COWRIE COAST-07-08

Coastal Process Modelling for Offshore Wind Farm Environmental Impact Assessment: Best Practice Guide

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Table of Contents

List of Figures

Executive Summary

This report provides an update to existing best practice guidance on the application and use of numerical models to predict the potential impact from offshore wind farms on coastal processes. As such, this report is of direct use to windfarm developers and environmental consultants, providing guidance on the scoping and design stages of the coastal processes part of an Environmental Impact Assessment (EIA). It provides guidance on the requirements for numerical modelling, and how to assess the extent and quality of any numerical modelling work proposed and undertaken.

Guidance for undertaking an EIA is typically aimed at addressing particular issues, incorporating conceptual and methodological understanding and data (the evidence or knowledge base) accumulated from past experiences. The key issues for coastal and seabed impact assessments that are considered to remain of particular interest in the context of an offshore wind farm EIA are*:*

- Suspended sediment dispersion and deposition patterns resulting from foundation and cable installation or decommissioning.
    - o Relevance: receptors sensitive to specific changes in burial depth, suspended sediment loads or textural change in sedimentary habitats.
- Changes in coastal morphology due to cable landfall installation and maintenance.
    - o Relevance: receptors sensitive to erosion or accretion including habitat, property, recreation and landscape.
- Scour and scour protection.
    - o Relevance: receptors sensitive to the introduction of new substrate
- Wave energy dissipation or focusing for sites very close (<5km) to an exposed shoreline, for foundation types and/or array densities which are considered more likely to affect wave height, period or direction.
    - o Relevance: Receptors sensitive to changes in coastline morphology.
- Wave and current processes controlling very shallow sandbank morphology, especially for relatively dense turbine arrays and/or less well understood foundation types.
    - o Relevance: ecological or navigation receptors sensitive to changing bed morphology including scour, channel migration sandbank mobility.

There is inevitably a lag in parts of the evidence base behind some foundation types. For example, the effect of complex or large (non-monopile) foundation types on waves, currents and local sediment processes, is a topic which requires further research to be added to the evidence base. Alongside these specific needs, the process of guidance review and complementary research continues to follow the move to even larger sites, located farther offshore as part of Rounds 2 and 3.

In support of offshore wind farm EIA's, guidelines to outline the general scope for 'coastal process' investigations are available for characteristic Round 2 developments and are also being updated to suit Round 3 requirements. The consideration of potential changes to the marine environment and the consequential response of an environmental receptor is anticipated to remain as part of the EIA approach. However, the most appropriate and efficient method to assess any potential impact should be considered in each case, in the following order:

1. What are the potential sensitive receptors by category or species? Are the sensitivity thresholds of the defined receptors understood and quantified?
2. What information about the physical environment is required to categorize the potential impacts on the identified receptors?
3. Can sufficient information be practicably and effectively provided by existing knowledge and available field data without the need for numerical modelling?
4. If the answer to Point 3 is 'no', can numerical models represent the processes involved sufficiently to provide the required information?

5. If the answer to Point 4 is ‘yes’, can sufficient field data be obtained to adequately calibrate and validate the model to provide confidence in the results?
6. Does the regulating authority agree with the proposed approach to the study?

In summary the guidance is intended to provide an objective approach for defining the basis for selecting field data collection and/or numerical modelling to support EIA studies. This can be thought of as follows: if the question(s) relating to completion of the EIA is well defined and can be answered on the basis of existing evidence (including existing site data or numerical model results), then the need to obtain new or more detailed data, either from the field or from numerical modelling studies, is questionable. Conversely, if the question(s) cannot be answered on this basis then field data collection or numerical modelling can be considered.

Specifically, if the question(s) is well defined and the procedure indicated in the list above is followed, then numerical modelling can be considered as an option, using the following general best practice advice.

- Choose a numerical modelling approach that is fit-for–purpose in reproducing the range of processes identified as important to the question being posed, including both baseline and scheme assessment.
- Ensure that a sufficient quantity, quality and resolution of data are available in order to support the modelling work being undertaken. The requirements will vary depending upon the complexity of the site dynamics and the accuracy required in order to answer the question being posed.
- Assess confidence in the model accuracy through an appropriate, quantitative, model calibration and validation process. Confidence in model accuracy is ultimately limited by the properties of the data used to build and test the model, and by the inherent limitations on accuracy of the modelling approach used, including the ability of the model to account accurately for baseline physical processes and for the effect of the wind farm structures.
- Assess the effect of the scheme as the difference between the modelled baseline and the modelled scenario. In doing so, uncertainty regarding the absolute accuracy of the model is reduced.
- Reduce uncertainty in the effect of the many potential scheme options by choosing an appropriate ‘realistic worst case’ scenario. If a realistic worst case scenario is demonstrated to pose no significant impact, relatively less intrusive options can be accounted for without explicit modelling.

Additional specific best practice guidance may be found in the main report on the following key topics:

- The presently available evidence base
- Assessing the requirement for numerical modelling
- Assessment of identified site specific EIA issues
- Sources of data in support of modelling and EIA
- Considerations relating to the application of numerical modelling
- Managing and assessing uncertainty

Acronyms

1D/2D/3D – (1,2,3) Dimensional
2DH – 2D vertically averaged model
2DV – 2D horizontally averaged model

ABP – Associated British Ports
ABPmer – ABP Marine Environmental Research
ADCP – Acoustic Doppler Current Profiler
AIAA – American Institute of Aeronautics and Astronautics
AWAC – Acoustic Wave and Current (measurement device)
BERR - Department for Business, Enterprise and Regulatory Reform
Cefas – Centre for Environment, Fisheries and Aquaculture Studies
CFD – Computational Fluid Dynamics
CPA – Coast Protection Act (1949)
DECC – Department of Energy and Climate Change
DEFRA – Department for Environment, Food and Rural Affairs
DHI – Danish Hydraulic Institute
DNV – Det Norske Veritas
DOE – Department of Energy
DTI – Department of Trade and Industry
DTLR – Department for Transport, Local Government and the Regions
EA – Environment Agency
ECMWF – European Centre for Medium range Weather Forecasting
EIA – Environmental Impact Assessment
ETSU – Energy Technology Support Unit
FEPA – Food and Environment Protection Act (1985)
GPS – Global Positioning System
HD - Hydrodynamics
MaRS – Marine spatial planning tool (The Crown Estate)
MFA – Marine and Fisheries Agency
MT – Sediment transport (cohesive, e.g. mud)
NOAA – National Oceanic and Atmospheric Administration
OSCR – Ocean Surface Current Radar
OWF – Offshore Wind Farm
POL – Proudman Oceanographic Laboratory
PPK – Post-Processing Kinematic
PT – Particle tracking
QA – Quality Assurance
RAG – (BERR) Research Advisory Group
RTK – Real Time Kinematic
SEA – Strategic Environmental Assessment
SSC – Suspended Sediment Concentration
ST – Sand transport (non-cohesive)
SW – Spectral waves
UK – United Kingdom

Units

All units are SI, unless otherwise stated.

GW – Giga Watt
MW – Mega Watt
nm – Nautical miles

1 Introduction

1.1 Background

In December 2007, the Secretary of State for Business Enterprise and Regulatory Reform (BERR) announced the commencement of a Strategic Environmental Assessment (SEA) to examine 25GW (gigawatts) of additional UK offshore wind energy generation capacity by 2020. This followed on from the combined capacity of 8GW planned for Rounds 1 and 2.

In June 2008, The Crown Estate announced proposals for the third round of offshore wind farm leasing. Unlike Rounds 1 and 2, The Crown Estate took a more active role, co-investing with developers.

Previous guidance written in support of Round 1 and Round 2 offshore wind farm developments in the UK has been focused upon marine environments where shallow water coastal processes were likely to be important. Round 3 developments are now considering larger sites, which in general are located further offshore, potentially in deeper water and, therefore, are less likely to impact on the coastline. It was identified by COWRIE and the authors of the present study that an update to guidance was required to incorporate additional information and design and construction challenges relating to the development of wind farms in these new marine environments. It was also identified that guidance for all marine environments would benefit from an updated summary of lessons learned from existing developments and additions to the evidence base.

1.2 Scope

This document provides guidance and some background for those people involved in reviewing marine processes studies submitted as part of Environmental Impact Assessment (EIA). These guidelines are primarily designed for use by developers, government departments and regulators to provide a standard for what should be considered as good practice with respect to undertaking numerical modelling studies. The principal aim of this document is to assist those people who are commissioning such studies, or who are required to review documents containing numerical modelling output from coastal process studies in support of offshore wind farm EIA; this report should not be seen as a 'how to' guide for modellers.

It is not the purpose of this document to provide detailed technical information or discuss the use of physical modelling, although the appendices provide some additional technical information that may be useful for regulators by providing reference sources. The advice presented in this guide covers the following areas:

- Best practice; and,
- Identification and management of error and uncertainty.

The scope of this guide is not directly aligned to the many engineering issues which also may be the subject of investigation through data collection or numerical modelling techniques.

1.3 Purpose of this document

The purpose of this guidance document is to specifically provide more information about:

- Presently available methods of assessing the environmental impact of offshore wind farms on coastal and offshore processes, in particular through numerical modelling;
- Identifying when quantitative analysis or numerical modelling is appropriate or when it may be unnecessary;
- The types of modelling tools which may be employed to make this assessment;
- The appropriate quantity and quality of data to use in the assessment;

- The sources of uncertainty in the assessment process and how to reduce or manage them; and,
- The potential effects of moving further into the offshore environment, as is happening in Round 3 of offshore wind farm development in the UK.

Separate to this report, the two guidance documents for undertaking environmental impact assessment (previously written by Cefas, 2004 and Defra and the statutory Nature Conservation Agencies, 2004) will be reviewed, merged and updated as part of Round 3 offshore wind farm development in the UK. These guidance documents are complimentary in the sense that they both provide additional information regarding the methods that can be employed to undertake environmental impact assessment, the present study also aims to inform the reader on how to reduce uncertainty in that assessment.

2 Background

2.1 A review of present understanding

Energy generation from offshore wind is in the process of becoming an established industry worldwide.

The UK experience is evolving through a sequence of commercial rounds called by The Crown Estate and guided by the regulatory process. In 2009, this has led to the delivery of five operating Round 1 projects, with several others nearing operational status..

2.1.1 Round 1

Round 1 projects provided a deliberate demonstration phase so that many untested concepts in offshore development could be introduced on a small scale.

Projects were required to be contained with a 10km^2 area of seabed, be within 12 nautical miles of the coast, have up to 30 turbines and development sites should be separated by no less than 10km. The lease period was also limited to 22 years. The outcome from the invitation was 18 projects at discrete sites around the coastline of England and Wales (Figure 2.1).

Early guidance was offered to assist the delivery of consents for these projects, based on a perceived set of issues which were considered at the time could lead to some form of environmental risk. For the subject of coastal process this guidance included:

a) **Consents guidance for Round 1 (Cefas, 2001 and DTI, 2002)** - which identified a list of environmental risk issues, the types of data that should be collected and recommended spatial and temporal scales for both.
b) **Potential Effects of Offshore Wind Developments on Coastal Processes (ETSU, 2002)** - which included guidance on practical methods for modelling physical processes as part of site specific studies.

Projects were advanced on the basis of these requirements, and considering any wider stakeholder concerns, leading to an assessment of potential environmental impacts. The approach always tended towards adopting a conservative realistic worst case to mitigate unknowns. However, levels of uncertainty in the outcomes of the EIA process generally remained high due to the lack of any direct observational evidence to substantiate the views offered in any Environmental Statements. Accordingly, consents were granted on the basis of these levels of uncertainty and with a range of monitoring conditions on licences intended to establish and develop the evidence base.

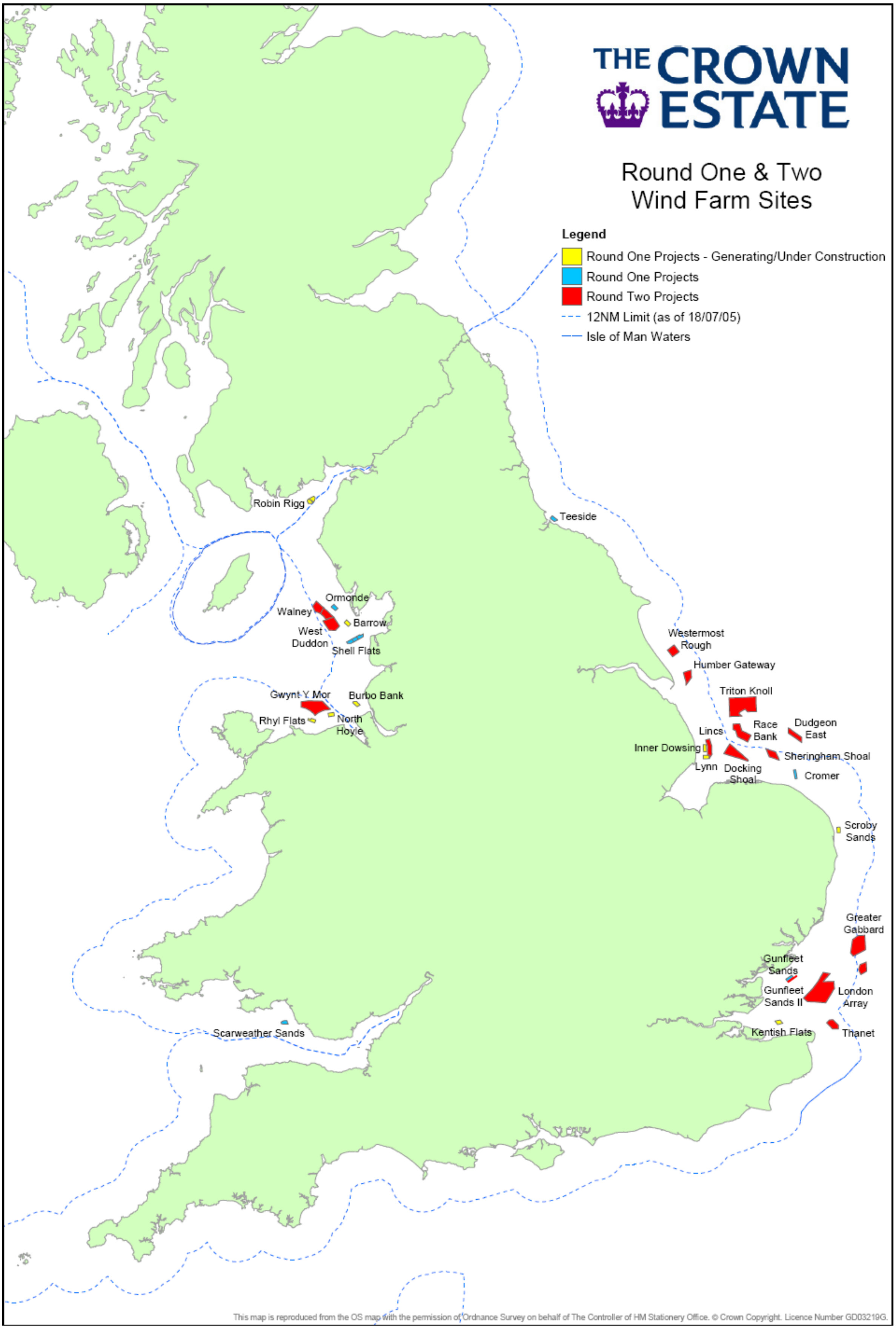

Figure 2.1 Locations of Round 1 and 2 Offshore Wind Farms (www.thecrownestate.co.uk/a4planuk_04_03_16.pdf)

The first project gaining consent was Scroby Sands. The physical process monitoring here was part-funded by DEFRA who funded two research studies:

AE1227: Assessment of the Significance of Changes to the Inshore Wave Regime as a consequence of an Offshore Wind Array

http://www.cefas.co.uk/media/49662/sid5_ae1227.pdf

This project studied the effect of an offshore wind farm on the local and adjacent wave regime. Scroby Sands was identified as a 'worst case' scenario for wave interaction due to the relatively large pile diameter to water depth ratio, a situation more likely to cause stronger wave-structure interaction. As part of the study, new field measurements of the wave regime were collected over wide areas using an X-band radar system, which were calibrated and validated using additional in-situ direct measurements. These data were also used for sensitivity testing the effect of the wind farm using numerical models.

The conclusions of the AE1227 study were that slender monopiles at typical spacing (6-8 rotor diameters) do not have a significant potential to cause measurable wave reduction, diffraction or interference and therefore do not have a significant potential to modify local or far-field sediment transport processes.

As a result of the AE1227 project, an assessment of wave diffraction effects by monopile foundations is no longer required as part of the EIA. However, assessment of wave attenuation effects is still required.

AE0262: Development of Generic Guidance for Sediment Transport Monitoring Programmes in Response to Construction of Offshore Wind Farms

http://www.cefas.co.uk/media/21503/ae0262-final-report-scroby-owf.pdf

This project studied the effect of an offshore wind farm on the local and adjacent patterns of sediment transport. Scroby Sands was again identified as a 'worst case' scenario, due to the relatively large pile diameter to water depth ratio. As part of the study, field measurements of the detailed seabed bathymetry were collected, along with in-situ direct measurements of tidal currents, wave and suspended sediment concentrations. Repeat data were collected during various pre- and post-construction phases.

The conclusions of the AE0262 study were that scour pits observed in the near–field were similar to those predicted by the EIA and that no significant or measurable effect could yet be observed at larger spatial scales. Scour pits and secondary scouring as a result of irregular placement of scour protection material should be assessed and reviewed thorough programmes of regular monitoring.

In the post-consent phase, detailed engineering solutions emerged to construct these projects. To date, there has been a preference to install monopile foundations with piling and/or drilling and cable laying with ploughing or jetting. Initially the regulator had concerns in the use of jetting which were reconciled through further studies. Drilling has also emerged as a concern especially where there is a perceived risk that chalk arisings might occur.

2.1.2 Round 2

In 2003, The Crown Estate invited a second round for commercial scale offshore wind development within three regions determined from a **Strategic Environmental Assessment (SEA) for Round 2 (BMT Cordah, 2003)**, commissioned by DTI.

The three strategic areas (The Greater Wash, The Thames Estuary, and The North West or Liverpool Bay) were identified on the basis of many diverse criteria. In addition to clustering the development activity, a precautionary exclusion zone of 8 to 13km from the coast was applied to reduce visual impact and to avoid certain shallow water feeding areas for particular bird species. In doing so, sites identified for development were further offshore and typically in deeper water than those selected during Round 1. Developments have 40 to 50 year lease periods and there was no stipulated limit on the number of turbines that could be installed, however, an initial limit on the total capacity of Round 2 was set at between 4 and 6GW which was subsequently extended to 7.5GW over the three strategic areas.

Figure 2.1 shows the location of the various Round 2 wind farm projects. The move further offshore and larger developments posed new issues on the EIA agenda, including greater potential for cumulative impacts with other seabed users and the potential use of alternative foundation designs.

In light of the anticipated differences to Round 1 the **EIA guidance for Round 2** was updated **(Cefas, 2004)**. The revised document contained similar requirements to the original, but with a number of small but notable differences to the coastal processes section:

- The timescales over which assessment should be made was extended to include the lifetime of the site and the decommissioning phase.
- Baseline requirements were reworded as a series of issues, rather than as a series of parameters.
- Constructive and destructive interference of waves as a result of wave diffraction around monopiles was removed as an explicit concern, as a result of the findings of Cefas project AE1227.
- Specific new requirements were introduced to account for the effects of cable laying, the effect of the wind farm on sediment transport (including potential effects of mixed sediments) and the potential impacts of climate change on hydro- and sediment-dynamic parameters.
- New requirements were also introduced for assessment of the potential for in-combination effects with other seabed users or developments.
- An explicit invitation was also included for the developer to present up-front recommendations for monitoring and other mitigation.

Further consideration was also given to marine processes and the SEA commissioned a study to look at **offshore wind farms and sandbanks (Kenyon and Cooper, 2004**). Another supporting technical investigation was also undertaken into the **potential impact of Round 2 offshore wind farm sites on sediment transport (ABPmer, 2005),** in order to better understand the effect of having longer term projects moving further offshore and into deeper water and as an extension to the previous ETSU work aligned to R1 projects.

The pan-Government Research Advisory Group (RAG) recognised the need for additional research to inform the consenting process for Round 2 projects and a set of targeted research was funded to evaluate lessons learnt and evidence becoming available from constructed Round 1 sites.

The three key projects related to physical processes and construction related issues were:

> **Seabed and Coastal Processes Research report SED01. 'Review of Round 1 sediment processes monitoring data – lessons learnt' (ABPmer *et al*. 2008).**
> **http://www.berr.gov.uk/files/file50440.pdf**
> This project studied the collective results of sediment monitoring activities (suspended sediment, seabed morphology and scour) that had been undertaken under the licence agreements for five installed Round 1 wind farms. Where available, reference was also made to wind farms belonging to other European countries. The methodology by which the data were collected was also assessed.

The conclusions of the study were that seabed morphology was only affected at a local scale (i.e. scour) at all sites apart from Scroby Sands, where more extensive scour tails have been observed. Also, the methodologies used to collect suspended sediment concentration (SSC) data were recognised as requiring a specialist and intensive measurement approach which should be standardised; a best practice method was recommended. Also, that the methodologies for bathymetric data collection were not sufficiently consistent between repeat surveys or between sites to support accurate inter-comparison of the data; again, a best practice method was recommended.

As a direct result of SED01, the requirement to monitor SSC has been removed from the Teeside FEPA licence and requirements for monitoring SSC will only be applied if and where jetting techniques are used at the Lincs and West-o-Duddon Round 2 sites.

Seabed and Coastal Processes Research report SED02. 'Dynamics of scour pits and scour protection – Synthesis report and recommendations (Milestones 1 and 2)' (HR Wallingford *et al.* 2008). www.berr.gov.uk/files/file50448.pdf
This project studied in more detail the data and findings relating to scour from the SED01 project. The same data from the same site were used to examine or validate the ability of the predictive equations used in the EIA to predict the maximum equilibrium scour depth and extent of scour around turbine foundations. In all cases, the predictions for maximum depth or extent were accurate, however, several sites proved to be more resistant to scour than originally anticipated, with the result that maximum scour may not (yet) have been achieved. In addition, issues of secondary scour around scour protection materials proud of the seabed were highlighted, as also observed previously in the AE0262 project (Cefas, 2006) which focussed only on Scroby Sands wind farm.

As a result of SED02, FEPA licences now require the development of a site specific scour protection plan to ensure that materials and methods are appropriate for the site conditions. Best practice recommendations from the study still to be applied in licensing, include that at sites where scour is evidently slow to develop, the frequency of monitoring activities can be reduced.

'Review of cabling techniques and environmental effects applicable to the offshore win farm industry' (Royal Haskoning and BOMEL, 2008). www.berr.gov.uk/files/file43527.pdf
This project studied the various options relating to cabling techniques in the marine environment. Many types of cables and different methods of cable burial and protection were considered. The guide provided both a qualitative and quantitative assessment of the impact of cable burial operations, informed by the data and results from the SED01 project (above). The report concluded that increased suspended sediment concentrations as a result of cable laying are likely to be small in comparison to natural levels in coastal environments and that the effect will be limited temporally and localised spatially, making in-combination effects unlikely.

No specific outcomes of the cabling techniques study have yet become evident in the EIA process, however, the results do support an argument for reducing requirements in this respect and are used to inform and reinforce the findings of SED01.

The present evidence base is principally informed by the outcomes of these projects.

2.1.3 Round 1&2 extensions (Round 2.5)

In late July 2009, The Crown Estate announced an opportunity for developers of any Round 1 or Round 2 site, to apply for an extension to their existing development plans. The announcement was in response to the UK government's ongoing commitment to renewable energy targets and aims to realise any additional offshore wind energy capacity that could be brought online ahead of Round 3. Separate announcements were made proposing extensions to both lease duration (up to 50 years) and to the size of the development (no upper limit on the number of devices).

Applications indicating initial interest in such extensions were registered in September 2009.

Applications for extensions to the extent of an existing or proposed development will require new or updated statutory consent and licensing, and as such must be accompanied by an appropriate full EIA.

2.1.4 Development in Scottish territorial waters

Additional sites have been identified for OWF development in Scottish territorial waters (within 12nm of the coast). Expressions of interest to develop sites were registered in mid 2008 and sites were awarded in early 2009. Similar requirements for statutory consent and licensing apply as for Round 2 and an appropriate full EIA will be required for each site. The locations of the sites awarded as part of this process are shown in Figure 2.2, alongside the proposed Round 3 zones located further offshore.

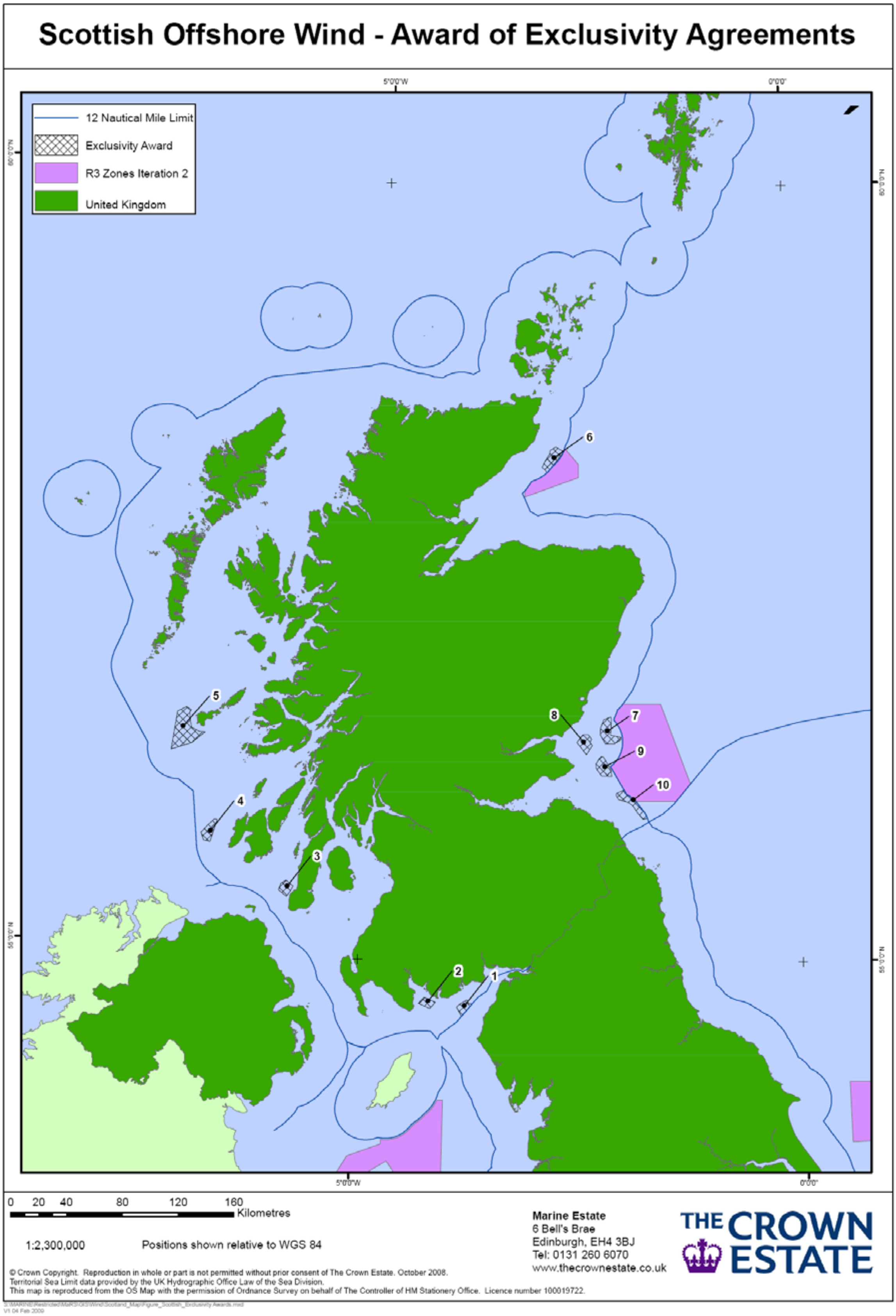

Figure 2.2 Locations of sites awarded for further development in Scottish territorial waters and Round 3 Offshore Zones (http://www.thecrownestate.co.uk/scottish_offshore_exclusivity_agreements.pdf)

2.2 Round 3 Developments

In 2006 the EU announced a revised renewable energy target of 20% for all member states by 2020. Related to this, in 2008 the UK government proposed increased target cuts in greenhouse gases of 80% (up from 60%) before 2050. Offshore wind is expected to contribute to these targets and so is being supported actively by the government and its agencies. Round 3 of offshore wind plans to deliver an additional 25GW by 2020. The DECC Round 2 SEA process for identifying Round 3 offshore wind development zones was initiated in Dec 2007 and, was completed in 2009 **(Hartley Anderson, 2009).**

The rights to develop each of the zones are tendered for by large developers or consortia, which will identify and facilitate development of wind farm sites within that larger area. Each development site still requires site specific EIA in order to obtain the necessary consents for development.

