites, which demonstrates that the governing processes, which are not disrupted, do have an over-arching influence on the dynamics of the sandwaves.

4.2.3 Norfolk Boreas cable route

The phased installation of the Norfolk Boreas cable route will follow the same format as described for the Norfolk Vanguard cable route (Section 1.2.2). This includes installation of a cable pair with a 6 to 24 month hiatus, followed by the installation of the second cable pair. The cable route for the Norfolk Boreas would be within the same cable corridor set out for Norfolk Vanguard and provided for this study. Based on the above assumptions, the same level of impact identified for the Norfolk Vanguard cable route (Section 4.2.2) can be expected for the Norfolk Boreas cable route if completed in isolation.

4.2.4 Cumulative effects from both cable routes

This section discusses the worst case cumulative effects of the installation of the Norfolk Vanguard OWF completed in isolation, followed by the installation of Norfolk Boreas OWF cable pairings 6 to 24 months later (refer to section 1.2.2).

Based on the planned 250 m separation between the cables from each OWF and the assessed migration rate for the sandwaves, there will not be enough time for sandwaves levelled for the Norfolk Vanguard OWF to migrate into the area to level for the Norfolk Boreas OWF. Therefore, there should be no additional impact on the sandwaves in implementing the phased approach at the specified schedule. The overall result would be a series of sandwaves that have been levelled and would naturally reshape and migrate on in the same form or converge or bifurcate in relation to governing processes.
The potential for repeated impacts on the sandwaves, (on their form, migration and partial recovery post dredge) is dependent on the separation between the cables for each wind farm and the length of the hiatus. As a large separation is being applied between the OWF cables with respect to the sandwave migration rates, there is very limited potential for such cumulative effects within the study area, based on the phased approach for both OWF. Instead any effects would be restricted to that described for

each OWF independently (Section 4.2.2 and 4.2.3). Due to the very limited potential for cumulative effects, the likelihood of altering the form and function of the sandwave field and the wider sandbank system is considered to be minimal and will not be beyond that described for each OWF. This is because all evidence suggests the study area is in a dynamic environment conducive to the development and maintenance of sandwaves. Sandwave bedforms are continually being modified, converging and bifurcating, also with new bedforms being created and migrating through the cable corridor. Also the evidence from the Race Bank export cable route would support the potential for this process within the study area.

4.3 Potential effects from sediment disposal

4.3.1 Disposal location

The indicative disposal zone is presently located down-drift of the proposed levelling with respect to the regional net transport direction, although there are likely to be spatial and temporal variations in the sediment transport characteristics (see Section 2.6.2). To ensure the ongoing maintenance and form and function of the sandwaves and sandbank system, the dredged material should be disposed nearby and back into the sandbank system where the bulk of material is removed. Ideally this would be close to and up drift from the proposed levelling works. The regional sediment transport pathways are generally in a northerly direction (Figure 3 and Figure 6). However on a more local scale there may be both northerly and southerly direction transport in relation to re-circulations around the sandbanks. It would therefore be relatively more beneficial to dispose of material up drift of the cable route relative to the more localised sediment transport characteristics. Based on the transect analysis carried out (Figure 4), this would mainly be south of the cable route. However, further analysis of local sediment transport processes would be required.

The dredged material would have very similar properties as the receiving environment, and therefore have the same response to the environmental conditions as the surrounding sediment, with no adverse effects on the sediment transport regime. As the proposal is also to dispose of material within the Haisborough SAC, no material will be removed and would therefore be available for transport in relation to the local and regional sediment transport characteristics.

