Inch Cape Offshore Wind Farm

New Energy for Scotland

Offshore Environmental Statement:

VOLUME 2B

Annex 10A.1: Development Area Baseline Description

REPSOL edp renewables

Partrac Consulting

ANNEX 10A.1

DEVELOPMENT AREA BASELINE DESCRIPTION:

INCH CAPE OFFSHORE LIMITED

May 2013

DOCUMENT CONTROL

Version History					
Version	**Date**	**Prepared by**	**Reviewed by**	**Approved by**	**Approved as**
V01	19.09.12	K Black E Osalusi/R Helsby	M Wright	K Black	Draft
V02	20.05.12	K Black E Osalusi/R Helsby	M Wright	K Black	Final

Changes from the Previous Version	
V02	Updated from V01 in response to client comments

Recipient	Distribution Method		
	Paper (copies)	PDF/Word	Online
K. McGovern, P. Taylor		X	
Holders of controlled copies will automatically be provided with subsequent approved versions of this document when they become available.			

CONTENTS

TABLES AND FIGURES

ABBREVIATIONS

ADCP	Acoustic Doppler Current Profiler
AREG	Aberdeen Renewable Energy Group
BGS	British Geological Survey
BODC	British Oceanographic Data Centre
CEFAS	Centre for Environment, Fisheries and Aquaculture
EIA	Environmental Impact Assessment
EOWDC	European Offshore Wind Deployment Centre
FTOWDG	Forth and Tay Offshore Wind Developers Group
FTMS	Forth and Tay Modelling System
HD	Hydrodynamic (model)
ICS	International Commission on Stratigraphy
ICOL	Inch Cape Offshore Limited
LAT	Lowest Astronomical Tide
NNG	Neart na Gaoithe OWF
OfTW	Offshore Transmission Works
OSP	Offshore Substation Platform
OWF	Offshore Wind Farm
SEPA	Scottish Environment Protection Agency
STW	Scottish Territorial Waters
SW	Spectral Wave (model)
UKHO	UK Hydrographic Office
WTG	Wind Turbine Generator

GLOSSARY

Acoustic Doppler Current Meter — A marine instrument for the measurement of water motions due to tidal currents, river currents and waves.

Bed roughness — The configuration of the bed surface and texture resulting in flow resistance.

Bedform — Morphological features at the seabed (e.g. ripples, dunes) formed in response to sediment transport driven by wave-induced and/or tidal currents.

Critical bed stress — τ_{ocr}; The value of τ_o at which sediments begin to move under flow.

Current Rose — A specific representation of tidal current data which shows magnitude, frequency and direction in a single plot.

Design Envelope — The Design Envelope describes a number of components and all permanent and temporary works required to generate or transmit electricity to the national grid including the Wind Farm and the Offshore Transmission Works (OfTW). The design envelope is detailed in Chapter 7: Description of Development.

Friction velocity — $u^*=SQRT\{\tau_0/\rho_w\}$; u^* is called the 'friction velocity' and has units of m s^{-1}; however, it is not a real velocity but a unit created for mathematical convenience

FTMS — The FTMS is a high resolution dynamic modelling system which uses an unstructured flexible mesh. It is a sophisticated two-dimensional modular based modelling system, and has the capacity to run both hydrodynamic and spectral wave models. It has within its build the detailed Development Area bathymetry from survey and it may be used to predict the physical properties of tidal currents and waves, and the interactions between these, for any specified area. A flexible mesh model has the advantage of using a spatial varying resolution, so that the complex bathymetries and coastal topographic features can be sufficiently resolved by the model.

Grain size — Reference to the physical size (diameter) of seabed sediments; specific metrics are often used e.g. median grain size (the size for which 50% of the deposit is finer, and 50% is coarser).

Gravel	Sediments which are greater than 2 mm in diameter.
Holocene	The Holocene is a geological epoch which began at the end of the Pleistocene (around 12,000 to 11,500 years ago) and continues to the present.
Hm0	The significant wave height as calculated from the wave energy spectrum.
Mbsf	Metres beneath the seafloor.
Megaripple	An intermediate scale bedform; McCave (1971) defines megaripples as of height up to 3 m, and wavelength of 0.6 to 30 m.
Neap tide	A tide that occurs when the difference between high and low tide is least.
Quaternary	The Quaternary Period is the most recent of the three periods of the Cenozoic Era in the geologic time scale of the ICS. It follows the Neogene Period and spans from 2.588 ± 0.005 million years ago to the present. The relatively short period is characterized by a series of glaciations and by the appearance and expansion of anatomically modern humans. The Quaternary includes two geologic epochs: the Pleistocene and Holocene.
Regional Study Area	The area covered by the regional metocean and coastal processes assessment. It extends from Cairnbulg Point in NE Scotland to St Abbs Head in England, in order to encompass the major coastal sediment cells close to the Wind Farm. The Regional Study Area extends far enough offshore to encompass the Firth of Forth Round 3 offshore wind farm zone.
Sand	Sediments which are greater than 0.062 mm in diameter but less than 2 mm in diameter.
Sandbank	A large, ridge-like primary structure resembling a water wave on the upper surface of a sedimentary bed that is formed by high-velocity air or water currents.
Scour	The vertical excavation of sediments around a maritime foundation; “clear water” scour is where sediment transport occurs only in the vicinity of the structure following acceleration of flow around the piling base; “live-bed” scour is where flow everywhere on the bed is sufficient to mobilise and transport sediment at all times.

Sediments	Granular deposits found on the seafloor, and generated by erosional process on the Earth's surface.
Sediment flux	The rate at which sediments are moving within a body of water; traditionally defined as the product of the sediment concentration and the flow velocity.
Shear (or bed) stress	τ_o; The drag force per unit area over the seabed exerted by flows.
Shields value	$\theta_\infty = \frac{\tau_0}{(\rho_s - \rho) g d_{50}}$; The ratio of tractive force (shear stress, τ_o) to inertia (ρ_s-ρ)gd_{50} (where ρ_s and ρ are the density (specific gravity) of sediment and water (respectively), g is the acceleration due to gravity, and d_{50} is the median grain size) for a sediment particle.
Significant Wave Height	Defined traditionally as the mean wave height (trough to crest) of the highest third of the waves in a given period.
Spring tide	A tide that occurs when the difference between high and low tide is greatest.
Storm surge	A storm surge is an offshore rise of water associated with a low pressure weather system, typically tropical cyclones and strong extratropical cyclones
Tidal excursion	The net horizontal distance over which a water particle moves during one tidal cycle of flood and ebb.
Till	Till or glacial till is unsorted deposited by glacial action.
Tz	Zero crossing wave period.
Vortex streets	Regions of higher turbulence formed downstream as flow diverts around maritime structures.
Wake	A general term relating to regions of higher turbulence formed downstream as flow diverts around maritime structures.
Wave Buoy	A floating device designed to follow the surface motions of a water body and thereby to measure wave properties.
Wave Period (Zero Crossing)	The average time interval between similar direction crossings of mean water level for a wave record.
Wave Refraction	The process by which the direction of a wave train moving in shallow water at an angle to the contours is changed.

Wee Bankie Formation	A stiff, variably matrix-dominated multiple grain size sedimentary deposit containing sand, pebbly sand and silty clay with boulders. See Till.

10A.1.1 INTRODUCTION

10A.1.1.1 Background

Inch Cape Offshore Limited (ICOL) is developing a Wind Farm and associated Offshore Transmission Works (OfTW). Definitions for the Wind Farm, OfTW, Development Area and Export Cable Corridor are as follows:

- Offshore Wind Farm/Wind Farm: Includes proposed Wind Turbine Generators (WTGs), inter-array cables, meteorological masts and other associated and ancillary elements and works (such as metocean buoys). This includes all permanent and temporary works required.
- Offshore Transmission Works (OfTW): The proposed Offshore Export Cable and Offshore Substation Platforms (OSPs). This includes all permanent and temporary works required.
- Development Area: The area which includes proposed WTGs, inter-array cables, OSPs and initial part of the Offshore Export Cable and any other associated works (see Chapter 7 Figure 7.1).
- Offshore Export Cable Corridor/Export Cable Corridor: The area within which the proposed Offshore Export Cables will be laid outside of the Development Area and up to Mean High Water Springs (see Chapter 7 Figure 7.1).

ICOL has commissioned Intertek Energy and Water Consultancy Services to undertake assessments of meteorological/oceanographic (metocean) and coastal processes relating to the Wind Farm and OfTW.

The Wind Farm and OfTW will potentially affect both the metocean and coastal processes regimes in and around the Development Area and Offshore Export Cable Corridor. Effects may range from short to long term, and the assessment will consider timescales up to 50 years. ICOL requires an understanding of the magnitude and significance of these effects, with a view to implementing, where necessary, appropriate mitigation measures in order to minimise impacts. These will be considered in the ES Chapter 10: Metocean and Coastal Processes.

The study requires the delivery of a calibrated and validated coastal hydrodynamic (HD) and spectral wave (SW) model, and the delivery of a coastal processes assessment using the models and available information. The proposed assessments will provide the developers and other stakeholders with the regional and Project-specific characterisation of the metocean and physical geomarine environment. This will allow the baseline environmental conditions to be determined, against which the effects of each individual development, and the cumulative effects of the Project and other projects can be considered. The study results will provide input to a technical report and the Environmental Impact Assessment (EIA).

This report presents an overview of the baseline (existing) oceanographic and coastal processes environment in and around the Inch Cape Development Area. This assessment is performed where possible using site specific data collected during marine survey and oceanographic monitoring operations. However, it is supplemented by other knowledge (where relevant) and includes relevant information reviewed as part of the regional baseline assessment. At present, there are some gaps in data which limit the format and width of the assessment, and these are clearly highlighted.

Due to a relative lack of measured data within the Offshore Export Cable Corridor, a separate baseline report for this part of the Project has not been prepared. Information on baseline conditions along the Offshore Export Cable Corridor is contained within Appendix 10F: Regional Coastal Processes Baseline Description. Furthermore, for the end of the Offshore Export Cable Corridor closest to the Development Area, some of the information contained within this Development Area Baseline Description is relevant, particularly for those environmental parameters that are relatively homogenous in space. Between the Regional and Development Area baseline assessments, sufficient information is available to characterise the Offshore Export Cable Corridor baseline for the purposes of the required metocean and coastal processes assessment.

This document presents a summary of the baseline (existing) oceanographic and coastal processes environment at the Inch Cape Development Area through an analysis of the following topics:

- Section A.1.3 Bathymetry.

- Section A.1.4 Geology and surficial sediment cover, including sediment features (bedforms).
- Section A.1.5 Physical oceanographic conditions.
- Section A.1.6 Fluvial inputs.
- Section A.1.7 Sediment transport regime, including transport due to waves, currents and waves plus currents.

10A.1.1.2 Scope of Work

To deliver an assessment of the hydrodynamic and sediment regime at the Inch Cape Development Area.

10A.1.2 DATA SOURCES

10A.1.2.1 Introduction

A wide variety of sources have been used in this assessment. Development Area specific geophysical and metocean data sets have been extensively used, and these have been supported through inclusion of regional and Development Area specific data from elsewhere. Table 10A.1.1 summarises the data sources used.

Table 10A.1.1 Summary of major data sources used.

Data Source	Study/Data Name	Data Theme (s)	Data Location
Partrac	Metocean survey: Partrac, 2011. P1127.05.14.D001s03 - Forth and Tay Final Data Report - SeaEnergy Renewables.	Metocean monitoring data (waves, tides, wind, suspended sediment concentration, particle size data)	In and around Development Area
HR Wallingford	Review of existing information: HR Wallingford, 2010. Firth of Forth and Tay Developers Group, Collaborative Oceanographic Survey, Specification and Design. Work Package 1: Review of Existing Information. Technical Note DER4539/01. 17 September 2010.	Environmental baseline	East coast of Scotland Firth of Forth
Fugro	Geotechnical survey overview report: Fugro, 2011. Geotechnical Survey. J11099 – 1 September 2011, Geotechnical Report – Field Data.	Sedimentology; geotechnics	Development Area
iXSurvey	Geophysical survey overview report: iXSurvey Ltd, 2011. Report of Survey for Senergy S&G on behalf of SeaEnergy Renewables. Site Survey – Inchcape, Volume 1 – Survey Results. JN3508.	Sedimentology; goephysics	Development Area
SNH	Coastal Cells in Scotland (Ramsay and Brampton, 2009 a,b) Cell 1 St Abbs Head to Fife Ness Cell 2 Fife Ness to Cairnbulg Point	Shoreline processes	Regional

Data Source	Study/Data Name	Data Theme (s)	Data Location
BGS	1986. Tay Forth, Sheet 56°N-04°W, Seabed Sediments, 1:250,000 series (Graham, 1986). 1987. Tay Forth, Sheet 56°N-04°W, Quaternary Geology, 1:250,000 series (Stoker, 1987). 1986. Tay Forth, Sheet 56°N-04°W, Solid Geology, 1:250,000 Series (Cheshire et al., 1986). Holmes *et al.* (1993); Holmes *et al*. (2004) Pantin (1981); Gatliff *et al*. (1994)	Geology, sedimentology, sediment features, sediment thickness and sediment transport	Tay and Forth
UKHO	UKHO Admiralty Chart 1407 Montrose to Berwick-upon-Tweed. UK Admiralty Co-tidal and Co-Range Charts around the British Isles (1994-1996). 2009	Bathymetry & tidal streams Bathymetry Water levels & tidal data	East coast of Scotland
BODC	Data Inventory Deployments (www.bodc.ac.uk)	Current measurements Wave measurements Surge data	Various sites
SEPA	River Inflows (verbal communication) SEPA 2000 Water Quality in the Forth Estuary 1980 – 1999 Report TW 07/00 July 2000.	Freshwater inputs	Major rivers
CEFAS	WaveNet Data Inventory (www.cefas.co.uk)	Wave measurements	Firth of Forth
Coastal Councils	SMPs [http://www.angus.gov.uk/ac/documents/roads/SMP/default.html. http://cmis.eastlothian.gov.uk/CMISWebPublic/Binary.ashx?Document=4117. http://fifedirect.org.uk/minisites/index.cfm?fuseaction=page.display&siteID=C03E446A-0241-A6A5-7462DD169B215841&pageid=C040877C-B767-3F71-8454BE5167C5BC58]	Shoreline processes, coastal processes	Tayside; Fife; East Lothian
AMEC	See Appendix 12A: Benthic Ecology Baseline Development Area	Surface sediments	Development Area
PhysE	PhysE 2011 R485_Inch Cape Metocean Criteria Vo1 D1 (3). 25 pp.	Extreme oceanographic parameters	Project Area

Data Source	Study/Data Name	Data Theme (s)	Data Location
The Tay Estuary Forum	The Tay Estuary Coastal References Database (http://www.dundee.ac.uk/crsem/TEF/review.htm)	Geology; sedimentology; fluvial flows	Tay and Forth

10A.1.2.2 Data Gaps

At the time of writing several data gaps exist. These data gaps dictate the approach that has been taken for the metocean and coastal processes assessment. Table 10A.1.2 outlines the data gaps and summarises the chief consequences. The principal issue is that no measured data are (yet) available on certain key parameters that would be useful in performing a coastal processes assessment. Preferably a description of the sediment transport at the Development Area would be based on quantitative data which indicate the transport processes directly (for example, time series of near-bed sediment concentrations showing wave resuspension), rather than on a more theoretical assessment which contains assumptions. However, in the absence of such site-specific data, an alternative, semi-theoretical approach is possible. The Inch Cape Development Area is characterised dominantly by non-cohesive ('sandy') sediments, and the current state of knowledge in relation to the prediction of transport of these particular sediments allows for a robust semi-theoretical assessment. This sort of approach is often adopted where site-specific time series data on suspended sediment concentrations are not available, and is considered an appropriate and suitably robust method for the purposes of EIA.

Table 10A.1.2 Summary of current data gaps with associated consequences for production of a coastal processes baseline assessment.

Data Gap/Issue	Chief Consequence
No quantitative time series information on near-bed sediment concentrations;	The assessment of resuspension at the bed relies on a semi-theoretical judgment.
No measurement data on the frequency-magnitude of sediment resuspension	The assessment of the frequency-magnitude of sediment resuspension relies on a semi-theoretical judgement.