Using its marine spatial planning tool 'MaRS', The Crown Estate identified nine zones in advance of the SEA report that it considered potentially viable for offshore wind farm development. The zones identified did not infer or influence the outcome of the SEA process; the location of the zones has subsequently remained essentially unaltered by the outcomes of the SEA process. The locations of the Round 3 zones are shown in Figure 2.3.

The Round 3 zones are distributed around the UK with the exception of the west coast of Scotland (where there are two sites identified for development in territorial waters – see Section 2.1.4). A notable difference with previous rounds is the widening of the spatial scope for development where zones might become available on the south coast of England, in the Bristol Channel, in the outer Moray Firth and Firth of Forth, and on Dogger Bank; extensions alongshore and offshore from the North West/Liverpool Bay, Greater Wash and Thames strategic areas are also proposed.

The size of the zones made available may vary considerably. Relatively larger zones may be of a similar extent to the Greater Wash and Thames strategic areas; relatively smaller zones may be of the order of one or two large Round 2 developments. As a simple result of the area locations, but supported by economies of scale, Round 3 developments are generally located much further from the coast. Some of the small/intermediate scale zones straddle and/or extend within the 12 nautical mile territorial limit (environments similar to Round 1 and Round 2) whilst other (typically larger) zones extend up to 100-300km (50-160nm) from the coastline.

The new challenges posed by R3 development are that:

- Depending upon the location, offshore environments may be relatively less well understood (data poor);
- they are generally in deeper water and more exposed;
- they potentially require alternative foundation design, the effects of which are presently unclear;
- the above three points have not yet been considered or observed in relation to offshore wind farm EIA which presents new associated uncertainties; and,
- commercial pressure to utilise the whole of a development zone may lead to a desire for more extensive developments, and less space between developments.

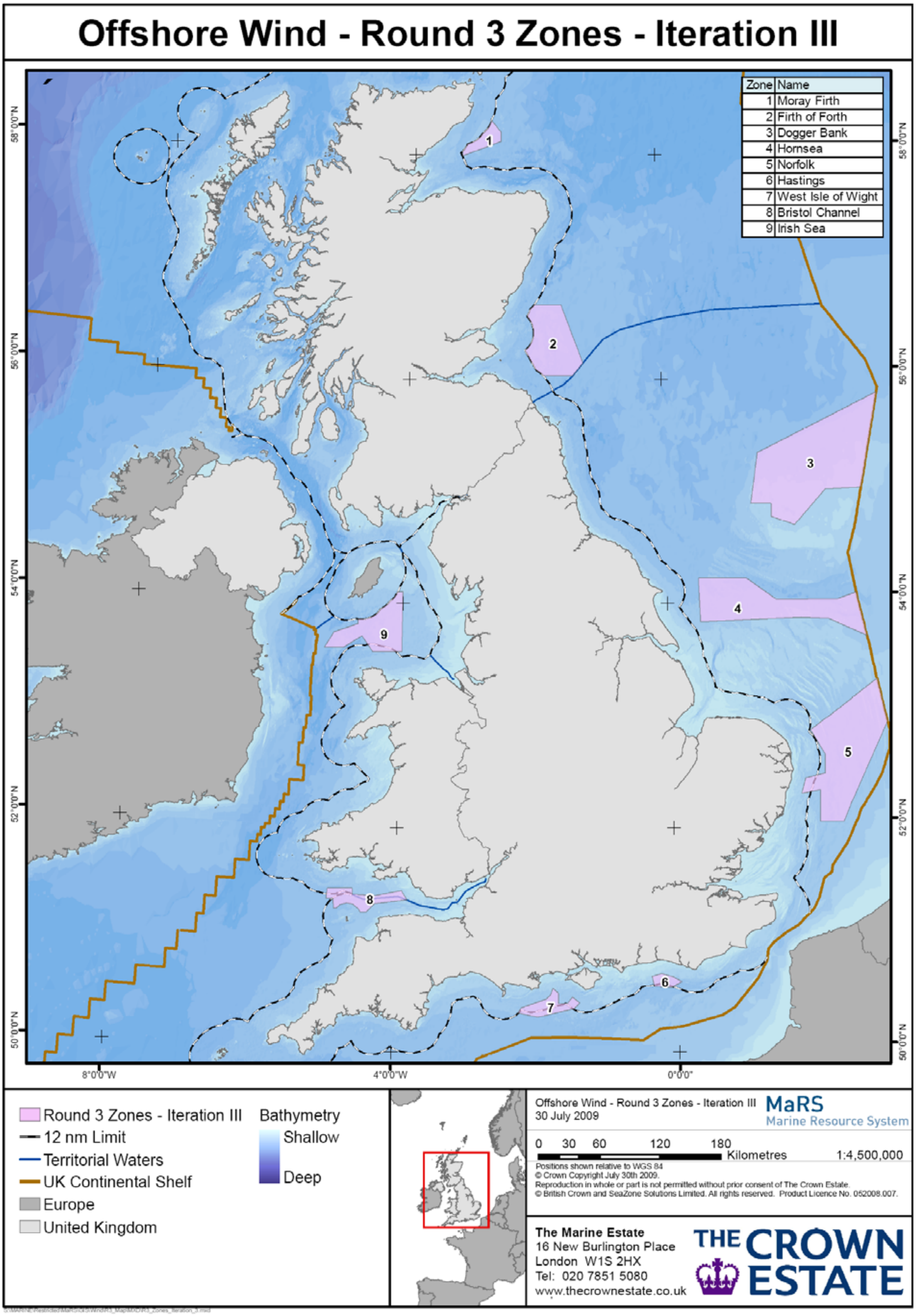

Figure 2.3 Locations of Round 3 Offshore Zones (http://www.thecrownestate.co.uk/newscontent/round3)

2.3 The Role and Requirements of Environmental Impact Assessment

The regulatory body which grants FEPA licenses for offshore wind farm development is the Marine and Fisheries Agency (MFA) which receives proposals for site development accompanied by comprehensive Environmental Impact Assessment reports. The MFA is officially assisted in its review of the 'coastal processes' section by Cefas and a series of statutory consultees (e.g. NE, CCW, JNCC, MCA).. Broadly speaking, the role of the EIA is to determine the extent to which the proposed scheme might impact on sensitive receptors in the wider environment within which it is located and develop design and mitigation measures to eliminate or minimise these impacts.

In support of coastal process EIA for Round 2 offshore wind farm, Cefas has previously produced guidance documents (Cefas, 2001, 2004) that describe the particular role of this section of the EIA and consider the requirements for data collection and the issues that must be addressed, together with an indication of the expected temporal and spatial scales of the assessment. It is intended that the 2004 guidance will be updated again by Cefas, MFA and the Statutory Nature Conservation Agencies in 2009, to account for the new challenges posed by Round 3; Cefas was consulted as part of the present study as to their intentions in this respect, but the new document was not completed at the time of writing. A summary of the recommendations from Cefas (2004) in the context of the present study is given below, together with a broad assessment of the new issues that might be posed by development further offshore.

2.3.1 Data collection:

Present EIA guidance (Cefas, 2004) by Cefas is summarised below in italics. *All offshore wind farm developments should be assessed:*

- *on a site-specific basis,*
- *to include direct impacts on hydrodynamics and sediment dynamics, and*
- *to include indirect impacts of these on other disciplines (e.g. benthos, fisheries, coastal protection, water quality, sediment quality, conservation-designated sites).*

For any wind farm proposal it is necessary to assess the magnitude, and significance of change, caused both directly and indirectly to the following:

- *Hydrodynamics (e.g. waves, tidal flows) – using surface and/or seabed-mounted buoys, ADCP. [Note: It is important that all field data provide information on seasonal variations such as calm and storm events; therefore deployment may be for weeks or months at a time.]*
- *Sedimentology (e.g. composition, geochemical properties, contaminants, particle size) – sample collection may usefully be combined with the benthic sampling programme, measurements of suspended sediment concentration (SSCs) should be undertaken using adequately calibrated instrumentation.*
- *Sedimentary environment (e.g. sediment re-suspension, sediment transport pathways, patterns and rates, and sediment deposition) – using charts, bathymetry, side scan sonar. [Note: The large-scale sediment transport patterns in many of the offshore wind farm sites have not been traditionally monitored, and may therefore be relatively unknown, which means that new field studies are essential to provide both baseline understanding and validation of any numerical modelling studies.]*
- *Geomorphology (e.g. channels, banks, large-scale bedforms, bioturbation, depth of mixed layers)*

Consideration of the above issues should be made with respect to the following spatial scales:

- *Near-field (i.e. the area within the immediate vicinity of the turbine grid)*
- *Far-field (e.g. the coastline, sites of scientific and conservation interest)*

And with respect to the following periods and timescales:

- *Baseline conditions.*
- *Development "construction" phase.*
- *Development "post-construction" phase.*

- *Sedimentary "recovery" phase, or period during which a new equilibrium position is attained with the wind array in place.*
- *Long-term "lifetime" of the wind array.*
- *Development "post-decommissioning" phase, with wind array no longer in place.*

In this generic format, these requirements for data collection and appropriate impact assessment can be equally relevant to both existing nearshore locations and to new offshore locations for wind farm development; this will be explored in more detail in the updated guidance from MFA/DECC in 2009.. Data concerning the actual effect of some already installed Round 1 and Round 2 wind farms has been gradually forthcoming as a result of monitoring requirements and related studies.

For Round 3, it is likely that the quantity, quality and density of existing data and the resolution or extent of previous studies are likely to decrease with distance offshore. This may increase the obligations of the developer to undertake new data collection, over longer periods of time and over larger areas (in comparison to Rounds 1 and 2), in advance of EIA and proposal submission. Requirements for data sourcing and collection are discussed in later sections of this report.

It is also important to note that sites further offshore may be developed on a much larger spatial scale (a greater number of larger turbine foundations, covering a wider area) and so a greater number of datasets might be required to describe natural spatial variability. Also, that the licences (hence the lifetime phase) for Round 2 and Round 3 developments are longer than for Round 1 and so longer data sets are required in order to assess the importance of natural temporal variability. The baseline understanding (evidence base) relating to Round 3 environments may also be lacking, making it more difficult to identify environmental receptors and to quantify their sensitivity.

When the EIA issues are clear but only insufficient or unsuitable field data are available to answer the questions posed, numerical modelling studies might then be used to provide further information. The move into deeper water for some sites may actually simplify somewhat the modelling of the far-field natural environment, provided that this is supported by appropriate data collection where gaps exist. Modelling near-field and far-field scheme effects may, however, pose new uncertainty and challenges where non-monopile foundation types are more likely to be considered but are presently less well understood in EIA terms.

2.3.2 Baseline conditions

Present EIA guidance (Cefas, 2004) recommends that in order to assess the potential impacts of a proposed OWF development, a full understanding of the natural physical environment of the site and surrounding area must first be established. The issues or questions posed in the present guidance are listed below in italics, followed by a short assessment of the implications or challenges posed by moving from a near coastal (<5km from land) to a more exposed offshore environment.

"Identification of processes maintaining the system, reasons for any past changes, and sensitivity of the system to changes in the controlling processes".

- <u>Coastal</u> – More dynamic, more complex, may be contained within discrete coastal cells. May be relatively more sensitive to change.
- <u>Offshore</u> – Potentially less dynamic due to deeper water and therefore less frequent exposure of the seabed to wave action, potentially more spatially uniform or homogeneous, evolving on longer time-scales. Larger scale of sources and sinks, gradual transfer of sediment along broader transport pathways. May be less sensitive to change as a result.

"Identification and quantification of the relative importance of high-energy, low frequency ("episodic" events), versus low-energy, high frequency processes".

- Coastal – Tides typically important to some degree in most areas. Waves can be important for sediment transport due to shoaling, generally shallow water depths and the effect on longshore drift at the coast itself.
- Offshore – Most regions around the UK are tidally dominated (Kenyon and Cooper, 2005); however, some relatively shallow offshore parts of the North Sea are tidally benign and are rather storm dominated.

"Identification of the processes controlling temporal and spatial morphological change (e.g. longevity and stability of bedforms), which may require a review of hydrographic records and admiralty charts".

- Coastal – Detailed historical charting more likely to be available, with reasonable positional accuracy. Bedforms are likely to be smaller and more dynamic.
- Offshore – Detailed bathymetry or charting may not be available for areas further offshore. Previous reports may only provide information at the regional level. This might require repeat bathymetric surveys as part of the initial data gathering exercise.

"Identification of sediment sources, pathways and sinks, and quantification of transport fluxes".

- Coastal – Generally greater degree of understanding due to greater interest in the coastal zone and more intensive previous study. Networks of sources, pathways and sinks may be more numerous and complex, likely also on a smaller spatial scale.
- Offshore – Historical direct evidence may be limited due to infrequent or spatially limited surveys. Scale of the OWF may be small in comparison to the scale of the sediment transport pathway; there is a larger scale of sources and sinks. Sediment transport pathways likely to remain offshore and not intersect sensitive coastal receptors.

"Identification of the inherited geological, geophysical, geotechnical and geochemical properties of the sediments at the site, and the depth of any sediment strata".

- Coastal – Generally greater degree of understanding due to greater interest in the coastal zone and more intensive previous study.
- Offshore – Direct historical evidence may be limited due to infrequent or spatially limited surveys. The seabed is more likely to be more stable at deeper offshore sites. Mobile seabed material more likely to be more heterogeneous or in equilibrium with the hydrodynamic conditions in offshore locations due to the longer transport distances and the resulting sorting process.

2.3.3 Impact Assessment of the development

Present EIA guidance (Cefas, 2004) recommends that, with knowledge of the site and its surroundings, informed by the above baseline assessment, the magnitude and significance of the impact of the development may be quantitatively and qualitatively assessed using hypothesis-driven investigation. Following the format of the previous section regarding the Baseline, the issues from the present guidance (again shown in italics) are listed below, followed by a short assessment of the implications or challenges posed by moving from a near coastal (<5km from land) to a more exposed offshore environment:

"Scour around turbine structures and the justification and requirements, if any, for scour protection material".

- Coastal – Typically, at present monopile foundations are being used and the processes controlling scour are relatively well understood. The functionality and secondary effects of certain scour protection methods are understood to variable degrees.
- Offshore – Gravity base or other hybrid structures may become more widely used, for which scouring processes and requirements for protection are presently not well understood. Schemes may use different scour protection materials, designs and methods of installation.

"Scour around any supply cables overlying the sediment surface and the resulting potential for higher SSCs, and the development of "free-spans" in the cable".

- Coastal – Typically, cables are buried to protect them from interference and so do not pose a scouring risk. Large mobile bedforms along the cable route must be taken into account when planning the burial depth to prevent the development of free span sections due to bedform migration.
- Offshore – Potentially much longer cable routes to shore; also, the potential installation of a long trunk cable down the east coast of UK, serving many of the existing and future development sites. If cables are suitably buried there may not be a need to account for scouring along the cable route in detail between the site and the coast. Large mobile bedforms along the cable route must be taken into account when planning both the cable route and burial depth, to prevent the development of free span sections due to bedform migration.

"Spatial design of the turbine grid array, offshore substations and the subsequent effect on the spatial distribution of wave patterns, tidal flows, and sedimentation (within the near-field) and additionally on wave direction and wave energy (at far-field and coastal sites)".

- Coastal – Turbine arrays tend to be less numerous or extensive closer to the coast and foundation designs may be smaller, thereby modifying waves and currents to a smaller degree. However, the footprint of the site is more likely to intersect the shoreline.
- Offshore – Turbine arrays will tend to be more numerous and extensive, and turbine foundations may be larger, potentially producing a greater cumulative effect and a more pronounced and/or extensive effect on waves and tides (depending upon the array spacing and foundation design). However, the footprint of the effect of the site is unlikely to intersect the coast due to the greater distances involved. The need for detailed wave modelling could also reduce if the site or surrounding area is deeper than the depth of wave closure (hence waves have limited effect on sediment transport, irrespective of modification); however, waves may be larger also (with a deeper depth of closure). The detailed effect of gravity base/hybrid structures on waves and currents are not yet well understood.

"Non-linear interaction of waves and currents and the subsequent quantification of the extent to which seabed sediment is mobilised".

- Coastal – Wave action is more likely to extend to the bed, more often, in shallower coastal areas. Sediment mobility may be more likely to be due to wave-current interaction.
- Offshore – Wave action may extend to the seabed less often at deeper water sites, however, waves may also be larger on average, so reducing this tendency. The resulting extent to which sediment is mobilised is the combined result of tidal regime, wave climate and water depth.

"Sediment mobility and the natural variability of sediment depth within the near-field and the effect on turbine strength/ stability, choice of foundation material and turbine structure, and burial depth for any cables".

- Coastal – Scouring of sediment in the near-field is dependant upon the foundation design, soil properties, hydrodynamic forcing (tidal currents or waves) and the water depth in comparison to the foundation diameter.
- Offshore – Similar control on scour. Wave forcing may dominate scour at some sites where waves are typically large relative to the water depth. Scour around gravity base and other hybrid foundations is presently not well understood. Cabling distances to the coast may be larger in R3 although the inter-array cables may be similar.

"Effect of seabed preparation, structure installation and cable laying procedures on local levels of SSCs".

- Coastal – Engineering works take place in an environment with naturally occurring relatively high levels of suspended sediment concentration (SSC). Experience has often shown that sediment resuspension as a result of the above tasks is small in comparison to the natural range.

- Offshore – Offshore SSCs may be naturally low and so engineering works may have an apparently greater effect. The importance of this effect must be assessed in the relative context of the more dispersed nature of sensitive receptors in the offshore environment.

"Assessment of the scales and magnitudes of processes controlling sediment transport rates and pathways. This may also include mixed seabeds (silts, sands and gravels), and therefore any interpretations from numerical model output should acknowledge and assess the effect of any differences in sediments (between model and actual), particularly when assessing the significance of transport fluxes".

- Coastal – Sediment transport pathways are likely to be smaller in scale and more complex.
- Offshore – Sediment transport pathways are likely to be larger in scale and more homogeneous in local rate and direction. The rate of sediment transport is dependant upon the local forcing in both cases. The effect of sediment sorting is also site specific but should be similarly considered in both cases.

"Assessment of the impacts of climate change on the hydrodynamic, sedimentological, and geomorphological regimes, e.g. changes in wave height, direction, and frequency of occurrence, changes in sediment mobility".

- Coastal – The coastal zone might be more sensitive to potential changes in wave height and direction, as waves interact with the seabed more frequently and to a greater extent in shallower water. Also, changes in mean water level as a result of climate change represent a greater proportional change in the total water depth.
- Offshore – Likely to be less sensitive to the effects of climate change due to generally greater water depths and/or distance from the coastline and/or scale of the sediment transport pathways involved.

"The presence of highly dispersive substrates such as chalk either disturbed during cable laying or arising from the installation of foundations should be assessed in terms of the extent duration and ecological consequences"

- Coastal – As for other types of sediment resuspension, relatively high naturally occurring levels of suspended sediment concentration are more likely to be experienced in the coastal zone. Experience has often shown that sediment resuspension as a result of construction activities is small in comparison to the natural range.
- Offshore – Again, offshore SSCs may be naturally low and so resuspension of highly dispersive substrates may have an apparently greater effect. The importance of this effect must be assessed in the relative context of the more dispersed nature of sensitive receptors in the offshore environment. In both offshore and coastal environments, the issue of highly dispersive substrates is only an issue if they are found to be present at the site.

3 Evaluating the Requirement for Numerical Modelling

3.1 Introduction

The first step in defining best practice for numerical modelling is to determine if and when modelling is appropriate, useful or even necessary for the EIA. This requires a clear understanding of the proposed assessment and consideration of any added value that modelling may provide, taking account of the high cost of obtaining good quality calibration data and undertaking the modelling itself.

As part of environmental impact assessment it is necessary to define relevant receptors (aspects of the physical or socio-economic environment) and their sensitivity to physical changes, and then define the changes that may result from wind farm construction, operation and decommissioning. Numerical modelling can be used to assist in the definition of the baseline wave conditions, current regime and sediment processes. Modelling can also be used to define the potential local and far-field impacts of a wind farm development on those conditions and processes. However, changes to waves, currents or sediment processes are not, in themselves, significant impacts on the environment. What is important is the impact of those physical changes on sensitive receptors such as marine / coastal habitats, marine / coastal structures and human activities (described in more detail in the following Section). If the impacts on the receptors can not be quantified and categorised as significant or not significant, there is little benefit obtained by undertaking complex and costly modelling; this is a clear lesson from the consenting procedure for Round 1 windfarms.

The UK continental shelf has been subject to study over the centuries for navigation, exploitation of resources and scientific research. At a broad scale there is available literature on most, if not all, of the subjects of interest to assessment of coastal and seabed processes, sufficient to support both SEA and EIA. Waves, currents, tides, sediment distribution, geology and geomorphology have been measured and analysed, with much information presented in standard reference texts or other publicly available sources. Further and more detailed information regarding specific sites is held by research institutes and specialist consultancies and may be accessible. Before any additional field work or modelling is undertaken these sources must be reviewed to determine if there any significant gaps in available knowledge for the site of interest.

3.2 Sensitive receptors and impact thresholds

Sensitive receptors may be environmental or socio-economic and may include, for example:

- Particular flora or fauna, including commercial species, that might be disturbed, displaced, weakened or even killed by changes to the physical environment (waves, currents, sea bed mobility, coastal erosion, suspended sediment load or increased levels of contaminated sediment or other pollutants);
- Navigation where safety or accessibility may be compromised by changes to water depths, wave conditions or currents ;
- Coastal communities, property, infrastructure, habitats, protected geological exposure or valued geomorphological features that may be disturbed or lost due to changing risks of coastal erosion, accretion or flooding;
- Marine structures, infrastructure, wrecks, dumped ordnance, etc that may be compromised by changes to the physical environment; and
- Coastal or marine recreation that may be influenced by changes to waves, currents, coastal processes, suspended sediment or landscape (due to structures intended to protect cables at the landfall).

The sensitivity of some of these receptors can be clearly defined in measurable terms, while for others there is presently insufficient understanding of the receptor to make anything more than a qualitative statement. For example, loss of 2m depth in a navigation channel may mean that vessels of a certain draught can not access a harbour, or may require regular dredging to allow continued use. Similarly, cable trenching close to a known shellfishery may cause suspended sediment concentrations or sediment deposition rates to rise above a specified threshold value over a defined time period, causing significant mortality rates and loss of fishery income. In these cases numerical modelling may be very useful in defining the intensity and extent of the physical change for comparison with the quantified threshold value.

In the cases where there is only an indeterminate possibility that changes to the physical situation may affect a receptor, but with no understanding of significant threshold levels or natural variation, then undertaking numerical modelling may well be of no more value than an expert opinion delivered for a fraction of the cost and time. For example, deposition of remobilised fine sediment on a nursery ground may be noted as a possible problem for survival rates, but with no information on the natural tolerance to deposition there is little point in defining the footprint of deposition rates to the nearest millimetre as would be possible with standard plume dispersion modelling – stating significance would be no more than conjecture.

3.3 Lessons learnt and key EIA issues

Based on research to date (Chapter 2) the studies undertaken during Round 1 and Round 2 and the evidence base from installed developments presently available, the key issues for coastal and seabed impact assessment that are considered potentially significant are:

- Suspended sediment dispersion and deposition patterns resulting from foundation and cable installation or decommissioning (receptors sensitive to specific changes in burial depth, suspended sediment loads or textural change in sedimentary habitats)
- Changes in coastal morphology due to cable landfall installation and maintenance (receptors sensitive to erosion or accretion including habitat, property, recreation and landscape)
- Scour and scour protection (receptors sensitive to the introduction of new substrate).
- Wave energy dissipation or focusing for sites very close (<5km) to an exposed shoreline, especially for relatively dense turbine arrays and/or less well understood foundation types (large diameter gravity bases, multi-leg or jackets) considered more likely to affect wave height, period or direction (receptors sensitive to changes in coastline morphology)
- Wave and current processes controlling very shallow sandbank morphology, especially for relatively dense turbine arrays and/or less well understood foundation types (ecological or navigation receptors sensitive to changing bed morphology including scour, channel migration sandbank mobility)

Regarding dispersion and deposition of fine sediments, including chalk, it is understood that there is no available research or evidence to define significant impact thresholds for commercial or other species in UK waters. Until this knowledge gap is addressed there is no purpose in undertaking plume modelling, except for public relations use if this is considered valuable.

Regarding cable landfall sites, coastal morphology changes in relation to small, groyne type structures are well understood. Expert opinion should be sufficient to define the likely extent and significance of construction and long term performance.

Regarding scour and scour protection, to date all such assessments have been carried out using empirical approaches based on published guidance and expert assessment without the need for numerical modelling. The use of more complex foundation types, potentially as part of Round 3 developments, may lead to greater uncertainty using these approaches due to significant gaps in the evidence base (Appendix A). Therefore, as part of Round 3 development there may be a requirement to undertake further research in this area, including the use of both numerical and physical modelling (the latter is not discussed explicitly in this report).

Regarding very near shore wave energy dissipation and shallow water wave/current processes, these may require numerical modelling as the wave, current and sediment interactions are potentially complex. It may not always be apparent when modelling is justified, and expert opinion from the regulators and specialist consultants should be sought. However, the proposed Round 2 and Round 3 wind farm sites all specifically avoid sites close to shore or on shallow sand banks, so it is unlikely that modelling will be necessary.

3.4 Checklist for evaluating the modelling requirement

As guidance for establishing the requirement for numerical it is necessary to consider the following checklist:

1. What are the potential sensitive receptors by category or species?
2. Are the sensitivity thresholds of the defined receptors understood and quantified?
3. What information about the physical environment is required to categorise the potential impacts on the identified receptors?
4. Can sufficient information be practicably and effectively provided by existing knowledge and available field data without the need for numerical modelling?
5. If no to Point 4, can models represent the processes involved sufficiently to provide the required information?
6. Can sufficient field data be obtained to adequately calibrate and validate the model to provide sufficient confidence in the results? The definition of 'adequate' in this case is, broadly speaking, that the model results are sufficiently accurate to establish the effect of the scheme relative to the sensitivity criteria of the receptor being considered.
7. Does the regulating authority agree?

The guidelines for modelling outlined in the following sections should be applied only after the requirement for modelling to provide clear definition of the potential significance of impacts on known sensitive receptors has been clearly established and agreed with the regulating authority.

4 Best Practice Methods for Modelling in Support of EIA studies

4.1 Choice of numerical modelling approach

After modelling has been identified as a requirement, the next step is to identify the particular modelling approach that will provide sufficient and suitable data to answer the question being asked. In the broadest possible sense, modelling includes any method that can be used to obtain new data not previously available, using a predictive process in conjunction with a limited amount of supporting information. For offshore wind farm EIA, modelling studies typically refer to relatively complex numerical modelling tools, but could also refer to simple equations and relationships, or physical modelling (scaled models in a laboratory). However, in the context of the current study physical modelling is outside of the scope of this report.

The choice of approach needs to address several issues or questions, including:

- What model type(s) is(are) required? (e.g. Tides/waves/sediments/water quality; 1D/2D/pseudo 3D/3D, etc)
- What type of computational mesh?
- What spatial and temporal resolution and extent?
- What boundary conditions?
- What parameter settings to use?
- How to ensure correct simulation of wind farm structures

A detailed discussion and example list of the various numerical modelling tools available for marine environment baseline and with-scheme assessment, is given in Appendix B. Further guidance on appropriate choice of spatial and temporal resolution and the processes

Best practice is to choose a numerical modelling approach that is fit-for–purpose in reproducing the range of processes identified as important to the study, including both baseline and scheme assessment. To this end, the important processes and the ability of the particular model chosen to reproduce them should be stated as part of the EIA report. Best practice is also to agree on the chosen approach with the regulator, in advance of the work being undertaken.

4.2 Data in support of modelling

A certain amount of data (discussed below) is required in order to set up a model that is potentially capable of performing its required function (e.g. model bathymetry and input boundary information). Additional data is then required in order to test that the model is performing correctly and accurately in its required function (e.g. calibration and validation).