4.3.2 Deposition extent and thickness

Introduction

This section sets out the discussion of potential effects from disposal of sediment based on a volume of 250,000 m^3 per cable pair, 500,000 m^3 per offshore wind farm (i.e. two cable pairs) and a total of 1,000,000 m^3 for both offshore wind farms (i.e. four cable pairs). The assessment is based on the single indicative disposal zone, which has an approximate total area of 2,400,000 m^2 and is located down-drift of net regional sediment transport pathway (noting the likelihood of local re-circulations). It also assumes a dredge hopper volume of 14,000 m^3, which relates to the volume that would be released with each disposal event, for which approximately 18 disposal events would be needed per cable pair (i.e. volume of 250,000 m^3). It sets out the potential resulting extent and thickness of the disposed material and any differences that may occur as a result of the disposal method, i.e. using a surface release or disposal at the seabed via a downpipe.

Table 8 sets out the estimated deposition extent and thickness in relation to the varying deposition scenarios. The quantitative outputs from these spreadsheet models are validated for consistency with ABPmer’s internal evidence base of sediment disposal for similar dredging activities in relation to offshore wind farm development.

The completed assessments set out values of potential (conservative) deposition thickness in relation to the varying scenarios. They provide an important basis from which to interpret bed level change. In the context of natural variation in the physical processes involved, results should be interpreted according to the order of magnitude (e.g. tens of centimetres thickness, etc.).

Table 8. Estimated deposition thickness and extent based on varying deposition scenarios

Deposition Scenario		Thickness of Deposit (m)1* 3*	Single Disposal Event (14,000 m³ Hopper Capacity)		18 Disposal Events (250,000 m³ per Cable Pair)	
			Nominal Radius of Influence (m)3*	Deposition Area (m²)3*	Total Deposition Area (m²)	Percentage of Disposal Site Area (%)4*
Cone	2 x radius of steepest cone2*	4.20	54	9,028	162,499	7
	3 x radius of steepest cone2*	1.90	80	20,312	365,623	15
Uniform thickness		1.00	63	12,600	226,800	9
		0.75	73	16,800	302,400	13
		0.50	90	25,200	453,600	19
		0.25	127	50,400	907,200	39
		0.05	283	252,000	4,536,000	188

1* Height of peak for cones and average uniform thickness. The dimensions of the steepest cone are not provided in this table as it is not realistically expected that cone deposits of greater thicknesses (e.g. >5 to 10 m) will be allowed to accumulate in practice. The assessment is based on a uniform sediment size, i.e. medium sand at 350 µm.

2* The "steepest cone" relates to the greatest possible thickness and smallest deposition area, associated with a cone that has the steepest possible slope angle (i.e. the angle of repose for such loose sediments = 32° (Section 3.3.2).

3* The deposition area and thickness are based on the 90% hopper volume which equates to the dynamic phase (Section 3.3.2).

4* The available area within the indicative spoil zone is 2,407,681 m².

N.B. All value pairs are part of a continuous scale of possible outcomes. Therefore the results should be interpreted according to the corresponding order of magnitude (e.g. tens of centimetres thickness, etc.).

Although the extent, thickness and shape of sediment deposited on the seabed can be highly variable, a range of potential alternative combinations can be calculated based on a disposal volume. Therefore, for a given sediment volume, a deposition area/extent will correspond to a greater thickness of accumulation, and vice versa. In addition, a steeper sided cone shape deposit will have a greater thickness and a smaller area than a less steep sided cone or flat and uniform deposit shape. A range of possible value combinations based on the proposed dredge volumes are set out in Table 8 for a single sediment size (i.e. medium sand at 350 µm). The table demonstrates the changing spatial scale of the impact between the maximum possible thickness (associated with the smallest footprint) and the largest deposition extent (associated with the smallest thickness of 0.05 m). However, it is noted that, in practice, very thick deposits in shallow water would not be planned or allowed to occur as these may affect safe navigation and/or other engineering considerations. Consideration of potential deposition extents and thicknesses are provided in the following sections.

Uniform deposition across disposal site

If the total volume of sediment per cable pair (250,000 m³) is returned to the seabed with an average uniform thickness of 0.5 m, an area of about 450,000 m² would be covered, which is equal to approximately 20 % of the indicative spoil zone area (Section 1.2.3). With the disposal associated with all four cable pairs related to both the Norfolk Vanguard and Norfolk Boreas OWF (to a uniform thickness again), approximately 80% of the site would be covered.