10A.1.3 BATHYMETRY

A hydrographic survey collected data on local water depths across the Development Area. General water depths within the Development Area boundary (~150 km^2) range from 34.5 m to 63.3 m LAT, plus a tidal range of up to ~5.5 m (IXSurvey, 2011) (Figure 10A.1.1). The general morphology of the seabed is convex in nature, extending from depths of 45 – 50 m at the northern area of the Development Area through a shallower region comprising a series of gravel banks, ridges and hollows in the central portion of the Development Area (depth centred on ~43 – 45 m) and then deepening the southern region of the area, with mean depths of ~50 m. Water depths > 50 m are limited to localised areas mainly in the north west and north east and on the periphery of the south eastern area, although there are a number of depressions within the southern part of the Development Area approaching 60 m in depth. Two distinctive transverse sand ridges are found at the northern area of the Development Area, and these form the shallowest parts of the Development Area. On a Development Area-wide spatial basis, the seabed can be considered largely flat (slopes < 0.5); steeper slopes, up to 5 ° (Figure 10A.1.1), are found only where sand waves are present (in the northern part of the Development Area) and on the slopes of localised hollows.

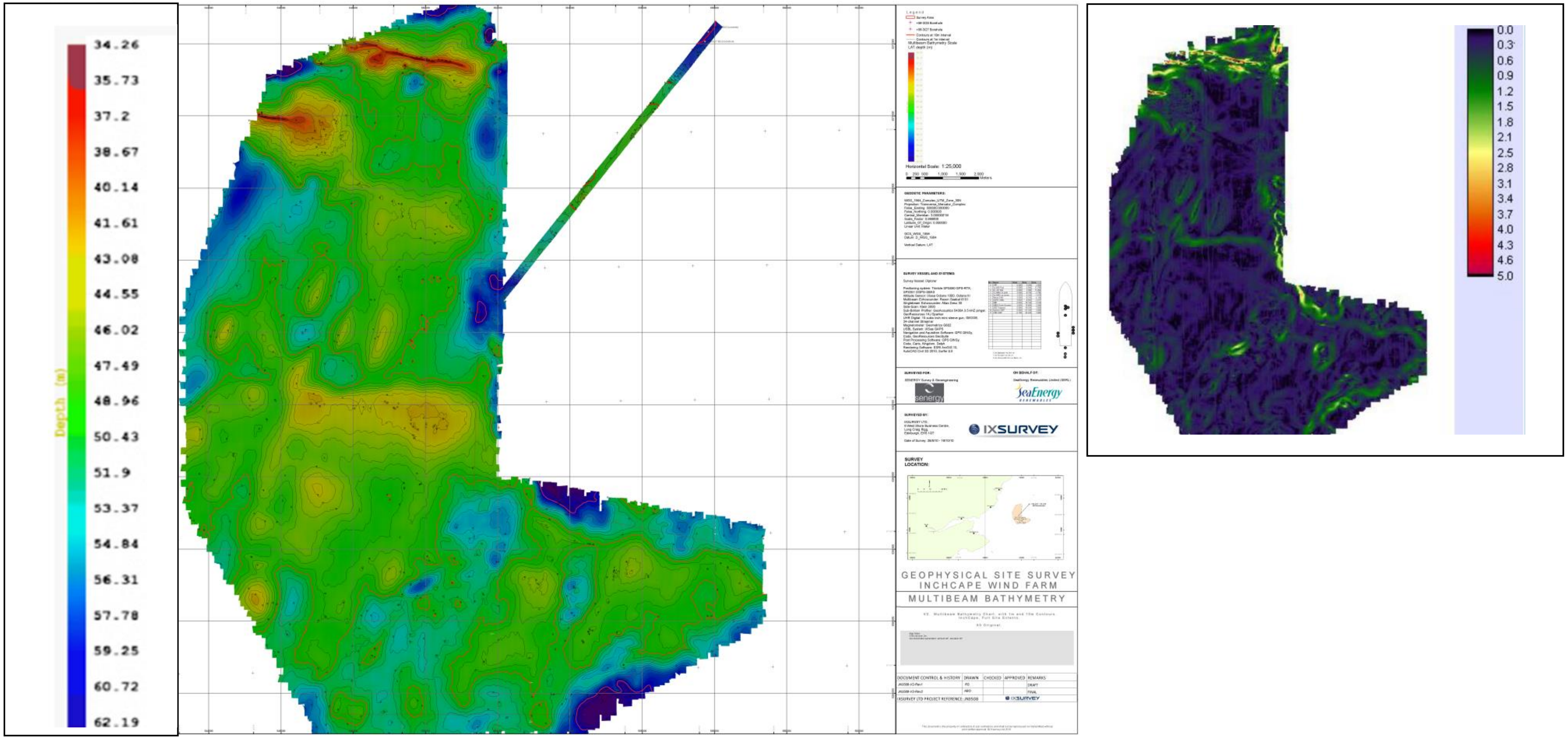


Figure 10A.1.1 Distribution of water depths (bathymetry) across the Inch Cape Development Area. Shown (inset) also is a bed slope. Source: Development Area Geophysical Survey (iXSurvey, 2011).

Frequency analysis of the depth data provides a distribution for the range of depths (Figure 10A.1.2). A summary of depth statistics is given in Table 10A.1.3. A representative value for a mean Development Area depth is ~50 m; the shallowest depth corresponds to the shallow sandwaves in the northwest of the Development Area.

Table 10A.1.3 Statistical summary of water depth data.

Statistic	Depth (m) LAT
Mean depth (m)	49.3
Minimum depth (m)	34.5
Maximum depth (m)	63.5
Modal depth (m)	49.3
Median depth (m)	49.3

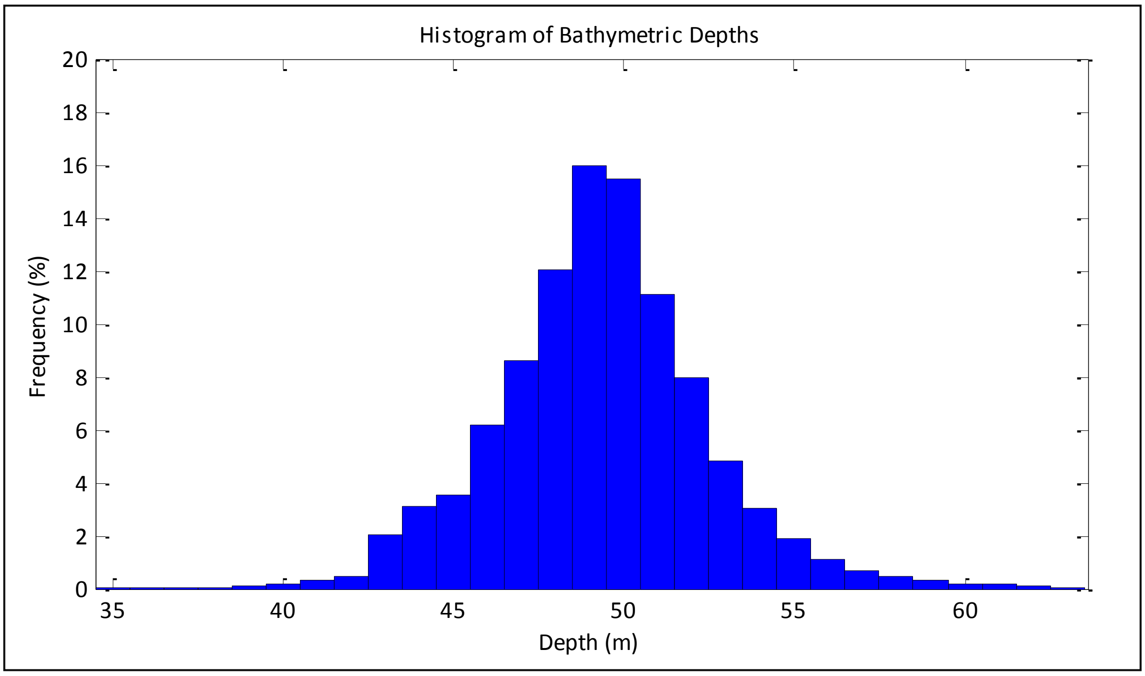


Figure10A.1.2 Distribution of water depths at the Inch Cape Development Area. Bin widths are 1 m.

10A.1.4 SEDIMENT COVER

10A.1.4.1 Introduction

Holmes, (1977) and Holmes *et al*. (2004) report Holocene (i.e. geologically recent) sediments comprising sand or gravelly sand present in a layer typically < 0.5 m thick across the Development Area, overlying Quaternary sediments. A side-scan sonar survey of the Inch Cape Development Area, which is a non-intrusive measurement (remote sensing) methodology for investigating seabed type, supports the above observations and reports two distinct acoustic reflectivity properties:

1. low reflectivity areas, which are interpreted as SAND; and
2. medium to high reflectivity areas which are interpreted as sandy GRAVEL.

10A.1.4.2 Surficial Sediment

The distribution of these sediment types across the Inch Cape Development Area derived from inspection of the acoustic data is given in Figure 10A.1.3. Sand is classified (following Wentworth; see Blott and Pye, 2001) as material between 0.063 and 2 mm; gravel is classified as material coarser than 2 mm up to and including boulder size material (~300 mm).

The sediments at the Development Area comprise a sand-gravel veneer. There is no exact correlation of sediment type with water depth; however, areas of gravel generally occupy shoal (shallower) areas. This is especially evident on the central, shallower region and within the south eastern area of the Development Area. In these locations megarippled sand is frequently found, likely a result of the presence of coarser sediment, whereas across more sandier areas of the Development Area megaripples are either absent or incipient. Gravel ridges or ribbons, elongated in the direction of flow, are found intermittently on in these two areas. Sand has been swept into several well-defined sandwave fields associated with larger sandbank features at the northwest of the Development Area; megarippled sand is also associated with these structures.

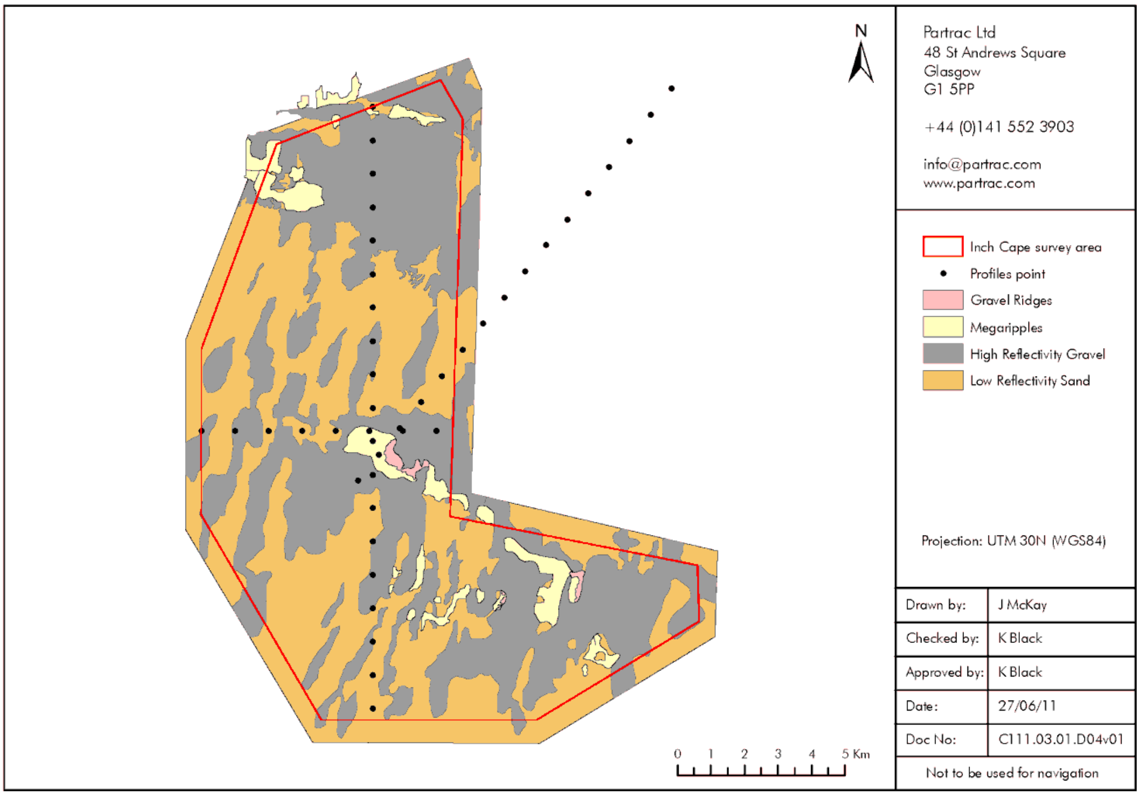


Figure 10A.1.3 Distribution of major sediment types and morphologies across the Inch Cape Development Area. Source Geophysical Survey.

In order to conduct a sediment mobility assessment for the Development Area it is necessary to have quantitative data on the specific range of particles sizes present on the bed. The hydrographic survey cannot provide quantitative data on the specific particle sizes comprising the seabed sediments as it is purely a non-intrusive methodology.

The geophysical survey was supplemented by an environmental (benthic) sampling programme which collected seabed samples from various locations across the Development Area (see Appendix 12A: Benthic Ecology Baseline Development Area). These samples have been analysed for the distribution of particle sizes present, and therefore form a useful quantitative dataset which can be compared with the acoustic classifications above to summarise sediment type for the Development Area. In total, 113 samples were collected across the Development Area and surrounding area at 97 sampling stations. Figure 10A.1.4 shows the results of the size analyses in the form of pie charts for each sampled location, and Table 10A.1.4 summarises quantitative data from the particle size analysis tests.

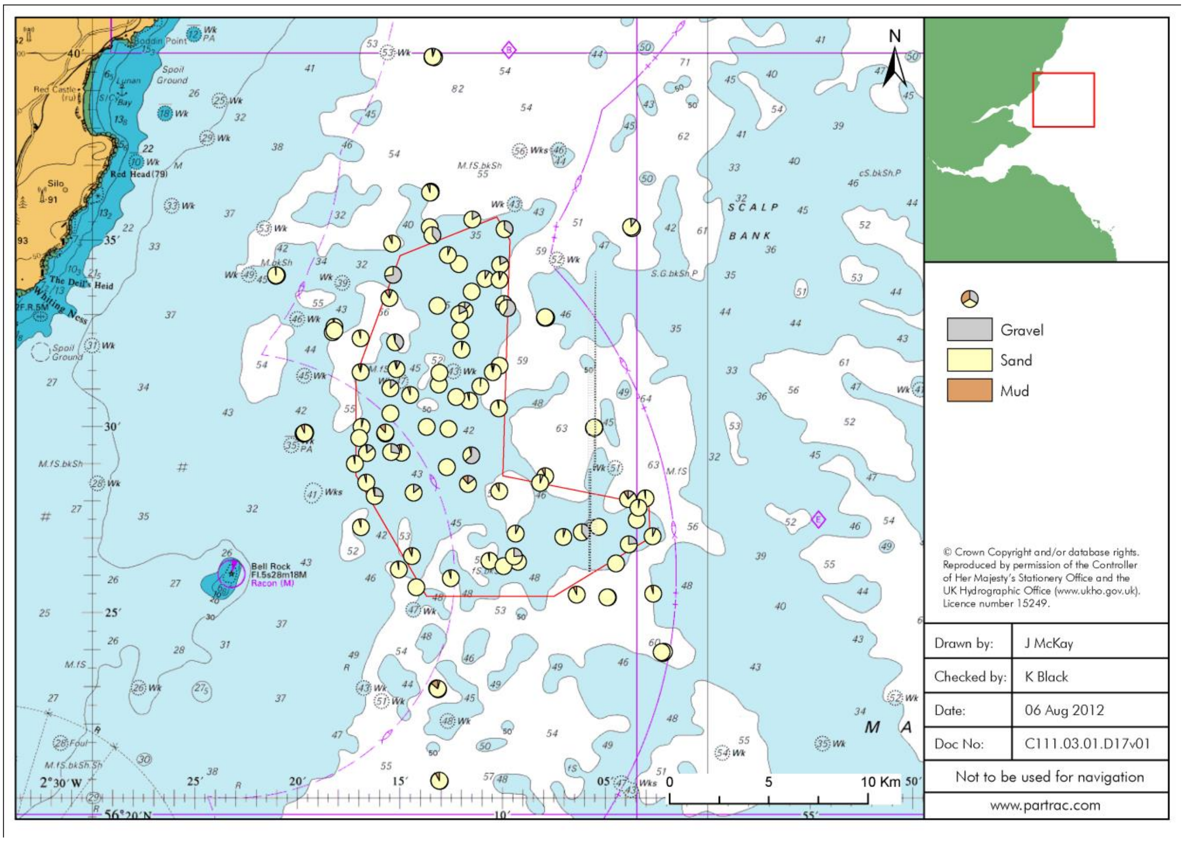


Figure 10A.1.4 Geospatial distribution of grain size (as gravel:sand:silt percent) within the Inch Cape Development Area. Source: Data re-processed from the Benthic Survey.