Typical data requirements for building, calibrating and validating numerical marine environmental models include:

- bathymetry/topography;
- tidal water levels;
- tidal current speed and direction;
- wave height, period, direction, spreading;
- seabed sediment/geotechnical information;
- turbidity;
- sediment transport rates and directions; and
- design outlines for the wind farm scheme, delivered by the developer through a Project Design Statement, in order to make informed model design choices.

More details regarding data sources for the above data types may be found in Appendix C.

There is a close correlation between the quality and accuracy of a numerical model and the quality and quantity of supporting data used. Best practice in collecting extant data therefore includes the following:

- Ensure thoroughness in finding sufficient sources of relevant extant data.
- Ensure that all data are accompanied by sufficient metadata (descriptions of the data source, location, date, time, time-step, instrument used, etc.) such that their context and limitations are understood.
- Sufficient data locations must be available to describe any flow complexity within the model domain, especially where that complexity overlaps or affects the particular regions of interest.
- Sufficient data length must be available at each site to characterise the process being observed, e.g. at least one spring-neap cycle for tides or a wave time-series that captures (ideally) at least two distinct storm events (one for calibration, one for validation) as well as other intermediate intensity and calmer periods. At least one of the storm events should ideally be of annually significant intensity (a 1 in 1 year event or greater).
- The data must have sufficient temporal resolution to resolve changes on a suitable time scale, e.g. tidal behaviour should be monitored at a time-step of no more than 10-20 minutes in order to capture peak values, whilst wave climate changes on longer timescales and a time-step of (no more than) 3 hours may be sufficient. Wave climate data in areas heavily influenced by wave-current interaction should ideally be closer to the recommended temporal resolution for tidal data.
- Data must also be of sufficiently high accuracy that potential inherent error in the field data is small in comparison to the absolute values (e.g. the tidal range) and to the natural range of the parameter in question (e.g. spring-neap variability in tidal range).
- Data time series should ideally be coincident in time between multiple sites.
- Undertake Quality Control procedures on any data used (an assessment of the data quality, checking whether the data conform to the expected ranges of values; non-conforming data are flagged or excluded) to reduce uncertainty and to assist in setting suitable calibration targets.

Furthermore, best practice also includes seeking the advice of the regulator with regard to the requirements for data and early confirmation of survey design. Further information with regard to the requirements for data collection may also be found in publications such as 'Guidelines for the use of metocean data through the lifecycle of a marine renewable energy development.' (CIRIA, 2006).

The purpose of these best-practice steps is to minimise the error and uncertainty contained within field data that may then be used either directly for the EIA or as part of modelling studies. In the latter case, this potentially improves the ability of the model to be calibrated and also reduces the error propagating through the modelling process.

4.3 Modelling the baseline

Best practices for designing a baseline numerical model can be specific to different modelling types (e.g. dimensional constructs, mesh types, numerical schemes, etc) and to the modelling of different physical processes (e.g. tides, waves, sediment transport, etc) or marine environments (estuarine, coastal, offshore, etc). More information about specific best practices might be found elsewhere but is not considered in detail for all permutations here. However, the following general guidance can be applied.

As described in the preceding Sections, an appropriate model (i.e. one which accounts for all of the important processes) must first be identified for use. If correctly designed, it has the potential to provide a representative estimate of the baseline environmental conditions. Baseline conditions are representative of the present day environment and broadly cover future scenarios within the lifetime of the development.

Best practice is then to use appropriate methods to minimise error and uncertainty in the model results, including data improvement, model calibration, model validation and Quality Assurance procedures. More details of these methods are given in Section 6.6.

Scheme assessment (including the effect of the wind farm structures) is covered in the following Section 4.6; best practice methods for reporting baseline results are also discussed.

4.4 Confidence and model accuracy

The degree of confidence that can be given to the results from any model depends upon:

- The ability of the model to accurately represent the processes being studied;
- The confidence that can be placed in the supporting data;
- The degree of calibration that can be achieved;
- The subsequent successful validation of the calibrated model; and
- The extent to which, and clarity with which these assessments are communicated to all parties.

The maximum possible degree of confidence and the performance potential of the model may ultimately be limited by the quantity and quality of the data used to build and to calibrate/validate the model.

4.4.1 Calibration and Validation

Numerical models can be used to provide predictions of marine environmental processes. How closely these predictions match the real world is dependent, principally, on how well the model can represent the processes being modelled and also how well the model parameters have been, or can be, 'tuned' to fit the real world situation being simulated.

The model parameters are the constants and coefficients that exist within the underlying mathematical relationships. Changing these parameters allows the model to be 'tuned' to produce a response closer to the expected result. The adjustment of tuning parameters to improve a model's ability to predict independently measured data is called model calibration.

A well calibrated model will be able to provide an acceptable prediction of the measured data against which it is being calibrated. However, having a well calibrated model does not necessarily mean that it will provide a good prediction of all similar data. For example, a model is well calibrated to reproduce a data set collected at a site of interest over a particular time period, but when it is used to try and reproduce, with no further calibration, a second data set of similar quality of the same parameter at the same location over a different time period, it may give a poor prediction. In this case, the calibration process must be repeated until the model gives satisfactory predictions for both sets of data. Proving the ability of the model to provide accurate predictions for data not used for model calibration is called model validation.

An uncalibrated model can be useful in providing a qualitative indication of processes and may be used to provide a 'quick look see', and these are sometimes called pilot models. Pilot models can be useful in identifying the relative importance of processes and thus assist in process understanding. Thus, in order of usefulness and certainty in results, models can be categorised as:

1. calibrated and validated model;
2. calibrated model; and,
3. uncalibrated – pilot model.

Only calibrated and validated model results should be used to inform the EIA.

4.4.2 Limitations of modelling

Limitations of modelling refer to the ability of a numerical model type to simulate a particular physical process (to a given level of accuracy), in order to provide useful data to inform an EIA.

Individual models or certain model types may be limited in their ability to replicate or account for certain processes at all, e.g. certain shallow water wave effects, near-field turbulent flow-structure interaction or realistic erosion or transport of sediments. Limitations may be simply due to that process being excluded from the model functionality or may be due to incomplete understanding of the process in question.

Individual models or certain model types may be limited in their ability to accurately replicate or account for certain processes. This is either due to incomplete understanding and uncertainty in the accurate representation of certain natural processes (e.g. sediment erosion and transport rates) or to absolute limitations in numerical accuracy in the form of the equations used in the model, the methods used to solve them and the accuracy of the computer itself.

Further, a numerical model can only be considered as accurate in representing a particular environment, as the accuracy of directly measured data used to calibrate and validate it. The ability to accurately simulate certain process will also depend heavily on the quantity and quality of input data used to set up and inform the model.

Further more detailed information on the limitations of numerical models for marine EIA may be found in Appendix B.

4.5 Representing structures in numerical models

In order to assess the potential effects of a wind farm scheme, an important basic requirement of a numerical model is the ability to first accurately represent baseline environmental conditions (see Section 4.3). Equally important is the ability to accurately represent the magnitude and extent of any effect of the proposed wind turbine foundation structures. Sections B.2.5 and B.3.5 discuss the numerical methods by which structures can be accounted for in tidal and wave models, respectively, and by extension in sediment transport models.

As wind farm development moves towards the environments more characteristic of Round 3, it is likely that monopile structures will not be appropriate due to cost or design considerations and alternative foundation types may be used in the interests of engineering best practice, practicality or economy. A more detailed discussion of the foundation structure types that might potentially be used for offshore wind farms may be found in Appendix D.

At present there is some uncertainty in how to represent the effect of these more complex (i.e. non-monopile) structures on marine processes. This uncertainty is primarily due to a lack of knowledge or evidence, with respect to parameterising their effects on the hydrodynamics.

At present, best practice for representing foundation structures is to review the contemporary evidence base regarding the structure type in question. In the same way that a baseline model is calibrated and validated, a short methodology description and the results of any sensitivity testing that support the chosen method for including the wind farm structures should be included.

Best practice is to represent the wind farm foundation type, number of structures and their relative locations as the worst-case-scenario based on the information contained in a Project Design Statement (PDS). A PDS is provided by the developer early in the EIA process and contains a description of the range of options being considered for the wind farm design (see Section C.8).

It has been established through the evidence base that little or no significant impact is posed by sediment resuspension as part of ground preparation, foundation installation and cable burial, including the rate and direction of suspended sediment transport and its fate (area and thickness of subsequent deposition). If, however, a particular sensitive receptor to such activities is identified, they can be included in a model as a point source of suspended sediment. The details of the point source (location, concentration and rate) can be determined using a worst-case-scenario based on the information contained in a Project Design Statement.

4.6 Assessing the impacts of the scheme

The results of calibrated baseline and with-scheme models both contain a certain residual amount of error and uncertainty relating to the accuracy or quantity of supporting data and to the ability of the numerical model to reproduce accurately all of the important physical processes. Best practice for both baseline and scheme modelling is therefore to manage and reduce error and uncertainty at all stages of the data collection and modelling process; any residual error should be quantified and reported in the context of the baseline values. Best practice for scheme assessment is to find the relative effect of the wind farm, i.e. [with-scheme] minus [baseline] data. These key best practice methods are discussed in more detail in Section 6.7.

Beyond the ability of the model to represent the baseline and the wind farm structures on an individual basis, the modelling study results must also account for uncertainty in the actual design and layout of the wind farm that will be installed. Final decisions may not be made until after the consenting process, regarding the foundation type or dimensions, the number of structures, their layout within the site, the method of foundation or cable installation, or the cable route.

Best practice in this case is to utilise the developers Project Design Statement (PDS) which outlines the various realistic foundation and layout options which are under consideration. These options may be used to define a ‘realistic worst case scenario’, which is used to represent the scheme. If the EIA can demonstrate ‘no significant effect’ as a result of the worst case scenario (the outer envelope of potential scheme-related impacts) then a similar verdict can be reached by logical deduction for the other options being proposed. In this way, licences can be approved with more confidence for a variety of wind farm options, so long as construction remains within the design envelope, whilst streamlining EIA requirements.

4.7 Post consent monitoring and mitigation

The SED01 report (ABPmer *et al*., 2008) demonstrated from the present Round 1 evidence base that suspended sediment concentrations (SSCs) as a result of cable laying procedures were within the range predicted by the EIA and also within the typical natural range of SSC for such shallow water sites. The evidence base covers both jetting and ploughing techniques. Consequently, the report recommends that best practice is to reduce the requirements for SSC monitoring during cable laying operations at similar sites using either technique.

Best practice at deeper locations characteristic of some Round 2 and many Round 3 sites may need to be reconsidered in more detail. The ambient levels of SSC offshore are naturally lower and further assessment must be made as to whether elevated SSCs during construction pose a significant impact to different, potentially more sensitive receptors. Adding confidence to the scheme assessment in this respect, the SED01 report suggests that SSCs will be adequately predicted by the modelling process.

The SED01 report also evaluated the results of post-construction bathymetric monitoring activities, principally focussed upon the development of scour and the effect of the wind farm on the regional seabed morphology or sandbank dynamics. It was recommended that best practice is to undertake monitoring with a greater degree of consistency, not only between surveys at the same site, but also between surveys conducted at different sites. A standard methodology for this was recommended. When trying to maintain a consistent horizontal and vertical datum, sites far offshore may have additional problems achieving accurate tidal correction, where there are limited local reference stations for this purpose. Best practice in this case would be to use RTK/PPK GPS techniques, possibly in combination with dedicated and surveyed in on-site tide gauges. Un-surveyed local tide-gauges can not be used in isolation because no absolute vertical datum for the survey is established. Coastal tide gauge information, either alone or in combination, is not suitable for tidal correction of offshore surveys. The coordinate system should also be carefully chosen – continental scale protocols (e.g. Lat/Long, UTM, WGS84) are more appropriate than nation scale (e.g. OSGB) ones.

The SED02 report (HR Wallingford *et al.,* 2008) also looked in more detail at the issue of local scour, again with evidence from Round 1 site monitoring. Best practice recommendations from the report are that predictions of maximum scour depth, made using certain empirical relationships, are effective in the case of monopiles. It can also be expected that scouring rates may be slow and maximum scour depth may not be achieved within time-scales of up to several years in some erosion resistant soils (typically with significant clay content); in this case, monitoring frequency might be reduced in agreement with the regulator. It was also recommended that scour protection should be carefully applied in order to avoid secondary scouring effects; this is independent of structure type or design.

5 Definition of Coastal and Seabed Issues

5.1 Overview

The EIA process assesses the capacity of the marine environment to accommodate the proposed scheme design(s) and the significance of any potential impacts. To this end, a clear understanding must be obtained, the extent of which is established in the EIA scoping phase and then addressed in the assessment phase, of the site specific baseline environment and of changes to that baseline as a result of the scheme, beneficial or adverse and in the context of the baseline.

Cefas has previously prepared a guidance note in support of marine environmental process EIA for Round 2 wind farms (Cefas, 2004) which describes the scope of a coastal impact study. A further update to this guidance in support of Round 3 is planned in 2009. Because Round 3 sites will be located, generally, further offshore than in previous rounds, the effect of a wind farm is less likely to impact the shoreline or coastal margin but may still potentially impact the local and surrounding seabed. In this case, the term ‘coastal process study’ might be misleading and it is recommended to replace this in the Round 3 process with the term ‘marine environmental study’.

The various stages of the wind farm development need to be evaluated as part of the EIA in both the near- and far-field, through pre-construction, construction, operation and decommissioning phases, and considering a variety of environmental issues (see Section 2.3).

According to present guidance, marine environmental studies need to consider the issues raised by the effect of the windfarm on waves, tides and sediments in an integrated manner since these process can be interdependent, depending upon the water depth.

In the following sections, the information requirements, methods for describing, and the effect of structures on the tidal, wave and sediment regimes are described. An additional section is also included, describing the issues relating to the installation and decommissioning of marine cables

5.2 Tidal behaviour

Tidally induced changes in local water level and associated tidal currents are an important feature of marine environmental process in UK waters. Tidal ranges are relatively large around much of the UK and tidal currents are the primary driver for sediment transport in many coastal and offshore areas. In relatively shallow water, the tidal regime may also exert a direct influence on local waves through water depth variations during the tidal cycle and by wave-current interaction.

An initial broad assessment of the characteristic behaviour of tides offshore in UK coastal waters can be made with reference to the Atlas of UK Marine Renewable Energy Resource (ABPmer et al., 2007), commissioned by BERR. Further detail of variable accuracy and resolution may be found in the many relevant charts, almanacs and publications describing local or regional tidal behaviour.

5.2.1 EIA Issues

Tides may be charachterised as low energy events but with a high frequency of occurrence.

Due to their typically significant impact on many marine environmental processes in UK waters, tidal behaviour at each site needs to be understood as part of the EIA. Tidal behaviour may be important in its own right (for purposes of navigation or to inform engineering and design – not part of the EIA process) or may be an essential requirement for assessing secondary processes, e.g. sediment transport. These requirements involve the detailed evaluation of water levels and tidal currents within and adjacent to the development site. The difficulty is that, in all of the Round 1-3 environments being considered, sufficient directly measured data are not usually available.

5.2.2 Information requirements

The EIA requires a description of the tidal regime for pre- and post-construction phases, to determine the potential changes to existing tidal current patterns if doing so may impact upon an identified sensitive receptor; furthermore, how these might affect both the sediment and wave regime (also with consequences for sensitive receptors). Tidal current data is also required for the assessment of scour potential.

5.2.3 Describing the local tidal regime

The baseline tidal regime local to the wind farm site can be determined in a number of ways.

<u>From measured data</u>
Examples of sources of tidal data, their pros, cons, typical usage and accuracy are given in Sections C.1 and C.2.

It is unlikely that measurements of tidal height and tidal currents will exist in the required format and at all of the locations required, especially in offshore locations. It is more likely that discrete measurement data sets may be available in the general area of the wind farm either from previous studies or as a result of dedicated data collection in support of the EIA. These data can be used to calibrate and validate tidal models, which can be used in turn to extend the spatial and temporal extent of the available data set, as below.

The measured tidal data should be at regular intervals sufficient to resolve the peak values (typically every 10-20 minutes); tidal current data should ideally consist of measurements made throughout the water column, converted then to a depth mean value unless significant three dimensional effects are considered to be important. There is no specific number of locations at which tidal data must be measured, but they must be sufficient to describe the broad flow characteristics of the wider area and also any areas of complexity which are considered important to the study.

Spatial variability in current speed and direction is likely to be greater in areas where the seabed is complex, especially where such complexity results in significant changes to the overall water depth. Vertical variability in currents can occur in response to spatially variable seabed roughness, sea surface wind stresses and superimposed wave action; however, these are not typically significant and so are not considered as part of EIA. In some locations (e.g. parts of the Irish Sea) vertical stratification of temperature and/or salinity may be important in controlling local currents but in most cases, vertical stratification is also not a significant issue. The potential for spatial variability in tidal behaviour is increased with the extent of the site (e.g. the potentially very large sites in Round 3), even if the bathymetry is relatively uniform.

The useful length of measured data sets depends upon the application for which it is required. For example:

- For harmonic analysis of tidal heights or currents (useful for making predictions of the same at other dates and times), a minimum of two spring-neap cycles are typically required; these data must be of suitable quality (1 hour timestep or better, with minimal effect of wind, waves, storm surges, etc…) otherwise a longer data set might be required.
- For calibration of local models, again typically two spring-neap cycles are required as a minimum, one for calibration and one for validation.
- For statistical analysis of water levels (useful for design criteria and flooding risk – an engineering, rather than an EIA issue), many years of data might be required in order to capture infrequent extreme events.

From local models
In the context of EIA and modelling, a local tidal model is one that encompasses only the domain extent necessary to include all of the important geographical and bathymetric features that control tidal behaviour in the area potentially affected by the wind farm. Such areas typically follow the concept of a 'coastal cell' – a unit coastal system which is physically separated from adjacent cells by a geographical feature such as a headland. Coastal cells may be tens or even hundreds of miles in length and so remain appropriate for the majority of Round 2 and Round 3 site locations.

Local models might be informed by regional models, which are greater in their extent but coarser in resolution. Regional models may be used to transform tidal behaviour from locations where it is well understood, to the boundary of the local model.

More information regarding tidal models and modelling may be found in Section B.2.

Local tidal models can be built using existing environmental data (bathymetry and predicted tidal water levels at the model boundaries). These models are potentially improved by the addition of a greater quantity and quality of data, and then calibrated to more accurately predict the tidal regime around the site and other areas of interest. Confidence in the model is obtained through model validation against additional data not used for calibration.

As a minimum, the model must encompass the wind farm site and all other locations which may be affected by it. A more accurate calibration/validation is more likely if the model also includes all significant physical features (e.g. headlands, sandbank systems, trenches, etc) that may influence tidal characteristics within the same area of effect.

A baseline description of the tidal regime will need to characterise the typical naturally occurring tidal variations in water level at the site and in the wider region. This assessment should be representative of the planned operational period of the development, as well as considering how the tidal regime might respond to climate change and sea level rise over the same period.

Data validation
The recommended method for validating modelled tidal data is to compare it directly with coincident short-term measurements, where these are available. Ideally, coincident observed and modelled data sources should be in agreement and the model should reproduce patterns and magnitudes of variance in tidal height, current speed and direction over a range of temporal scales.

To this end, it has become a common requirement to undertake measurement of tidal behaviour at the wind farm site which is then used to validate the model results; this has the advantage that the data validation is carried out at the actual site. Large sites with significant variation in tidal flow over them may require more than one validation point within the site itself (see Section 4.2 for best practice recommendations).

5.2.4 Effects of the turbine support structures on tides

Previous studies have shown that for slender structures (monopiles) the effect of the presence of the wind farm foundations is likely to be minimal (ETSU 2002; ABPmer, 2005). For larger or more complex structures (e.g. gravity base, multi-legged foundations, etc.) the evidence base is currently lacking and further work at a project or research level is required in order to understand their interaction with tidal currents and to confidently represent these structures in numerical models.

5.3 Wave regime

Waves and wave action are an important feature of marine environmental process in shallow water, characteristic of typical environments for Round 1 and also for some Round 2 sites. Some Round 2 and many Round 3 sites will tend towards intermediate or deeper water depths where, despite occasionally larger waves, wave action will reach the seabed less frequently and have a less dominant effect. Some examples of deep but wave dominated sites do however exist, e.g. the Celtic Sea, where observed bedforms are aligned to the dominant storm fetch, rather than the tidal axis.

Waves may have primary control on sediment transport patterns and rates at the coastline and in shallow water, which may be affected by the presence of a nearby wind farm. Larger waves found offshore may be important in controlling sediment transport on the crest of large sandbank systems which may also be affected by the presence of a nearby wind farm.

5.3.1 EIA issues

Waves and wave action may be charachterised as high energy events but with a low frequency of occurrence.

The wave conditions at each site may need to be investigated as part of the EIA if the format of the design (foundation type, number and spacing) exceeds the envelope of the evidence base presently demonstrating that wave-structure interaction with typically spaced monopiles does not present an issue. The EIA approach would then involve the detailed evaluation of wave climate statistics and the fate of waves passing through the development site. The difficulty is that, in all of the Round 1-3 environments being considered, sufficient directly measured data are not usually available.

Wave climate may be important in its own right (for purposes of navigation or to inform engineering and design – not part of the EIA process) or may be an essential requirement for assessing secondary processes, e.g. scour and/or sediment transport, at sites where waves are large relative to the water depth.

5.3.2 Information requirements

The EIA requires a description of the wave climate for pre- and post-construction phases, to determine the potential changes to existing wave patterns and resulting sediment transport, if doing so may impact upon an identified sensitive receptor. Wave data may also be required for the assessment of scour potential.

5.3.3 Describing the local wave climate

The wave climate local to the wind farm site can be determined in a number of ways. Examples of sources of wave data, their pros, cons, typical usage and accuracy are given in Section C.3.

<u>From measured data</u>

Detailed long term data sets may be obtained for point locations from real-time and archive data sources such as the Channel Coastal Observatory (CCO), the Wavenet programme and the British Oceanographic Data Centre (BODC). Only the BODC provides ‘offshore’ data in this regard – the CCO and Wavenet programmes only operate in the near-coastal zone, i.e. inshore of many areas being considered in Round 2 and Round 3. The CCO provides archive data from many wave buoys deployed to inform coastal management between the Bristol Channel and the Thames Estuary. The Wavenet programme devices are more dispersed around England and Scotland, including some locations further offshore. Historical offshore data of variable quantity and quality are available through the BODC archive, typically originally collected by the offshore oil and gas industry hence most data are from the northern North Sea.

If a relatively long data set of wave measurements is available from the site, then the problem is comparatively straightforward. The data set should ideally consist of measurements made at regular intervals of around 3 hours or less (in order to capture peak values) and extend over many years (in order to describe inter-annual variability). Unfortunately, this is rarely the situation, especially in offshore locations, and other approaches have to be considered.

It is more likely that short-term measurements (order of 1-12 months, at a similar temporal resolution) are available in the general area of the wind farm as a result of dedicated data collection in support of the EIA. These data can be used to calibrate and validate wave models, which can be used to extend the data set spatially and temporally, as below. There is no specific number of locations from which wave data must be provided, but they must be sufficient to describe the broad characteristics of the wider area and also resolve any areas of complexity which are considered important to the study. The period of data collection should also be representative of a broad range of wave conditions, including calm, intermediate and annually significant storm events which are seasonal in nature; therefore, the deployment period is most likely to be during the late autumn/winter/early spring months when storm events are more likely.

From deep water model hindcast data
Offshore wave conditions can be predicted or 'hindcast' using historical wind data, however, this can be a time consuming and expensive exercise because large areas which are not of interest must also be modelled.

The Met Office wave model databases are one example of an extant source of wind and wave hindcast data for the past 20 years and constitute a valuable data resource. However, the Met Office model is primarily designed to predict waves in deep water (i.e. 'offshore' locations) and are only available at the resolution of the source model; also, the coast constitutes a boundary of the model but can only be defined to the model resolution, so cells close to land or in areas of complex or shallow bathymetry may not be wholly reliable. The typical resolution of The Met Office 'UK waters' model, is of the order of 12km; the 'European' model is coarser at approximately 35km. Both of these models have been superseded (since November 2008) by a third generation model with 12 km resolution and European coverage (including UK waters), but only a short data set duration is available at present. It is likely that the rolling programme of improvements in the quantity and quality of such hindcast data will continue into the future.

An initial broad assessment of the characteristic 'offshore' wave conditions in UK coastal waters can be made with reference to the Department of Energy Wave Climate Atlas for the British Isles (DOE, 1991) or to the Atlas of UK Marine Renewable Energy Resource (ABPmer et al., 2004), commissioned by BERR and based upon extensive wave climate hindcast datasets from The Met Office.

Other example sources of hindcast wind and/or wave data include Meteogroup, Oceanweather inc., NOAA, ECMWF etc.

The main benefit of regional hindcast models is that they potentially offer data coverage over a wide area and over long time-scales. The information provided by this data source includes spectral characteristics of wave height, period and direction, which are important for the process of transforming the predicted waves to the local (wind farm) position.

From local models
In the context of EIA and modelling, a local wave model domain is one that is sufficiently large to permit wave development (fetch) and to account for significant geographical or morphological features (e.g. headlands and sandbanks) which may affect the development or propagation of waves from a particular directional sector. Depending upon whether waves and/or winds are used as boundary conditions, the extent of the local model may vary greatly from project to project. Best practice is to use a suitable model domain that is capable of being successfully calibrated and validated.

More information regarding wave models and modelling may be found in Section B.3.

It is typically the case that sufficient measured wave data are not available from the development site directly, or from other locations of interest when attempting model calibration or validation.

For sites located far enough offshore that the bathymetry of the site is relatively deep and uniform and the coastline does not intersect the model mesh element being used climate (including some Round 2 and potentially most Round 3 sites), Met Office hindcast data may be appropriate for direct use; however, these data will still need to be calibrated if necessary and validated using suitable measured data. If the bathymetry is not uniform and/or if the site is sufficiently shallow that waves interact with the seabed (despite being in an offshore location and the coastline itself being absent), then more detailed numerical modelling may be required (similar to that described above for coastal locations, below).

For sites located near enough to the coastline or in shallow enough water that shoaling effects potentially affect the local wave climate (including Round 1, some Round 2 and potentially some Round 3 sites), it may also be the case that hindcast model data is not suitable for direct application due to the proximity of the site to the coast, or shallow or complex local bathymetry. In this case, the (more reliable and readily available) hindcast data can be transformed from offshore to other locations using numerical models which can account for refraction, shoaling and other shallow water wave processes (where appropriate). The conventional approach is to select an offshore wave hindcast data point as near as possible to seaward of the site and to use the local wave model to transform the waves from offshore to the location of the wind farm.

Data validation

The recommended method for validating wave data from hindcast or local numerical models is to compare it directly with any short-term measurements available within the model extent, i.e. collected by organisations as part of strategic monitoring programmes, or, as this is commonly not available, collected as part of site investigation works. Coincident observed and modelled data sources should be in agreement, reproducing patterns and magnitudes of variance in wave height, period and direction over a wide range of conditions (from calms to storms).

To this end, it has become best practice to undertake measurements of waves at the wind farm site which are then used to validate the transformed data; this has the advantage that the data validation is carried out at the actual site. These data may be fit-for-purpose for addressing some local issues of sediment transport etc, but a single point source might not be enough to address issues regarding the overall effect of the wind farm and the extent of its footprint of effect.

Data might also be available from locations other than the wind farm site. If these coincide with the location of the hindcast data, direct comparison might be drawn. Otherwise, they can be used also in the calibration and validation of the local wave model.

5.3.4 Effects of the turbine support structures on waves

If turbine foundations significantly affect the magnitude or direction of wave energy exiting the development site, there is potential for impact on receptors sensitive to the result of long term wave action, e.g. littoral drift rates at the coastline, morphological stability of sandbank systems and the seabed immediately surrounding the structure (scour) or organisms adapted to a particular wave dominated environment.

Previous studies have shown that for typical wave conditions (those occurring many times each year) and for slender structures (monopiles) the effect of the presence of the wind farm foundations is likely to be minimal (ETSU 2002; Cefas, 2005) with regard to both the development of scour and to transient wave propagation. For larger or more complex structures (e.g. gravity base, multi-legged foundations, etc.) which are more likely to be used at the sites proposed in Round 3, the evidence base is currently lacking and further research is required in order to understand their interaction with waves and to represent these structures appropriately in numerical models. Certain existing empirical relationships suggest that typical gravity base structures in typical Round 3 environments might have the potential to cause wave diffraction.

5.4 Sediment regime

The sediment regime is characterised by sediments with varying properties which may be either static, *in situ* on and within the seabed, or may be transported at variable rates and directions through the marine environment in response to tidal currents and waves. Sediment may become mobile either as bedload (potentially resulting in bedform features), or as suspended load (transported in the water column). Resuspension may be a result of natural forcing or the result of anthropogenic disturbance. The particular rate, direction and mode of transport is related to the amount of energy in the water column and the properties of the local sediment.