Minimum area of deposition

The smallest deposition area that could be impacted is related to the dimensions of a single steepest sided cone, where the maximum thickness is in the centre of the deposit and thickness decreases gradually from the centre towards the edges. Such a cone could potentially form if the dredge spoil is all released instantaneously with no lateral displacement and there is minimal redistribution of that sediment by natural processes. The thickness associated with the steepest cone and associated smallest deposition area is a cone height of 16.7 m, with a nominal radius of 27 m and deposition area of around 2,300 m^2 per disposal event. Such a cone would result in an unrealistic thickness that would not be allowed to occur, therefore, the cone associated with the second steepest is discussed here. From a single disposal event, the second steepest cone would have a nominal radius of 54 m and approximate base area of 9,000 m^2, with an associated maximum thickness of 4.2 m at its centre. With 18 disposal events and multiple non-coincident cones associated with a cable pair, the total deposition area would approximately be 161,000 m^2, at 7% of the indicative spoil zone and up to 28% for all cable pairs at the same thickness (Table 8). If depositional cones were to occur, the area and thickness would vary due to variations in the environmental conditions during each disposal event and is therefore best considered as a range between the estimates set out in Table 8.

Discussion

In reality, the absolute width, length, shape and thickness of sediment deposition as a result of individual and all (combined) disposal events cannot be predicted with certainty. Instead it is more likely to vary due to the nature of the dredged material, the local water depth, the ambient environmental conditions during disposal, the disposal method (surface or through a down-pipe) and the vessel speed. Therefore, the most likely occurrence for a single disposal event is within a range of possible combinations of shape, area and thickness of sediment deposition as illustrated in Table 8. Irrespective of the deposition scenario, it is noted that the sandwaves within the indicative spoil zone typically have amplitudes of over 3 m and wavelengths of about 100 m. Therefore, there is already some variation in seabed depths within the indicative spoil zone and depending on the deposition characteristics (i.e. location, thickness and extent); the result would potentially be within the range already encountered within the indicative spoil zone.

4.3.3 Disposal method

Natural England has questioned the effects of the different disposal methods, i.e. is there the potential for varying deposition thickness and extent depending on the disposal method between a surface release or disposal at the bed via a downpipe.

Theoretically there is very little difference in the potential deposition thickness associated with either disposal method. The deposition thickness and extent will mainly be determined by the nature and final shape of the active phase of the dredge disposal plume (containing approximately 90% of the sediment volume). A range of possible realistic outcomes are provided in Table 8. The main difference between a surface release or disposal at the bed via a downpipe instead arises in relation to the passive phase (sediment plume), which may be subject to a greater degree of advection and dispersion before settling to the seabed (Section 3.3.2).

The deposition thickness associated with each disposal event (as a result of the passive sediment plume) is less than 0.02 m (and up to 0.3 m per cable pair). This is based on a surface release into a water depth of 31 m (i.e. representative depth within the indicative spoil zone), a current speed of 0.5 m/s, 350 µm grain size and 0.05 m/s settling rate. For each disposal event, the deposition extent would be over an approximate area of 86,000 m^2. Theoretically, the deposition area would vary with each disposal event due to variations in the tidal states and hydrodynamic conditions, meaning the overlap from each disposal plume would vary so the actual thickness per cable pair, (i.e. 18 disposal events) would be less than 0.3 m. Also, although the deposition extents may be larger per disposal event, the actual resulting thickness is far smaller (closer to. 0.02 m) and would largely be indiscernible on the seabed, due to the sandwave amplitudes present.