These data show that the dominant matrix across the Development Area is sand, with generally a minor mud fraction and a variable gravel component. Gravel is found in greater proportion in sediments on the shallower areas across the central (e.g. sample 71, gravel = 62.5%) and northern areas of the Development Area (e.g. sample 109, gravel = 72.4%). Within all non-gravel rich samples, sand forms >90% of the substratum, and generally the sand is moderately sorted. A statistical assessment of average, median grain size for the Development Area (excluding specifically the gravel-rich samples) gives a value of 320 μm, with a standard deviation of 67 μm. This indicates that the majority of the sand across the Development Area is MEDIUM sand (defined as 250 – 500 μm in diameter).

Where gravel is present in minor amounts is generally very fine to fine (2 – 8 mm), whereas in richer gravel deposits particle sizes can range up to ~20 – 30 mm, or even greater in isolated pockets.

Table 10A.1.4 Summary of particle size distribution data. Source: AMEC Benthic Survey (2011).

Sample	% Gravel	% Sand	% Silt	Median Grain Size (µm)	Folk Sediment Classification (Folk, 1954)
41	0.0%	100.0%	0.0%	352.3	Moderately Sorted Medium Sand
72	23.7%	76.3%	0.0%	384.0	Very Coarse Gravelly Medium Sand
66	13.9%	86.1%	0.0%	403.4	Coarse Gravelly Medium Sand
26	3.5%	96.5%	0.0%	337.2	Slightly Fine Gravelly Medium Sand
91	12.8%	87.2%	0.0%	300.8	Medium Gravelly Fine Sand
39	0.0%	99.2%	0.8%	286.2	Moderately Sorted Medium Sand
113	57.2%	42.2%	0.6%	4521.1	Sandy Medium Gravel
109	72.4%	27.6%	0.0%	38563.2	Sandy Very Coarse Gravel
105	0.0%	100.0%	0.0%	373.2	Moderately Well Sorted Medium Sand
64	17.4%	82.6%	0.0%	369.7	Medium Gravelly Medium Sand
107	0.0%	99.1%	0.9%	297.7	Moderately Sorted Medium Sand
25	12.2%	87.8%	0.0%	347.5	Fine Gravelly Medium Sand
63	5.6%	94.4%	0.0%	338.6	Fine Gravelly Medium Sand
24	0.0%	100.0%	0.0%	358.9	Moderately Well Sorted Medium Sand
53	8.8%	90.4%	0.8%	316.2	Medium Gravelly Medium Sand
79	17.3%	81.4%	1.2%	416.2	Fine Gravelly Medium Sand
80	6.6%	91.5%	1.9%	341.1	Fine Gravelly Medium Sand
58	74.4%	25.6%	0.0%	36022.2	Sandy Very Coarse Gravel
45	0.0%	100.0%	0.0%	312.6	Moderately Sorted Medium Sand
81	3.7%	93.1%	3.2%	314.5	Slightly Fine Gravelly Medium Sand
54	1.7%	98.3%	0.0%	322.7	Slightly Very Fine Gravelly Medium Sand
7	0.0%	96.6%	3.4%	256.2	Moderately Sorted Medium Sand
106	0.2%	99.8%	0.0%	309.5	Slightly Very Fine Gravelly Medium Sand
27	0.0%	99.2%	0.8%	285.1	Moderately Sorted Medium Sand
38	0.0%	100.0%	0.0%	380.6	Moderately Well Sorted Medium Sand
1	0.0%	100.0%	0.0%	317.0	Moderately Sorted Medium Sand
C7A	0.0%	88.7%	11.3%	116.6	Very Coarse Silty Very Fine Sand
C7B	0.0%	90.3%	9.7%	119.4	Moderately Sorted Fine Sand
C7C	0.0%	88.3%	11.7%	116.0	Very Coarse Silty Very Fine Sand

Sample	% Gravel	% Sand	% Silt	Median Grain Size (μm)	Folk Sediment Classification (Folk, 1954)
78	14.3%	83.8%	1.9%	328.2	Very Coarse Gravelly Medium Sand
28	4.1%	95.9%	0.0%	330.0	Slightly Fine Gravelly Medium Sand
44	5.4%	84.9%	9.7%	490.2	Coarse Gravelly Coarse Silty Coarse Sand
30	0.0%	99.1%	0.9%	342.7	Moderately Sorted Medium Sand
99	28.3%	71.7%	0.0%	354.3	Medium Gravelly Fine Sand
119	3.5%	91.2%	5.3%	246.2	Slightly Medium Gravelly Fine Sand
93	25.5%	71.3%	3.1%	347.2	Coarse Gravelly Medium Sand
22	0.0%	96.0%	4.0%	274.7	Moderately Sorted Medium Sand
71	62.6%	34.0%	3.4%	14402.8	Sandy Coarse Gravel
40	0.0%	96.0%	4.0%	288.4	Moderately Sorted Medium Sand
31	0.0%	100.0%	0.0%	377.6	Moderately Sorted Medium Sand
32	0.0%	99.3%	0.7%	322.0	Moderately Sorted Medium Sand
121	0.4%	94.1%	5.6%	287.4	Slightly Very Fine Gravelly Medium Sand
6	7.8%	88.5%	3.7%	285.7	Very Coarse Gravelly Medium Sand
21	40.8%	55.4%	3.8%	401.3	Sandy Very Coarse Gravel
8	0.0%	97.0%	3.0%	325.3	Moderately Sorted Medium Sand
11	0.0%	95.8%	4.2%	276.1	Moderately Sorted Medium Sand
55	7.0%	93.0%	0.0%	374.4	Coarse Gravelly Medium Sand
33	1.3%	92.3%	6.3%	280.1	Slightly Very Fine Gravelly Medium Sand
67	14.4%	74.0%	11.6%	292.7	Medium Gravelly Medium Silty Medium Sand
46	0.2%	93.1%	6.8%	197.3	Slightly Very Fine Gravelly Fine Sand
23	0.0%	96.9%	3.1%	308.2	Moderately Sorted Medium Sand
49	0.0%	97.0%	3.0%	283.2	Moderately Sorted Medium Sand
14	0.0%	92.7%	7.3%	278.2	Poorly Sorted Medium Sand
97	39.7%	60.3%	0.0%	968.7	Sandy Fine Gravel
83	4.5%	95.5%	0.0%	341.9	Slightly Very Fine Gravelly Medium Sand
68	0.0%	100.0%	0.0%	368.5	Moderately Sorted Medium Sand
69	0.0%	100.0%	0.0%	349.8	Moderately Well Sorted Medium Sand
82	2.8%	97.2%	0.0%	340.0	Slightly Fine Gravelly Medium Sand
34	0.0%	100.0%	0.0%	331.0	Moderately Well Sorted Medium Sand

Sample	% Gravel	% Sand	% Silt	Median Grain Size (µm)	Folk Sediment Classification (Folk, 1954)
57	23.0%	76.6%	0.4%	376.9	Very Coarse Gravelly Medium Sand

Sediment Quality (Contamination Levels)

Data on sediment quality i.e. concentrations of common chemical contaminants (Copper, TBT, PCB etc.) available for the Inch Cape Development Area are detailed in Appendix 12B: Contaminated Sediments Baseline.

10A.1.4.3 Sub-Surface Sediments

Holmes (1977) and Holmes *et al*. (2004) outline the vertical sequence of sediment layers across the Inch Cape Development Area (Table 10A.1.5). The vertical sequence of sediments, and their varying geological and hydraulic (sediment mobility) properties, is a key factor in the prediction of scour potential across the depth of any piled structures.

Table A1.1.5 Summary of approximate thicknesses of the major Quaternary formations at the Inch Cape Development Area. Source: Holmes (1977) and Holmes *et al*. (2004).

Approximate Thickness of Unit (m)	Unit	Anticipated Soil Description
>0.5m thick	Holocene	Sand or gravelly sand
Typically 0- 5m, locally up to 20m	Quaternary (Forth Formation, with sub-formations)	Predominatly SAND with clay and slit layers
<5 -10 m	Quaternary (West Bankie Formation)	Stiff to hand CLAY with interbeds of SAND and silty CLAY

Quaternary sediments, referred to as the Forth Formation and with typical thicknesses 0 - 5 m, underlie the Holocene sands and gravels (Table 10A.1.5). Beneath this is a sediment layer, also of Quaternary age, known as the Wee Bankie Formation which can reach up to 40 m in thickness. This comprises stiff boulder clay, interbedded with silt and sand layers. These sediments overlie mostly Triassic or Permian bedrock. Across the Development Area the thickness of the Quaternary sediments i.e. the depth to the rock head (a factor which impacts on scour prediction) is judged to be between < 10 m thick over the northern and southern areas of the Development Area, and 10-20 m over the central portion of the Development Area.

A geophysical survey (iXSurvey, 2011) was conducted to investigate the distribution of the rock layers and sedimentary formations across the Development Area in more detail, and this confirms the more general assessment provide above. Figure 10A.1.5 shows a contour plot of the thickness of the overlying Quaternary sediments i.e. the recent sediments + Forth Formation + Wee Bankie Formation. The thickness of these sediment formations ranges between 5 m and 20 m over large areas of the Development Area. Notably thicker formations are observed to the north and southeast of the Development Area. The maximum thickness is ~140 m. Figure 10A.1.6 shows a contour plot of the depth to the Wee Bankie formation i.e. it is equivalent to a plot of [Forth plus Holocene] formation thickness. The Forth formation is observed across the majority of the Development Area forming a blanket-like cover of variable thickness and variable sub-surface depth. This unit varies from muds and silty muds to interbedded sands and clays with components of pebble and shell. In the west the Forth Formation is only intermittently present as a thin veneer over the Wee Bankie Formation. In some localised areas where the Wee Bankie Formation is absent the Forth Formation directly overlies bedrock

The geophysical survey does not, in fact, differentiate the contemporary surficial sediment layer from the Forth Formation, and therefore the thickness of this unit across the Development Area cannot be determined. All that may be discerned are the specific locations where the underlying formations come close to the surface, where it may be surmised the thickness of the Holocene sediment cover is especially thin. This occurs in the western and south eastern regions of the Development Area; at these locations the Wee Bankie Formation as noted is present at, or very close to, the seabed.

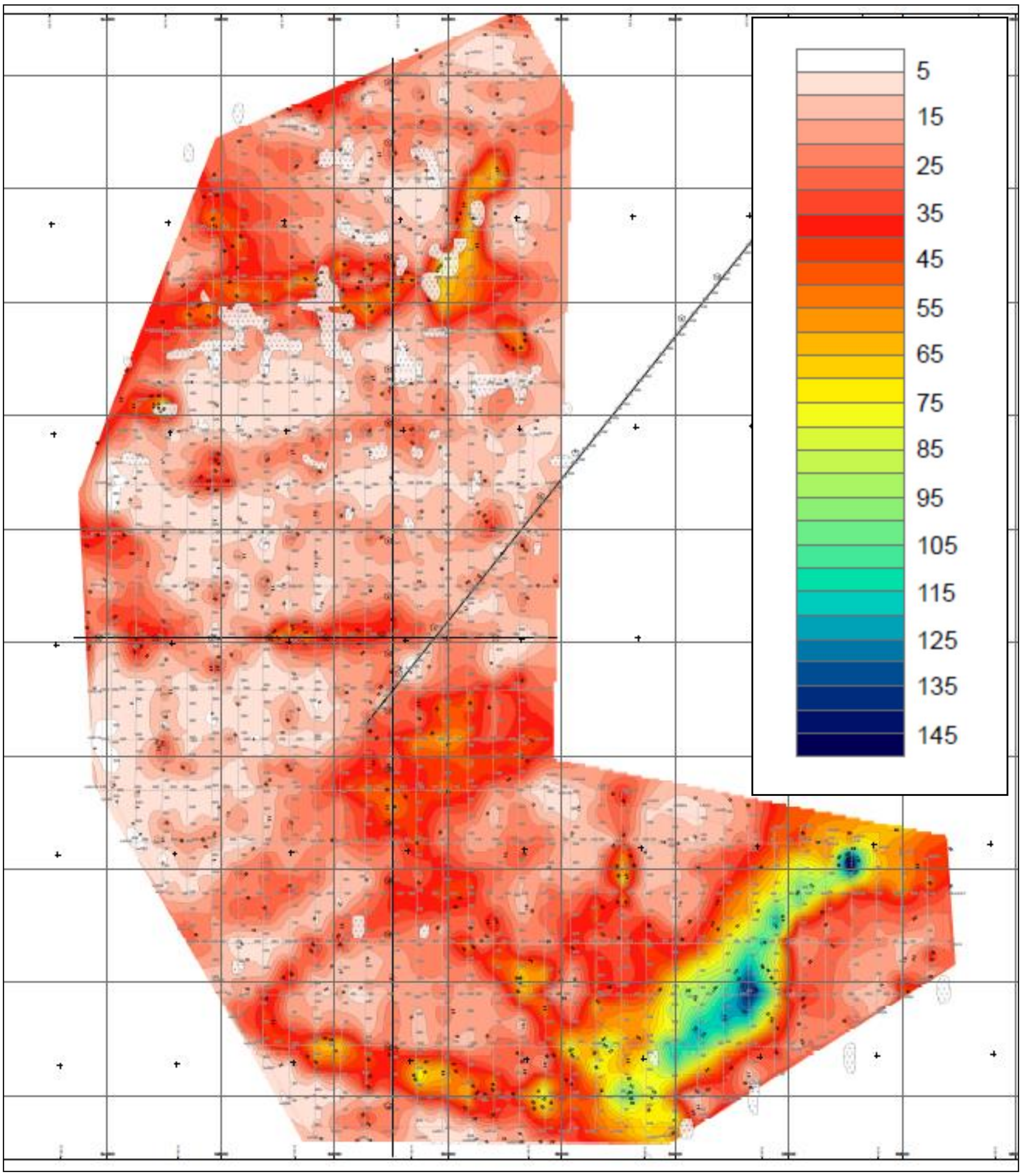


Figure 10A.1.5 Colour contour of the depth to rockhead (i.e. the thickness of all Quaternary sediment cover: the recent sediments+Forth+WeeBankie). Legend units are metres. Source: Geophysical Survey.