5.4.1 EIA issues

The sediment characteristics at each site need to be investigated as part of the EIA, including the natural transport characteristics of mobile sediment, the properties of sediment that may be resuspended as part of the development, the fate of any artificially resuspended material and the potential for scour around individual turbine foundations. These requirements involve the detailed evaluation of sediment characteristics in conjunction with tidal and wave conditions within and adjacent to the development site. The difficulty is that, in all of the Round 1-3 environments being considered, directly measured sediment property and sediment transport data sufficient to characterise the site are not usually available.

Sufficient information is required to characterise the range of sediment transport rates as both bedload and suspended load on semi-diurnal, spring-neap and seasonal/annual time scales. This information is used to inform understanding and perhaps modelling of the magnitude and variability of the driving forces behind sediment transport and also to place any predictions made regarding the impact of the development into a local context. Sufficient information is also required to characterise the particle size distribution (proportion of sediment volume in each size grading) and any variation of the grading or mixture with depth. This information is used to inform predictions of the rate, extent or fate of any material resuspended by construction activities (bed preparation, drilling, cable laying, etc) or by the presence of the wind farm (regional and local sediment transport, including scour).

5.4.2 Information requirements

For the EIA, information on changes to the sediment regime is required in terms of any modification to sediment pathways, suspended sediment concentrations, erosion and deposition patterns. The likely depth and extent of scour also needs to be assessed. This will require knowledge of the *in situ* sediment properties, the hydrodynamic regime, the likely type and distribution of structures (including turbine structures and the operational characteristics of any support vessels, e.g. jack-up or gravity base platforms) and the likely location and rate of any related anthropogenic sediment resuspension.

5.4.3 Describing the local sediment regime

As recommended in Cefas (2006), a useful method for assessing the sediment transport characteristics of an area is through a shear stress exceedance analysis. In order to evaluate the proportion of time during which particular grades of sediment are potentially mobile, the following procedure is applied:

- A time series of tidal current and/or wave data are converted to an equivalent bed shear stress value.
- The shear stress values are sorted into rank order (largest to smallest) and plotted against a linear scale of frequency of exceedance (from 0% to 100% in steps of 100/(N-1) where N is the total number of samples).
- The percentage of time where a particular grainsize is potentially mobile is determined as the frequency of occurrence corresponding to the critical shear stress value required for threshold of motion of the grainsize in question.
- The same procedure is repeated for tides alone, waves alone and then combined.
- The results are interpreted in the context of the known sediment particle size distribution and abundance at the site. In this way, an assessment can also be made of the relative importance of tidal and wave forcing on sediment transport at a variety of spatial scales.

- The direct relevance of the result is dependant upon the presence of a receptor sensitive to changes in sediment mobility. However, in isolation this analysis does also provide an alternative means by which to contextualise the relative changes or impact on the baseline environment.

Thus, a description of the sediment regime can be formed with reference to:

Previous publications
An initial broad assessment of characteristic 'offshore' sediment transport patterns may be found in publications such as Stride (1982), HR Wallingford *et al.* (2002), Kenyon and Cooper (2004) or Dronkers (2005). Further detail of variable accuracy and resolution may be found in the many publications describing local sediment transport behaviour.

Measured data
Examples of sources of sediment property data and sediment transport data, their pros, cons, typical usage and accuracy are given in Sections C.6 and C.7. Estimations of the rate of sediment transport (reported through shear stress exceedance analysis) require hydrodynamic data inputs of tidal currents and waves; similar information for sources of hydrodynamic data may be found in Sections C.2 and C.3.

The geology and sediment types for each site will need to be investigated thoroughly, as conditions of sediment type, thickness and mobility and underlying bedrock conditions may vary appreciably from site to site; there may also be extensive variability across large offshore sites. Such data can, in combination with suitable hydrodynamic data, enable quantification of localised sediment erosion and subsequent transport, including suspended sediment. In support of the EIA, broad scale descriptions of sediment properties from preceding Strategic Environmental Assessments may be sufficient to inform the EIA; detailed site specific geophysical survey data may feed into the EIA, validating regional scale information, but are more likely to inform the engineering and design.

Seabed data may be derived from geotechnical studies, including borehole and grab samples to determine local soil conditions, type and thickness. A variety of geophysical methods can also be used, including: multi-beam swath, to obtain accurate baseline bathymetry; sub-bottom seismic profiling, to ascertain both local and a more regional view of sediment type and thickness; and, side-scan sonar to describe seabed surface sediment distribution and the form and extent of mobile bedforms. If potential for significant sediment mobility is observed then there might be a need for a repeat series of bathymetric and side-scan surveys to attempt to measure this mobility.

Existing sources of sediment type data may be found (e.g. from the British Geological Survey or other large scale seabed charachterisation studies) but these may be of coarse resolution in locations further offshore. In this case, existing data will need to be supplemented with new data at higher resolution and in both cases will need to be validated.

Multiple and repeated measurements of suspended sediment concentrations are also required to describe typical values and ranges, which may vary spatially (both horizontally and vertically) and on hourly to seasonal timescales. Offshore environments tend to be more consistent and have generally lower concentrations due to the reduced influence of wave action in deeper water and being more remote from coastal sources (e.g. rivers and coastal erosion).

If the site potentially interacts with the coast (much less likely for Round 3 sites), information is required about the naturally occurring sediment transport along adjacent beaches or coastlines. Studies may exist which provide estimates of longshore transport rates and/or historical beach profile change.

Data regarding hydrodynamic characteristics of tidal currents and waves (if they have a significant effect in shallow enough water) are also required. Waves become significant when they are large enough, compared with the water, such that they induce water motion at the seabed with a measurable effect on sediment transport. Sediment property information is combined with the hydrodynamic data at coincident locations in order to estimate natural sediment mobility or to estimate the transport rate and direction of artificially resuspended material.

Local sediment transport models
More information regarding sediment models and modelling may be found in Section B.5.

Any sediment transport model needs to consider the extent to which waves and tides affect sediment transport. It is typically the case in offshore environments in the UK that tidal currents dominate sediment transport processes; however, some environments in the central northern North Sea were identified by Stride (1982) and again more recently in Kenyon and Cooper (2004) as being wave dominated as a result of relatively small tidal currents and occasional but severe wave action.

Sediment transport models use tidal and/or wave data output from hydrodynamic models and so these data must first be appropriately created (see Sections 5.3 and 0). Measured data describing the distribution of sediment characteristics are then added to the model and calculations of instantaneous sediment transport potential are made over the model domain.

A baseline description of the sediment regime will need to consider a representative range of naturally occurring variations likely to be present in the planned operational period of the development. This will include high frequency-low energy events, i.e. tidal forcing from semi-diurnal to spring-neap cycles, and low frequency-high energy events, e.g. storm wave events and storm surges. The assessment should also consider how the sediment regime might respond to even longer term potential climate change and sea level rise scenarios.

The advantage of using a numerical modelling approach in this case is that hydrodynamic data and therefore calculations of sediment mobility are made available at many more locations and possibly over longer time periods than would otherwise be available through field monitoring alone. Sediment property information is then combined with the hydrodynamic data at in order to estimate natural sediment mobility or to estimate the rate and direction of transport, but also the fate (effect on suspended sediment concentration, footprint of deposition) of artificially resuspended material.

5.4.4 Effects of the turbine support structures on sediments

Previous studies have shown that for typical hydrodynamic conditions (those occurring many times each year) and for slender structures (monopiles) the effect of the presence of the wind farm foundations on regional sediment transport is likely to be minimal (ABPmer, 2005; ABPmer et al., 2007; HR Wallingford et al., 2007). Local scour which may develop around the turbine foundations can be predicted using analytical solutions with variable accuracy depending upon the particular foundation type, hydrodynamic conditions and seabed sediment properties.

For site specific investigations this conclusion requires further validation against actual data. For larger or more complex structures (e.g. gravity base, multi-legged foundations, etc.) the evidence base is currently lacking and further work is required in order to understand their interaction with tidal currents, waves and by extension sediment transport. These additional studies will be required to provide confidence in representing these structures in coastal area numerical models currently used in studies as well as for predicting local scour around the foundations.

The potential effect of the wind farm on the shape and volume of large geomorphologic features (e.g. sandbanks) must be assessed in the context of the potential for change due to natural causes.

5.5 Marine cables

Marine electrical cables are used to connect turbines within the wind farm site to a central point for electricity export. Presently, one cable route (but possibly with more than one cable) is created between the wind farm and a suitable export location at the coast.

In Round 3, sites closer to the shore may use the same approach; however, this may become inefficient for sites further offshore. A study by The Scottish Crown Estate (The Crown Estate, 2007) has demonstrated the feasibility of plans for a trunk cable serving multiple wind farms and other offshore renewable energy developments along the East coast from the Orkneys to the Greater Wash area. Other plans for EU scale submarine grids, serving multiple developments may also be found. Such schemes, if implemented, would reduce the length of cable routes from individual wind farms to the grid connection and would reduce the number of landfall locations.

There are a number of methods currently available for protection against scour around cables traversing the seabed. The primary method of protection is cable burial, which removes it from the seabed surface (so that any likely effects of scour are minimised or removed) and affords protection from other disturbances (e.g. anchors, trawling, etc.). A summary of devices and methods presently available for cable burial, their capabilities and implications for environmental impact are provided in a review publication for BERR (Royal Haskoning and BOMEL, 2008); the key findings of this study are outlined in Section 5.5.1 below.

Other protective measures for cables near to the seabed surface or at intersections between cables/pipelines include: aprons, rock dumping, mattresses, concrete saddles, cable anchors, and flow energy reduction devices.

It is anticipated that, in the majority of cases, the main export cable will be buried to a nominal depth below the seabed surface of around 1 to 2m to ensure adequate protection from fishing activity, anchoring and accounting for possible seabed erosion. Burial depth specification requires a risk assessment as part of the engineering design process. Burial is most likely to be carried out by some form of ploughing or jetting:

> <u>Ploughing</u>
> Ploughing involves cutting the seabed with a plough towed by a vessel. As the seabed is cut, the cable drops into the bottom of the trench and the seabed then falls back into place. Thus, the plough both buries and back-fills, giving instant cover and protection. However, ploughing methods are difficult to use in areas of hard seabed such as boulder clay, and are impractical to use close to structure foundations. Ploughing is a preferred option where possible due to the low disturbance of the sediment resulting in minimal sediment resuspension.
>
> <u>Jetting</u>
> Jetting tools, which can be near-bed-free-swimming or tracked, use alternating high and low pressure water jets to cut a trench or fluidise a section of seabed into which the cable is laid. If sediment is displaced, tidal currents are relied upon to cause gradual backfill over a period of time. Jetting tools can be used in areas of hard seabed, including some soft rocks. Jetting is more energetic and places a greater amount of sediment into suspension, so is of more concern during EIA.

The developers Project Design Statement can be used to identify the worst-case-scenario method of burial, the potential rate of burial and the cable route options being considered.

5.5.1 Potential Effects of Installation

The following is a partial summary of the impact and mitigation issues identified in the review of cabling techniques and environmental effects by Royal Haskoning and BOMEL (2008) for BERR.

Ploughing and jetting cause only local and temporary disturbance of the seabed. With ploughing, the seabed settles back in place on top of the cables as they are laid. Any trenches formed by jetting will often naturally backfill with sediments moving in under the influence of tidal currents though monitoring will be necessary to ascertain its effectiveness. If natural backfill rates are slow or unlikely to occur then a jetted or cut trench will need to be backfilled with appropriate erosion-resistant materials. Typically, a seabed corridor around 4-6m wide may be disturbed directly by the burial device during installation of the cables. The width of disturbance is dependent on the depth of burial, the size of the burial device 'footprint', and the installation technique.

Disturbance of the seabed during cable burial may place sediment into suspension, which will contribute to a temporary local increase in suspended sediment concentrations, close to the seabed. The initial increase in concentration will depend upon the particular method of burial, the rate of burial and the properties of the sediment. The subsequent persistence and transport of the increased suspended sediment concentration depends upon the hydrodynamic conditions at and following the time of release, and the properties of the sediment in suspension. Chalk can persist in suspension for long periods but as no sensitive receptors can be quantitatively described, it is presently considered to be more of an aesthetic issue.

Suspended sediment plumes can cause small, localised increases in turbidity and oxygen demand in the water column. Resettlement of particulate matter could cause short-term alterations to the physical characteristics of the seabed, but recovery of the original seabed geomorphology is usually relatively rapid, especially in areas characterised by relatively energetic hydrodynamic conditions and in areas of gravely seabed.

In many cases, suspended sediment levels can be expected to be already high due to the ambient current regimes, occasional storm activity and fisheries activities (particularly beam trawling) along the cable route. Therefore, the increase in suspended sediments above background levels will be short-term and generally not significant, but this will need to be confirmed as part of the EIA. Offshore sites tend to experience generally lower ambient levels of suspended sediment concentration but the area affected is relatively small.

Further direct evidence showing no significant impact on suspended sediment concentrations from cable installation was presented in the SED01 report (ABPmer *et al*. 2008). On this basis, the evidence base is clear that the potential impacts of cable installation are not significant; however, some concern does still remain for the method and impact of the landfall part of the cable route. As a direct result of these findings, the requirement to monitor suspended sediment concentrations has been reduced or excluded in several Round 2 FEPA licences.

5.5.2 Pipeline or Cable Crossing

The export cable route may involve crossing an existing pipeline or another cable. Such intersections may become more commonplace if a trunk cable or offshore grid system is developed.

Where post-lay burial cannot be undertaken, rock armouring or concrete mattresses may be installed over a simple cable crossing to provide adequate protection. This could raise the seabed profile by approximately 0.25 to 0.5m at the location of the crossing, which may encourage limited accumulation of sediment at the crossing, or sediment scouring around its margins, depending upon the design. The impact on seabed topography, although long-term, can be expected to be relatively small and localised, hence, no specific modelling or additional EIA should be required.

Connections between the wind farm export cable and a trunk cable may be protected by larger three-dimensional housings or be given more extensive scour protection. In this case, the seabed profile may be raised by a greater amount. It is still unlikely that such a structure will have significant effects in the far-field. For engineering purposes (not for EIA), specific numerical modelling studies (if undertaken at all) might be undertaken using local CFD models, used to improve predictions of scour.

5.5.3 Offshore substations

Long cables servicing wind farms far offshore may need offshore substations in order to maintain a suitable and stable voltage for efficient electrical transmission. Offshore substations for the windfarm itself are typically mounted upon similar foundations to the wind turbine structures or may simply be built into one of the turbine towers. It is not expected that additional substations will be required along the cable route. The 64km long High Voltage Direct Current (HVDC) cross-Channel cable connection between the national grids of France and the UK does not require intermediate substations, however, Round 3 sites may potentially be located even further offshore.

5.5.4 Shore-end / Landfall

Cables can either be ‘trenched’ across the foreshore and beach, or may be led through a sub-surface conduit created by directional drilling. In the case of the former, the trenches would be back-filled with the removed beach materials (e.g. sand, shingle, cobbles), with care taken to restore material to previous profiles where differences have been found during excavation. Directional drilling would be a preferred option as it does not disturb the existing coastline and therefore can not impact on littoral processes.

Given the small diameter of the cable, the depth of burial and assuming a well-planned and professionally executed installation operation, there should not be any significant effects on the beach profile and mobility of coastal sediments. In this case, numerical modelling is not required.

5.5.5 Operation and Maintenance

Once buried, the cable is not expected to have any significant impact on sediments or seabed morphology. As mentioned above, mattresses installed at pipeline/cable crossings would cause a localised, long-term impact on seabed topography, and may also result in some sediment accumulation but this impact is not expected to be significant.

Maintenance of the cable is not anticipated. However, if a fault occurred which necessitated repair, the cable would have to be excavated, repaired and re-buried. Potential impacts would be similar, but on a much smaller scale, to those during installation. Hence there should be no further modelling or EIA requirement.

5.5.6 Decommissioning

‘The Energy Act has yet to provide any clear guidance on the legislation relating to offshore wind farms’ (Royal Haskoning and BOMEL, 2008). There are complex issues regarding the removal of disused submarine cables where removal of deeply buried cables may induce more environmental impact than leaving them in situ as a known hazard. Ultimately, if removal is attempted, an appropriate EIA is required.

At the stage of wind farm decommissioning, it is suggested by Haskoning and BOMMEL (2008) that buried sections of the intra-array and export cables would most likely be secured at either end and abandoned *in situ*, with their location remaining marked on charts as an obstacle. The cables could potentially be recovered to remove them as potential obstacles and to realise any remaining value; however, removal will require some form of mechanical dragging or excavation, which would result in disturbance to the seabed with associated environmental impact. However, as with cable installation, impacts are likely to be localised, short-term and not significant in comparison to ambient levels; hence the EIA should not require explicit modelling or monitoring.

6 Managing Uncertainty

6.1 Introduction

The AIAA guide for the verification and validation of computational fluid dynamics simulations (1998) defines error and uncertainty by the following:

Error: A recognisable deficiency that is not due to lack of knowledge
Uncertainty: A potential deficiency that is due to lack of knowledge

These definitions can also be applied to the wider EIA process, where 'knowledge' refers to the existing resource of science, methods, and supporting contextual information that are available, i.e. the knowledge or evidence base. There is a clear distinction between the two terms as stated which implies that error can be minimised or removed through appropriate action, whilst uncertainty can only be reduced by additional research as it is based in a deficiency in the evidence base. However, in practice there is some overlap between the two terms and limitations on the degree to which each can be reduced, due to the chaotic and complex nature of the natural environment.

Uncertainty in the conclusions of an assessment, such as those undertaken as part of EIA, is the combined and potentially cumulative effect of error (contributing to a lack of knowledge in the assessment) and uncertainty in each basic stage of the assessment process, namely:

- Identifying the problems or issues to address in the EIA;
- Quantifying the sensitivity of identified receptors;
- The evidence base;
- Collecting field data;
- Creating numerical model data if required; and,
- Assessment of all the available data, using the available knowledge, to address the original problem or issue.

Error and uncertainty should be identified and then reduced or managed at each stage in this process in order to increase confidence in the overall assessment. Error and uncertainty must be managed at their source in the first instance otherwise they could propagate throughout the assessment process. An assessment of error and uncertainty should be appropriately presented for the study which will allow the end-users of that study (regulators and developers) to attribute a suitable level of confidence to the results.

6.2 Error and uncertainty in identifying EIA issues

The breadth and depth of issues accounted for by an EIA may vary, but the basic requirements are provided in a small number of brief, structured documents. Uncertainty is reduced to some extent by the production and ongoing review of peer reviewed guidance notes and best practice guides, presently exemplified by Cefas (2004) and subsequently by the anticipated Round 3 update.

This process has already been applied to wind farm EIA from Round 1 to Round 2, informed by the (limited) data becoming available from the Round 1 sites. For example, wave diffraction effects were considered potentially important during Round 1 EIA (DEFRA, Cefas and DTLR, 2001). Following the installation of Scroby Sands wind farm and informed by the monitoring carried out there (published later in Cefas, 2005), i.e. improving the evidence base, wave diffraction effects were found to be insignificant and are no longer required as part of the EIA process for the case of slender monopiles (Cefas, 2004). It is anticipated that this process will continue to incorporating longer data sets for existing Round 1 sites and new data sets from new developments as they are installed.

The requirements of these documents are not prescriptive and do not assume to account for all possible impacts of the development, so the possibility that an issue might be overlooked or omitted from such lists might be considered as either an error or an uncertainty. Error and uncertainty (omissions) are reduced over time by maintaining, developing and applying a robust evidence base, delivered through regularly updated guidance.

This process is informed by reviewing the effectiveness of the EIA approach, ongoing applied research and also the requirements for ongoing environmental monitoring (part of the evidence base).

6.3 Error and uncertainty in quantifying the sensitivity of receptors

An EIA issue might identify a receptor which, if present, might potentially be negatively impacted by the presence of the OWF development. In order to assess the significance of any impact on that receptor, the sensitivity thresholds of the receptor must first be quantified and criteria established under which further assessment can be undertaken.

Presently, uncertainty in the quantitative sensitivity thresholds or impact significance criteria for a variety of receptors is a major source of overall uncertainty in the outcomes of an EIA. In comparison, error and uncertainty in the prediction of physical impacts of a scheme is likely to be much smaller.

Uncertainty in the sensitivity of receptors is presently managed by avoiding absolute quantitative expressions of significance. Instead, the relative change in the baseline condition as a result of the scheme is assessed and presented in the context of the range of natural variability.

6.4 Error and uncertainty in the evidence base

Uncertainty in the knowledge or evidence base is, by definition, associated with its finite, limited nature. There is always more that can be known or understood about a particular process; also, certain process might be well understood in one environment but not so well in another. Uncertainty in the evidence base is an ongoing issue and is of concern to all parties in the development process. Uncertainty poses risk to the regulator, who, as a consequence, places a greater requirement on the developer for EIA, monitoring and mitigation, which, as a consequence, potentially makes the development process more complex, lengthy and expensive.

Uncertainty in the evidence base is reduced or managed through ongoing research and review of existing procedures, guidance notes and best practice guides, and monitoring reviews.

Presently, the evidence base for the UK relates primarily to that reported for the five operational Round 1 wind farm sites. These are charachterised by shallow water and close proximity to the coast. Turbine foundations are all monopiles; there is limited additional information available other foundation types. Data from other European wind farms are not directly relevant to many UK Round 1-3 locations due to the typically smaller tidal range and effect of tidal currents. Further details of the UK evidence base, including relevant research and guidance publications, may be found in Section 2.1.

Sources of error in the evidence base are not necessarily easy to identify. Errors may exist in the form of long standing hypotheses or assumptions that have since been disproved or amended by ongoing research but are still contained within the evidence base.

Errors are reduced or prevented from entering the evidence base to some extent by the processes of peer review, guidance notes and best practice guides.

6.5 Error and uncertainty in data from the field

Sources of error in all field data are primarily related to the limited accuracy or capability of the equipment used. More details of the usage, pros, cons and accuracy of a variety of typical field data sources may also be found in Appendix C.

Sources of error in field data are primarily managed through appropriate choice of equipment and improvements in equipment accuracy, resolution or design; also, the development and use of appropriate methodology (e.g. equipment calibration, deployment location, equipment setup, data post-processing, etc.) and Quality Assurance procedures. Accurate and correct data may also contain noise inherent in the natural system, due to chaotic or complex process interaction.

The primary sources of uncertainty in field data, and how to reduce or manage them, are described in Appendix C for general data types of:

- Hydrodynamics (water levels, tidal currents, wave climate, etc)
- Sediment properties (grain size, sorting, layering, etc)
- Suspended sediments (concentration)
- Sedimentary structures (type, size, orientation, location, mobility, etc)

6.6 Error and uncertainty in data from numerical models

Sources of error and uncertainty in the results of numerical models are outlined in Appendix B.

The results obtained from a modelling study are often principally dependent on the experience and competence of the particular modeller. Other sources of error arise from the inherent limitations of the model in accurately representing some processes, the spatial or temporal resolution of the modelled processes, the quantity and quality of the data used to build the model, or from the accuracy limitations of the computer. More details regarding sources of error and uncertainty in data from numerical models may be found in Appendix B.

However, errors can be minimised by applying a number of procedures, as follows:

6.6.1 Checklists

To avoid mistakes due to lack of attention to detail or due to user ignorance a checklist can be developed, listing all the issues that need to be addressed. Checklists in the form of guidance documents can form part of the formal Quality Assurance procedure.

6.6.2 Formal Quality Assurance

A formal Quality Assurance procedure is particularly important when the user is inexperienced. The procedure should cover guidance on:

- Problem definition
- Solution strategy
- Model use
- Analysis and interpretation of results
- Documentation of the modelling work undertaken

Quality Assurance is considered to be a best practice for many types of business and is not often formally reported. However, evidence of formal Quality Assurance procedures (typically in the form of accreditation from a nationally recognised body) is usually provided if used.

6.6.3 Data quantity and quality

The quantity and quality of data used for model set up should be sufficient for its intended purpose and as free from error and uncertainty as possible. The recommended quantity and quality of data required for model set up are described in Section 4.2. Sources of error and uncertainty in different field data types are discussed in Appendix C. Any error or uncertainty in field data measurements will propagate through the modelling process and must be presented in the final assessment, as described in Section 6.7.

6.6.4 Calibration and validation

As part of the process of reducing uncertainty and error in model simulations, the processes of model calibration and validation are important and defined as follows:

> Calibration:
> Model calibration allows the adjustment of certain model parameters in order to optimise the ability of the model to predict a set of measurements from the field. Calibration involves the iterative or systematic tuning of various model parameters; the results of the adjusted models are compared with field data using an objective comparison method, preferably quantitative in nature, until the optimal solution is reached. Calibration reduces error in the resulting modelled data and in doing so reduces uncertainty in addressing the issues of the EIA.
>
> The optimal solution for calibration must, as a minimum, meet certain criteria for acceptable model calibration. There is no existing consensus or generally accepted guidance regarding these criteria and so they should be agreed between the developer (and EIA contractor) and the regulator (MFA) prior to submission of the EIA.
>
> Validation:
> The validation exercise determines whether a model is 'fit for purpose'. The model is applied to a new set of measurements with no alteration or further calibration. The ability of the model to reproduce these new data is used to assess the model's predictive performance. Validation provides an estimate of the sign, magnitude and variance of the error of the model and so further reduces uncertainty in addressing the issues of the EIA.

Residual differences that remain between the model and field data following calibration and validation represent the combined error of the model (see Section 4.4) plus that of model input data and data used to calibrate and validate the model (see Section 4.2). The fundamental (fixed) level of error in the model is equivalent to the error margin of the field data used to create it. Ideally, residual error in the model should be of a similar (or smaller) magnitude than the known error in the field data, in which case no additional error has been introduced by the modelling process.

Model calibration, validation and resulting estimates of the model accuracy should be made available as part of the EIA process as they are of relevance to all users of the results. The estimated accuracy of any data used in the EIA report itself should be quoted at that point; the details of model calibration and validation might be presented in an appendix or as a separate supporting document. Model accuracy should be described quantitatively and in relation to the known natural ranges of variability in that parameter.

6.6.5 Assessing error

There is no standard guidance for objectively assessing error during the modelling calibration and validation exercise. Only the lowest level of confidence is given to 'visual comparison' as it is subjective and provides no quantifiable level of error. Visual comparison on its own should not be considered as good practice.

Many objective or statistical methods exist to compare model derived data against measured field data; the most appropriate method might vary depending upon the particular requirements for the project, e.g. whether only peak values or values at all time steps are considered important. Analytical or comparative methods are typically bespoke numerical analysis tools which quantitatively compare the instantaneous or peak magnitude and the timing of predicted and observed data. Differences between predicted and observed data sets are obtained and consolidated, typically providing a mean difference value with an indication of the variability.

The data being assessed may be a scalar (varying in magnitude but with no associated direction) or a vector (with magnitude and direction) quantity. In the case of vector data (e.g. current speed and direction), both magnitude and direction must be considered at the same time (although possibly using different assessment criteria weightings depending upon the relative importance of each parameter). Time-series data (e.g. tidal height or tidal current magnitude or direction) can be assessed in several ways, including:

- Agreement in the magnitude of peak values
- Agreement in the phase of peak values
- Agreement in the magnitude of all values
- Agreement in the phase of the overall signal

The degree of similarity between observed and predicted values and therefore confidence in the ability of the model to simulate the target natural environment, increases as more of the above criteria are met. However, not all of the above criteria must be met for the data to be fit for purpose, e.g. peak or extreme values typically correspond to the worst-case-scenario and so the absolute phase or the magnitude of non-peak values is not so important.

6.6.6 Best practice

At all stages of the modelling process, including field data collection, best practice as described in Chapter 4 should be applied when and where available. Best practice helps to ensure that the most appropriate methods are used in the configuration of the baseline model and in the inclusion of the wind farm structures. Best practice also helps to streamline the EIA process where it can identify the circumstances under which the evidence base already supports an assessment of no-significant impact, without the need for extensive further research.

A review of best practice methods in relation to offshore wind farm marine environmental process EIA may be found in Chapter 4.

6.7 Managing overall uncertainty

Generally speaking, best practice acts to reduce and manage uncertainty and error consistently and progressively at each stage in the assessment process. The sources of error which are likely to propagate and accumulate through field data collection and numerical modelling (where undertaken) in the assessment procedure have been described in the preceding sections of this Chapter. The cumulative effect of individual sources of uncertainty must be considered where several data sources, models or analysis techniques are applied in series.