With the deposition of the sediment at the seabed, the surface exposed material would immediately become part of the northerly sediment transport regime (Figure 3). The results from the progressive vector analysis also illustrate a northerly pattern across much of the cable corridor (Figure 6). The estimated transport rates for sand across the study area range between 0.01 and 3.4 m^3/m/hr for the assessed tidal conditions associated with annual waves (Table 5), with lower estimates for tides only. The assessed rates are within the range modelled for the wider region within the Southern North Sea sediment transport study (HR Wallingford *et al*., 2002), whereby spring net transport rates on the order of 1,000 to 10,000 kg/m/tide (approximately 0.34 to 3.78 m^3/m/tide) were determined for medium sand. Any deposited sediment would be transported based on these existing rates. In addition, if any mounds were formed during disposal, these would have relatively low heights per release. The mounds would be quickly winnowed down to levels that can be expected to resemble nearby bedforms, which have heights in the order of metres.

As stated in Section 4.1, the potential for material to be lost from the Haisborough SAC as a result of disposal is again minimal, as the net transport pathway is typically to the north and the associated boundary is many kilometres away. Any loss would therefore be within the existing sediment transport processes.

4.4 Potential effects on the form and function of the Haisborough SAC

Estimated sediment volumes for three sandwave fields, which interact with the cable corridor are summarised in Table 6, using the approach described in Section 3.3.5. The estimates illustrate the volumes that may be available for transport, based on their migrating properties. The volume of sediment present within each bedform field is in the order of tens to hundred millions of cubic metres (Table 6). These three sandwave fields are in themselves a small component of the volumes within the wider Haisborough SAC with estimates of several billions of cubic metres (based on Annex I sandbank habitat coverage of at least 66,900 ha, with depths ranging from less than 10 m to 50 m (JNCC, 2010; JNCC, 2017).

Although the proposed bed levelling area and volumes within the Haisborough SAC are not insignificant amounts, they are very much smaller than the volume present within the wider sandbank system. The total volume of material within the local sandwaves (i.e. on and around Newarp Banks) and the whole Haisborough SAC is one to several orders of magnitude larger than the proposed bed levelling area and volume (Section 1.2.3). This means the proposed levelling only comprises a very small percentage of the total volume of sediment within the Haisborough SAC.

Sediment will generally not be removed from the local sandbank system, as the proposed method is to dispose of material on or around the Newarp Banks system. Therefore, the dredged sediment volume will only be displaced by a short distance from individual bedforms, presenting minimal impacts to local sediment availability and budget. The nature of the sediments being dredged (mineralogy and grain size) is and will remain similar to the receiving environment. In order to ensure the ongoing form and function of the sandwaves and sandbank system the dredged material would ideally be disposed of nearby and up-drift (i.e. to the south) from the proposed levelling works. This would effectively keep the displaced sediment volume within the local area of the affected sandwave, with the highest chance of it being naturally returned to the dredged area over time. Also, no sediment volume is being removed or made more likely to leave the associated sandbank system. Once redeposited to the seabed, the disturbed sediment will immediately re-join the local and regional sedimentary system, presenting minimal potential to affect to the form and function of the sandbank system as a whole.

In the event that material is removed from sandbanks not local to the disposal location, sediment will still be maintained within the Haisborough SAC and there would be no net sediment loss. In addition to the northerly and southerly transport pathways, studies also indicate there is an offshore sediment transfer mechanism through the sandbanks, which occurs over a long time frame (Burningham and French, 2016; Cooper, *et al.*, 2008; Collins, *et al.*, 1995). The mechanism is such that sediment moves from the sandbanks located in the nearshore to the more offshore bedforms, through the sinusoidal characteristics of the sandbanks. Therefore, any material deposited within the indicative disposal zones would be distributed across the wider SAC, including the sandbanks located further offshore. It is also noteworthy that the volume of material being dredged from any individual sandbank is minimal compared to the total sediment volume contained within the sandbank and for these reasons, the form and function of the sandbank systems within the Haisborough SAC would not be disrupted by the proposed bed levelling works.