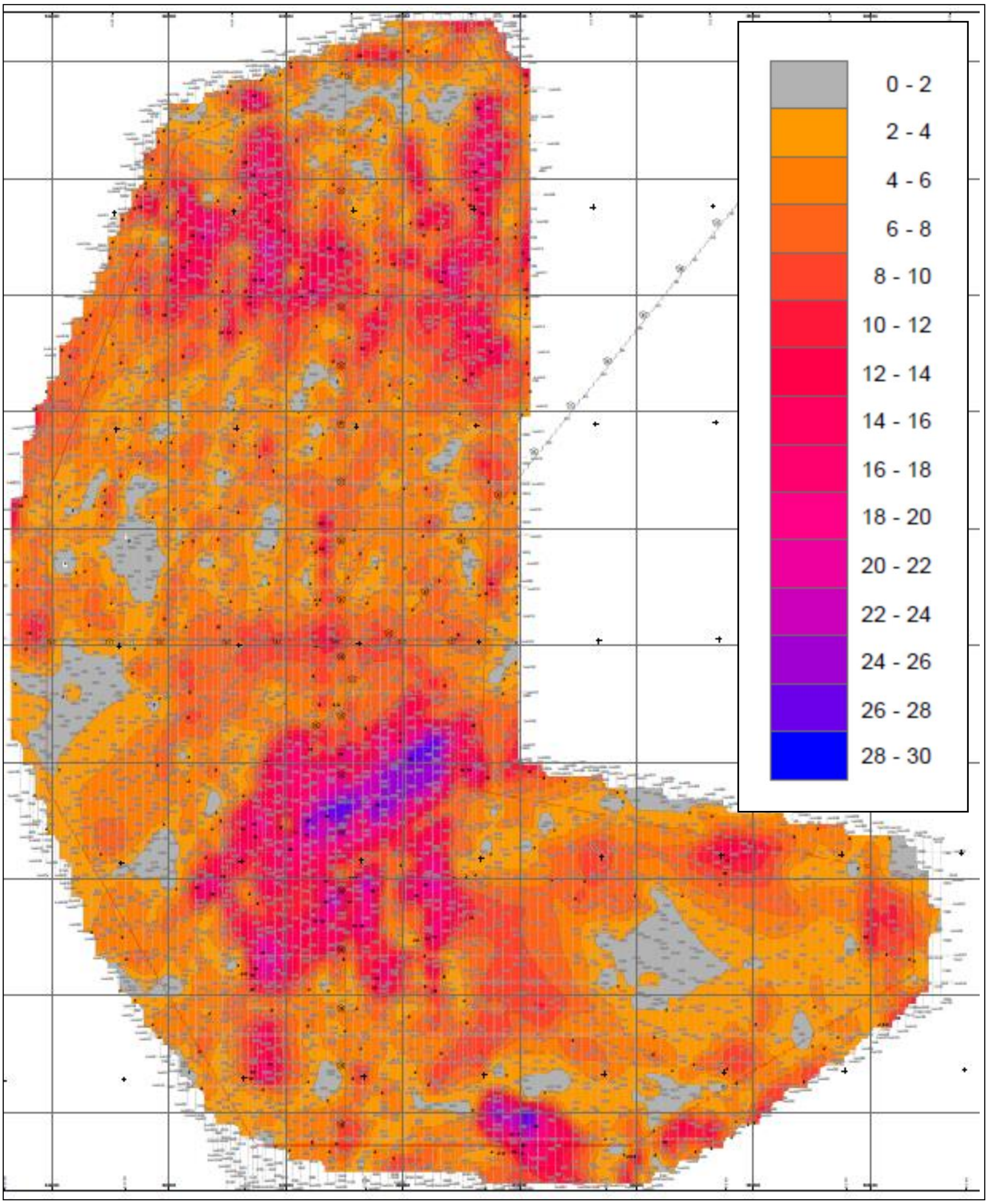


Figure 10A.1.6 Colour contour plot of the depth to the Wee Bankie formation. This is equivalent to representing the thickness of [Holocene + Forth] sediment formations. Legend units are metres. Source: Geophysical Survey.

The grain size of the sediments comprising the differing vertical formations, which form primary input data into any scour potential analysis, can only be deduced from the physical analysis of samples collected through boreholes at the Development Area. To date, six boreholes have been drilled at the Development Area, but the results from physical analyses were not available in time to assimilate the data for this report. However, there is a British Geological Survey borehole (+56-3/27) approximately 15 km from the Inch Cape Development Area in a northeast direction in which some semi-quantitative sediment descriptions are presented.

Table 10A.1.6 Down-core geological description and inferred grain size statistics. Source: BGS Borehole +56-03_27_BH.

Depth	Geological Description	Inferred Particle Size Range (μm)
Holocene (surficial) 0 – 1.5 m	Fine-medium, poorly sorted sand, 85% quartz, 10% CO_3	0.125 – 0.5 mm
Forth 1.5 – 6 m	Silty clay with pebbles, large shell fragments (stiff brown clay)	0.001 – 63 μm (matrix)
Wee Bankie> 6 m	Pebbly, silty, sandy till (boulder clay)	0.02 – 60 mm

10A.1.4.4 Bed Features

A side-scan sonar survey of the Inch Cape Development Area was undertaken (iXSurvey, 2011). This is a non-intrusive measurement methodology used for investigating seabed type and for definition of bedforms on the surface of the bed. A record from the side scan sonar is presented in Figure 10A.1.7.

The surficial sediments within the Inch Cape Development Area exhibit occasional megaripples and less frequently sand waves. This is consistent with a regional assessment (Graham, 1986 Tay Forth, Sheet 56°N-04°W, Seabed Sediments map) where there is evidence of sinuous and linear sandwaves / megaripples being present across the seabed to the west of Inch Cape.

Sand has been swept into several well-defined sandwave fields at the northwest of the Development Area (Figure 10A.1.3). Megaripples are an intermediate scale of bedform[1] and are observed to vary between 0.1 m and 0.5 m in height with wavelengths approximately 9 m to 17 m. Megaripples are found often in shallow regions (~43 – 48 m), often in association with gravel ridge deposits (Figure 10A.1.7; Pantin and Evans, 1984), but are also associated with the two large scale sand wave features in the northwest of the Development Area. The association with the periphery of large sand waves is well known (Pantin, 1981). An in depth analysis of the geophysical survey data (to support biotope definition) shows more firmly that megaripples are associated with all slope regions covered in sand and < 50 m depth.

Across the sandier areas of the Development Area, megaripples are either absent or incipient. Across the Development Area their general orientation is normal to the principal tidal axis. Although no data on bedform symmetry is available from the hydrographic survey, this alignment suggests that these structures are most likely to be tidally formed. However, at the Development Area dominant wave direction is parallel to that of the principal tidal axis and therefore these bed features could potentially be due also to nearbed wave orbital velocities.

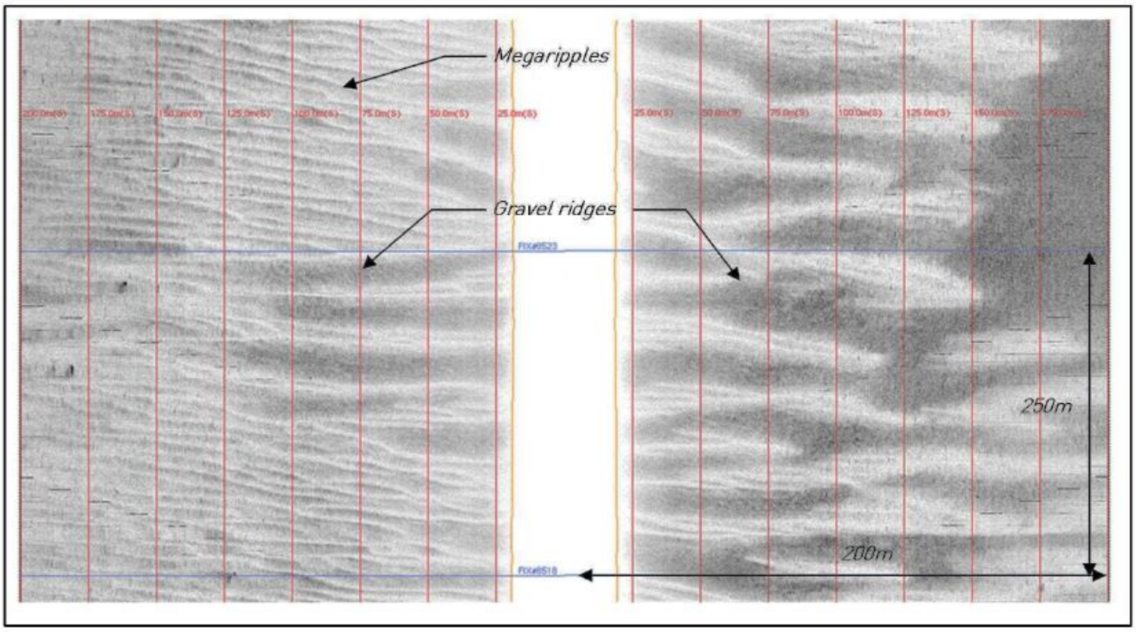


Figure 10A.1.7 Side scan sonar showing mega-ripples and gravel ridges (Line IncA041). Source: iXSurvey Geophysical Survey (2011).

1 McCave (1971) defines megaripples as of height up to 3 m, and wavelength of 0.6 to 30 m.

Gravel ridges or ribbons are found intermittently on in these two areas; megarippled sand is also associated with these structures (Figure A.1.7).

The resolution of the survey is insufficient (due to vertical noise level limitations) to differentiate whether the widespread areas of sand are rippled or featureless.

Two significant sandbanks are also present within the Development Area. They strike at approximately ESE/WNW i.e. not parallel to the tidal axis, and have a relief of approximately 17 m and 12 m above the surrounding seabed. The slight asymmetry of these features suggests a south to north transport direction. The northern most feature is approximately 3 km in length of which slightly over 2 km is within the confines of the Development Area boundary. A similar albeit much smaller sandwave is located in the south eastern area of the Development Area; its length is 1.9 km with relief approximately 3 m.

10A.1.5 PHYSICAL OCEANOGRAPHIC REGIME

10A.1.5.1 Introduction

A metocean data acquisition programme, commissioned by the Forth and Tay Offshore Wind Developers Group (FTOWDG) consortium members ICOL and NNG, collected data on current magnitudes and wave parameters at the Inch Cape Development Area (Partrac, 2011). Data were collected using wave buoys and acoustic current meters continuously through the period 10.12.09 – 12.07.10. No digital time series data were acquired on either near-bed or water column suspended sediment concentrations. The precise location of oceanographic monitoring equipment within the Inch Cape Development Area boundary is shown in Figure 10A.1.8 and detailed in Table 10A.1.7. Table 10A.1.8 summarises the wave and current statistical data from this monitoring campaign.

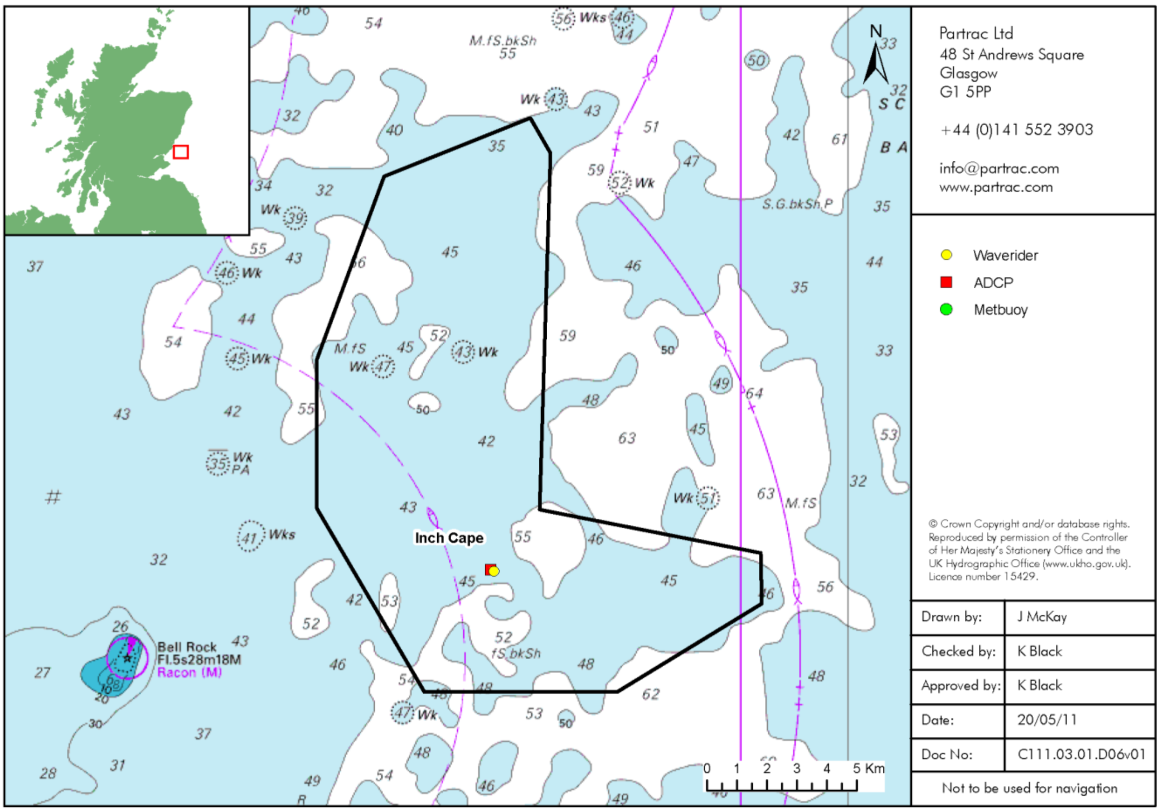


Figure 10A.1.8 Deployment locations of the oceanographic monitoring equipment at the Inch Cape Development Area. Source: Oceanographic monitoring campaign.

Table 10A.1.7 Location details for the oceanographic monitoring equipment within Inch Cape Development Area.

Development Area	Instrument	Deployment Date/Time (UTC)	Latitude (WGS84)	Longitude (WGS84)	Water Depth (m)
Inch Cape	Waverider	10/12/09 13:30	56° 27.539 N	002° 11.422 W	52
Inch Cape	ADCP	10/12/09 13:10	56° 27.575 N	002° 11.516 W	52

Table 10A.1.8 Summary of oceanographic statistical data at the Inch Cape Development Area from the oceanographic monitoring campaign.

Parameter	Value
Maximum Significant Wave Height – Hm0 (m)	6.24 m
Mean Significant Wave Height – Hm0 (m)	1.18m
Modal Peak Direction Dir_p (°)	NNE
Modal Wave Period – Tz (s)	5.01
Mean Wave Period – Tz (s)	4.85
Maximum Wave Period – Tz_{max} (s)	9.04
Minimum Wave Period – Tz_{max} (s)	2.36
Maximum Depth Averaged (Spring) Current Velocity ($m\ s^{-1}$)	1.05 $m\ s^{-1}$
Maximum Depth Averaged (Neap) Current Velocity ($m\ s^{-1}$)	0.36 $m\ s^{-1}$
Mean Depth Averaged Current Velocity ($m\ s^{-1}$)	0.28 $m\ s^{-1}$
Principal Current Axis (°)	NNE / SSW

In addition, an extreme parameter value analysis has been performed on the collected wave and current data (PhysE, 2011). This analysis derives the values of specific parameters (e.g. significant wave height, mean sea level) for specified return periods (e.g. 1 in 1 year, 1 in 10 year return periods). These are summarised in Table 10A.1.9. Together the data in these two tables provide a robust assessment of the oceanographic conditions at the Development Area.

Table 10A.1.9 Extreme oceanographic conditions expected across the Inch Cape Development Area from an analysis of the oceanographic monitoring data. Source: PhysE (2011).

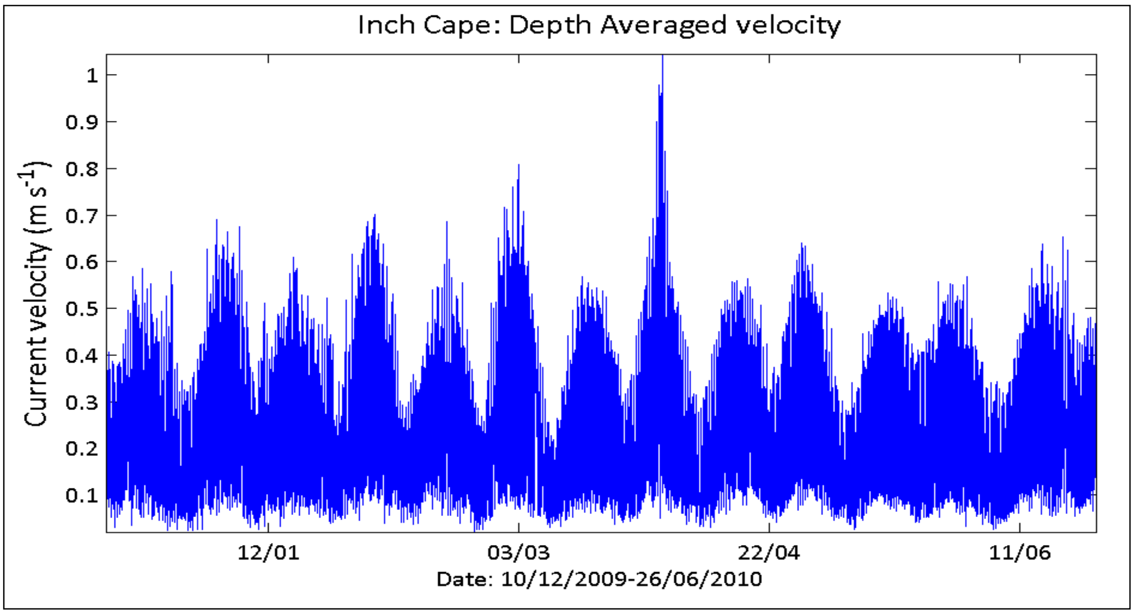
Return Period (Years)	Hm0 (m)	H_{max} (m)	T_z (central) (s)	Depth Averaged Total Current Speed@0.01% water depth (m s^{-1})	Notes
1	6.0	10.5	7.8	0.55	Depth mean current associated with 100 yrH_{max}=0.89 m s^{-1}
10	7.4	13.0	8.7	0.59	
50	8.4	14.7	9.3	0.62	
100	9.8	15.4	9.5	0.63	

10A.1.5.2 Tidal Currents

Overview

The tidal currents are strongly rectilinear in form with a principal tidal axis oriented N-NNE / SSW (Figure 10A.1.9). Peak (depth-averaged) current velocities can reach ~1.05 m s^{-1}, but these currents largely are < 0.6 – 0.7 m s^{-1}. The value observed of 1.05 m s^{-1} is likely due to a concurrent surge current or significant wind drift, or possibly is contaminated by wave-induced currents. A storm is known to have coincided with this moment in time.