Even if best practice is followed, some residual error and uncertainty will remain due to inherent limitations in the methods and resources available at the time. This residual error and uncertainty can be further managed or reduced at the assessment stage, either when reporting absolute values (i.e. baseline information) or when reporting relative difference values (i.e. the effect of the scheme in comparison to the baseline).

6.7.1 Residual uncertainty in actual values

The baseline section of the EIA requires quantitative characterisation of the marine environment, i.e. descriptions of naturally occurring tides, waves, suspended sediment concentrations, sediment transport and longshore drift (if appropriate). Reported values include the residual cumulative error and uncertainty from field data collection and the modelling process.

Confidence in the overall assessment may be maintained if residual error and uncertainty are small in comparison to:

The natural occurring typical values and variability in the parameter being reported
If the reported values, including allowances for error, remain representative of observed values and within the expected range of that marine environment, then the reported values are at least representative of that environment, even if they do not describe the actual values and timing with exact detail. Also, if such a small change were to occur following scheme construction, potentially then as a result of the scheme, it would not be possible to clearly attribute the event to either the development or to natural processes.

For example: Peak spring tidal current speeds at a location vary naturally between 0.6-0.8m/s. The field data available for calibration and validation is assessed to be accurate to within ±0.05m/s. Model calibration and validation demonstrates that the model can reproduce the observed peak tidal currents to within ±0.08m/s. Firstly, the model is shown to reproduce the field data well, the best that the model could be expected to achieve is ±0.05m/s and so it is only introducing an additional error of ±0.03m/s. Secondly, the model is capable of reproducing the natural range of tides present. When used for baseline and scheme assessment, the model simulates an average tide (peak 0.7m/s); therefore, the results, accounting for the greatest potential error will fall within the known range of values and so will be representative of the site.

The reasonable accuracy of field measurement devices
If the error is equivalent to the accuracy of typical relevant field measurement devices (i.e. when no additional error is introduced by the modelling process), no amount of additional data collection or improvement in the modelling process could provide a result with a greater degree of confidence.

For example: Another numerical model indicates that the maximum thickness of sediment deposition following drilling for a monopile installation will be 0.02m ±0.005m. Assuming that the model is generally correct (ABPmer et al. (2007) has shown that such models typically are) it would not be possible to measure the difference between a 0.015 and a 0.025m change in bed level during post construction monitoring using presently available technology and so the error cannot be reasonably challenged on these grounds.

The sensitivity of the marine environment
If the reported values, including allowances for error, remain within the known tolerances of sensitive receptors in the marine environment, then the reported values are tolerable and therefore potentially acceptable to that environment, even if they do not describe the actual values and timing with exact detail.

For example: the same model result (above) is used to assess the impact on sessile epi- and in-fauna. It is known that such organisms can tolerate up to a 0.05m increase in bed level. Making allowance for the greatest potential error, the maximum predicted bed level change is 0.025m, which is still within the tolerance of the environment and so the issue is resolved.

6.7.2 Residual uncertainty in relative values

The scheme assessment section of the EIA requires a quantitative assessment of the potential effect of the scheme, in comparison to the baseline, i.e. effect of structures on waves, tides, sediment transport, suspended sediment concentrations and longshore drift (if appropriate).

The data used to describe the baseline environment and the data used to describe the 'with-scheme' environment contain the same residual errors and uncertainties with regards to the natural environmental processes being simulated. When the difference between the two data source is found to assess the impact of the scheme, the majority of errors and uncertainties are therefore cancelled out to a large extent. The major remaining source of error comes from the with-scheme data which contains additional error and uncertainty relating to the ability of the model to accurately reproduce the presence of the wind farm structures; however, this uncertainty is reduced by choosing a conservative ‘worst case’ scheme.

A pre-requisite for confidence in the overall assessment is that residual error and uncertainty in the baseline data (and hence the naturally driven part of the with-scheme data) are small in comparison to the items as described above in Section 6.7.1.

If this requirement is satisfied, then confidence in the overall assessment is maintained if residual error and uncertainty in the effect of structures are also small in comparison to the items described above in Section 6.7.1. It should be noted that gaps in the knowledge and evidence bases for gravity base or other more complex structures present some difficulty in the assessment of error.

7 Summary and Conclusions

This report provides an update to existing best practice guidance on the application and use of numerical models to predict the potential impact from offshore wind farms on coastal processes. As such, this report is of direct use to windfarm developers and environmental consultants, providing guidance on the scoping and design stages of the coastal processes part of an Environmental Impact Assessment (EIA). It provides guidance on the requirements for numerical modelling, and how to assess the extent and quality of any numerical modelling work proposed and undertaken.

Guidance for undertaking an EIA is typically aimed at addressing particular issues, incorporating conceptual and methodological understanding and data (the evidence or knowledge base) accumulated from past experiences. The key issues for coastal and seabed impact assessments that are considered to remain of particular interest in the context of EIA are*:*

- Suspended sediment dispersion and deposition patterns resulting from foundation and cable installation or decommissioning.
  - Relevance: receptors sensitive to specific changes in burial depth, suspended sediment loads or textural change in sedimentary habitats.
- Changes in coastal morphology due to cable landfall installation and maintenance.
  - Relevance: receptors sensitive to erosion or accretion including habitat, property, recreation and landscape.
- Scour and scour protection.
  - Relevance: receptors sensitive to the introduction of new substrate
- Wave energy dissipation or focusing for sites very close (<5km) to an exposed shoreline, for foundation types and/or array densities which are considered more likely to affect wave height, period or direction.
  - Relevance: Receptors sensitive to changes in coastline morphology.
- Wave and current processes controlling very shallow sandbank morphology, especially for relatively dense turbine arrays and/or less well understood foundation types.
  - Relevance: ecological or navigation receptors sensitive to changing bed morphology including scour, channel migration sandbank mobility.

There is inevitably a lag in parts of the evidence base behind some foundation types. For example, the effect of complex or large (non-monopile) foundation types on waves, currents and local sediment processes, is a topic which requires further research to be added to the evidence base. Alongside these specific needs, the process of guidance review and complementary research continues to follow the move to even larger sites, located farther offshore as part of Rounds 2 and 3.

In support of offshore wind farm EIA's, guidelines to outline the general scope for 'coastal process' investigations are available for characteristic Round 2 developments and are also being updated to suit Round 3 requirements. The consideration of potential changes to the marine environment and the consequential response of an environmental receptor is anticipated to remain as part of the EIA approach. However, the most appropriate and efficient method to assess any potential impact should be considered in each case, in the following order:

1. What are the potential sensitive receptors by category or species? Are the sensitivity thresholds of the defined receptors understood and quantified?
2. What information about the physical environment is required to categorize the potential impacts on the identified receptors?
3. Can sufficient information be practicably and effectively provided by existing knowledge and available field data without the need for numerical modelling?
4. If the answer to Point 3 is 'no', can numerical models represent the processes involved sufficiently to provide the required information?
5. If the answer to point 4 is 'yes', can sufficient field data be obtained to adequately calibrate and validate the model to provide confidence in the results?
6. Does the regulating authority agree with the proposed approach to the study?

In summary the guidance is intended to provide an objective approach for defining the basis for selecting field data collection and/or numerical modelling to support EIA studies. This can be thought of as follows: if the question(s) relating to completion of the EIA is well defined and can be answered on the basis of existing evidence (including existing site data or numerical model results), then the need to obtain new or more detailed data, either from the field or from numerical modelling studies, is questionable. Conversely, if the question(s) cannot be answered on this basis then field data collection or numerical modelling can be considered.

Specifically, if the question(s) is well defined and the procedure indicated in the list above is followed, then numerical modelling can be considered as an option, using the following general best practice advice.

- Choose a numerical modelling approach that is fit-for–purpose in reproducing the range of processes identified as important to the question being posed, including both baseline and scheme assessment.
- Ensure that a sufficient quantity, quality and resolution of data are available in order to support the modelling work being undertaken. The requirements will vary depending upon the complexity of the site dynamics and the accuracy required in order to answer the question being posed.
- Assess confidence in the model accuracy through an appropriate, quantitative, model calibration and validation process. Confidence in model accuracy is ultimately limited by the properties of the data used to build and test the model, and by the inherent limitations on accuracy of the modelling approach used, including the ability of the model to account accurately for baseline physical processes and for the effect of the wind farm structures.
- Assess the effect of the scheme as the difference between the modelled baseline and the modelled scenario. In doing so, uncertainty regarding the absolute accuracy of the model is reduced.
- Reduce uncertainty in the effect of the many potential scheme options by choosing an appropriate ‘realistic worst case’ scenario. If a realistic worst case scenario is demonstrated to pose no significant impact, relatively less intrusive options can be accounted for without explicit modelling.

Additional specific best practice guidance may be found on the following key topics:

- The presently available evidence base (Chapter 2, Appendix A and Appendix D)
- Assessing the requirement for numerical modelling (Chapter 3)
- Assessment of identified site specific EIA issues (Chapter 5)
- Sources of data in support of modelling and EIA (Appendix C)
- Considerations relating to the application of numerical modelling (Chapter 4 and Appendix B)
- Managing and assessing uncertainty (Chapter 6)

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Appendix A. Lessons learnt from Round 1 post-construction monitoring

A.1 Sediment Monitoring

A consortium of research partners comprising ABPmer, Cefas and HR Wallingford was commissioned to carry out the BERR research project SED01: Review of Round 1 sediment process monitoring data – lessons learnt. This work was funded through the pan-Government Research Advisory Group (RAG).

The aim of this project was to draw together the sediment process monitoring work carried out on Round 1 developments and review the methods, data, results and impacts in order to identify lessons learnt and to provide relevant recommendations for monitoring of Round 2 developments. A further aim for the project was to consider if the Round 1 monitoring assisted in any way the consideration of broader scale effects relevant to Strategic Environmental Assessment (SEA) review requirements.

At the time, the evidence base consisted of four operational Round 1 offshore wind farms in the UK and one in Ireland:

- Barrow
- Kentish Flats
- Scroby Sands
- North Hoyle
- Arklow Bank.

Additional information was also obtained for Blyth and Burbo Bank developments in the UK and for the Horns Rev and Nysted wind farms in Denmark.

The UK evidence base is presently limited to the few years of post-construction monitoring data that have become available from these few Round 1 projects. This evidence base continues to grow but does not yet include any Round 2 developments or developments similar to Round 2 and Round 3 in the UK. In many ways, Round 1 projects are not directly representative of the potential Round 3 developments, which will likely be larger and in deeper water further offshore potentially utilising alternative foundation or installation technology. However, Round 1 wind farms may also represent a worst case scenario in the sense that the move into deeper water and away from the coast will tend to reduce, rather than enhance, the broad potential for environmental impacts, especially at the coastline. In this way, if an impact is considered negligible at a nearshore location, then this may provide additional confidence when applying lessons learned to an offshore environment.

A.1.1 Conclusions of SED01

From the study a number of key outcomes arose including:

Data management:

- A key lesson learnt from the process of data collation from Round 1 projects is a requirement for improved data management.

Evidence Base:

- SED01 achieved an important and valuable evidence base of sediment process monitoring data from the four completed Round 1 projects, supplemented with further data from other built offshore wind farms from Europe.

Suspended Sediment Concentrations:

- The review of SSC monitoring revealed that the assumptions made through the environmental impact assessment process are generally upheld by the available evidence, with short-term localised impacts occurring around construction activities which disturb the seabed, in particular cable laying and foundation installation (drilling).

- The effects of different cable laying methods appears to indicate that jetting is not a major concern, and with sediment plumes tending to remain close to the seabed (up to 2m displacement above the seabed). Knowledge of the relative position of any sediment plume should assist further monitoring strategies.

- Despite any apparent weaknesses in present monitoring arrangements, the general interpretation of relative changes in turbidity above background levels shows that the majority of effects fall within natural variations due to waves and tides for the shallow water sites, concluding that there is unlikely to have been any significant impact due to offshore wind farm construction.

- Preferred use of OBS devices calibrated against water samples spanning the range of monitoring conditions, ideally a minimum of 20 samples to provide a robust statistical correlation;

- Deployment at a fixed height above the seabed, notionally 1m or less together with a vessel deployed sensor sampling through the water column;

- Water samples analysed for mass concentration, particle size, inorganic and organic content;

- Consideration for use of sediment traps to monitor fate of drill cuttings;

- Associated metocean data and local seabed sediment sample to judge natural sediment disturbance; and

- Near-field sampling at no more than 500m from the sediment source.

Morphology:

- Scroby Sands OWF project showed that the natural dynamics of the sandbank remain very high with overall changes to the sandbank as well as general patterns of bedform movement (e.g. large sandwaves).

- One surprise from the detailed monitoring conducted on Scroby Sands was the faint appearance of secondary sour described as ‘tails’ or ‘wakes’ in the direction of net sediment transport and for distances of around 400m. These features had not been anticipated in any part of the EIA or engineering design process.

- The continued use of swathe bathymetry remains as an important technique to reveal the detailed form and features of the seabed which has not always been practical or possible using single beam methods;

- For ease of comparison between sequences of surveys it is preferred that as much consistency remains in the execution of surveys as possible; and

- Further investigation of secondary scour from new developments sited on mobile seabeds.

The issues relating to scouring around Round 1 foundation structures was considered in more detail in the SED02 project (see Section A.2 below). In general, SED01 stated that it remained the responsibility of the developers to consider, on a case-by-case basis, if their site presents a significant risk to any environmental receptor. If the available evidence is suitable to their specific application then it is reasonable to expect that further monitoring requirements can be avoided.

By continually adding to the evidence base the level of uncertainty associated with the licensing of projects will be further decreased, allowing the regulators to decide with more confidence where monitoring requirements remain and where these requirements can be reconsidered in light of lessons learnt. For further details see ABPmer *et al*. (2007).

A.2 Scour

HR Wallingford in conjunction with ABPmer and Cefas carried out the BERR research project SED02: Dynamics of scour pits and scour protection. This work was funded through the pan-Government Research Advisory Group (RAG). The principal items covered by this study are listed below:

- Identification, collation and review of all available field evidence for scour from built Round 1 wind farm projects and, in addition, any further data available from other relevant European marine projects. The Round 1 wind farm data was brought together by the project SED01 – ABPmer et al. (2008).
- Review of past UK and European research relating to scour and scour protection for the wind farm industry.
- Review of publications and guidance relating to scour and scour protection within other marine industries (oil and gas, cables, jetties, met masts and other one-off structures), including types of scour protection and their potential impact on coastal processes and navigation.
- Review the design and installation of scour protection for Scroby Sands, and relate to performance as recorded by earlier DTI funded investigations.
- Review the design and installation of scour protection for other UK and European sites, potentially including scour in relation to cabling as well as foundations.
- Identification of gaps in the scour and scour protection evidence base, especially on mobile sandbanks. Make recommendations for the research required to fill these gaps.

Four Round 1 UK offshore wind farm projects and one Irish offshore project formed the principal datasets used in this study (see Figure 8.1 for locations):

- Barrow
- Kentish Flats
- Scroby Sands
- North Hoyle
- Arklow Bank

These datasets were supplemented by a conference paper describing some of the scour measurements undertaken around the met mast at

- Scarweather Sands (Harris et al., 2004).

The sites studied, whilst sharing some characteristics were all unique. This was both a benefit, as it allowed the study of different physical conditions in relation to scour, and also a problem as it made it more difficult to draw common conclusions based on the datasets. In terms of the wind turbine foundations, all sites used monopile structures, although North Hoyle was unique in using a tripod structure for one of its meteorological masts. The sites have the following characteristics:

<u>Barrow</u>:
Moderately exposed to waves, moderate currents, sand/gravel and clay, stable seabed environment, deep water.

<u>Kentish Flats</u>:
Moderately exposed to waves, moderate currents, superficial fine sand overlying stable seabed environment, shallow water.

<u>Scroby Sands</u>:
Exposed to waves, strong currents, sand, dynamic sandbank environment, presence of mobile bedforms, shallow water.

<u>North Hoyle</u>:
Moderately sheltered from waves, moderate currents, stable seabed environment, deep water.

<u>Arklow Bank</u>:
Exposed to waves, strong currents, sand/gravel, dynamic seabed environment, shallow water

<u>Scarweather Sands</u>:
Very exposed to waves, strong currents, medium sand, dynamic seabed environment, shallow water.

Figure 8.1. Locations of wind farm sites for which data was analysed in the SED02 study

A.2.1 Conclusions from SED02

Various conclusions were drawn from the SED02 study, the main points are given below:

It was noted that the data analysed supported the view that scour is a progressive process where the seabed sediment is naturally mobile and there is an adequate thickness of that sediment for scouring to occur. Where the seabed is comprised of stiff clay, there is a superficial layer of sediment overlying clay or the wave and current conditions are not generally strong enough to cause the seabed sediment to be naturally mobile, the scour will be slower or limited in depth.

In comparison with the existing predictive formulae in guidance (DNV, 2007) and the Opti-Pile method (den Boon et al., 2004) DNV guidance suggests that with current-induced scour the scour depth S in relation to the foundation diameter D can be taken as S/D = 1.3 and the Opti-Pile method assumes the greatest scour depth that can be achieved is S/D = 1.75. The data available to the present study indicates the maximum depth of scour observed is S/D = 1.38. This is slightly larger than the value provided in DNV guidance but it is not clear whether that value (observed at Scroby Sands prior to placement of scour protection) was fully developed and what range of wave and current forcing had been experienced prior to the measurement being made.

Scour will arise from a continuously operating combination of tidal currents, either with negligible or a moderate amount of wave stirring, on a day by day basis. Based on laboratory experience the stronger currents occurring under spring tides can be expected to produce deeper scour than under neap tides. Under more extreme conditions, e.g. storm surges, larger currents may be generated and wave action can become significantly more energetic. Under these conditions the seabed sediment will be naturally more mobile. However, it is not clear whether the scour in an unlimited thickness of sandy sediment will be deeper or shallower during a storm with strong wave action. The range of tidal, seasonal (including storm events) and longer term variations in currents, wave action and water levels can be expected to influence the way in which scour develops at a foundation, and this has an influence on monopile stability.

It is considered good practice for scour evaluation that during the design process of the foundation an appropriate analysis is made for local scour arising from the influence of waves and currents taking account of spring and neap conditions and the influence of storm events, as well as the relative magnitude of waves and currents which will vary from location to location. In those locations where a strong reversing tidal flow exists it would be advisable to evaluate the influence of that current pattern on scour development. The potential for scour interaction between adjacent foundations needs to be assessed. Finally, the influence of variation in bed level over the design life of the wind farm needs to be considered; this may arise from regional changes or local changes due to migration of seabed features such as banks, sandwaves or channels.

The scour protection that has been placed appears to be effective in preventing bed lowering adjacent to the foundations. The interaction of the placed scour protection with the surrounding seabed levels has been examined from the available data. Where material has been placed in the scour hole formed around the foundation and the top level of the protection is above the level of the surrounding seabed level it is evident that the mound of protection material has produced a secondary scour response. The data that is available does not presently have the resolution to evaluate whether there has been any displacement of the protection material itself by wave and current action.

The scour protection design needs to take appropriate account of the factors considered relevant to good practice for scour evaluation outlined above. For further details refer to HR Wallingford *et al*. (2007).

A.3 References

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Appendix B. Modelling tools

A number of numerical modelling tools are available for the assessment of physical marine environmental issues as part of offshore wind farm EIA. The types of data and information required from these numerical models typically include:

- Hydrodynamics (e.g. waves, tides, separate and combined)
- Sedimentary environment (e.g. sediment erosion and deposition, sediment transport pathways, patterns and rates)
- Suspended sediment concentrations (suspended sediment concentration)

In order to assess the potential impact of the wind farm on the physical marine environment, numerical models must firstly be able to provide an adequate representation of the ambient baseline conditions. Equally importantly, they must then be able to correctly account for the presence of the wind farm structures within the context of the baseline case in order to assess the impact of the scheme. A more detailed discussion of how numerical models account for structures may be found in Section B.2.5 in relation to tidal currents and in Section B.3.5 in relation to waves.

The following sections consider firstly in a generic sense, the types and features of numerical models, sources of error and uncertainty and a typical model life cycle. Following this, more detail is provided for hydrodynamic (tide and wave) and sediment (bedload, suspended load, longshore drift and scour) modelling studies; these sections include information on typical model type sub-divisions, requirements for different spatial scales, required user inputs, model packages available and methods for including the potential effect of wind farm structures.

B.1 All numerical models

B.1.1 Model types

Various numerical model types exist that can be usefully applied by an experienced user to simulate environmental processes. These different methods can be separated into the following broad types:

- Process-based numerical models
- Behaviour-based numerical models
- Empirical or statistical models
- Geomorphological analysis
- Parametric equilibrium models

This document will mainly consider process based numerical models, which generically include the following:

- one-line and n-line models (point information e.g. describing longshore and cross-shore sediment transport)
- 1DH (a line model providing information about horizontal processes e.g. flow down a river or through a simple estuary – not normally used in wind farm EIA)
- 1DV (a line model providing information about vertical processes, e.g. a single vertical profile through the water column)
- 2DH (a model with detail in plan view but the vertical dimension is averaged or parameterised, e.g. a tidal propagation model of a given area)
- 2DV (a model resolving the detail of depth dependant processes but only along a single transect line, e.g. sub surface wave induced orbital motion as waves approach a beach)
- 3D (a model where the full 3D flow equations are solved, e.g. flow through an area of complex bathymetry or around a turbine foundation).
- Pseudo-3D (a series of horizontal planes through the vertical with the vertical terms accounted for by continuity, e.g. shelf sea tidal models where vertical density gradients are important in controlling local flow conditions)

For the majority of tidal and sediment studies, 2DH and pseudo-3D models are typically used; wave models typically use a 2DH construction. Fully 3D models are less frequently used in studies of this type as 2DH or pseudo-3D models typically provide an acceptable solution; fully 3D models introduce further uncertainty and are also less efficient due to the relatively higher time and resource cost of construction and use. Empirical models (a form of one-line model) are also typically used for the assessment of scour.

B.1.2 Model mesh types

All models require some form of grid or mesh which provides the spatial framework on which input data and results are stored, and over which the actual model calculations are made. Intersecting mesh lines form 'cells' or 'elements' of the mesh. Depending upon the particular modelling software, a number of different horizontal mesh types can be used, including:

- Regular or Cartesian grids – consists of elements of rectangles or squares.
- Rectilinear grid – this is a type of regular grid whereby the rectangles or parallelepipeds that form it are not all congruent to each other
- Curvilinear grid – has the same basic structure as a regular grid, however, the cells consist of quadrilaterals or cuboids rather than rectangles or rectangular parallelepipeds.
- Unstructured or flexible mesh – a network of interlocking shapes of variable size, skewness and orientation. Typically, triangular elements are used but polygons with any number of sides can theoretically be used (for example Telemac and MikeFM use unstructured grids). The shape of flexible mesh elements can also be mixed (e.g. triangular and quadrangular in MIKE21/3, 2008 release).

In the case of regular or cartesian meshes, horizontal resolution can be increased by 'nesting' (replacing an area of coarse resolution with an area of the same perimeter shape but of higher resolution). Curvilinear grids can be refined either through the use of nesting or by refining the grid density in certain areas, although this the latter method can lead to refinement in areas where it is not required. The resolution of flexible meshes can be varied by design in order to provide high resolution where required for accuracy and detail, or lower resolution where detail is not required in order to improve model efficiency. Guidelines for the appropriate choice of mesh resolution around wind farm structures may be found in Sections B.2.5 and B.3.5.

When using 3D modelling techniques, depending upon the particular modelling software a number of different vertical mesh types can also be chosen, including:

- Z-layers – layers of constant depth. The number of layers at any location is dependant upon the local water depth. Can be used to increase vertical resolution of the model near the water surface or in shallow water, but with the option of keeping coarse resolution for efficiency in deeper water.
- Sigma layers – a specified number of layers that each occupy a specified proportion of the water column. The number of layers is the same in all locations and so the thickness of each layer varies in proportion to the local water depth. Layers remain locally parallel to the underlying bathymetry.
- Combined – some software tools (e.g. MIKE software, 2009 release) permit a dynamic combination of different vertical co-ordinate types (e.g. MIKE software, 2009 release can apply a hybrid sigma- and z-layer co-ordinate system).

B.1.3 Spatial scales

In the use of numerical modelling for offshore wind farm studies, two principal spatial scales exist, namely, near-field and far-field scales. The near-field is concerned with impacts local to the development, whilst the far-field looks at the impact of the development at a regional level. Far-field studies may also involve the investigation of in-combination effects with other developments, whether existing or planned.

The choice of model must permit the user to obtain the required information at the appropriate spatial scale. For example, if far-field effects are the concern, then the model must be able to represent the appropriate processes and accurately translate them into the far-field, near-field processes are less important and can be simplified for efficiency; if near-field effects are important, simplification of the near-field is not appropriate and a different type of model may be required, however, the additional complexity required means that only a small domain is practicable and the effect can not be modelled into the far-field.

As part of choosing the correct spatial scale, the user must also make a choice on the spatial coverage of the model in terms of dimensions (1D, 2D, 3D) and resolution. Models of all three dimensional constructs can be used to obtain useful information, depending upon the application.

The choice of spatial resolution may vary between and within models depending upon the requirements of the study and the particular choice of model used. In general, models with a greater spatial extent tend to have a relatively coarser resolution for reasons of efficiency. Far-field (e.g. regional tidal) models typically have a coarser resolution than near-field (i.e. CFD) models but this is due to the difference in the scale and type of physical processes included in the different model types.

All model types may potentially vary the spatial resolution applied to a particular modelling study within the limitations of the software and the hardware. Resolution can be increased where detailed information is required or where the complexity of local processes is important to the local or overall result. In particular, resolution is commonly increased within and adjacent to the wind farm to resolve the far-field effect of turbine structures; more information about including structures in numerical models may be found in Sections B.2.5 and B.3.5. Resolution can also be decreased in other areas in order to improve model efficiency.

Resolution can be varied using various nesting techniques for regular mesh types where an area of the mesh is replaced by, but linked to, another mesh of the same outline dimensions but of greater resolution. The resolution of flexible mesh types can be smoothly varied, as required, throughout the domain.

In all cases, the user's final choice must be reasoned and justified.

B.1.4 Temporal scales

Temporally, there are also two scales, namely: short-term (days/weeks/(months)) and long-term ((months)/years/decades). Short-term effects are largely the instantaneous or relatively swift response of processes occurring on these time-scales (e.g. tidal movements, waves, storm events, initial scour in mobile sediments). Long-term effects tend to describe the cumulative impact of short-term effects, e.g. morphological adjustment of the wider seabed or coastline to a development, but also include time dependant events such as extreme tidal events, storms or climate change.

The choice of model must permit the user to obtain the required information at an appropriate temporal scale. For example, a model that is required to simulate the effect of structures on tidal currents must be able to resolve changes in tidal height or current speed and direction on suitable time-scales (i.e. minutes to hours); a model that is required to simulate long-term morphological change does not need to resolve individual waves or tidal cycles but rather calculates the net response to the statistically described wave climate or to long-term residual transport pattern.

B.1.5 Processes and complexity

The model must be able to adequately simulate, with sufficient accuracy, the important processes that control the process of interest. This requirement is not necessarily considered explicitly or in detail when commercial software is used for the purpose for which it was intended. Such software packages are under continuous peer review and development which identify and reduce model limitations or errors and provide a degree of quality assurance whilst keeping the software at the cutting edge of accepted science and technology.

Models should therefore be applied within the limits of their scientific capability. Commercial software packages are accompanied by detailed technical manuals and user support facilities which can be used to find out what processes are included and how. Unless accompanied by suitable supporting information and evidence, bespoke modelling tools with little or no history of application should be treated with more caution.

Models of greater complexity do not necessarily produce a 'better' result than a simpler one. The most appropriate model, whilst trying to balance accuracy against efficiency and reliability, is one that is complex enough to capture the important processes, but no more. Increased model complexity may introduce added uncertainty and more extensive requirements for model setup, calibration and validation; this may potentially compromise confidence in the model results and add cost.

B.1.6 Error and uncertainty in data from numerical models

Models account for the various inter-related processes that they describe through a series of equations or relationships which may be simple or complex in nature. For mathematical or for practical reasons, many of these equations are simplified to some extent (discretisation) or the computer used to process the equations will be limited in the accuracy with which it can produce a solution. These limitations imply that the solution obtained will only be an approximation of the true result of the equation used to represent the process. Further, the equations used to represent physical processes are also often only an approximation of the actual processes being studied.

Further to these inherent errors, additional uncertainty can be introduced by the model user, through poor definition of the problem, incorrect choice of solution strategy, errors introduced during model set up and errors in the analysis and interpretation of results.