The large coverage of the Haisborough SAC means it is exposed to range of environmental conditions from the coast to its offshore extent. The tides, waves, sediment supply and transport regime occur at the scale of the Southern North Sea, which is significantly larger than the Haisborough SAC itself and which will also continue unaffected.

The study results indicate that the proposed levelling will have little to no long term impact on the sandwave or seabed morphology, as the overarching governing processes are not disrupted (Section 4.1 and 4.2). In addition, the environment and processes within and around the Haisborough SAC are conducive to the development of new bedforms including sandwaves, which could form within or migrate into the Haisborough SAC. In fact, the environmental processes along with the sediment supply and water depths are the principal factors that influence the sandwaves and directly contribute to maintaining the form and function of the Haisborough SAC. Therefore, as the proposed works do not alter these factors across the Haisborough SAC, there is no reason why the form and function of the Haisborough SAC should be altered. The ongoing sediment supply, onward migration of the features in response to the tide and potential for new sandwave bedforms, will mean the form and function of the sandbank systems within the Haisborough SAC should be maintained. Information from the monitored sites along the Race Bank export cable route would also support this conclusion as there is evidence of sandwaves reforming and the ongoing evolution of these bedforms post levelling (DONG Energy, 2017). With respect to the seabed, the resulting levelled area or marginally raised seabed as a result of disposal are not considered to create a barrier to sediment movement across the sandbank systems and through the Haisborough SAC (Section 4.1). Therefore, the form and function within the Haisborough SAC will again be maintained.

5 Conclusions

An assessment has been made of the potential nature, magnitude, extent and duration of effects on the physical environment within the Haisborough, Hammond and Winterton SAC as a result of proposed bed levelling works and cable installation for the Norfolk Vanguard and Norfolk Boreas Offshore Wind Farms. This includes assessing the potential for any impacts on the seabed and sandwave morphology within the study area and any onward effects on the conservation objectives and designated features of the Haisborough SAC. The assessment is based on the existing baseline understanding of the present nature of sediments and morphology in the area, the processes controlling the morphology, and consideration of the potential for the proposed bed levelling activities to cause an impact.

A summary of the study conclusions are provided below.

5.1 Sediment transport and sandwave migration

- The varying bedform sizes, migration characteristics, bifurcating and converging sandwaves all observed within the study area are strong indicators of a very dynamic and active environment. In addition, they highlight the presence of governing processes that occur at a scale that is much larger than the proposed levelling. The factors which particularly influence the bedform properties are the water depth, tidal flow speeds and sediment availability, which are also conducive for the development of new sandwaves and maintenance of existing features.

- Calculated migration rates varied between 5 to over 30 m/year across the different bedform fields along the cable corridor. Between 2014 and 2016, the assessed sandwave properties demonstrate both northerly and southerly migration trends across different bedform fields. A northerly trend occurred on the sandwaves to the east of Newarp Banks, while a southerly trend was observed on the western flank of the Newarp Bank. The variation in migration characteristics potentially relate to the presence of a bedload parting zone and local re-circulations through the study area.

- The representative sediment size across the section of the offshore cable corridor within the SAC is medium sand, at about 350 µm. This sediment size, at average depths across the study area, is mobile for over 70% of the time (i.e. over the assessed 11-year period), but increased to over 85% with the combined influence of waves.

5.2 Effects on sandwaves

- There is the potential for partial recovery of the levelled sandwaves within the Haisborough SAC, although they are unlikely to reform to their original state following the dredging of the crest. This is due to the ongoing migration properties of the sandwave field. It, whereby is likely the sandwaves will continue to migrate in their new form, moving away from the levelled area, during which time also the crests would partially recover to a naturally stable shape.

- As the levelled sandwaves move away from the levelled area, new sandwaves would also form and migrate into the area, as the sandwave migration properties are unimpeded by the proposed bed levelling works.