Corresponding peak Neap current magnitudes are ~ 0.3 - 0.4 m s^{-1}. Fortnightly variation is evident in the Spring-Neap cycle in terms of peak currents; these are seen to differ between the same tidal stage. This variation will have consequences for sediment entrainment and transport.



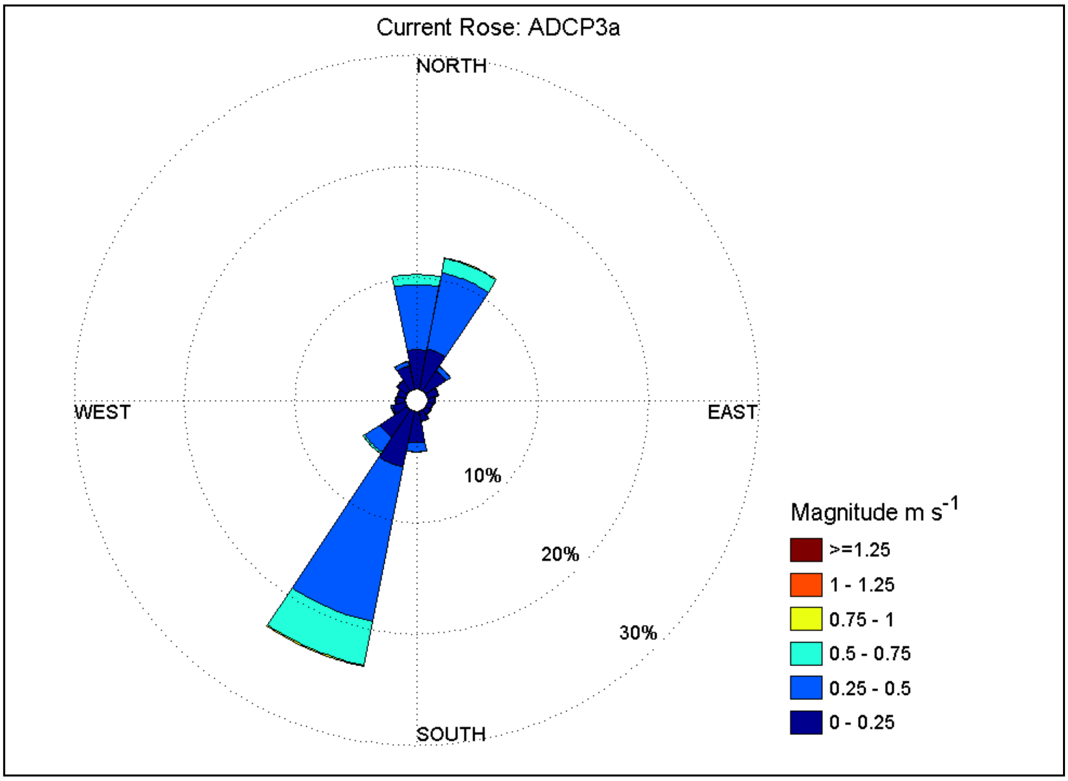
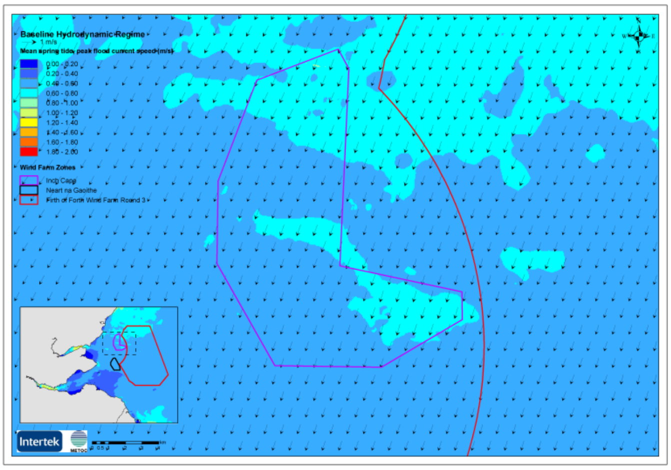
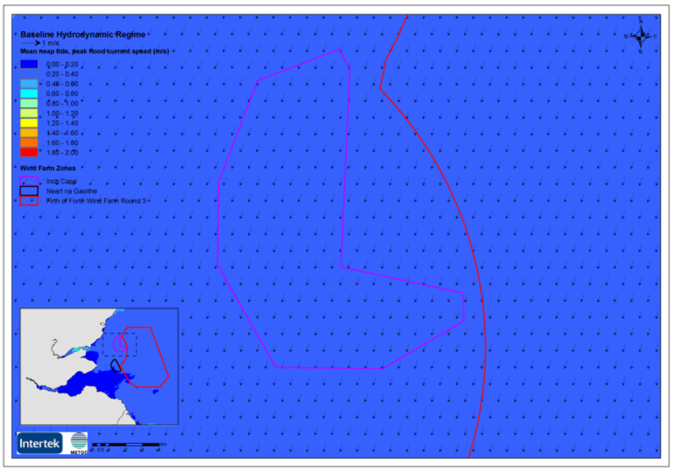
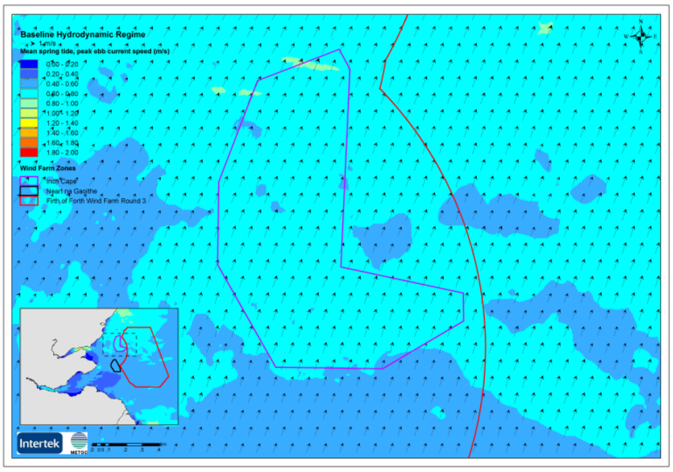
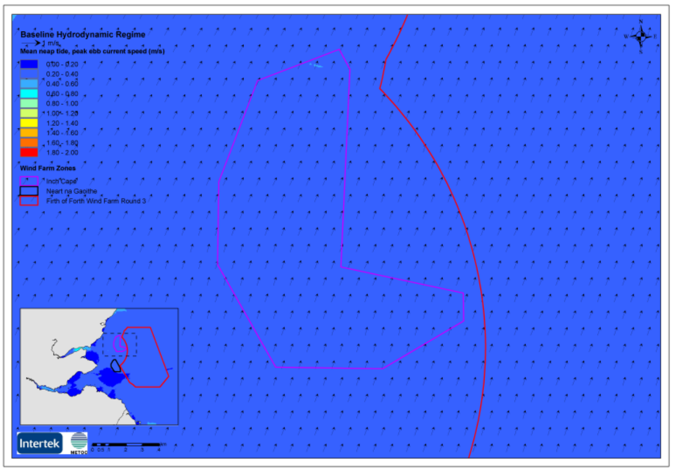


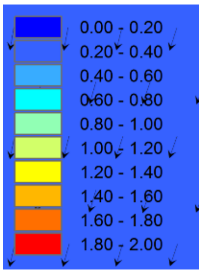
Figure 10A.1.9 Time series (upper panel) and polar plot (bottom panel) representation of the tidal currents at the Inch Cape Development Area. The polar plot depicts both the current magnitude, frequency and direction in a single plot.

An understanding of the spatial distribution i.e. the uniformity, of currents across the Development Area is provided through use of the Forth and Tay Modelling System[2]. The bathymetry data (Figure 10A.1.2) are incorporated within the model and thus predictions of tidal and wave processes at the Development Area reflect Development Area bathymetric gradients and features. The uniformity (or otherwise) of currents across the Development Area is central to understanding any differences in sediment transport across the Development Area. Differences may arise due to such factors such as varying water depth, changes in seabed slope and the presence of medium to large scale bedforms and bed features. Tidal current vectors, which show the direction of the current and the magnitude (proportional to arrow length), are presented for peak currents during flood and ebb for Spring and Neap tides (Figure 10A.1.10).

For Neaps, it is clear that both current magnitudes (0.2 to 0.4 m s^{-1}) and flood-ebb current direction across the Development Area are uniform and consistent. Similarly, the spatial current field for the Spring ebb period for both current magnitude and direction is uniform and consistent. However, during the Spring flood regions of higher velocity (0.6 – 0.8 m s^{-1}) are found along the central east-west/south-east trending ridge and to the northern extremity of the Development Area (the remainder of the Development Area is characterised by velocities in the range 0.6 – 0.6 m s^{-1}). These regions are thought to be more gravelly (Figure 10A.1.3; Figure 10A.1.4).

2 The FTMS is a high resolution dynamic modelling system which uses an unstructured flexible mesh. It is a sophisticated two-dimensional modular based modelling system, and has the capacity to run both hydrodynamic and spectral wave models. It has within its build the detailed Development Area bathymetry from survey and it may be used to predict the physical properties of tidal currents and waves, and the interactions between these, for any specified area. A flexible mesh model has the advantage of using a spatial varying resolution, so that the complex bathymetries and coastal topographic features can be sufficiently resolved by the model.. Further details are presented in Appendix 10C.

	
Spring tide, peak flood	Neap tide, peak flood
	
Spring tide, peak ebb	Neap tide, peak ebb



Current Velocity m s^{-1}

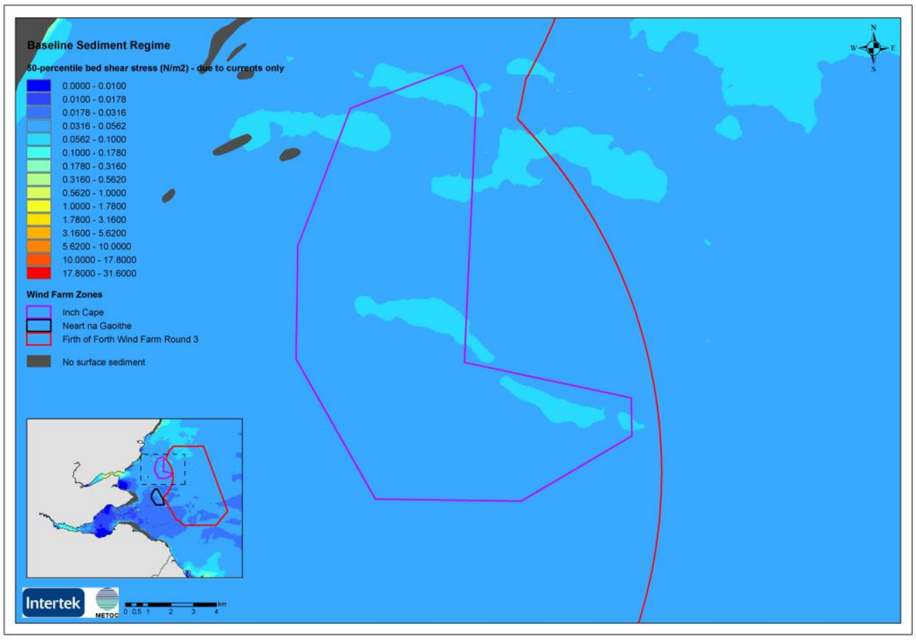
Figure 10A.1.10 Spatial distribution of peak flood and peak ebb currents across the Development Area for peak Springs and Neap tides. Source: FTMS.

Tidal Current Bed Stress

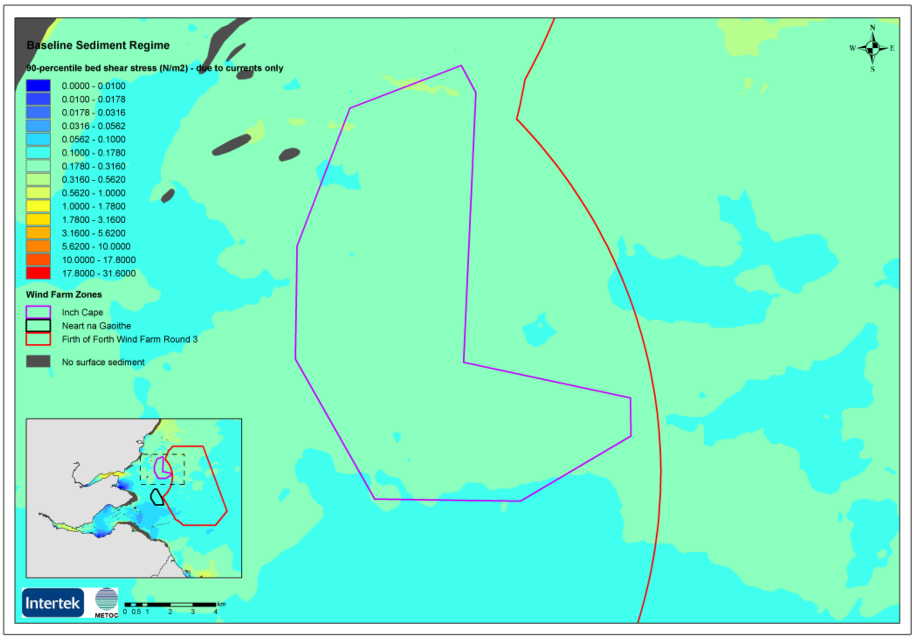
The motion of the tidal currents exerts a frictional drag ('bed stress', $\tau_{0current}$) on the bottom sediments, and this is responsible for inducing sediment transport. The stress at the bed is a function of both the flow velocity, the roughness of the sediment-water interface and to a lesser extent water depth. Greater turbulence, and therefore greater stress, is generated over coarser sediments. The distribution of bed stress across the Development Area (computed using the FTMS) is presented in Figure 10A.1.11. An understanding of the spatial distribution i.e. the uniformity, of bed stress across the Development Area is central to an evaluation of sediment transport potential.

The 90th percentile $\tau_{0current}$ data indicate the maximum bed stress experienced by sediments across the Development Area (i.e. during peak Spring tides). With the exception of lower values at a localised region to the north-east and along the southern boundary of the Development Area, $\tau_{0current}$ = 0.316 – 0.562 N m^{-2}) across the greater proportion of the Development Area.

The 50th percentile $\tau_{0current}$ data show that stress is non-uniform across the Development Area, with higher stresses (0.100 – 0.178 N m^{-2}) over the shallower central ridge and in areas at the northern part of the Development Area.



Current bed stress 50th percentile



Current bed stress 90th percentile

Figure 10A.1.11 Spatial distribution of current bed stress across the Development Area for two percentile values. Source FTMS.

Tidal Asymmetry

Tidal asymmetry is where the currents are different in magnitude and duration for consecutive flood – ebb tides. Asymmetries such as this can drive a residual net direction to the sediment transport which to a first order is in the direction of the stronger of the two currents. At the Inch Cape Development Area flood currents are stronger than the ebb currents (Figure 10A.1.12), with the difference being slightly more pronounced for Neap tides. The ratio of flood to ebb tide current magnitude for Springs is 1.4 whereas that for the Neaps is 1.6. The durations of these respective tide phases is given in Table 10A.1.10.

Such asymmetry can drive a residual (i.e. net) sediment transport in the flood (i.e. southerly) direction for both bedload and suspended load sediments. Although there is no information of megaripple symmetry from the geophysical survey data, their crest orientation indicates that they are probably tidally formed and thus it is likely - given these hydrodynamic conditions - which they are asymmetric with steeper lee slopes facing south.