To limit these potential errors and uncertainties the modeller should have a suitable method in place of identifying and quantifying these errors, whether due to the model user or limitations in the modelling strategy and model equations. There is currently no single accepted method for doing this. Previous publications such as Bartlett (1998) were created for use in estuaries and provide recommended levels of accuracy in terms of a percentage or absolute error margin. However, these recommendations do not take into account the different requirements of site specific studies and although adjustments for near-coastal locations are suggested, the guidelines are not designed for use in an offshore environment.

For the purpose of these guidelines the sources of any potential error or uncertainty have been grouped as follows:

Potential sources of error when modelling include:

- error in the supporting data;
- error in representing the physics;
- error as a result of interpolation;
- discretisation errors;
- convergence errors;
- rounding-off errors;
- coding errors; and
- user errors.

Error in the supporting data:

Ultimately, a numerical model can only be as accurate, or be given as much confidence, as the data used to build it, calibrate it and validate it. Issues relating to the quality of field data are outlined in Section 6.5 and further quantitative detail is provided in Appendix C.

Error in the physics:

An obvious potential for error exists in the representation of real-world physics through model equations. The representation of a given process in a model is often not practical or possible due to an incomplete understanding of the process or due to the complexity of the process and its interaction with other inter-related processes. Therefore, models should generally be considered a simplified representation of a process. Therefore, uncertainty may exist as a result of:

- the physical process not being well understood;
- the parameters used in the model are not clearly defined or known
- simplification of the relevant models
- experimental corroboration of the model is not possible or is only partial

Even when a physical process is very well understood, a simplified model may be chosen to represent it, to ensure a more efficient computation.

<u>Error as a result of interpolation:</u>
Data interpolation is the method used to infer new data from locations between existing data points. Data interpolation assumes that the surrounding data is part of a smooth or predictable surface; there are several interpolation methods that may be used which assume some form of linear or non-linear variation in the surface between adjacent data points.

Data used to build a model may be available at a higher or lower resolution than is actually required and is unlikely that data will be available only at the exact locations where data is needed (e.g. bathymetry data or variable sediment grain size distribution data being applied to a horizontal mesh). In this case, data interpolation is used to infer values (e.g. of depth) at the node locations from the scatter of data points available.

If sparse bathymetry data is interpolated onto a fine mesh, the mesh resolution may be high, but it may not correctly reflect the actual complexity of the bathymetry at that resolution; this may not be an issue if the bathymetry does not vary significantly at the resolution of the observed data. Conversely, if high resolution bathymetry data is interpolated onto a coarse mesh, the detail of complex bathymetry may be simplified and processes affecting local flow may not be correctly included in the model; however, this may not be an issue if the area of complexity is far from the site of interest and does not intersect the footprint of potential wind farm effects.

The issue in this case is that the processes are not being accurately represented in the model, either due to insufficient or incorrect detail in the model input data.

Data is created by a numerical model at the location of the mesh nodes or elements. If these particular locations do not correspond exactly to the location where model output is required, a value may be obtained via data interpolation. Assuming that the model is producing correct results, a degree of uncertainty is introduced by extracting data from intermediate locations where the model is not making explicit calculations; this uncertainty increases with distance from the calculation nodes. It was shown above that local process detail is potentially lost by interpolating over a coarse mesh, it is therefore more likely that results interpolated from between coarsely spaced mesh nodes may not be correct.

It is for these reasons that a generally higher mesh resolution is typically applied to the wind farm site and to areas considered important for understanding the footprint of its potential effect.

<u>Discretisation errors:</u>
Discretisation errors can be simply defined as the difference between the result of the equations as used by the model and the true, full numerical solution of those equations. In a more technical sense, they are the errors that result from the representation of the governing equations as algebraic expressions in a discrete domain of space (the mesh, which may be finite-difference, finite-volume or finite-element) and time (the time-step).

Discretisation errors are controlled to some extent by the quality of the model mesh construction, although identifying a link between the mesh and solution accuracy is often difficult prior to starting the simulation. Therefore, the model grid should be constructed or overseen by an experienced modeller with consideration of issues such as resolution, density, aspect ratio, stretching, orthogonality, grid singularities, and domain boundary interfaces.

Also associated with the discretisation of the model equations is truncation error, defined as the difference between the implicit partial differential equation (PDE) and the explicit finite equation. The truncation error is also a function of the mesh quality but also flow gradients (so is greater in more energetic or complex environments). Truncation error relates to those terms of the full equation which have been excluded from the discretised equation.

<u>Convergence errors:</u>
Convergence errors are related to the iterative methods used to find a solution to certain types of equations. The model will iterate towards a solution but stop short of an ideal solution in the interests of efficiency. Errors arise from the solution not properly converging with respect iterating to the steady-state solution or within a single model time-step.

Convergence errors are also related to model grid spacing. As the model grid or mesh is refined, the solution should become less sensitive to the grid spacing and approach the continuum solution. This is called grid convergence. Such an approach also applies to the time-step. By undertaking a series of model simulations using different levels of grid refinement the grid can be optimised and the level of discretisation error determined for the given numerical problem.

<u>Rounding-off errors:</u>
Computer rounding-off errors are due to the representation of floating point numbers on the computer and the accuracy at which numbers are stored. As computers have developed over time the floating point numbers are now typically stored with 32 or 64 bits. Rounding-off errors are not considered significant when compared with other errors.

<u>Coding errors:</u>
Coding errors refer to 'bugs' or incorrect instructions that may exist within the software programme. In commercial codes, whilst extensive testing is undertaken before the release of the latest version of the software, it is likely that the user will eventually come across an error, whether due to an unintentional programming error in the implementation of a particular routine, or as a result of a compiler error on a particular computer hardware system. In general the obvious bugs are removed before software release and so residual coding errors can be difficult to spot as they are often very subtle.

<u>User errors:</u>
User errors are generally due to mistakes and carelessness by the modeller and are difficult to quantify. Although this type of error is reduced through the experience of the operator, mistakes can happen. User errors can include:

- poor data preparation;
- incorrect selection of options, parameters or supporting data inputs during model set up;
- incorrect analysis and interpretation of results;

The potential for user error increases with the level of complexity in the model and in the range of options and choices that the user must make. These errors are minimized through training, experience, Quality Assurance procedures and the use of method statements and written guidance.

B.1.7 The numerical model life cycle

As previously described, an initial assessment is made of the available data and evidence base and whether they are sufficient to answer the question being posed. If not, a further assessment is made as to whether numerical modelling will provide a suitable tool for further investigation. If the numerical modelling route is chosen, generally speaking the following process is followed:

1. All of the necessary information and data are collected together. An assessment is made of the correct model type to use and the requirements for that model.
2. Gaps in the data are identified and addressed through additional data collection.
3. There is an initial phase of model building where data from different sources are combined. Source data may be of varying resolution and quality within the domain and so multiple data sources may be used.
4. Large or high resolution data sets may be sub-sampled; low resolution data sets may be supplemented by integration with other data where an overlap exists.
5. The horizontal and vertical datum of all spatial data sets should be adjusted (if necessary) to the chosen working datum.
6. Boundary or driving time-series are obtained for the desired time period.
7. An initial design for the model mesh is decided upon, increasing resolution around the region of interest whilst possibly reducing resolution in other areas to reduce model run times.
8. An initial model is created, based on the best information available at the time and using default parameters. An initial model run is carried out.
9. If carefully constructed, this initial model will likely produce results that are not too dissimilar from that which is expected based upon background knowledge of the site and initial comparison with calibration data. At this stage, it is likely that: the timing of peak tidal water levels and current speeds will be approximately correct (although the range may be too great or too small); the spring-neap cycle will be correctly included; tidal current directions will be approximately correct.
10. The overall fit of the model results to the calibration data and other established knowledge of the site is evaluated and iterative changes are applied to the model in order to minimise the overall difference between predicted and observed results.
11. At this stage, it is likely that: the timing and range or magnitude of peak tidal water levels and current speeds will be very similar.
12. A final model setup is chosen which produces optimal predictions of the observed calibration data.
13. The interim calibration stages are not normally presented. A small subset may however be used to demonstrate the sensitivity (or not) of the model results to the inclusion/exclusion of certain data. This process is useful as it removes uncertainty from the results, so long as a comprehensive set of relevant parameters have been considered.
14. The overall fit of the calibrated model results to a validation data set is evaluated. The model is likely to provide a very good prediction of the validation data set, but perhaps not quite as good as at the calibration stage. The residual error at this stage is used to evaluate the error of the model.
15. The model is used to investigate the baseline issues of the EIA.
16. The effect of the wind farm is added to the baseline model. If calibration/validation data for the effect of individual structures is available (the evidence base is limited at present), then this is tested.
17. Environmental scenarios are re-run with the added effect of the wind farm. The effect is isolated by comparing the baseline and with-scheme data and is assessed in the context of the baseline information, supported by any other relevant data (perhaps not used in the modelling process). The accuracy of the effect assessment is partly controlled by the accuracy of the baseline model, but primarily by the ability of the model to account for the wind farm structures. See Section 6.7.2 for more information on comparative assessment of results.

B.2 Tidal hydrodynamic models

Tidal heights and tidal current speed and direction are directly related and so are modelled at the same time. There are a variety of models that can be used for this purpose. Depending upon the particular requirements of the study, these typically use 2DH or 3D constructions and any of the mesh types described in the Section for all models.

B.2.1 Far-field models

For far-field studies (the effect of the wind farm as a unit on the surrounding area), numerical models are used which may parameterise some sub-grid-scale processes; these are considered in more detail below.

Purely tidal models reproduce only the astronomically induced patterns of water level fluctuation and so do not typically include the effect of winds, atmospheric pressure or waves, e.g. storm surges. Depending upon the sophistication of the model, such time variable effects can potentially be included, however, the purely tidal part alone represents the long-term average case and all other effects are effectively noise with a statistical return period.

B.2.2 Near-field models

Near-field studies (including interaction between structures and the effect of the wind farm within the site perimeter) will typically utilise the same models as described above for far-field studies but using greater local model resolution within the area of interest.

For very near-field studies (the local effect of isolated structures), ‘CFD’ models might be applied (which resolve fine scale detail of the flow around the structure itself in three dimensions) but only a short time period and limited spatial extent are typically modelled. CFD models are not typically used for EIA directly, but are rather used through research to inform the evidence base.

B.2.3 Required user inputs

Hydrodynamic models generally require user inputs of, or specifications for:

- The model start time, time-step and duration
- Model mesh, including the land outline and bathymetry
- Water levels, current speeds or volume fluxes at the open boundaries
- Bed friction (default values might be used)
- Eddy viscosity (default values might be used)

Additional user specified inputs might include:

- Variable salinity and temperature (if locally important)
- Significant local sources or sinks of water volume (e.g. large rivers, precipitation, evaporation)
- Wind forcing
- Wave radiation stresses
- Atmospheric pressure

Coincident field measurements or other data regarding the expected tidal height, current speed and direction at locations within the domain are required for model calibration and validation.

B.2.4 Model packages available

Examples of commercially available modelling packages that might be used to undertake tidal behaviour hydrodynamic studies (baseline and effect of structures) include:

- 2DH (med-large scale study area)
    - MIKE21; MIKE21FM; DELFT3D; TELEMAC; DIVAST
- Pseudo-3D horizontal layers resolved through the vertical (med-large scale study area)
    - MIKE3; MIKE3FM; DELFT3D; TELEMAC

Examples of commercially available modelling packages that might be used to inform the evidence base concerning the effect of structures on very near-field tidal behaviour include:

- Fully-3D vertically resolved (small scale study area using CFD)
    - Fluent, CFX, STAR-CCM, NS3, OPENFOAM

B.2.5 Representing structures in tidal models

Introduction

Structures such as wind farm foundations interact with any tidal currents present, causing modification of local current speeds and directions. The effect is greatest close to the structure and dissipates with distance downstream; it has been previously suggested that significant effects are dissipated over distances less than typical turbine foundation spacing and so in-combination effects may not occur. The effect of multiple structures depends on the design, relative alignment, spacing and number of the structures involved. The effect of an individual structure may be divided into near-field and far-field effects.

Near-field effects occur within a short distance from the structure (less than approximately 5 times the obstacle length scale) and are characterised by complex three dimensional patterns of flow acceleration and deflection, including time variable vortices and recirculation patterns. Near-field processes are important as they control the forces imparted to the structure and, in part, the development of sediment scour, they also control the far-field response.

Near-field processes are not resolved explicitly by the types of numerical models used for offshore wind farm EIA, due to the resolution and numerical design of such models (which do not resolve and can not account for small scale turbulence); near-field effects are instead normally parameterized (simplified) into an overall effect.

Very near-field processes can be studied in more detail using local CFD models to support design of structures or validate sub-grid scale parameterization through the evidence base. These models require significant time and expense to set up and only provide information for a relatively small area (typically less than the distance between adjacent structures), hence are not generally considered for direct use as part of the EIA.

Far-field effects describe the more distal wake of the structure. Current speed in the near-field is reduced and turbulence is increased relative to the ambient flow, due to the frictional and blocking effect of the structure. This zone extends downstream, stabilizing in direction and complexity, becoming the far-field.

Current speed in the far-field wake returns (increases) gradually to ambient values with distance downstream, through lateral transfer of momentum from the ambient flow. The size of turbulent eddies and overall levels of turbulence similarly return (reduce) gradually to ambient values over a similar distance. Far-field processes are important as they describe the modification of the flow which then may interact with neighbouring structures or the surrounding seabed. Far-field effects are typically less significant than near-field, but are much more extensive. Far-field effects can be accounted for in 3D and 2D vertically integrated models, provided that the near-field effect of the structure is correctly parameterized and the model is correctly designed to resolve the downstream wake.

The near-field response of simple structures (i.e. monopiles) is reasonably well understood, however, the near-field response of complex or bespoke foundation types (e.g. gravity bases, tripods or quadrupods of varying design) is presently less well understood. Detailed CFD models might be used to inform the evidence base on this issue where the results can be used to parameterize the net near-field effect of complex or bespoke structures, which can then be used to calibrate or define the effect of those structures in the far-field.

Numerical methods

A sub-grid parameterisation method is typically used to describe the current-induced drag force acting on a structure by equating this force with an equivalent bed shear stress contribution (DHI, 2008). In all of the modelling packages listed above, the total drag force exerted upon the flow (F) by a single structure is calculated as follows:

$$F = \frac{1}{2}\rho_w C_D A_e V^2$$

Where
ρ_w is the density of water
C_D is the drag coefficient of the structure
A_e is the effective area of the structure that is exposed to the tidal current
V is the depth mean current speed

The effect of the structure on the flow is applied in the model by increasing the apparent roughness (friction to the flow) of the element containing the structure. This method theoretically takes into account:

- Changes in current speed at each time step.
- Changes in water depth at each time step.
- The existing bed roughness determined by seabed type or baseline calibration requirements.
- The dimensions, orientation and cross-sectional shape of the structure.
- The vertical profile of the structure, theoretically including simple gravity base structures.
- The size of the structure in relation to the size of the mesh cell or element.
- Any type of structure, so long as the near-field may first be parameterized with sufficient confidence.

This method ignores any contribution made by lateral forces (e.g. caused by vortex shedding) which is reasonable because these forces are oscillatory in nature and are of equal and opposite sign. Consequently, when averaged over time, the two opposite forces cancel each other and make a zero net contribution. Furthermore, at peak tidal current flow, the Reynolds' number for steady flow past the structures is of the order of 10^7. Under these circumstances, the in-line force is likely to be approximately 2½ times the fluctuating lateral force. The latter cannot therefore contribute greatly to the total force acting on the cylinder.

This method was previously applied in all of the example 2DH and pseudo-3D modelling packages listed in Section B.2.4; the user would manually calculate the appropriate modified bed roughness value and apply it directly within the model. More recently, the MIKE21 Hydrodynamic Model (MIKE21HD) has automated this process to some extent where the user provides information about the location and dimensions of each structure and the modification to bed roughness is calculated by the software using the same numerical approach. Automation may remove some procedural uncertainty in the correct representation of the structures but it does not improve the accuracy of the prediction. Other software packages may incorporate similar automation facilities.

The value of the drag coefficient (C_D) characterises the net interaction between the structure and the flow, i.e. it does not describe the complex very near-field, but it does provide the far-field effect. The value of C_D also varies for a given structure shape with the system Reynolds number (a combination of the actual structure dimensions and the current speed). More complex structures (e.g. gravity base and multi-legged foundations) can also be accounted for using this method, if the appropriate value of C_D to use is available from the evidence base. The evidence base is presently clear on values of C_D for simple monopiles, but additional research needs to be carried out to confidently characterise more complex structures.

Practical considerations

The numerical method described above is a parameterisation of the near-field effects of the structure, which occur at a scale far smaller than the resolution of the model mesh. As such, flow acceleration immediately around the structure and the increase in turbulence in the wake is not reproduced by the model and the effects of these (i.e. scour) must be assessed separately. The reduction in depth mean flow speed in the far-field is however reproduced and will be propagated through the model, allowing the user to estimate the degree of interaction between structures and the overall area of effect of the wind farm.

The chosen mesh resolution is important, both at the structure and over the area where the wake may extend. At the source of the effect, if the structure is located in a mesh cell very much larger than itself, then the local frictional effect of the structure is averaged out over a larger area and consequently reduced. As a result, the magnitude of the local effect of the structure is locally underestimated.

As the wake extends downstream, the rate at which it spreads laterally and therefore, the rate at which it will recover to ambient values, is sensitive to the resolution of the model mesh. A coarser mesh results in a shorter wake with a wider extent and visa versa. Best practice will be to find an appropriate mesh resolution that provides a balance between the true wake extent (which needs to be established separately) and the efficiency of the model (run time and file size), which is affected by the need for more extensive areas of higher resolution.

If the effect of a particular structure has been established using another method (e.g. field observation, physical modelling or other types of numerical modelling), the effect of a structure at its source and further downstream can be calibrated or tuned to some extent using user defined shape parameters during model setup. Sensitivity testing of the appropriate choice of mesh resolution might be presented as part of the EIA report.

B.3 Wave hydrodynamic models

Similarly, there are a variety of models and modelling approaches that can be used for simulation of the wave regime. Wave models typically use 2DH mesh constructions in rectilinear, curvilinear or flexible mesh modes.

B.3.1 Far-field models

Far-field wave models of regional size areas do not resolve individual waves or the actual motion of water underneath them. Rather, the wave conditions at each location on the model mesh are represented as a directional wave spectrum, which is modified by spatial gradients in the wave/current climate and underlying bathymetry (wave refraction, reflection, shoaling, energy loss, etc) and by spatial or temporal variation in the forcing applied (input wave boundary conditions, local wind speed and direction, etc). Time-series calculations can either develop with time (quasi-stationary mode) or may be calculated as a series of independent solutions which are in equilibrium with the input forcing (instationary mode). The accuracy and complexity with which the wave climate is modelled depends upon the particular modelling package used.

B.3.2 Near-field models

Near-field studies (including interaction between structures and the effect of the wind farm within the site perimeter) will typically utilise the same models as described above for far-field studies but using greater local model resolution within the area of interest.

Various commercially available models also exist to describe the near-field (as defined above) at an intermediate spatial and temporal scale including the Danish Hydraulics Institute's Boussinesq Wave model (MIKE21-BW) and Delft Hydraulics TRITON model. The TRITON model can also be coupled with the SWAN far-field model and used to resolve the wave conditions in areas where SWAN provides unreliable results, e.g. in the nearshore area in front of the sea defences. These type of wave models are meant for use for detailed simulations of wave dynamics around structures with less parameterisation required than 'far-field' models. Their primary application is to the design of harbours, breakwaters and wave transformations over shallow foreshores.

Individual waves are modelled with relatively high spatial resolution as they move through the area, accounting for wave refraction, reflection, constructive/ destructive interference, shoaling and breaking. The model only does this in a two dimensional sense, i.e. wave induced water motion is not modelled explicitly and sub-surface wave-seabed interaction is parameterised. The plan shape effect of structures may be included directly to the extent that the resolution of the model will allow (typically in the order of a few meters), hence the final detail of the cross-sectional shape of the structure (e.g. square versus circular) and sub-surface profile (e.g. monopile versus gravity base) can not be accounted for directly. Model results are a timeseries of water elevation at each mesh element or node; these data can be analysed in the same manner as field data to obtain wave spectrum statistics. These models require relatively long run times and so are typically only used to demonstrate the effect of particular low frequency, high energy extreme wave conditions, e.g. a 1:10, 1:50, 1:100 year event, etc, perhaps from different directional sectors.

For very near-field studies (to study the local effect of isolated structures), CFD models might be applied at small spatial scales. CFD models resolve finer scale detail of wave interaction with the structure, but only a short time period and limited spatial extent are modelled. At present, CFD models are not used as part of offshore wind farm EIA; however, they might be used as part of research to inform the evidence base, improving confidence in the sub-grid scale parameterisation techniques applied in larger scale models or in the detailed assessment of scour potential.

B.3.3 Required user inputs

Spectral wave models generally require user inputs of, or specifications for:

- The model start time, time-step and duration
- Model mesh, including the land outline and bathymetry
- Input wave and/or wind conditions (e.g. wave or wind time-series)
- Field records of waves (for calibration and verification)
- The mode of wave modelling (quasi-stationary /instationary, high-order/low-order schemes)

Boussinesq wave models generally require user inputs of, or specifications for:

- The model start time, time-step and duration
- Model mesh, including the land outline and detailed bathymetry data (resolution in order of meters, admiralty chart is often not detailed enough)
- Detailed problem definition (e.g. structure location, harbour or breakwater alignment)
- Input wave conditions (e.g. 1 in 50 year design wave)

B.3.4 Model packages available

Examples of commercially available modelling packages that might be used to undertake wave climate hydrodynamic studies (baseline and effect of structures) include:

- 2D vertically integrated (med-large scale study area)
    - MIKE21 SW; SWAN; STWAVE; WAM
- 2D vertically integrated (small scale study area)
    - MIKE21 BW; TRITON; BOUSS-2D

Examples of commercially available modelling packages that might be used to inform the evidence base concerning the effect of structures on very near-field wave regime include:

- 3D vertically resolved (small scale study area using CFD)
    - Fluent, CFX, STAR-CCM, NS3; OPENFOAM

B.3.5 Representing structures in wave models

<u>Introduction</u>

The interaction between structures and waves, and the calculation of structural wave loading conforms broadly to two regimes, which, to a certain extent, overlap with each other.

The first regime occurs when the structure is large enough, relative to the incoming wave, to cause significantly wave scattering. Under these circumstances, the primarily mode of wave-structure interaction and the cause of structural wave loading is wave diffraction. The limit at which structures interact significantly with waves through diffraction depends on the diameter of the structure (D) compared to the length of the incoming wave (L). For D/L values of more than 0.2 (Sumer and Fredsoe, 2002), diffraction becomes increasingly important as the length of the structure becomes similar to or greater than the to-and-fro distance that a single wave moves water. Wave diffraction has the effect of scattering some wave energy from its original propagation direction. Wave streaming (the creation of residual currents around the structure) can also become important.

Wave diffraction effects around monopiles at the Scroby Sands wind farm were shown to be minimal during field studies reported by Cefas (2005). For reasonably slender structures (e.g. typical monopile foundations), the wave length (period) must be quite short before wave diffraction occurs. However, such short waves typically carry less energy and do not interact with the seabed significantly within the footprint of potential effect. For this reason, EIA guidelines (Cefas 2004) do not explicitly require the study of wave diffraction.

The second regime occurs where the structure is relatively small compared to the length of the incoming wave (values of D/L of less than 0.2, e.g. typical monopiles under normal wave conditions). In this case, the to-and-from motion of the wave is larger than the structure and is more akin to a reversing unidirectional current of short duration and the structure causes little scattering of the incoming waves. Under such circumstances, the wave-structure interaction and the cause of structural wave loading is usually expressed as the sum of drag and inertia forces. The drag force is induced by separation of the flow as it passes around the structure and is a function of the velocity. The inertia force is induced by the acceleration of water around the structure, resulting in a transfer of momentum. Under such circumstances, the normal procedure would be to apply 'Morison's equation' to predict the wave force, expressing the wave force as the sum of drag and inertia forces. Force transfer coefficients are combined with the predicted velocity and acceleration of water particles in the wave, to generate the total predicted wave force. The velocities and accelerations have to be predicted using an appropriate wave theory.

The basic far-field result of interaction between waves and structures is that, after passing through the wind farm site, the wave field will be of lower energy, lower wave height and possibly with a less well defined direction of propagation. These parameters may recover with distance from the structures due to lateral mixing of energy from ambient waves and (in the case of wind waves) due to continued energy input from local winds. It is therefore more likely that the effect of Round 3 wind farms of a similar specification to existing Round 1 and proposed Round 2 developments, but located further offshore, will reach adjacent coastlines.

Conversely, the magnitude and extent of effect is likely to increase if larger structures are used, (possibly but probably not at a smaller spacing) and if a more extensive area/number of structures are located close enough together that they interact with each other producing cumulative effects. Therefore, the potential for in-combination effects should still be examined on a site specific basis.

<u>Numerical methods</u>

The MIKE21 Spectral Wave Model (MIKE21SW) is a commonly used tool for the assessment of wave propagation over large areas for purposes of EIA and provides a method to include the presence of structures using a sub-grid scaling technique (DHI, 2008). The effect of the structure is taken into account by introducing a decay term to reduce the wave energy behind the structure. In this software, wave reflection is not taken into account. Other software packages may incorporate similar facilities or users might be able to calculate and specify the wave attenuation effect of the structure manually.

Specifically, the effect of the structure (S) is calculated as:

$$S = -\frac{R}{A} C_g E(\sigma, \theta)$$

Where
R is the reflection coefficient of the structure
A is the area of the cell or element in the mesh where the structure is located
C_g is the incoming wave group celerity
$E(\sigma,\theta)$ is the energy density of the local wave field

The reflection coefficient is specific to the structure and can be calculated by the software for relatively simple monopiles but, for more complex structures, a pre-existing knowledge of wave response to the structure, or a comprehensive method of evaluating the same is required. As described previously for drag coefficients in tidal models, this may need to be provided through more research, informing the evidence base for more complex designs.

Wave attenuation effects are observed in the results of models by using this approach. Diffraction effects may also be included. The effect of groups of structures can also be assessed as the effect of one structure can then form the input to the next one downstream.

Practical considerations
Similar to tidal current models, structures included in wave models are parameterisations of the near-field effect. Detailed local interaction between structures and waves, including local flow acceleration, eddy shedding and streaming, are not resolved (although are not needed) by the models usually used as part of offshore wind farm EIA.

The very near-field response of simple structures (i.e. monopiles) is reasonably well understood, however, the very near-field response of complex or bespoke foundation types (e.g. gravity bases, tripods or quadrupods of varying design) are presently less well understood. Detailed CFD models might be used to inform the evidence base on this issue where the results can be used to parameterize the net near-field effect of complex or bespoke structures, which can then be used to calibrate or define the effect of those structures in the far-field.

Mesh resolution is important when assessing the transmission of the local effects of wind farm. The issue of resolution is the same as was discussed previously for including structures in tidal models in Section B.2.5.

Wave induced motion of water decreases in magnitude with depth, from the water surface, to zero at the 'depth of closure'. When the depth of closure occurs above the level of the seabed, waves do not 'feel the bottom' and therefore do not interact (significantly or directly) with bed or contribute (significantly or directly) to sediment transport. In this case, the local water depth is described as 'deep'; relative depth is a flexible description and may change depending upon the state of the tide (affecting total water depth) or the size of the wave (affecting the depth of closure).

The depth of closure principle can also be applied to interaction with structures, whereby if the non-monopile part of a gravity base or multi-member foundation is below the depth of closure, then the wave only interacts with the upper part as if it were only a monopile. If the structures are located in particularly deep water, some of the uncertainty relating to modelling of complex structures might be reduced if the structure can be (justifiably) conceptually simplified in this way (e.g. to a monopile structure).

B.4 Wave-current interaction

Wave-current interaction can be an important process in both coastal and offshore areas where water depths are shallow enough that wave action frequently penetrates to the seabed (approximately less than 10-15m depth in the coastal zone, possibly a little deeper in offshore locations due to the likelihood of larger waves) but deep enough that tidal currents remain strong enough to provide a significant contribution to sediment transport. Under combined wave-current flows any resulting sediment transport is not simply the sum of the two component parts, due to complex non-linear interaction.

At such nearshore locations and at offshore locations far from the coast but with relatively shallow water (such that wave action penetrates to the seabed), wave-current interaction can be important in controlling sediment transport over long time scales. However, the interaction is more likely to occur as a series of episodic events with a joint probability of occurrence; in reality, any wave conditions (within the expected range) might occur at any state of the tide which varies on semi-diurnal, spring-neap, solstice-equinox and other timescales. This has made it more appropriate to consider waves and tides separately during EIA and to then provide a discussion of the degree and effect of any interaction.