- The worst case scenario would be phased levelling at adjacent locations, with a short separation distance between the cables, aligned in an approximately north-south direction, with the works progressing in the same direction as sandwave migration (from south to north) and relative to the migration rate.). In this worst case scenario, the adjacent or nearby areas of a sandwave could be repeatedly levelled up to four times. This would also mean that, as the sandwave is reshaped (or partially reforms) it could be modified up to four times, which would repeatedly alter the form of the sandwave. However, the total area and volume of sandwave to clear, and the overall area of sandwaves affected could also be proportionally reduced.

- The likelihood of this altering the form and function of the sandwave field and the wider sandbank system is considered to be minimal. This is because all evidence suggests the study area is in a dynamic environment conducive to the development and maintenance of sandwaves. Sandwave bedforms are continually being modified, converging and bifurcating, also with new bedforms being created and migrating through the cable corridor.

- The conclusions with respect to recovery of the levelled sandwaves within the study area (including both recovery through sediment volume replenishment and shape through migration of the sandwave feature) is supported by evidence from the levelled sandwaves along the Race Bank export cable route. The monitoring images showed evidence of partial recovery and reformation *in situ* over a 5-month period, without migrating away (DONG Energy, 2017). This is in part likely to be due to sediment volume replenishment, either through transport or contribution from smaller mega-ripple bedforms within the same area.

- The study area is an active and dynamic sediment environment with converging and bifurcating sandwaves evident in the available bathymetry data. The sandwave behaviour and responses are determined by the governing processes (tidal forcing, water depth and sediment supply) that occur at a much larger and regional scale than the proposed works. As these will not be disrupted by the proposed works, all available indicators point towards the form and function of the sandwaves, sandbanks and the Haisborough SAC being maintained.

5.3 Effects of disposal

- The absolute width, length, shape and thickness of sediment deposition as a result of disposal cannot be predicted with certainty and is likely to vary due to the nature of the dredged material, the local water depth and the ambient environmental conditions during disposal. A range of realistically possible combinations of shape, area and thickness of sediment deposition are provided in Table 8.

- There is not expected to be any significant difference in the thickness or extent of spoil deposits associated with either a surface release or disposal at the seabed via a downpipe.

- Following disposal, the material will most likely remain within the Haisborough SAC on the same time frame as currently occurring. This accounts for the fact that the Haisborough SAC is not a closed system but has sediment moving in from the south and out at its northern boundary. Different validation methods confirm a dominant northerly net sediment transport direction

- In the short term, sediment transport will be directed to the north-northwest and south-southeast of the indicative spoil zones in line with the prevalent sediment transport pathways. In the long term, the transport direction will be determined by the location of the spoil zone with respect to the regional scale bedload parting zone and local re-circulation patterns. Material deposited to the east of the bedload parting would more likely move to the north-northwest in the long term and sediment deposited to the west of the parting would more likely move to the south-southeast in the long term.

- It is noted that the SAC boundary to the north is many tens of kilometres away in this direction, and that individual sediment grains or bodies of sediment will not be transported independently of the other sediment which is present.

5.4 Effects on the Haisborough SAC

- The Haisborough SAC is not a closed system and it presently has sediment both entering and leaving it around the boundaries. The proposed works are some distance from the boundaries (at over 6 km from the southern boundary) and are unlikely to bring about any disruption to the transport regime. Therefore, the movement in and out of the Haisborough SAC as occurs at present will continue, irrespective of the proposed dredging or disposal activities.

- The area and volume of sediment to be dredged from the sandwaves as part of the proposed bed levelling works is very small in proportion to the area and volume of the Newarp Banks sandbank system. It is even smaller when considered in relation to the sandbank systems within the Haisborough SAC.

- Any sediment dredged from the sandwaves is to be returned to the seabed within the Newarp Banks sandbank system. There should be limited or no net removal of sediment from the system. Also, as sediment is only being locally displaced, the nature (texture) of surficial sediments, regional patterns of tidal currents and waves affecting the area will remain largely unchanged. Any deposited material will re-join the local sedimentary environment. Therefore, the form and function of the local Newarp Banks sandbank system and wider systems within the Haisborough SAC are not likely to be affected.