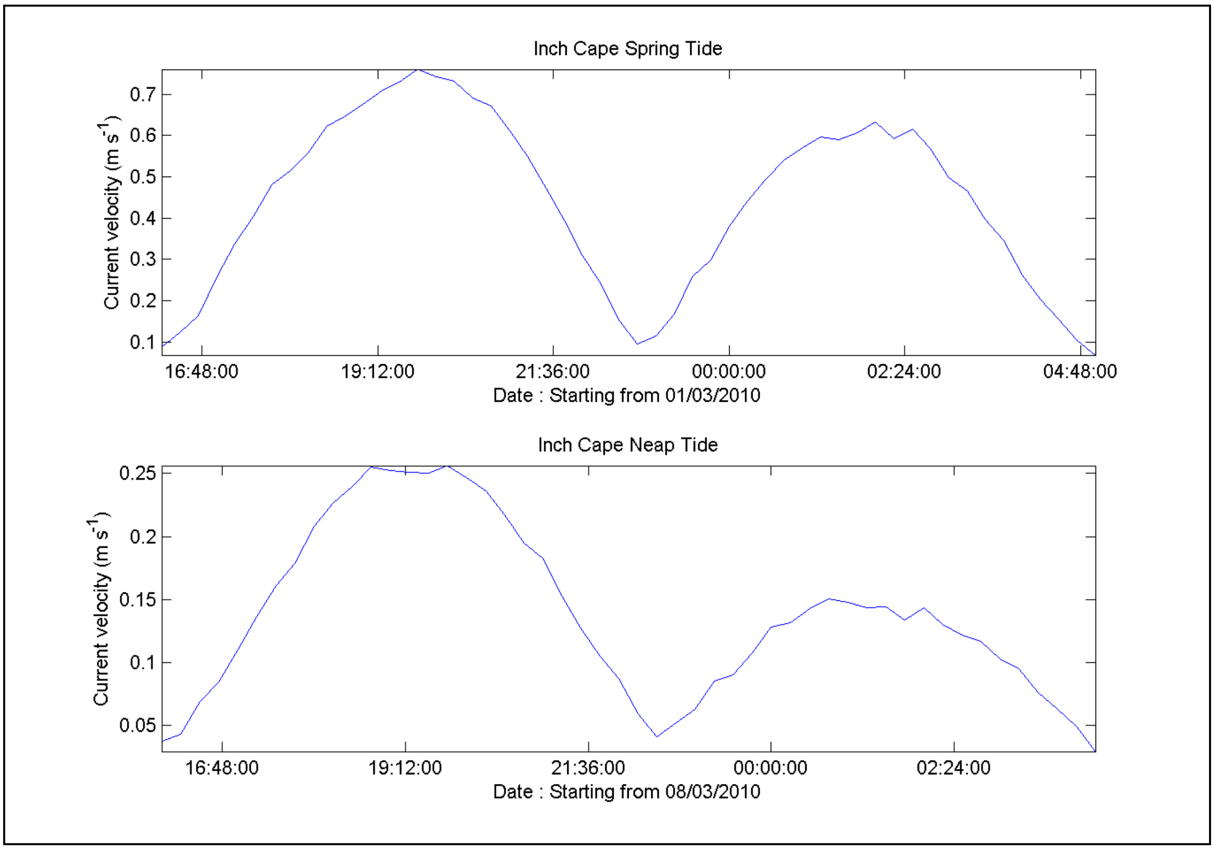


Figure 10A.1.12 Current velocity magnitudes during individual flood and ebb tides for Spring tides (upper panel) and Neap tides (lower panel).

Table 10A.1.10 Durations of flood and ebb phases for Spring and Neap tides.

	Duration (hrs)	
	Flood	Ebb
Spring	6.25	6.50
Neap	6.50	6.75

Tidal Excursion Distances

Figure 10A.1.13 shows the tidal excursion distances during the Spring tides. These represent the net horizontal distance a water particle moves during a tidal cycle, and the values for the Spring tide represent the maximum distances possible. Distances during Spring tides are 8.7 km during flood tides and 7.2 km during ebb tides. Equivalent excursion distances are naturally less for the Neap tide and are 3 km during flood tides and 2 km during ebb tides. Knowledge of these distances is central to several areas: it provides an understanding of the maximum distances resuspended sediment will be transported away from their source .g. during scour and release around structures. It is also important to assessments of the fate of any contaminants which might also be resuspended, and it will provide an indication of the ‘residence time’ for other components e.g. river sediments, which may be transported into the Inch Cape Development Area boundary.

Figure 10A.1.14 shows the extent of tidal excursion distances for both Springs and Neaps on a map which enables a good visual assessment of these distances in relation to the Development Area boundary and surrounding sea area.

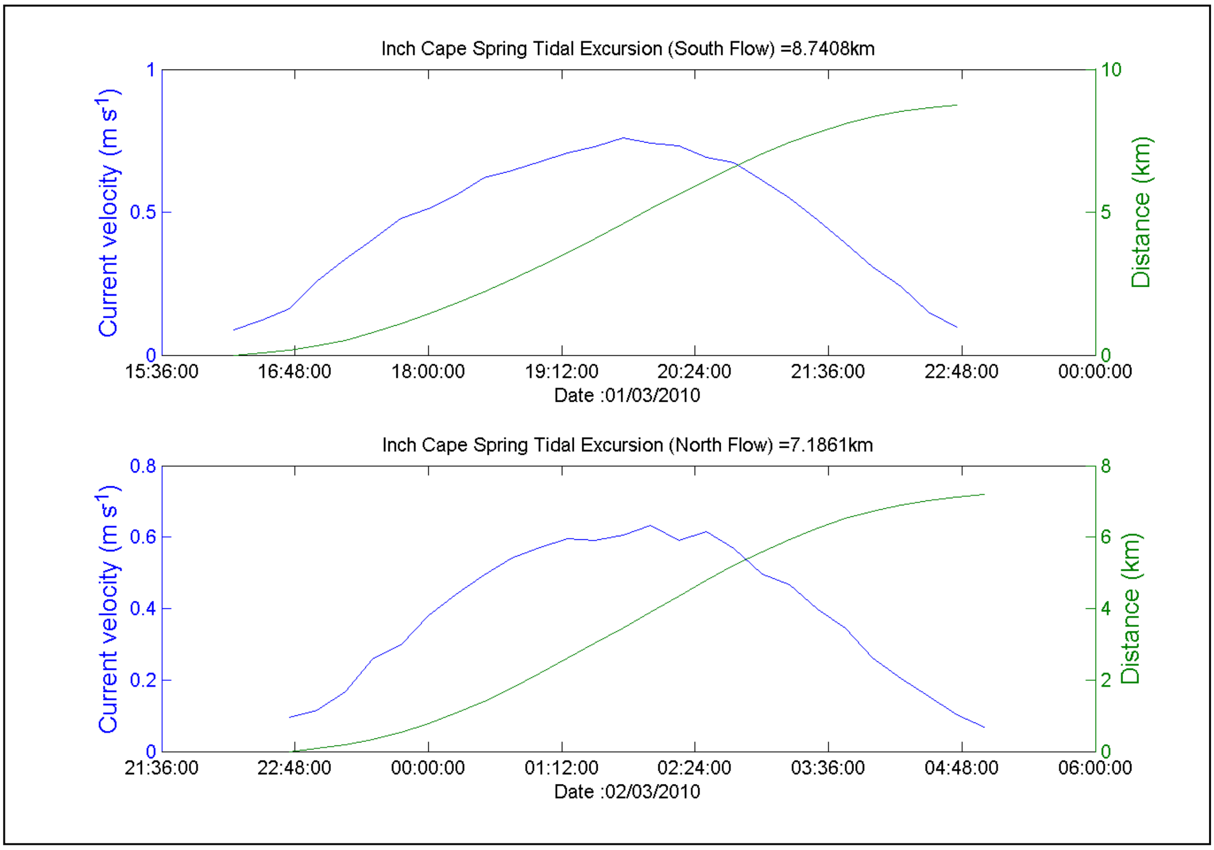


Figure 10A.1.13 Tidal excursion distances during flood (north flow) and ebb (south flow) tides during the Spring tide phase.

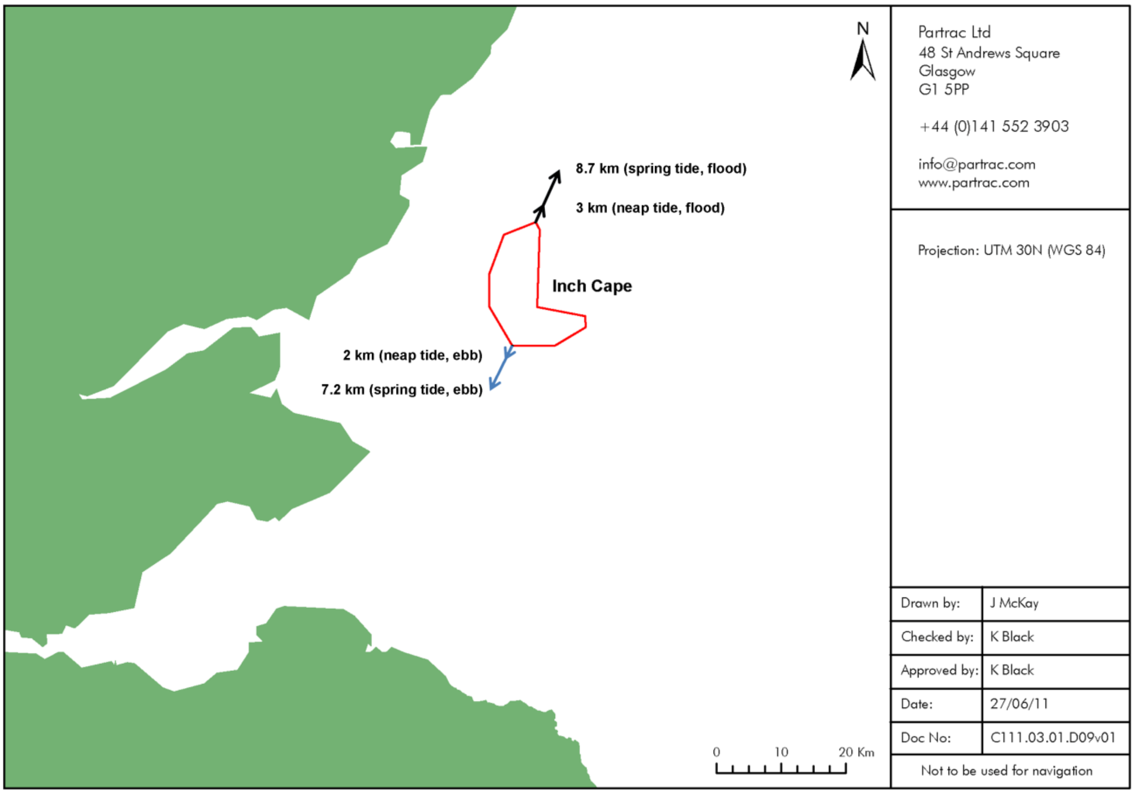


Figure 10A.1.14 Graphical representation of the Spring-Neap tidal excursions distances from the north-eastern and south-western boundaries of the Inchcape boundary.

10A.1.5.3 Non-Tidal Currents

Superimposed on the regular tidal behaviour, various random non-tidal effects may be present. Many of these non-tidal effects originate from meteorological influences. Persistent winds can generate wind-driven currents, set-up water levels and develop sea states that lead to wind-wave generation. The peak measured (depth-averaged) current velocity of 1.05 m s^{-1} at the Inch Cape Development Area, which is significantly above the mean peak Spring tide current magnitude (~0.6 – 0.7 m s^{-1}), is likely a function of such influences. Atmospheric pressure variations can also depress or raise the water surface to generate positive or negative surges, respectively, and surges can give rise to enhanced bottom current flows. Surges are formed by rapid changes in atmospheric pressure with an inverse relationship, i.e. low atmospheric pressure raises the water surface (positive surge) and high atmospheric pressure depresses the water surface (negative surge). These effects can cause water levels to fluctuate considerably above or below the predicted tidal level. The enhancement of bottom currents is not entirely understood by scientists, and it is not possible to predict (using simple approaches) the effects of coastal tidal surges on bottom currents.

Table 10A.1.11 lists the top ten positive and negative surges obtained from existing tidal records at Leith. The maximum surge measured is 1.38 m (positive) i.e. local water levels were this amount above tidally expected values. At the Inch Cape Development Area such a surge would generate a difference in local water depth of ~2-3 per cent.

Table 10A.1.11 Top ten positive surges recorded at Leith port.

Date and Time	Surge (m)	Date and Time	Surge (m)
TOP 10 POSITIVE		TOP 10 NEGATIVE	
1989/02/14 02:00	1.38	1998/12/27 00:30	-1.36
1990/02/20 01:00	1.30	1996/11/06 08:30	-1.07
1998/11/10 02:00	1.26	1998/11/09 12:45	-0.87
1997/02/20 05:15	1.25	1996/03/12 07:00	-0.87
1993/02/20 22:30	1.15	1981/11/20 16:00	-0.85
1995/01/10 00:45	1.14	2006/10/26 17:30	-0.83
1991/12/19 20:00	1.13	1995/01/31 05:15	-0.80
1993/01/17 17:00	1.07	1993/01/24 00:15	-0.80
2006/01/11 07:15	1.06	1994/01/26 21:45	-0.79
2000/01/30 02:30	1.03	1994/01/29 12:30	-0.78

10A.1.5.4 Wave Regime

Overview

Time series plots for the chief wave parameters (significant height, peak period, direction) are presented in Figure 10A.1.15. The time series wave records extend through the winter months through to June, and the greater frequency of storms during winter months is clear; winter storms generate frequent higher energy episodes with significant heights approaching 5 m. In comparison, heights during summer months rarely exceed 2 m. In terms of generation of sediment transport it is the magnitude and duration of the most energetic events that drive sediment motion at the seabed. However, whether wave energy penetrates to the seabed is also a function of wave period.

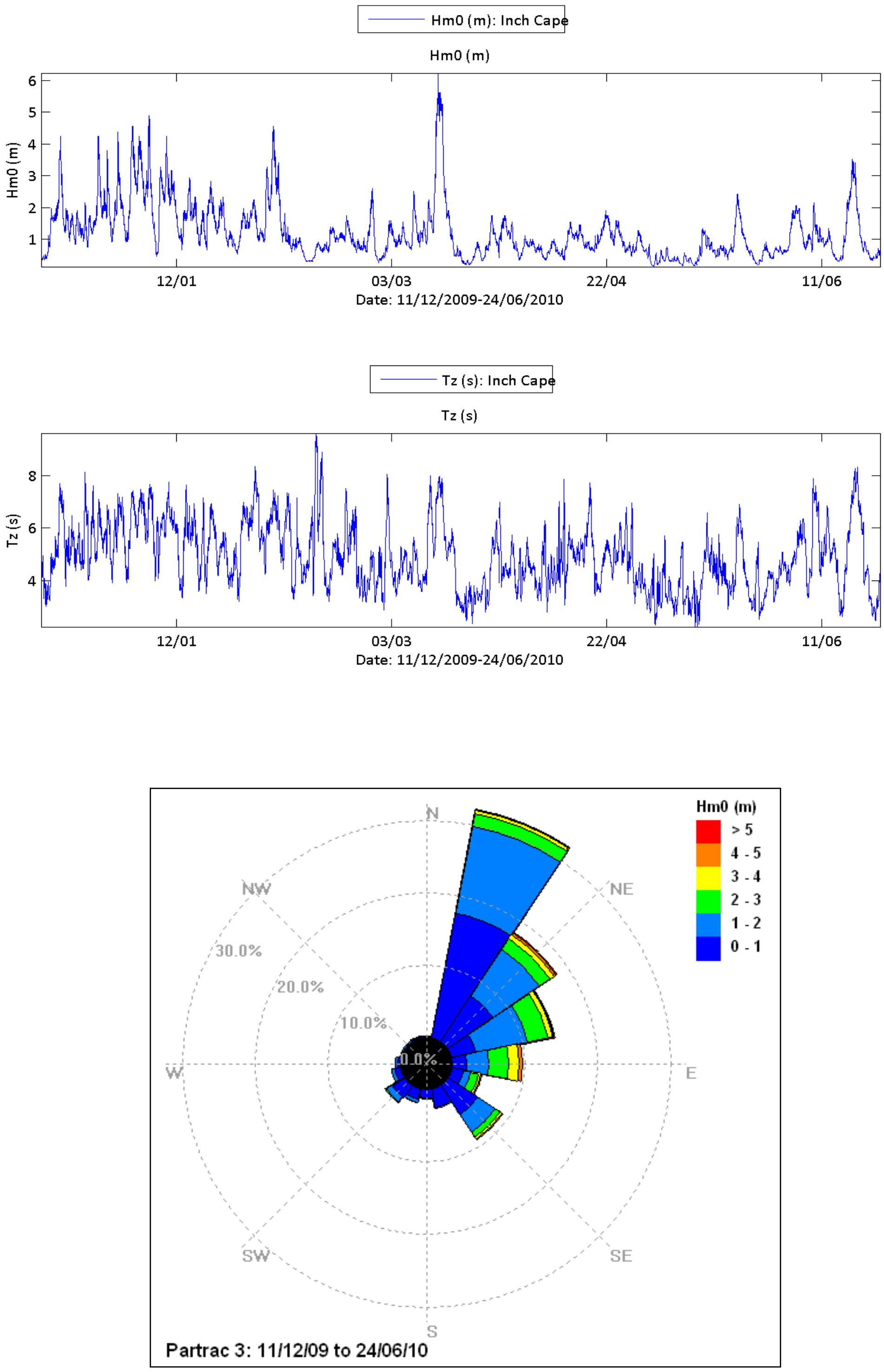


Figure 10A.1.15 Time series of significant wave height Hm0 (upper panel) and peak wave period (Tz) (middle panel) at the Inch Cape Development Area **during the oceanographic monitoring. The polar plot depicts both the (significant) wave height, frequency and direction in a single plot. The polar plot is associated with the data in Table 10A.1.8.**