If wave-current interaction is considered necessary following assessment of the relative importance and identification of a sensitive receptor, it can be estimated by coupling a wave and tidal model, which then run in parallel providing feedback or input at each time-step; the tidal model accepts inputs of wave radiation stresses from the wave model, which in turn also accounts for the effect of the current on the waves. The same principle can be applied in a decoupled sense where, for example, a tidal model might be run once and the results are used as input to multiple wave models, however, the wave radiation stresses are then not accounted for in the tidal model (or visa versa).

2DH models and even most 3D models do not fully account for true wave-current interaction, which is instead parameterised to a large extent. Local, high resolution CFD models can potentially be used to calculate wave-current interaction with a greater degree of accuracy, but are unsuitable for EIA due to the spatial and temporal scales required.

B.4.1 Required user inputs

Combined wave-current models require the same inputs as the two individual model types (see sections above). Coincident field measurements or other data regarding the expected wave-current response at locations within the domain are required for model calibration and validation.

B.4.2 Model packages available

Examples of commercially available modelling packages that might be used to undertake combined wave-current hydrodynamic studies (baseline and effect of structures) include:

- 2D/pseudo-3D vertically integrated (med-large scale study area)
    - MIKE21; MIKE3; TELEMAC; DELFT3D

Examples of commercially available modelling packages (unsuitable for EIA, suitable for engineering and research informing the evidence base) that might be used to assess the effect of structures on very near-field wave-current interaction include:

- 3D vertically resolved (small scale study area using CFD)
    - Fluent, CFX, STAR-CCM, NS3, OPENFOAM

B.5 Sediment models – bedload and suspended sediment transport

Sediment transport models use tidal and/or wave data output from hydrodynamic models and so these data must first be appropriately created. Measured data describing the distribution of sediment characteristics are then applied to the model and calculations of instantaneous sediment transport potential are made over the model domain. The potential effect of the wind farm on sediment transport in the far-field (i.e. not scour) is therefore assessed via its effect on the hydrodynamics.

Sediment movement in submerged areas of the domain may be modelled either:

- As a bulk quantity which is evaluated in and exchanged between each mesh element. Resulting spatial patterns describe sediment transport pathways and can quantifiably

identify areas tending towards net accumulation or erosion. (Referred to as 'Sediment transport modelling')
- As a series of discrete particles released at a particular rate from a source location, which are allowed to advect and disperse through the domain with the calculated flow conditions. Particles may be assigned a settling rate and so their eventual pattern of deposition can also be studied. (Referred to as 'Particle Tracking').

The first method is typically used to evaluate ambient sediment transport over the whole of the model domain. Either method may be used to investigate the impact of specific events causing a predictable rate of sediment resuspension at a known location (e.g. bed preparation, structure installation, cable laying, etc.)

B.5.1 Sediment Transport Models

Sediment transport models do not exist alone, but rather as sub-modules of hydrodynamic models. The two parts then interact generally as follows:

1. Instantaneous sediment transport is calculated as a function of the hydrodynamic conditions and local sediment properties, according to predictive equations available from the wider environmental engineering literature.
2. Results of the calculations can include: the rate of bedload transport, the rate of suspended sediment transport and the rate of sediment deposition. The net balance between rates of resuspension and deposition are calculated for the model time-step and an appropriate adjustment is made to the local suspended sediment concentration.
3. Net exchange of sediment between adjacent mesh elements is also calculated as a function of the rate of transport, the size and orientation of the interface between elements, and the direction of the tidal flow or of residual currents set up by waves. The level of the seabed might then be adjusted locally to account for net sediment loss or accumulation from the element. In this way sediment can be moved through the model domain; coherent patterns in the individual values describe the sediment transport pathways.

There are many analytical solutions for the estimation of sediment transport and the proportion of which will occur as bedload or as suspended load. Methods may be specific to tidal currents or to waves, or to combined wave-current flows. Very different rates of transport (up to an order of magnitude) can be obtained, depending upon the choice of solution (Soulsby, 1997). Different modelling packages may differentiate between cohesive (finer grained clays and muds) and non-cohesive (coarser grained silts, sands and larger) sediment types.

This broad functionality is used during EIA to investigate baseline sediment transport rates and pathways. The potential effect of the wind farm on these patterns can then also be assessed.

Modular software packages may also help the user to introduce time-dependant sediment release, simulating dredging or other operations in sediment transport modelling studies. However, this is rather a simplification or streamlining of the previous more manual process where the time, rate and location of release had to be calculated and provided as a separate input file. This functionality, in either manual or automatic application, might be used during EIA to investigate the release of sediment as a result of foundation installation or cable laying, or to investigate in-combination effects by also including marine aggregate dredging works.

B.5.2 Particle Tracking Models

Particle tracking models are Lagrangian models and represent fine sediments as 'particles', which are moved around in the model area by the instantaneous current field. Particle movements are considered independently using a random-walk process, e.g. the Monte Carlo technique.

The horizontal transport of a particle during one time-step consists of the sum of the advective component (e.g. the tidal current) and the longitudinal and transverse dispersion (i.e. diffusion) components, relative to the direction of the current. This means that each particle is moved separately and that dispersion occurs in a predefined manner, appropriate to the material and environment. The current field is determined from the hydrodynamic (HD) simulation. 3D models directly provide additional detail of differences in flow speed through the water column; if a 2DH model is used, a logarithmic vertical profile is typically assumed. The longitudinal and transverse dispersion rates can be related to the current speed or can also include factors such as wind mixing and vertical stratification.

The vertical transport of a particle is determined by gravitational (settling) and turbulent (resuspension) forces. A particle close to the bed has the possibility of being deposited if the bed shear stress is below the critical threshold value for deposition or the possibility of being re-suspended if the bed shear stress is above the critical bed shear stress threshold. The model can consider the effects of both waves and currents on re-suspension and deposition. The detailed interaction between particles either on the seabed or in the water column is not resolved by these models (e.g. effect of mixed grain size sediments).

The 'history' of each particle is then traced throughout the model run (that is, its transport within the water column, its deposition on the bed or its re-suspension); transport rates, transport routes and the spatially varying concentration of the particles are calculated by interpolation and spatial analysis of the distribution of all particles at given time-steps.

This model type can be used to estimate the dispersion rate and ultimate fate (deposition footprint and thickness) of sediments resuspended as a result of foundation installation or cable laying activities.

B.5.3 Model packages available

Examples of commercially available modelling packages that might be used to undertake far-field sediment transport studies (baseline, effect of structures and other in-combination effects) include:

- Sediment transport models:
  - MIKE21/3-ST; MIKE21/3-MT; DELFT3D; and TELEMAC.
- Particle tracking models:
  - MIKE21/3-PT; DELFT3D-SED; and SED-PLUME (HR Wallingford - couples with TELEMAC).

B.6 Sediment models – longshore drift and coastline evolution

An assessment of sediment transport along the coastal margin is only required if the wind farm development directly affects hydrodynamic conditions at the coastline. Therefore, these types of models are less likely to be required as part of Round 3 wind farm development. Their use remains potentially relevant to Round 2 and some (nearer-shore) Round 3 sites if it is demonstrated that the extent of potential effect of the development overlaps a sensitive morphological receptor. Potential interruption of the supply of sediment to the coastline by the wind farm (which may also affect coastline evolution) is investigated using the regional sediment models described in the above Section.

If a wind farm scheme potentially changes the wave climate at the adjacent shoreline, an assessment of the effect (in comparison to the baseline) on the rates and directions of sediment transport at the coastal margin (e.g. on adjacent beaches) is needed as part of the EIA. This will require a different modelling approach to that used in open water (Section above). Longshore sediment transport models consider non-cohesive sediment transport in response to waves and currents in the littoral zone (i.e. littoral or longshore drift) leading to predictions of coastline evolution and profile development along quasi-uniform beaches. Again, if the wind farm does not affect waves or tides at the coastline, then natural processes will continue with no influence from the wind farm and so is not an issue in the EIA.

In the first instance, an analysis of alongshore transport is made using a littoral drift model. The model returns the net rate of sediment transport and the direction (effectively, left or right along the beach).

Once longshore transport rates have been determined at a number of point locations along the coastline, further information (and the effect of structures) on coastline evolution can be obtained by finding the net volumetric effect of the spatially variable drift rates. However, it is often found, especially for wind farms located further offshore, that drift rates and therefore predicted coastline evolution are not significantly affected by the presence of the structures.

B.6.1 Required user inputs

Longshore drift models typically require:

- Bathymetric profile data at the location of interest from above the Highest Astronomical Tide line to at least the depth of wave closure;
- Wave data (height and period) from the seaward end of the profile, generally for a time-series of at least one year (or a time period considered to be representative of one year) or the wave climate;
- preferably also water levels but these are not essential;
- Grain size data (mean grain size, settling velocity and sediment grading) at as many locations along the profile as possible;
- Calibration data – usually just an indication of the drift rates and direction, which may be available from previous studies or other conceptual/observational evidence.

Wave and current data can be provided from hydrodynamic models but not typically in a directly coupled mode, due to the long run times required. The effect of the wind farm is assessed by providing the model firstly with hydrodynamic input data derived from the baseline hydrodynamic model and then with data derived from the 'with scheme' hydrodynamic model.

B.6.2 Model packages available

Examples of commercially available modelling packages that might be used to estimate longshore sediment transport rates and directions (baseline and effect of structures) in this way include:

- LitPack (DHI), BEACHPLAN (HR Wallingford), GENESIS (USACE), UNIBEST (DELFT).

B.7 Sediment models – local scour

For the purpose of the Environmental Impact Assessment it is usual to undertake an assessment of the maximum potential for scour around the foundation structures. This is usually in the form of an empirical assessment, i.e. using predictive equations as part of a desktop assessment, rather than detailed numerical modelling. Such assessments have proved effective (HR Wallingford *et al*., 2007) in predicting the maximum scour that might be anticipated around certain structure types, i.e. the worst-case scenario.

If the rate or the detailed pattern of scour is considered to be important (not for EIA, but perhaps for design criteria) a more detailed assessment might be required. Also, if the soil type is complex and/or if the response of the flow to a particular structural design is not well understood, a non-empirical approach may be required. These data may inform design considerations, e.g. when planning the type, distribution and timing of implementing scour protection. These more complex assessment methods might include physical (scaled) modelling or detailed high-resolution local CFD numerical modelling. The latter can be used in a purely hydrodynamic mode to identify regions prone to scour; combining hydro- and sediment-dynamic modules at this scale for direct prediction of scour has been attempted in a research format, informing the evidence base, but is presently expensive and impracticable for use in EIA.

There are numerous empirical methods available to assess scouring around monopile structures in non-cohesive material; within the DNV design standard for offshore wind turbine structures

(DNV, 2007) the approach of Sumer et al. is adopted for scour around vertical piles in non-cohesive soils. However, there are a range of suitable formulations including those of Breusers et al. (1977), Richardson and Davis (2001) and Escarameia and May (1999) that have been successfully applied to scouring in the marine environment. All these empirical methods have limitations and assumptions and it is important to understand these when carrying out the scour assessment. A summary of some of these quantitative methods for monopiles can be found in HR Wallingford *et al*. (2007).

For cohesive soils (with significant mud content) scour assessment is more complex and there are far fewer methods available to use, most of which refer to monopiles. One such method is the SRICOS method (Briaud et al., 1999). This approach was originally developed to predict the scour depth at a cylindrical pier under steady flows, uniform soils and a water depth greater than two times the pier diameter. Clay can erode due to:

- hydraulic forces from waves, currents and turbulence
- abrasion from the transport of sand and gravel particles over the surface of the clay.

(DNV, 2007) the approach of Sumer et al. is adopted for scour around vertical piles in non-cohesive soils. However, there are a range of suitable formulations including those of Breusers et al. (1977), Richardson and Davis (2001) and Escarameia and May (1999) provide rough estimates of values for erosion of cohesive sediments.

A different empirical approach to predicting scour, is the Earth Materials methodology from Annandale (1995, 2006). This takes information on the soil mass properties and structure and produces an erodibility index K. This approach requires some coefficients regarding the effect of the structure on the flow, which must be first made available either from the evidence base, or from other supporting physical or detailed numerical modelling studies. The erodibility index is compared with the stream power supplied by the wave and current action to determine whether erosion is likely to occur or not. This method can be used for any soil type, but is more complex to apply than most typical empirical scour approaches.

For more complex foundations such as gravity bases, multi-legged and jacket structures, scour assessment is more difficult due to the lack of specific methodologies for carrying out empirical assessment. Whitehouse (2004) undertook a series of physical model experiments to investigate scouring around a monopile and three large gravity base type structures under currents and waves. Based on these experiments Whitehouse presented a number of simple expressions to describe the equilibrium scour depth for these types of structures. These empirical equations also draw on the evidence base from (different types of) gravity base structures used in the offshore oil and gas industry.

Currently, jacket and multi-leg foundations are assessed as the summation of scour profiles calculated for the individual piles and cross-members.

B.8 References

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Appendix C. Data in support of modelling and EIA.

The following sections provide some background on the different types of data required in order to undertake physical marine Environmental Impact Assessment for offshore wind farms. The importance of the data type and its relationship to other data types is also considered. A number of potential data sources are then provided with a brief description, their pro's and con's, examples of typical usage and a broad assessment of their accuracy based on expert opinion and quoted accuracy (where available and in a form broadly representative of most makes and models typically used in the UK).

Additional information regarding sources of metocean data and further detail regarding data analysis methods are available from CIRIA (2006) and the supporting documents and publications referenced therein.

C.1 Water levels

C.1.1 Overview

Tidal fluctuations in local water level occur in direct response to the combined gravitational pull of the sun and the moon. The movements of these astronomical bodies are regular and predictable, resulting in similarly regular and predictable local tidal water levels at many locations.

Patterns in tidal water level repeat on different timescales, e.g.:

- 12.42 hours: semi-diurnal/diurnal cycle (flood and ebb, high water and low water)
- 13.89 days: spring-neap cycle (spring tides generally higher, neap tides generally lower)
- 6 months: seasonal cycles (greater exaggeration of spring-neap cycle at the equinox, springs and neaps more equal at solstice)
- 18.6 years: longer term cycles in the movements of the sun and moon produces inter-annual variability in the spring-neap cycle also.

The pull of the sun and the moon creates a tidal wave that progresses around the UK continental shelf. The speed and height of the wave is locally affected by the Coriolis (spinning) force of the earth, the water depth and the shape of the basin, embayment or estuary. As a result, the absolute time of high and low waters, the tidal range and the shape of the tidal curve can vary between locations.

The range and shape of the local tidal curve is important because it controls:

- The strength, asymmetry and direction of tidal currents.
- The total water depth and therefore the change of water volume in an area (e.g. affecting dilution and dispersion rates)

C.1.2 Sources of data

Tidal water level data can be obtained from:

<u>Coastal tide gauges</u>

- *Description*: National network, local harbour masters, ports, commercial organisations
- *Pro's*: typically well maintained, long-term records, to a known datum
- *Con's*: limited number of fixed locations, located far from offshore development sites and therefore not representative of them, large sections of data or established quality assurance procedures may be missing from secondary sources
- *Usage*: Normally used for long-term analysis and model calibration/validation where the model extent encompasses a tide gauge at the coast.
- *Accuracy*: Good. Order (0.001-0.01m)

Local tidal height predictions – primary sources

- *Description*: The result of analysis of long-term, high quality local tide gauge data. Available in many digital sources including the internet and UKHO TotalTide software. The important periodic constituents in the local tide are identified and used to predict water levels at the same location on other dates and times.
- *Pro's*: Provides an accurate prediction for any date and time if properly undertaken
- *Con's*: Does not include meteorological effects, does not provide information about other locations.
- *Usage*: Normally used for long-term analysis and model calibration/validation
- *Accuracy*: Good for the astronomical tide (order mm-cm), can not predict or include meteorological effects (error up to approx ±1m).

Regional tidal height predictions – primary sources

- *Description*: Charts of co-tidal and co-range contours, the result of analysis of long-term, high quality local tide gauge data which is then extrapolated over space. Can be expressed for different constituents allowing the astronomical tidal signal to be predicted at other locations. Similar product to 'Satellites and remote sensing' (below) but different data source.
- *Pro's*: Provides a reasonable prediction for any date and time if properly undertaken
- *Con*'s: Does not take detailed bathymetry into account and so may be spatially inaccurate, not usually accessible in a digital form, must be obtained from paper charts with associated addition of error, only a limited number of tidal constituents are typically available.
- *Usage*: If in an accessible digital form, can be used for long-term analysis of the astronomical tide at offshore locations and for model calibration/validation
- *Accuracy*: Good for the astronomical tide (typically order cm), can not predict or include meteorological effects (error up to approx ±1m).

Remote devices

- *Description*: Deployed survey equipment (either dedicated tide gauges or secondary device on current meters/other equipment)
- *Pro's*: independent data, can be collected at the site of interest
- *Con's*: can be short data sets, some corrections must be made introducing further error, true datum difficult to establish
- *Usage*: Normally used for model calibration/validation
- *Accuracy*: Good. Dedicated devices typically quoted as <0.02% of the water column depth (e.g. ±0.6cm at 30m depth); secondary devices typically <0.25% of the water column depth (e.g. ±7.5cm at 30m depth).

Satellites and remote sensing

- *Description*: Satellites and other aerial devices monitor the elevation of the ocean surface in many locations over long time periods but at sometime widely spaced intervals. Tidal predictions may then be made but are often restricted to only a limited number of tidal constituents.
- *Pro's*: covers a large area, can be extrapolated to any time period
- *Con's*: detail of complex tides may be inaccurate due to the large 'footprint' of the information, the irregular nature of the observations made and the use of only simplistic tidal analysis/reconstruction.
- *Usage*: Often used to provide boundary inputs to a model.
- *Accuracy*: Good to intermediate. Accuracy of measurements ±5cm; of reconstructed water levels in deep water ±order cm's; of reconstructed water levels in shallower water ±order 10's of cm.

Numerical models

- *Description*: The results of other well calibrated and validated numerical models might be used to provide water levels either indirectly as boundaries for the local numerical model or directly for a particular site of interest.

- *Pro's*: could potentially provide predictions for any date, time and location within the model extent, depending upon the setup of the model.
- *Con's*: use of pre-existing models may be prohibited by ownership, confidentiality or licensing issues.
- *Usage*: Often used to provide boundary input to local models. Not often used to provide point data for calibration/validation.
- *Accuracy*: Good to intermediate. Theoretically equal to or better than the accuracy required when calibrating a model. Dependant upon the setup of the model and the degree of resolution/calibration around the area of interest.

C.1.3 Sources of uncertainty in water level data

Sources of uncertainty for all types of hydrodynamic data area considered in Section C.4.

C.2 Tidal currents

C.2.1 Overview

Tides represent a relatively low-energy, high-frequency event (in comparison to infrequent storm events). As a result of changes in water level, the tidal wave moves large volumes of water with every ebb and flood. The volume of water that must be moved is related to the overall change in the water level (i.e. the tidal range), hence, tidal currents tend to be relatively greater during spring tidal periods, especially around the equinox. The actual speed of the current needed to transfer the required volume of water is related to: 1) the time over which the water must be moved; 2) the total water depth; and 3) the cross section through which the volume is passing.

The strength, asymmetry and direction of local tidal currents are important because they control, in part:

- The rate and direction of bedload sediment transport.
- The speed and direction of transport for suspended sediment and other passively transported substances.

C.2.2 Sources of data

Tidal current data can be obtained from:

<u>Remote devices – seabed mounted</u>

- *Description*: Seabed deployed survey equipment (either single point or profiling current meters)
- *Pro's*: independent data, can be collected at the site of interest
- *Con's*: Single site only. May be short data sets, single or multiple discrete measurements must be converted to depth mean values introducing some error.
- *Usage*: Normally used for model calibration/validation
- *Accuracy*: Good. Point devices typically <0.5% ±0.1cm/s (e.g. ±0.0035m/s for 0.5m/s flow); profiling devices typically <1% ±0.5cm/s (e.g. ±0.01m/s for 0.5m/s flow). Directions within ±2°-5°.

<u>Remote devices – ship mounted</u>

- *Description*: Ship mounted survey equipment (typically a profiling current meter).
- *Pro's*: independent data, can be collected at the site(s) of interest. Mobile and flexible in time and location of measurement.
- *Con's*: collects only short data sets at each unique location, discrete measurements must be converted to depth mean values introducing some error.
- *Usage*: Can be used for model calibration/validation
- *Accuracy*: Good if vessel motion can be accounted for. Profiling devices typically <1% ±0.5cm/s (e.g. ±0.01m/s for 0.5m/s flow). Directions within ±2°-5°.

Remote devices – land mounted

- *Description*: Radar based survey equipment (e.g. OSCR, RASCAL) measures the water surface flow speed and direction over a radial area.
- *Pro's*: independent data, can be collected at the site of interest
- *Con's*: Small area only. May be short data sets, discrete measurement from the water surface only which must be converted to depth mean values introducing some error.
- *Usage*: Not commonly available or used.
- *Accuracy*: Unknown; system and deployment specific.

Numerical models

- *Description*: The results of other well calibrated and validated numerical models might be used to provide current speeds and directions for a particular site of interest.
- *Pro's*: could potentially provide predictions for any date, time and location within the model extent, depending upon the setup of the model.
- *Con's*: use of pre-existing models may be restricted by ownership, confidentiality or licensing issues.
- *Usage*: Not often used to provide point data for calibration/validation.
- *Accuracy*: Good to intermediate. Theoretically equal to the accuracy specified during model calibration. Dependant upon the setup of the model and the degree of resolution/calibration around the area of interest.

Tidal current predictions – secondary sources

- *Description*: Commercially available software (e.g. Total Tide) that provides predictions of current speed at a variety of locations. These are typically based upon a simplified analysis of observed drift rates or (less frequently) current meter data which may also be of variable quantity and quality.
- *Pro's*: provides predictions for any date and time at a larger but still fixed number of locations
- *Con's*: accuracy typically low, limited number of fixed locations
- *Usage*: may be used for model calibration/validation, but should be considered a secondary source.
- *Accuracy*: Relatively poor.

C.2.3 Sources of uncertainty in tidal current data

Sources of uncertainty for all types of hydrodynamic data area considered in Section C.4

C.3 Waves

C.3.1 Overview

Waves represent a relatively high-energy, low-frequency event (in comparison to frequent periodic tidal action). Waves are created by winds agitating the water surface, either locally or some distance away. The resulting wave height and length (or period) is controlled by the strength of the wind, the distance over which it acts on the sea surface (the fetch) and the local water depth. The direction of travel for waves will correspond initially to the wind direction but can be subsequently modified locally by currents or changes in water depth.

If the water depth becomes less than the depth to which wave action is felt (the depth of closure), waves are said to be in shallow water. This is likely to be a common occurrence at Round 1 and some Round 2 sites, but is likely to be progressively infrequent at some Round 2 and many Round 3 sites. Shallow water potentially causes wave refraction and gradually shoaling water depths can result in wave steepening, wave breaking and energy loss due to friction which may modify the wave field locally. Structures may also reduce the height and affect the period of waves passing around them through wave reflection or diffraction.

In reality, a local wave field will likely be a combination of waves of differing height and period, possibly originating from different directions, superimposed together. For convenience, this apparent complexity is represented instead by a suitable distribution or spectrum shape which is then reported in terms of key wave parameter values.

The local wave climate is important because it controls, in part:

- Patterns and rates of sediment transport in intermediate and shallow water depths (typically <10-15m depth, i.e. Round 1 and some Round 2 sites, but potentially deeper during large storms, i.e. some Round 2 and Round 3 locations).
- Longshore drift rates and directions at the coast if the wind farm interacts significantly with the coast (which is not an expected feature of most Round 3 sites).

C.3.2 Sources of data

Wave climate data can be obtained from:

Remote devices – surface deployed

- *Description*: Deployed survey equipment (wave measurement buoys)
- *Pro's*: independent data, can be collected at the site of interest
- *Con's*: may be short data sets, discrete time-series measurements must be converted to spectral values with some error introduced.
- *Usage*: Normally used for model calibration/validation
- *Accuracy*: Absolute accuracy difficult to evaluate. During tests, relative agreement between certain surface deployed and seabed instruments was found to be: wave height ±0.1m; period ±1-2s; direction within ±2°-5°.

Remote devices – seabed mounted

- *Description*: Deployed survey equipment (Acoustic Surface Tracking, combined pressure and current sensors, pressure sensors)
- *Pro's*: independent data, can be collected at the site of interest
- *Con's*: may be short data sets, discrete time-series measurements must be converted to spectral values with some error introduced.
- *Usage*: Normally used for model calibration/validation
- *Accuracy*: Good. Absolute accuracy difficult to evaluate. During tests, relative agreement between certain surface deployed and seabed instruments was found to be: wave height ±0.1m; period ±1-2s; direction within ±2°-5°.

Numerical models

- *Description*: The results of other well calibrated and validated numerical models might be used to provide wind and wave parameters for a particular site of interest, e.g. the Met Office hindcast model.
- *Pro's*: could potentially provide predictions for any date, time and location within the model extent, depending upon the setup of the model.
- *Con's*: use of pre-existing models may be restricted by ownership, confidentiality or licensing issues.
- *Usage*: Normally used for providing model boundary conditions and for subsequent calibration/validation.
- *Accuracy*: Good to intermediate. Theoretically equal to or better than the accuracy required when calibrating a model. Dependant upon the setup of the model and the degree of resolution/calibration around the area of interest.

Remote devices – land based

- *Description*: Deployed survey equipment (e.g. X-band radar)
- *Pro's*: independent data, can be collected at the site of interest
- *Con's*: may be short data sets, discrete time-series measurements must be converted to spectral values with some error introduced.
- *Usage*: Not normally collected or used for model calibration/validation
- *Accuracy*: Variable, dependant on setup.

C.3.3 Sources of uncertainty in wave data

Sources of uncertainty for all types of hydrodynamic data area considered in Section C.4.

C.4 Sources of uncertainty in hydrodynamic data

Sources of uncertainty in describing water levels, current speeds and directions and wave climate at a given site (through field data collection) include / *can be reduced* by:

- The relative and absolute accuracy of the measurement system.
  - *Most dedicated systems are sufficiently accurate for this purpose but absolute accuracy of some equipment can be reduced in deeper water.*

- The duration of time for which measurements are collected.
  - *Tidal parameters should be measured over at least 2 spring-neap cycles (approximately 30 days) in order to have sufficient data to characterise the long-term tidal signature at the measurement location or to calibrate a numerical model.*
  - *A longer tidal data set is useful if the wave climate is severe during the deployment so that the purely tidal part can be confidently extracted.*
  - *Wave climate is a collection of episodic events of variable intensity. It is unlikely that sufficient wave data will be collected in situ to describe the long-term wave climate for the whole site; observed data must be at least long enough to provide calibration / validation data for a wave model or hindcast data (at least 4 weeks, including at least one event of annually significant intensity).*
  - *Use numerical models (calibrated using short duration field data), in combination with hindcast or other data sources, to extend the duration of the data set.*

- The distance between the location of the measurement and the location of interest, (if there is a significant range of values or difference in the timing of the event, over the wider area being studied). The greater the offset distance and the greater the spatial complexity, the less representative the data will be of the key site of interest.
  - *Obtain data from as close to the particular site of interest as possible.*
  - *Uncertainty is also reduced if flows in the area are less complex.*
  - *Use numerical models (calibrated using short duration field data), in combination with hindcast data sources, to extend the spatial extent of the data set.*

- The number and distribution of measurements made in an area (if there is a significant range of values or difference in the timing of the event, over the wider area being studied).
  - *Obtaining data from the largest possible number and widest distribution of locations within the wider area, sufficient to resolve areas of complexity and the site of interest.*
  - *Use numerical models (calibrated using short duration field data), in combination with hindcast data sources, to increase the spatial resolution of the data set.*

- The complexity, magnitude and regularity of the interaction between winds, waves and tides.
  - *Obtain data over a sufficiently long period of time and at a suitable time of the year in order to capture a broad range of wind/wave conditions and tidal conditions. Minimum requirement is to provide sufficient data to calibrate tide and wave models, from which additional long-term data can be derived and utilised.*
  - *Use numerical models (calibrated using short duration field data), in combination with hindcast data sources, to increase the duration and spatial extent & resolution of the data set.*

C.5 Bathymetry

C.5.1 Overview

Bathymetry is the collective term for data describing the spatial variation in depth of the seabed. On a large scale (100's-1000's meters) bathymetry describes the shape of the basin which largely controls processes of tidal wave propagation and the resulting tidal currents, also large scale wave refraction, shoaling and breaking. At a relatively finer resolution (0.1 to 100's of meters), bathymetry controls the same processes to a finer degree but also provides information about the dynamic nature of the seabed through sediment bedform size, orientation and asymmetry.