- The proposed bed levelling works are not considered likely to disrupt the form and function of the sandwaves locally or at the sandbank systems scale within the SAC. These are governed by processes that occur at a much larger scale than the proposed works. The sandwaves are expected to continue to evolve in response to the natural regional scale processes, which will continue unaffected.

- The same is considered likely for the seabed morphology, as the tides and sediment supply and transport regime are the governing forcing. The proposed works will not alter these; therefore the sediment transport properties are not likely to be disrupted.

- The disposal will also not affect the form and function of the Haisborough SAC. The transport direction will be determined by the location of the spoil zone with respect to the regional scale bedload parting zone and local re-circulation patterns. The SAC boundary to the north is many tens of kilometres away in this direction, and individual sediment grains or bodies of sediment will not be transported independently of the larger scale sediment transport processes.

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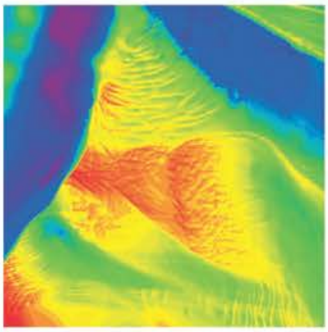
7 Abbreviations/Acronyms

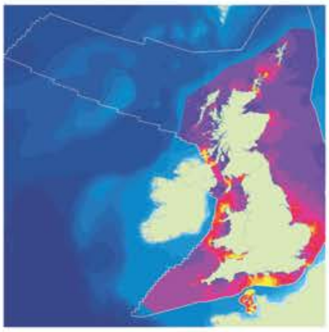
BGS	British Geological Survey
BODC	British Oceanographic Data Centre
Cefas	Centre for Environment, Fisheries and Aquaculture Science
D_{50}	Median grain diameter
EAOW	East Anglia Offshore Wind Ltd
ECREC	East Coast Regional Environmental Characterisation
EIFCA	Eastern Inshore Fisheries and Conservation Authority
ETRS89	European Terrestrial Reference System 1989
GIS	Geographic Information System
HRA	Habitat Regulations Assessment
Hs	Significant wave height
HVDC	High Voltage Direct Current
JNCC	Joint Nature Conservation Committee
LAT	Lowest Astronomical Tide
MESL	Marine Ecological Surveys Ltd
MFE	Mass Flow Excavator
mLAT	metres below Lowest Astronomical Tide
MMO	Marine Management Organisation
MSL	Mean Seal Level
OWF	Offshore Wind Farm
PSA	Particle Size Analysis
PVA	Progressive Vector Analysis
SAC	Special Area of Conservation
SCI	Site of Community Importance
SEA 2	Strategic Environmental Assessments Area 2
SNSSTS	Southern North Sea Sediment Transport Study Phase II
TSHD	Trailer Suction Hopper Dredger
UK	United Kingdom
UKCP09	United Kingdom Climate Projections (2009)
UKHO	United Kingdom Hydrographic Office
ZEA	Zonal Environmental Assessment

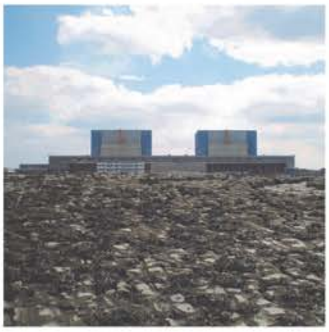
Cardinal points/directions are used unless otherwise stated.

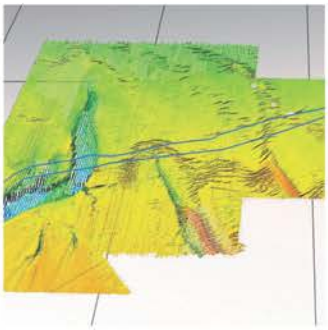
SI units are used unless otherwise stated.