The wave period data (Figure 10A.1.15) show that wave periods are largely between ~3 and 8 seconds. The shorter period waves correspond to locally generated swell waves which enter into the outer Forth-Tay coastal area (from the SE and SW) whereas the longer period waves correspond to (larger) swell waves. Table 10A.1.12 provides a summary of wave frequency by direction. Waves from the SW form only a very minor component of the wave direction spectrum, as they are fetch limited due to the presence of the land (Table 10A.1.12). Swell waves are generated by northerly winds blowing down the eastern seaboard of Scotland; the wave rose data show the dominant wave direction at the Inch Cape Development Area is centred on 22.5 ° (i.e. NNE), with over 35 per cent of measured waves arriving from this direction (Table 10A.1.12). It is of interest to note that this direction is co-aligned (largely) with the principal tidal current axis, which can give rise to direct superposition of flows close to the bed for energetic events. Towards the spring-summer period, the minimum wave period decreases to ~2 – 3 seconds (Figure 10A.1.15). This probably reflects an increase in the frequency of locally generated waves during this time.

Table 10A.1.12 Summary of wave frequency of occurrence by direction

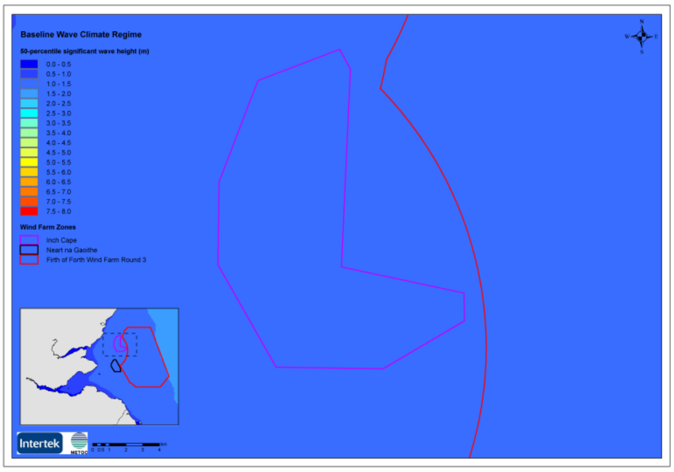
Centre Bin	Frequency	%
0.0	20	0.28
22.5	2489	35.14
45.0	1410	19.91
67.5	796	11.24
90.0	534	7.54
112.5	272	3.84
135.0	670	9.46
157.5	223	3.15
180.0	103	1.45
202.5	145	2.05
225.0	228	3.22
247.5	99	1.40
270.0	27	0.38
292.5	24	0.34
315.0	12	0.17
337.5	31	0.44

An appreciation of wave conditions across the Development Area i.e. spatially, is available using the Forth Tay Modelling System. A model build was developed to provide information on the local wave climate from 10 years of UKMO wind data. This effectively reconstructs the wave climate for the Development Area over a nominal 10 year period, and from this the dataset is then processed to generate statistics such as median wave period, median significant wave height and a range of percentile values for these parameters. Figure 10A.1.16 and Figure 10A.1.17 show the distribution of significant wave height and wave period with respect to four percentile values (50, 90, 95, 99[3]). These allow an assessment of the uniformity of wave conditions over the Development Area, but also indicate the maximum expected value for each parameter on a long-term basis.

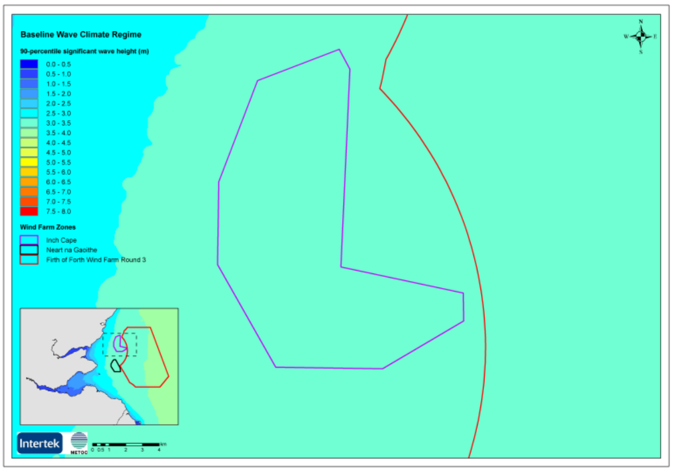
Irrespective of the wave period percentile value selected, the data indicate a uniform spatial distribution of wave period across the Development Area. Wave periods expected at the Development Area 4.5 – 5.0 s (T_{z50}) up to 8 – 8.5 seconds (T_{z99}). Given that the penetration of wave energy to the seabed (and thus the potential to generate sediment transport) is strongly dependent upon wave period, the maximum value here can be considered as an upper limit to wave periods expected at the Development Area over long timeframes. The absence of any non-uniformity of wave period across the Development Area indicates, in addition, that shoaling effects (as waves shoal their period decreases) are negligible.

There is also uniformity in conditions across the Development Area if the (significant) wave height parameter is inspected for conditions other than 99th percentile (i.e. the most energetic sea states). Wave heights expected at the Development Area range from 1.0 – 1.5 m ($Hm0_{50}$) up to 5.5 – 6.0 m ($Hm0_{99}$). 99 per cent of all waves expected at the Development Area will have a significant wave height of no more than 5.5 – 6.0 m. This is true for the majority of the Development Areaarea, but during the most energetic sea state there is a zone of slightly lower wave height (5.0 – 5.5 m) down the western periphery of the Development Area.

3 For example, T_{z99} = 9 s indicates that 99% of all waves arriving at the Development Area would be expected to have a period equal to or less than 9 seconds.

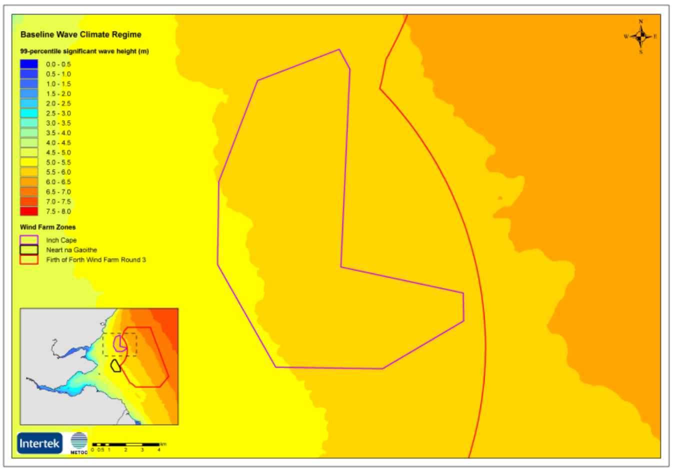


Median significant wave height ($Hm0_{50}$) (m)

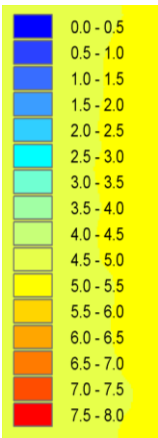


90th Percentile significant wave height ($Hm0_{90}$) (m)

95th Percentile significant wave height ($Hm0_{90}$) (m)

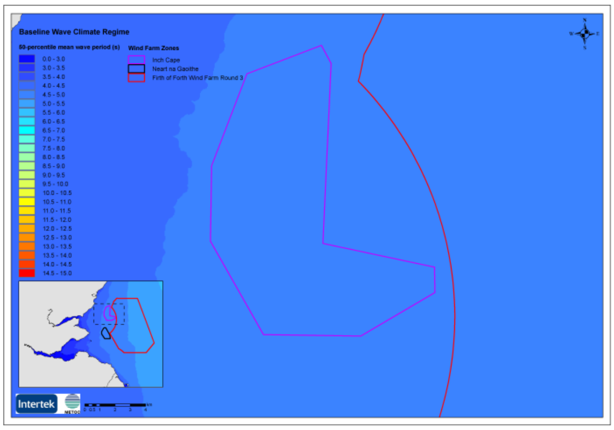
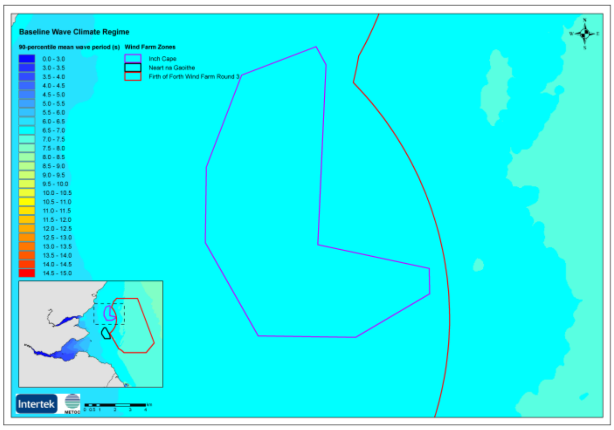
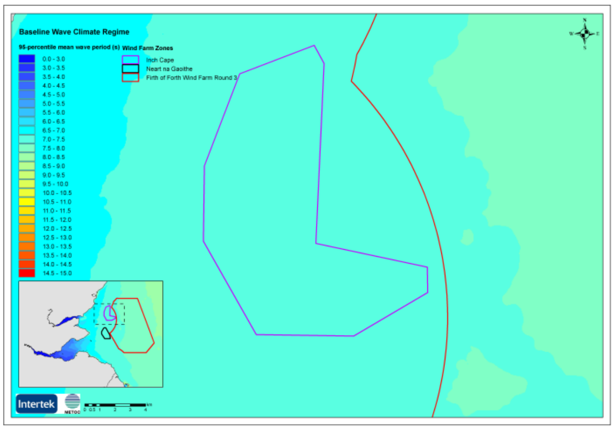


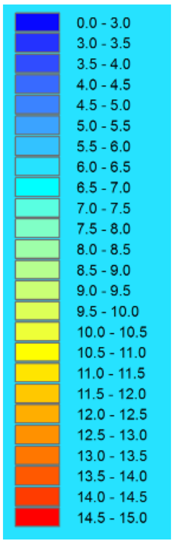
99th Percentile significant wave height ($Hm0_{90}$) (m)



Significant Wave Height (m)

Figure 10A.1.16 Spatial distribution of significant wave height (Hm0) across the Development Area (four different percentiles). Source: FTMS.

	
Median wave period (*T_{z50}*) (s)	90th Percentile wave period (*T_{z90}*) (s)
	
95th Percentile wave period (*T_{z90}*) (s)	99th Percentile wave period (*T_{z90}*) (s)



Zero Crossing Wave Period (s)

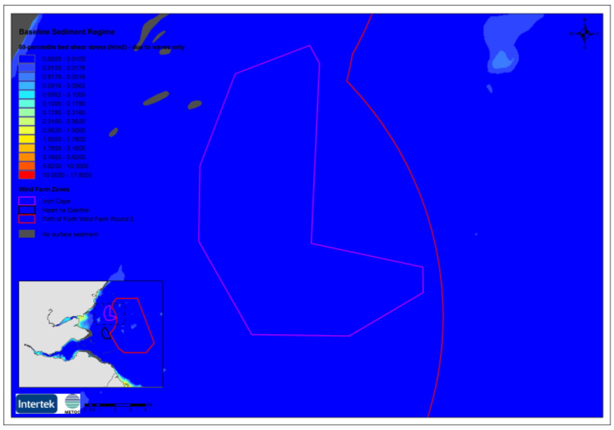
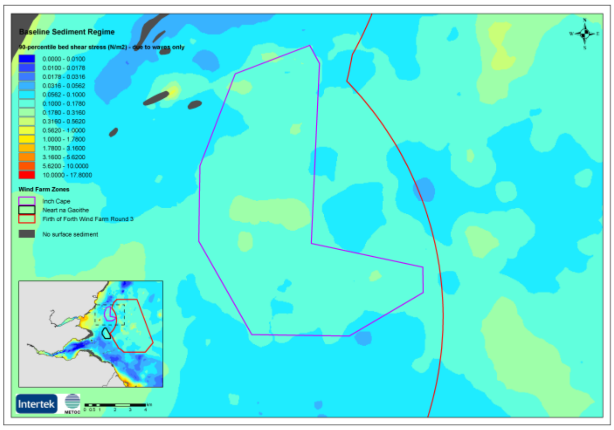
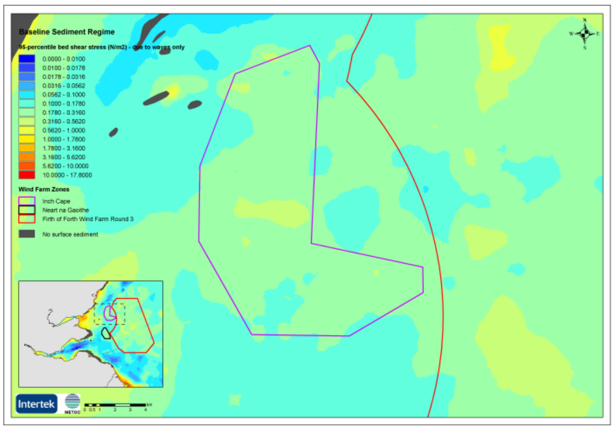
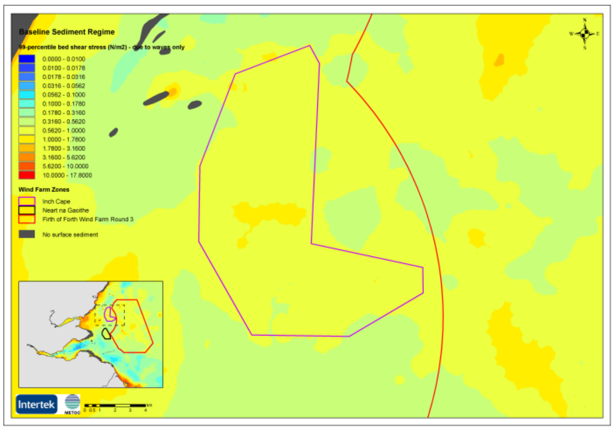
Figure 10A.1.17 Spatial distribution of wave period (*T_z*) across the Development Area (four different percentiles). Source: FTMS.

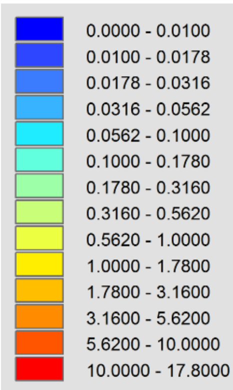
Wave Bed Stress

In a similar manner to tidal currents, wave-related currents exert a frictional drag ('bed stress', τ_{0wave}) on the bottom sediments if the wave energy can penetrate to the bed, and this is also responsible for inducing sediment transport. The stress at the bed is a function of both the wave height and period, the roughness of the sediment-water interface and (unlike for tidal currents) water depth. Greater turbulence, and therefore greater stress, is generated over coarser sediments. The distribution of bed stress due to the native wave climate across the Development Area (computed using the FTMS) is presented in Figure 10A.1.18. An understanding of the spatial distribution i.e. the uniformity, of wave-related bed stress across the Development Area is central to an evaluation of sediment transport potential.