Bathymetry is important because:

- It controls the way in which tides and waves behave both locally and regionally
- It is a physical reflection of other locally occurring sedimentary processes

C.5.2 Sources of data

Bathymetry data can be obtained from:

<u>Geophysical survey (UK Hydrographic Office regional survey)</u>

- *Description*: direct measurement of the local water depth (echo-sounder or other depth measurements by agents of the). Sold directly by the UKHO or their agents, or obtained from published charts.
- *Pro's*: Data available for all areas in UK waters. Better coverage around areas of national interest (ports, hazardous navigation areas).
- *Con's*: Only UK waters available, also sparse in some offshore areas. Some data may be very old and of questionable accuracy. May be expensive for large areas. Licensing issues may apply. Typically not at a suitable resolution for detailed bathymetric analysis. Vertical datum may vary between regions.
- *Usage*: Normally used in model setup (model bathymetry for all model types in UK waters).
- *Accuracy*: Generally good (order of metres).

<u>Geophysical and other survey (regional survey)</u>

- *Description*: direct measurement of the local water depth (echo-sounder or other depth measurements by agents of other national hydrographic offices). Sold directly or indirectly by the hydrographic offices or their agents, or obtained from published charts. Less detailed data have been collated into coarse but free to use global data sets (e.g. GEBCO, ETOP02).
- *Pro's*: Data available for all UK continental shelf if larger area needs to be included in the model.
- *Con's*: May be sparse in some offshore areas. Some data may be very old and of questionable accuracy. May be expensive for large areas if licensing issues apply. Typically not at a suitable resolution for detailed bathymetric analysis. Vertical datum may vary between regions.
- *Usage*: Normally used in model setup (model bathymetry for all model types on UK continental shelf).
- *Accuracy*: Generally good (order of metres).

<u>Geophysical survey (local survey)</u>

- *Description*: direct measurement of the local water depth (single beam or swath bathymetry echo-sounder devices by developer or contractor)
- *Pro's*: Better control on extent and resolution of the data as can be defined in advance. Very high resolution can be obtained from swath systems.
- *Con's*: Impractical and expensive to survey large areas (approx. >10km^2). Requires calm weather conditions to obtain best data.
- *Usage*: Normally used in model setup (model bathymetry for all model types). Can also be interpreted to infer sediment transport pathways.

- *Accuracy*: Generally good, depending upon the extent and density of the sampling program. Accuracy of vertical datum and measurements can be affected in offshore areas if tidal correction is not adequate.

C.5.3 Sources of uncertainty in bathymetry data

Sources of uncertainty in describing seabed bathymetry at a given site (through data collection) include / *can be reduced* by:

- The method of data collection, preparation, analysis and reporting.
  - *Following appropriate and standard procedures*.

- The duration of time over which measurements are collected and the number of repeat surveys.
  - *Assess the likelihood of significant changes in bathymetry over time, i.e. is the seabed in the area potentially dynamic, e.g. presence of large sandbanks or sand waves.*
  - *Better to collect samples from the area over a short period of time in any one survey and to then undertake repeat surveys if there is any evidence of temporal variability at the site.*

- The extent and resolution of measurements made in an area (if there is significant variation in bathymetry over the wider area being studied).
  - *Obtain a broad scale understanding of the distribution of topographic features prior to survey and target these for more detailed measurement if appropriate.*
  - *Sites with more variability in seabed types will therefore require a greater resolution of measurement.*
  - *Resolution requirements variable depending upon the end use, e.g. observation of bedforms requires higher resolution, probably over a small area, versus providing bathymetry for regional models which requires less resolution over a larger area.*
  - *Vertical resolution improved by undertaking survey in calmer weather. Need to convert relative depth measurements to an absolute datum using a local reference tide gauge or highly accurate RTK/PPK GPS technology.*

- The method and resolution of data interpolation to a model mesh.
  - *Ensure that the model mesh reproduces or describes all significant bathymetric features. This will involve the deliberate and appropriate placement and spacing of mesh nodes prior to data interpolation.*
  - *Use an appropriate method of data interpolation (e.g. linear vs spline vs nearest neighbour) to reproduce the shape of significant bathymetric features.*
  - *Use an appropriate method and degree of data smoothening to preserve the shape of significant bathymetric features whilst removing anomalous data.*
  - *An inappropriate approach to mesh design or interpolation of data will usually limit the ability of the model to be subsequently validated and calibrated. Hence, uncertainty is reduced if these tasks can be adequately completed.*

C.6 Seabed sediments, sedimentary environment, sedimentary structures

C.6.1 Overview

In most areas of the UK continental shelf, the upper seabed is composed of sediment. In this context, sediment refers generally to rock mineral fragments of varying size, shape, angularity, density, hardness and geochemical properties. Sediments may be homogeneous or may be composed of a mixture of sediment fractions; the composition of sediment may vary over space and time. The bulk geotechnical properties (e.g. strength, erodibility, etc) of a particular sediment are dependant upon the mixture of sediment fractions present, the manner in which the sediments were deposited and the time since deposition. The seabed may consist of different overlying layers of sediment with varying thickness and composition. Marine organisms can also affect the strength and stability of the sediment through colonisation (stabilising) and bioturbation (destabilising).

The sedimentary environment describes the spatial variation in sediment transport rate and direction. Transport directions can be estimated by observing the asymmetry of sediment bedforms or can be measured directly. Sediment is typically only mobile in a thin upper layer and the thickness of this mobile layer will vary depending on the mobility of the sediment and the strength or persistence of the erosive forces. If the sedimentary environment at the wind farm site is very active then the potential effect of the wind farm is greater; if not, then the effect of the wind farm might be more limited.

Sedimentary structures refer to the classification of particular features in the seabed bathymetry. Channels, banks and other large scale bedforms are important as they may indicate the location of potential sources or sinks of sediment which may be the origin, destination, or significant storage point of a sediment transport pathway.

Sediment properties are important because they control, in part:

- Patterns and rates of sediment transport.
- The magnitude and persistence of suspended sediment concentrations.
- Susceptibility to scour.

The sedimentary environment is important because it controls, in part:

- The potential magnitude of the effect of the wind farm.
- The direction of propagation and the likely destination of any effect.

Sedimentary structures are important because they correspond, to some extent, to:

- Sources, sinks or storage areas for sediment, which might be affected by the presence of the wind farm.

C.6.2 Sources of data

Sediment data can be obtained from:

<u>Geophysical survey (direct sampling)</u>

- *Description*: Grab sampling of the upper seabed or deeper coring (can indicate the thickness of the upper mixed layer).
- *Pro's*: provides actual samples which may be tested in the most appropriate manner to obtain the required information.
- *Con's*: finite number of sampling locations means that the spatial resolution is limited. Surface grab samples only provide information from approximately the top 10cm of sediment and no information regarding sediment layering. There can often be significant variability between the results of repeat grab sample due to inherent difficulties in obtaining a representative sample.
- *Usage*: Normally used for model setup (sediment transport modelling). Can also be used to infer sediment transport pathways.
- *Accuracy*: Variable, depending upon the extent and density of the sampling program and the suitability and proper use of the sampling equipment. Accuracy of subsequent sediment analysis can be good if suitably controlled in the laboratory.

<u>Geophysical survey (remote sampling)</u>

- *Description*: Side scan sonar is used to map the texture of surface sediment; sub-bottom profilers (e.g. boomer, chirp, etc) are used to measure vertical profiles of the sediment layers (possibly indicating the thickness of the upper mixed layer). Data are calibrated to actual sediment type by direct sampling methods of grabbing or coring ('ground truthing').
- *Pro's*: Easier to obtain wider spatial coverage and resolution.

- *Con's*: More expensive, relies on adequate ground truthing.
- *Usage*: Normally used for informing model setup and scenario testing (sediment transport modelling). Can also be used to infer sediment transport pathways. This methods provides additional information on bed form orientation
- *Accuracy*: Generally good (approx 1-5m resolution), depending upon the equipment quality, the weather conditions at the time of the survey and the extent and suitability of the ground truthing program.

Geological publications

- *Description*: Summary of results from historical geophysical surveys. Typically collected by British Geological Survey, available either directly from BGS or from tertiary sources, e.g. Admiralty publications and almanacs. Data may also be available from previous environmental reports in support of commercial marine work licence applications.
- *Pro's*: provides information with significant spatial coverage
- *Con's*: variable resolution and little consideration for temporal variability. Detail is rarely provided about the layering or detailed composition of seabed sediments at large scales.
- *Usage*: Can be used to identify broad seabed sediment character and to obtain indications of the proportion of different sediment grain size (to the resolution of the broad categories used: mud, sand, gravel, etc.)
- *Accuracy*: Variable, depending upon the extent and density of the underlying data. Only qualitative descriptions of sediment type are available.

Conceptual studies

- *Description*: Previously undertaken analysis and collation of available environmental data sources, used to conceptually identify and possibly quantify the likely connection between or distribution of sediment sources/sinks/pathways including transport rates and spatial and temporal variability. Data may be available from previous environmental reports in support of commercial marine work licence applications.
- *Pro's*: Provides an interpretation of the system on the basis of multiple data sources and the available scientific evidence base, hence provides some advantages over spatially and temporally discrete or incomplete data.
- *Con's*: The accuracy of the analysis is limited by the quantity and quality of data available at the time of the study. The study may not cover the whole region of interest or may have different research objectives, making the results less relevant to the task in hand.
- *Usage*: Can be used as a basis for identifying the potential for impact, prior to modelling studies being chosen. Can also be used for model results validation and as a baseline from which to assess relative impact.
- *Accuracy*: Variable, depending upon the quantity and quality of data available at the time of the study. Also, upon the skill, experience and objectives of the original author.

C.6.3 Sources of uncertainty in sediment properties data

Sources of uncertainty in describing seabed sediment properties at a given site (through data collection) include / *can be reduced* by:

- The method of sediment sample collection, preparation, analysis and reporting.
  - *Following appropriate and standard procedures*.

- The duration of time over which measurements are collected and the number of repeat surveys.
  - *Better to collect samples from the area over a short period of time in any one survey and to then undertake repeat surveys if there is any evidence of temporal variability at the site.*

- The number and distribution of measurements made in an area (if there is significant variation in seabed properties over the wider area being studied).

  - *Obtain a broad scale understanding of the distribution of different seabed types prior to survey, e.g. using side scan sonar survey; then plan the survey in order to characterise (with multiple measurements) each of the distinct seabed types and regions identified.*
  - *Sites with more variability in seabed types will therefore require a greater density of sediment sampling.*

C.6.4 Sources of uncertainty in sedimentary structures data

Sources of uncertainty in describing the location of sedimentary structures at a given site (through data collection) include / *can be reduced* by:

- The presence of potentially mobile sediment or sedimentary features.
  - *If none are present (over significant time periods), then there is no uncertainty.*

- The resolution and quality of bathymetry and seabed type data, controlling the ability to identify and interpret the structures present.
  - *Collecting high resolution (e.g. swath bathymetry) data in suitable conditions to resolve bedforms. This is more difficult in deeper water due to the operating method/limitations of the equipment and the likelihood of non-calm conditions during the survey in offshore locations.*

- The number of repeat surveys of sufficient quality to make direct timeseries comparison.
  - *Repeat surveys can be compared to assess the mobility of bedforms and features. The interval should be long enough to capture displacement or change, but not so long that bed features have moved more than ½ wave length.*

C.7 Suspended sediment concentration

C.7.1 Overview

If sufficiently energetic, the action of waves and tides at the seabed may resuspend sediment above the level of the seabed. In perfectly still water, all except the finest muds will gradually settle out back to the seabed and be redeposited and the rate of settling is related to the shape, size and density of the sediment. More realistically, turbulence in the marine environment will cause intermittent upwards motion of the grain and so acts to maintain it in suspension for longer. The naturally occurring level of suspended sediment concentration can vary both spatially and temporally in response to variability in the tide (on semi-diurnal, spring-neap and seasonal timescales) and in the wave climate (which is variable on daily, seasonal and annual timescales). Natural spatial variability also results from spatial variability in seabed sediment properties (the quantity available and its susceptibility to resuspension).

Sediment in suspension is moved passively within the body of water and so moves at the same velocity and in the same direction as the local tidal current in a Lagrangian sense. Therefore, suspended sediment concentration at a given location may be the result of resuspension in another location, some time in the past. As such, suspension is a mode of sediment transport where sediment can be moved over large distances in the direction of the residual tidal current. In general, waves may encourage sediment resuspension but do not affect the rate or direction of transport, unless in very shallow water where residual currents might be induced.

Sediment can also be resuspended artificially as part of anthropogenic marine activities, e.g. seabed preparation, structure installation, cable burial, aggregate dredging, fishing or trawling, etc. Once put into suspension, sediment will then behave according to the previously described natural processes.

Suspended sediment concentrations are important because:

- The marine environment has evolved to be tolerant of naturally occurring levels, which can influence water chemistry, feeding, seabed character and rate of seabed accumulation.
- Naturally occurring levels will fall within a typical range which, if significantly exceeded, may be detrimental to the local environment.
- Advection and accumulation of natural and anthropogenic sediment in suspension can result in excessively high concentrations of suspended sediment.

C.7.2 Sources of data

Suspended sediment concentration data can be obtained from:

Field survey (direct sampling)

- *Description*: Sampling of the water column and subsequent analysis. Usually carried out at different depths, locations and times of the year.
- *Pro's*: provides actual samples which may be tested in the most appropriate manner to obtain the required information. Organic material contribution can be removed prior to analysis.
- *Con's*: finite number of sampling locations means that the spatial resolution is limited. Suspended sediment concentration can be variable over small distances or over short time periods.
- *Usage*: Normally used for sediment transport model calibration in a general sense. Used as context for describing the significance of the impact of a particular event.
- *Accuracy*: Good locally but variable over wider areas, depending upon the extent and density of the sampling program. Accuracy of subsequent sediment analysis can be good if suitably controlled in the laboratory. Suspended sediment concentration can be variable over small distances or over short time periods and so it is difficult to quantify absolute accuracy for a large area or over a long time period.

Field survey (indirect measurement, optical)

- *Description*: Optical Backscatter Sensors (OBS). Usually mounted on a seabed frame, carried out at different locations and times of the year.
- *Pro's*: provides a detailed time-series at the sampling locations. Better at detecting fine grained sediment fractions.
- *Con's*: finite number of sampling locations means that the spatial resolution is limited. Suspended sediment concentration can be variable over small distances or over short time periods; measurement only made at fixed height above the bed – vertical profile not resolved. Instrument requires calibration using water and sediment samples from the same site. Organic material contribution is also measured. Not so good at detecting coarse grained sediments.
- *Usage*: Normally used for sediment transport model calibration in a general sense. Used as context for describing the significance of the impact of a particular event. Typically used to quantify the transport rate of fine sediments (clays-silts); not so effective for larger sediments.
- *Accuracy*: Good locally but variable over wider areas, depending upon the extent and density of the sampling program and quality of the calibration. Accuracy of calibration can be good if suitably controlled in the laboratory. Suspended sediment concentration can be variable over small distances or over short time periods and so it is difficult to quantify absolute accuracy for a large area or over a long time period.

Field survey (indirect measurement, acoustic)

- *Description*: Acoustic Doppler current Profilers (ADPs or ADCPs) can be used to assess vertical concentration profile. Can be mounted on a seabed frame or vessel mounted, carried out at different locations and times of the year.
- *Pro's*: provides a detailed time-series and vertical profiles of data at the sampling locations. Better at detecting coarse grained sediment fractions.

- *Con's*: finite number of sampling locations means that the spatial resolution is limited. Suspended sediment concentration can be variable over small distances or over short time periods not resolved by the instrument. Instrument requires calibration using water and sediment samples from the same site. Organic material contribution is also measured. Not so good at detecting fine grained sediments.
- *Usage*: Normally used for sediment transport model calibration in a general sense. Used as context for describing the significance of the impact of a particular event. Provides a better method for observing coarser sediment transport (silts-sands).
- *Accuracy*: Intermediate to poor locally and variable over wider areas, depending upon the extent and density of the sampling program and quality of the calibration. There are still many uncertainties in the quantifiable relationship between acoustic backscatter and suspended sediment concentration.

C.7.3 Sources of uncertainty in suspended sediment data

Sources of uncertainty in describing suspended sediment concentrations at a given site (through data collection) include / *can be reduced* by:

- The method of sediment sample collection, preparation, analysis and reporting.
  - *Following appropriate and standard procedures*.

- The duration of time over which measurements are collected and the number of repeat surveys.
  - *Better to collect samples from the area over a short period of time in any one survey and to then undertake repeat.*

- The number and distribution of measurements made in an area (if there is significant variation in SSC over the wider area being studied).
  - *Obtain a broad scale understanding of the distribution of SSC prior to survey, e.g. using previous studies, remote sensing data, etc; then plan the survey in order to capture (with multiple measurements) the overall pattern of SSC distribution and any strong spatial gradients.*

- The proportion of organic (marine growth) to inorganic (sediment) particles in the water column.
  - *An assessment must be made as to the relative contribution of each if absolute rates of sediment transport alone are required.*
  - *The SED01 publication (ABPmer et al. 2008) recommends best-practice methods for the collection of suspended sediment data.*

C.8 Structures and Site Layout

C.8.1 Overview

The effect of a wind farm development within the extent of any given site will depend upon: the type of foundations used; planned ground preparation work options; the density (spacing) and relative positions of the structures; their total number and the total area covered; intra-array cables and onshore cable routes and the planned installation method options; and any planned scour protection options. In order to account for the wind farm in the assessment process, data must be obtained describing possibilities for all of these options.

Developers often want to maintain flexibility at the EIA stage regarding any or all of the above options. To allow for this within the EIA, the developer is encouraged to present the range of options being considered in the form of a Project Design Statement (PDS) and assessment is then undertaken on the basis of the 'worst case option' identified as having the greatest potential for impact.

Descriptions of the foundation design, number and locations are required in order to correctly account for the effect of individual wind turbines on the near-field and their collective effect on the far-field hydrodynamic environment. Details regarding the position and method of installation for foundations and cables are generally required to assess the potential for sediment resuspension.

C.8.2 Sources of data

Information regarding site development options can be obtained from:

The Project Design Statement (PDS)

- *Description*: A preliminary design document from the developer describing: the range of foundation types and site layout (turbine number and spacing) options being considered; the programme for development; and the methods to employ. It may possibly come in conjunction with a suggested worse case scenario to use.
- *Pro's*: A PDS is a singular source of data and provides a clear blueprint for the options to assess as part of the EIA.
- *Con's*: The contents of the PDS may change in the early stages of the EIA, but the resulting EIA should reflect the 'realistic worst case' option and therefore all option combinations less likely to cause impact.
- *Usage*: Normally used to define the structure properties and site layout in EIA studies.

C.8.3 Sources of uncertainty in structures and site layout data

Sources of uncertainty in describing site development options at a given site (through data collection) include / *can be reduced* by:

- The PDS may not cover the full range of options or may not be correct if other development options are considered.
    - o *Review the PDS at regular intervals with the developer.*
    - o *Ensure that the identified 'realistic worst case' scenario exceeds that of all options being considered, especially where uncertainty exists for less intrusive options.*

- The regulator may not agree with the choice of 'realistic worst case' scenario chosen.
    - o *Agree the choice of 'realistic worst case' scenario as early as possible with the regulator and update this choice if required as a result of any significant revisions to the PDS.*

C.9 References

CIRIA (2006). Guidelines for the use of metocean data through the lifecycle of a marine renewable energy development. CIRIA report C666. 134pp.

Appendix D. Foundation Types

To date, only monopile foundations have been installed at existing wind farm developments in the UK. Within the rest of Europe both monopile and gravity base structures have been used. For Round 3 developments it is likely that a greater range of foundation options will be used. However, there is currently a significant knowledge gap in how to represent the more complex foundation types in the coastal area numerical models currently in use in wind farm studies as well as uncertainty in how to undertake an appropriate assessment of the scour potential around such foundations. This lack of knowledge can only be addressed by additional research or through a much broader evidence base. It is not intended to discuss the range of foundation types in any detail and the following provides a brief overview of the principal types:

D.1 Monopile foundations:

Currently, the monopile represents the only foundation type used in all major offshore wind farms built in the UK. It is simple in design and consists of a large diameter cylindrical steel tube (typical pile diameters used to date are 4-5m) with a transition piece connecting the pile to the turbine tower. The monopile is driven, hammered or drilled and grouted into the seabed and is generally unsupported, although supported piles have also been used in offshore construction.

The advantages of monopiles are that minimal seabed preparation is required, they are resistant to seabed movement, scour and ice flow damage if constructing in areas susceptible to icing. Because of their typically small diameter to wave length ratio, wave diffraction effects are typically not considered to be important. They are also relatively inexpensive to manufacture. Monopiles are relatively simplistic structures to account for in numerical modelling studies.

The disadvantages of using monopiles is that installation can be expensive and time-consuming depending on turbine size and seabed geology, there is sub-structure flexibility at greater depths and decreased stiffness relative to other foundation types. There have been issues in the past relating to spillage of the grout material used during installation at some Round 1 sites. Monopiles are also difficult to remove which may have implications for decommissioning wind farms.

The limiting design condition for the monopile is the overall deflection and vibration of the structure in response to loading. Based on current standards monopiles are generally suitable for relatively shallow water depths up to about 25m. To limit the pile length, it is considered best to avoid the use of monopiles in deep soft soils.

D.2 Gravity base foundations:

Gravity base foundations typically consist of a slender steel or concrete sub-structure mounted onto a single large circular foundation, although other base shapes have been used in offshore foundations (e.g. square and hexagonal). There is no standard gravity base design and the shape and size of all foundation components may vary depending upon the application, hydrodynamic environment, water depth and soil type. The bases are constructed of reinforced concrete or a ballast-filled steel shell. Gravity base foundations can be skirted, which has the advantage of trapping any soft soil layers and transferring the gravity load to the bearing soils, improving the hydraulic conditions, reducing the scour potential, and facilitating conditions for base grouting.

Gravity base foundations are generally well suited to homogeneous soils due to settlement and bearing capacity distribution. However they can be used in virtually all soil conditions in water depths between 0 to 25m. They require a flat base and scour protection requirements are dependent on local site conditions. The gravity foundation is designed to handle tensile loads between the bottom of the support structure and the seabed by providing sufficient self-weight dead loads to maintain stability. The overturning moment is resisted by a “push-pull” action where equal and opposite vertical loads (i.e. soil resistance on the downwind side and self-weight on the upwind side) act at the foundation level.

There are several advantages to using gravity base foundations including ease of transportation and low cost of installation as they can be designed without any requirement for the use of heavy lift vessels or other specialised installation vessels. Gravity base foundations are also easily removed upon decommissioning. In addition, gravity base structures are considered to be economically competitive when used in locations with modest environmental loads.

Gravity base structures are generally more difficult to transport due to their size, shape and weight, particularly with increasing distance offshore, when compared with steel foundations. Monopile foundations generally are easier to erect having lower capacity crane requirements. If the gravity base is placed proud of the surrounding seabed then it is possible that it will be subject to increased wave and current loading. They are unlikely to prove a cost-effective solution in situations where the seabed requires a lot of preparation to create a suitable surface upon which the structure can be placed.

Gravity-based or caisson structures have been used successfully in several projects sited in the Baltic Sea where conditions are relatively benign and more recently at Middelgrunden and Thornton Bank. These foundations have been made of concrete or steel filled with ballast. At Middelgrunden for a 2MW turbine the gravity base weighs around 2,000 tonnes in air and submerged about 1,500 tonnes.

D.3 Suction Caissons:

Suction caissons are similar in design to gravity base foundations, but fundamentally differ in the installation method and principal stability mode. Simplistically, these structures consist of a column connected by flange reinforced shear panels to an inverted steel bucket called a caisson. The shear panels distribute load from the centre of the column to the edge of the caisson. The caisson is comprised of vertical steel skirts that extend down into the seabed from the horizontal base, while the base rests on the seabed. The length of the steel skirts is equal to the caisson width, approximately, and the soil volume inside the caisson acts as the gravity base foundation. Typical dimensions for suction caissons in water depths of 5m or less range from 2m to 4m in diameter, whilst in deeper water depths typical diameters can be up to 15m. Suction caisson designs can also consist of tripod or quadrupod configurations, with the caissons replacing piles or gravity base foundations in a conventional multi-leg structure. Such configurations have advantages for use in deeper water, with a requirement for smaller caissons, and an easier capability to level the structure.

The principal limiting factor for a monopod suction caisson design is the overturning moment, while for a multi-leg suction caisson layout, the resistance to tensile loads is of principal concern. At present, there is no design guidance for suction caissons subject to large moment load to vertical load ratios, therefore, suction caissons should be designed on a case-by-case basis.

Suction caissons are installed through the use of a pressure differential, once the rim of the caisson has a sealed contact with the seabed water is pumped out through the top of the caisson, producing a net downward pressure, or suction and forcing the caisson into the seabed. Once installed to a sufficient depth, the pumps are removed and the valves are sealed. Suction caissons are removed from the seabed by reattaching the pumps and pumping water back into the cavity within the caisson, forcing it out of the seabed.

Suction caissons are best applied in homogenous soils due to differential settlement and bearing capacity issues, but have also been shown to work well in sands and soft clays in a range of water depths and tidal conditions. Suction caissons foundations have the ability to be floated to the site avoiding the need for heavy lifting and pile driving equipment. This can make installation quick and inexpensive, as well as easy removal upon decommissioning. The short installation time and minimal amount of material necessary for ballast make this a cost effective method. However, it is important to ensure that the seabed soils can be penetrated and that they are not prone to scouring as suction caissons are vulnerable to scour in shallow water. There is also a lack of proven installation data for different soil types, resulting in the need for undertaking analyses prior to design. In sandy soils piping may occur below the caisson bucket lip.

D.4 Multi-leg foundations (Tripod / Quadrupod structures):

Multi-leg foundations are defined as tripod or quadrupod structures. They are constructed of cylindrical steel tubing and are attached to the seabed using either angular or vertically-driven leg piles or suction caissons. These types of structure are suitable for water depths typically in the range 25m to 50m and to date have primarily been used in the oil and gas industry. An example of multi-leg foundations are Amoco UK's Davy and Bessemer gas platforms in the North Sea. The Davy and Bessemer platforms are installed in 43m and 23m of water, respectively.

Multi-leg structures have several advantages including resistance to wave and current loading. This is because their design provides greater structural stiffness which may result in less deformation of the tower under extreme loading conditions. Multi-leg structures are also relatively inexpensive to fabricate. However, they are expensive to construct and install and like monopiles are difficult to remove from the seabed during decommissioning.

D.5 Jacket foundations:

Jacket foundations consist of a multi-leg foundation connected to a steel braced sub-structure. The jacket structure is attached to the seabed using piles driven to depth inside pile sleeves for structural stability. Jacket foundations are suitable for water depths of 20m to 40m. Jacket structures are ideal for deeper water sites under extreme environmental conditions as they have a stiff, dynamic response. Like multi-leg foundations, in locations that have ice flows they are vulnerable to ice loading due to the slender nature of their structural members. However, as they can be fully assembled prior to float-out, this makes installation easier. Due to their slender design scouring around the structure is often less of a problem than other piled foundation types.

D.6 Floating structures:

The use of floating structures for offshore wind developments is still in its infancy and is not likely to be used in the short-term, however, several novel designs have been proposed. StatoilHydro are currently trialling a floating wind turbine that became operational in 2009 and are also involved in another novel floating turbine concept, SWAY. Primarily, there are two types of floating structure that are considered appropriate for offshore wind turbines; the tension-leg platform and the low-roll floater. The latter type is far more cost-effective due to the installation cost of moorings and/or anchors. Floating structures are generally suitable for deep water environments greater than 50m.

Tension-leg platforms use technology developed by the offshore oil industry, and are attached to the seabed using tensioned vertical anchor legs and may or may not have ballast tanks. These structures can be floated to site in a fully-commissioned condition and then only require connection to the anchoring or mooring system. The wind and wave loading is dampened by the base structure. Tension-leg platforms have the advantage of easy disconnection to allow transport for repair or maintenance and can also be installed in water depths of over 1000m.

Low-roll floaters utilise mooring chains and anchors to stabilize the structure by dampening the motions of the platform. They also have a stabilizer attached at the bottom of the floater to reduce roll. As with tension-leg platforms, the installation is relatively simple.