Appendix









Innovative Thinking - Sustainable Solutions

A Bed Shear Stress and Sediment Mobility Calculation

A.1 Method

Estimates of sediment mobility and rates of sediment transport are made using equations and relationships summarised in Soulsby (1997) 'Dynamics of Marine Sands'. This reference is a standard text for such information and is often used for this purpose. More than 50 equations and tables of coefficients are used in the full spreadsheet of calculations and these are not all repeated here. The following is a summary of the approaches used. The equation reference in Soulsby (1997) is provided for key values. Full details of each equation, in some cases including a discussion of relative accuracy and limitations, may be found in Soulsby (1997).

The user specifies:

- Sediment grain size (250, 350 and 500 µm are considered in the present study).
- Sediment mineral density (representative 2650 kg/m^3).
- The density of seawater (representative 1027 kg/m^3).
- Water depth including any tidal variation (representative -28 mLAT for most examples, 16, -31 and -50 mLAT are also considered in relation to the progressive vector analysis (PVA)).
- Current speed (various values, m/s).
- Wave height (various values, m).
- Wave period (various values, s).

The water depth of -28 mLAT used for most examples in the report is representative of the general depth of the sea bed in the wider study area. Shallower water depths are present in some limited areas, mainly the crests of the sandbanks and individual sandwave features. In such shallower areas, the resulting bed shear stress estimates will be higher, hence sediment will be more mobile and with a higher transport rate. The greater depth used therefore provides a conservatively low estimate of the minimum level of mobility and transport rates in the wider area including between sandwave crests and between sandbank features. A range of water depths (-16, -31 and -50 mLAT) are used to illustrate this variability in the PVA.

Various representative values of current speed, wave height and wave period are used for most examples in the report to summarise the level of mobility (maximum grains size mobile) under characteristic every day and annually significant storm conditions, which are most likely to contribute to regional sediment transport and bedform migration. The sediment transport rate and direction estimates informing the PVA use a continuous hourly hindcast time series of coincident total current speeds, directions and water levels (including tide and surge components), and wave height, period and direction.

The following equations are used in the further analysis of the user specified input:

- Wave length is estimated from wave period and water depth following (Example 4.1). Near bed orbital velocity amplitude (Eq54) and orbital excursion (Eq77) are also estimated to be used as inputs for other relationships below.
- The critical bed shear stress for initial mobilisation of the sediment is estimated using the Shields Criterion (Eq77).

- The bed shear stress as a result of currents alone is estimated using a quadratic stress relationship with drag coefficient (Eq37 and 30) assuming a bed roughness coefficient of z0=0.006, representative of rippled sands.
- The maximum (peak) bed shear stress as a result of waves alone is estimated using a quadratic stress relationship (Eq57) and an appropriate choice of smooth (Eq62a) or rough (Eq63) bed friction factor depending on the particular user inputs.
- The mean bed shear stress under waves and currents combined is estimated using the current and wave alone shear stress values (Eq69), and the maximum (peak) value is estimated using the mean combined shear stress and wave alone shear stress values (Eq70). These calculations follow (Example 5.1) and use the GM79 (Grant, W.D., Madsen, O.S., 1979) coefficients.
- Sediment mobility (whether the specified sediment type is likely to be mobile or not) is tested by comparing the estimated bed shear stress for given water depth, current and/or wave conditions, and the critical (threshold) shear stress value.
- Sediment (total load) transport rates for currents and waves combined are estimated using an empirical relationship fitted to a range of field observations (Eq136).

A.2 References

Soulsby, 1997. Dynamics of Marine Sands. Thomas Telford, London. pp249.

Grant, W.D., Madsen, O.S., 1979. Combined wave and current interaction with a rough bottom. Journal of Geophysical Research 84 (C4), 1797–1808.

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