The 50th percentile τ_{0wave} data show that wave stress is uniform across the Development Area and very low (τ_{0wave}< 0.01 N m^{-2}). This indicates that the energy from these waves barely penetrates to the seabed. As the wave climate becomes increasingly energetic, the wave stress field becomes progressively non-uniform with some seabed areas experiencing greater stress than others. Higher stresses are found generally over the central shallower region (~43 – 45 m). Higher stresses generally indicate the potential for greater transport, but it is frequently *not* the case where the sediments might be exceptionally coarse (e.g. gravel lag deposits).

The 99th percentile plot corresponds to the most energetic wave climate for the Development Area; for most of the Development Area τ_{0wave} ranges between 0.562 – 1.00 N m^{-2} but over the central shallower region wave stresses between 1.00 and 1.780 N m^{-2} are found.

	
Median wave stress (N m^{-2})	90th Percentile wave stress (N m^{-2})
	
95th Percentile wave stress (N m^{-2})	99th Percentile wave stress (N m^{-2})



Wave Bed Stress (N m^{-2})

Figure 10A.1.18 Spatial distribution of wave bed stress across the Development Area (four different percentiles). Source: FTMS.

Wave Refraction and Diffraction

Wave Refraction

As offshore waves move from deep water into shallower water a number of important modifications occur as they begin to interact with the seabed. These are:

- Shoaling and refraction (depth and current);
- Energy loss due to breaking;
- Energy loss due to bottom friction; and
- Momentum and mass transport effects.

Waves affected in this way are normally termed *shallow water* waves. From consideration of the incident wave heights and periods above, it is possible to determine whether the waves at the Inch Cape Development Area will 'feel' the seabed boundary, and from this information it is possible to judge if significant shoaling and refraction are likely, or whether dramatic steepening and wave breaking is also likely.

Waves produce an oscillatory velocity in the water column which is a function of wave properties (namely, height and period) and which decreases in amplitude (magnitude) with depth. Whether the seabed 'feels' this flow therefore depends on the ratio of the water depth to wave height and period. The FTMS model data shows largely uniform conditions during the most energetic storms with respect to both wave height and period (Figure 10A.1.16; Figure 10A.1.17); this would indicate that if 'shallow water' effects are at work (stresses are higher on the central shoal region and therefore some wave modification could occur), the effect on the waves is negligible. This would be expected on a general basis given the water depths across the Development Area. Certainly transmission of refraction (e. changes to wave height) effects onwards and towards the coastline (especially the Angus coastline cf. south easterly waves) will not occur on the basis of distance alone. Changes in between the Inch Cape Development Area and the shoreline will result in more profound changes to wave properties than will occur as waves pass across the Development Area.

Wave Breaking

As waves move into shallower water and begin to feel the sea bed, changes to wave length and period can occur which give rise to a steepening of the wave face. If this continues to occur eventually the wave over-steepens and will break. A means to assess whether waves at the Inch Cape Development Area will break is to determine the height at which a monochromatic wave of a given wavelength/period in a constant water depth breaks, and to compare this with wave spectra for the Development Area. Table 10A.1.13 summarises the result of this analysis.

These data show that mean annual significant wave climate (regardless of direction[4]) across the Development Area would *not* comprise breaking waves; only if the wave period of the peak recorded significant wave (5.9 m; Figure 10A.1.15) was ≤ 5 s would this particularly large wave break. Even the largest waves expected during a 50 year storm event (Hmax ~ 14 – 15 m; Table 10A.1.9) are unlikely to break. This analysis indicates that waves across the Development Area are wholly non-breaking for mean conditions and for most winter storms. Even in very extreme circumstances breaking is unlikely.

Table 10A.1.13 Threshold heights for breaking waves in various water depths and for a range of wave periods. For example, a wave of period 7 seconds in 45 m water depth would need to be over 10.82 m high before it would steepen and break.

Water Depth (m)	Wave Period (s)			
	5	7	9	11
35	5.54	10.66	15.73	19.26
40	5.54	10.77	16.45	20.78
45	5.54	10.82	16.95	22.05
50	5.54	10.84	17.3	23.09
55	5.54	10.85	17.53	23.93

4 This means that waves from the southeast, which finally will arrive on the Angus coastline, are unmodified when crossing the Development Area.

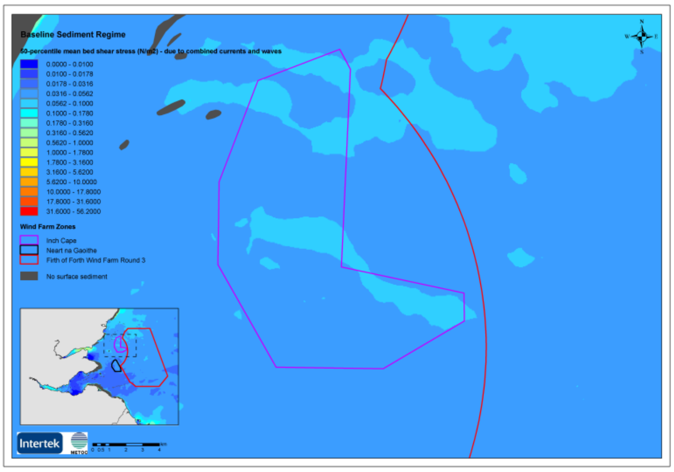
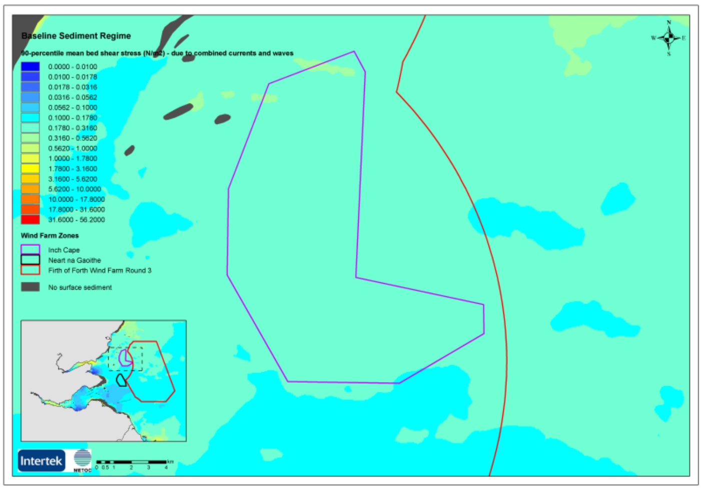
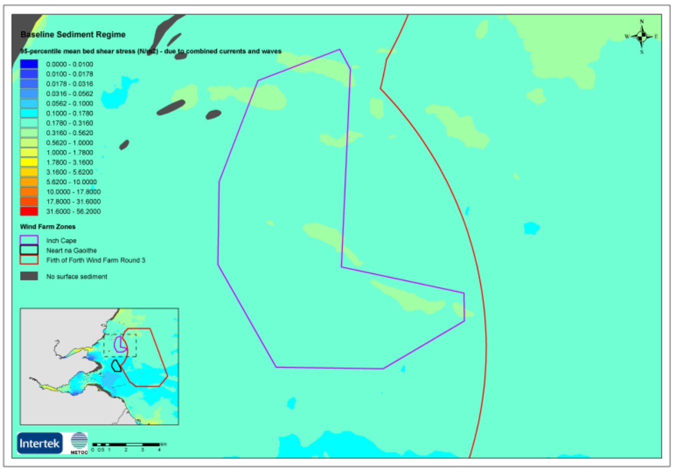
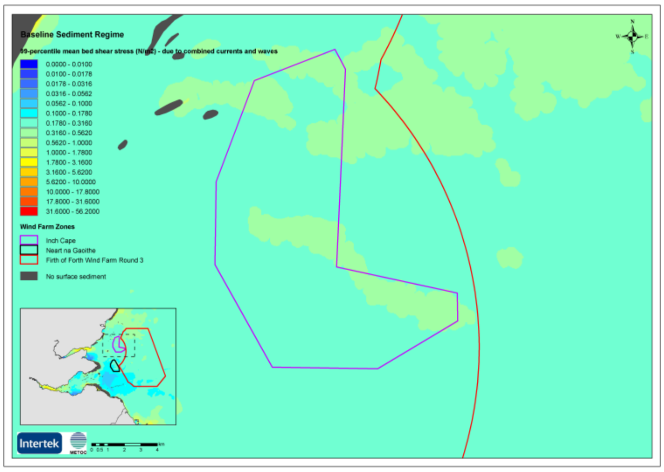
10A.1.5.5 Wave – Current Regime

In reality the fluid motions in the sea are a function of tidal, non-tidal and wave influences. Whereas non-tidal influences are generally infrequent, waves and tides are frequently co-occurring, particularly during winter months. When this happens, the bottom sediments experience a drag force ('bed stress', τ_{0wc}) which is a combination of that due to the wave component and that due to the tidal current component.

The distribution of (maximum) bed stress due to the waves and currents in combination across the Development Area (computed using the FTMS) is presented in Figure 10A.1.19. An understanding of the spatial distribution i.e. the uniformity, of wave-current bed stress across the Development Area is central to an evaluation of sediment transport potential.

The wave-current stress maps for each percentile metric closely resemble the corresponding wave only stress maps both qualitatively and quantitatively (Figure 10A.1.18). This reflects the fact that the wave stress component generally dominates over the tidal stress component. For median conditions (50th percentile) the wave-current stress is largely uniform and everywhere < 0.100 N m^{-2}, although the shallower regions of the Development Area are differentiated as areas of greater combined stress.

As the hydrodynamic energy level increases and wave influence increases (90thpercentile condition), stress distribution is uniform with the entire Development Area experiencing τ_{0wc} = 0.178 - 0.316 N m^{-2}. For the 95th and 99th percentile conditions combined stress at the seabed increases, and the central shallower region and the northern sandbank region show up as distinct regions of higher combined stress. For the 99th percentile condition τ_{0wc} on the shallower parts of the Development Area ranges 0.316 – 0.562 N m^{-2} whereas across the deeper parts of the Development Area it is lower (0.178 – 0.316 N m^{-2}). The model outputs in Figure 10A.1.19 show the *mean* combined wave+current bed stress. It is possible to compute the *maximum* combined wave+current bed stress, which represents the maximum observable bed stress for any given location on the Development Area (not shown graphically). The greatest combined wave+current bed stress is 1.780 – 3.16 N m^{-2} and naturally this is found on the shallower parts of the Development Area (corresponding stresses for the deeper Development Area are 1-1.78 N m^{-2}).

	
Median wave current stress (N m^{-2})	90th Percentile wave current stress (N m^{-2})
	
95th Percentile wave current stress (N m^{-2})	99th Percentile wave current stress (N m^{-2})

Wave+current stress (N m^{-2})

Figure 10A.1.19 Spatial distribution of mean wave+current bed stress (τ_{0wc}) across the Development Area (four different percentiles). Source: FTMS.

10A.1.6 FLUVIAL INPUTS

10A.1.6.1 Introduction

Various rivers and estuaries discharge into the study area with the freshwater inputs contributing to the overall hydrodynamic regime. The Scottish Environment Protection Agency (SEPA) monitors flow in these rivers with gauging stations at strategic points commonly upstream of tidal limits. Table 10A.1.14 summarises details of freshwater input from the main rivers discharging into the Development Area.

It is evident that the Rivers Tay and Forth are the dominant sources of freshwater flow into the proposed development area, accounting for around 97 per cent of the total mean flow. The table is not exhaustive in providing a list of river discharges into the Development Area; however, our understanding is that the remaining rivers contribute negligible freshwater inputs. In relation to the Inch Cape Development Area, it is considered that the volume of freshwater received into the inshore zone is small in relation to the tidal (marine) volume and the conclusion is that these do not form significant freshwater influences at the Development Area.

Sediment concentration data have been provided by SEPA for the three main rivers (Table 10A.1.14), and these reveal universally low concentrations (< 43 mg l^{-1}, maximum). The gauging Development Areas are upstream (beyond the tidal limit) and therefore represent the true sedimentary inputs from the river catchment to the estuarine zone and beyond (i.e. into nearshore coastal waters). The data indicate delivery of low sediment loads, with highly similar mean concentrations amongst the three rivers. Since the freshwater inputs into the coastal region are negligible it may be concluded also that input of fluvial sediments is also negligible.

Table 10A.1.14 River and suspended solids inputs to the development area. Source: National Rivers Archive website, 2009; query to SEPA July, 2011/SEPA 2000.

River	Catchment area (km^2)	Mean flow (m^3 s^{-1})	95% exceedence (m^3 s^{-1})	10% exceedence (m^3 s^{-1})	TSS Gauging Station	Monitoring Period	Total Suspended Solids Conc. (mg l^{-1})		
							Min	Max	Average
Forth	1036.0	46.98	5.50	115.50	Craigforth	17.01.10 – 22.11.10	1	28	10
Tay	4587.1	169.20	43.04	335.20	Queens Bridge	4.02.08 – 22.08.11	1	26	5
Eden	307.4	3.93	0.96	8.06	Kemback	17.08.11 – 20.09.10	2	43	10
Total	5930.5	220.11	49.5	458.76					

The key issue is whether sedimentary material discharging from the rivers Forth and Tay impact upon the Inch Cape Development Area and/or forms an important part of the sediment regime at the Development Area. Geological evidence (Pantin, 1981) suggests that most sediment is ether trapped in the estuaries or deposited in nearshore muddy deposits (e.g. including mudflats), examples of which can be found in the Forth of Firth and offshore of Montrose/Lunan Bay. McManus (1986) notes that ~50 per cent of sedimentary inputs to the Forth and Tay are low settling velocity, organic particles, which are not liable to accumulate permanently in the Inch Cape Development Area region, and which will eventually be mineralised (transformed into dissolved material). Additional data from Balls (1992) indicates very low (~ 20 mg l^{-1}) concentrations of suspended sediments in the outer Firth of Forth area, which suggests that riverine sediment (mud), here, does not transport offshore in significant quantities. Mineralogical and tracer studies by McManus et al. (1993) directly endorse this view, with most offshore sediments found to be derived from the offshore region (e.g. seabed redistribution; erosion of Quaternary sediments) itself. The small quantities of mud found in seabed samples across the Development Area (Figure 10A.1.4) may thus arise from *in situ* seabed erosion.

This evidence indicates the impact of fluvial sediments, in terms of accumulation within the Development Area boundaries or as an important component of the sediment regime, is considered negligible at the Inch Cape Development Area.

10A.1.6.2 Suspended Sediment Concentrations

Highly limited data on near-bed and water column suspended sediment concentration at the Inch Cape Development Area are available, but some were collected within the benthic environmental survey (Table 10A.1.15). These data were collected during Spring tides at various tidal states. It can be assumed that the conditions were calm during sampling (in order that good quality samples could be collected), and thus these can be regarded as fair-weather (wave-free) summer-time concentrations.

The data indicate universally extremely low concentrations throughout the water column. Maximum near-bed concentrations of 15 mg l^{-1} (this value was recorded during early flood on a Spring tide), but largely concentrations are beneath the limit of detection (3 mg l^{-1}). Collectively the data indicate a zero or very negligible tidal resuspension of bottom sediments.

Table 10A.1.15 Suspended solids concentration at the Inch Cape Development Area collected on 21-24.05.12. Source: Environmental Survey.

Depth	Time	Sample	Depth	Lat	Long	Suspended Solids Concentration (mg l^{-1})	Tide Phase
21/05/2012	19:20	1	surface	56 26.670	2 14.421	5	Springs; Late ebb
21/05/2012	19:20	1	mid	56 26.670	2 14.421	3	
21/05/2012	19:26	1	bed	56 26.670	2 14.421	5	
21/05/2012	19:35	2	surface	56 26.410	2 14.520	<3	
21/05/2012	19:35	2	mid	56 26.410	2 14.520	7	
21/05/2012	19:39	2	bed	56 26.410	2 14.520	5	
22/05/2012	11:00	99	bed	56 29.35	2 15.32	15	Springs; Early flood
22/05/2012	12:32	32	bed	56 28.556	2 12.480	<3	
22/05/2012	13:37	39	bed	56 33.259	2 11.490	<3	
23/05/2012	08:35	55	bed	56 27.057	2 09.038	<3	Springs; Early flood
23/05/2012	10:14	97	bed	56 27.015	2 05.876	4.5	
23/05/2012	11:05	82	bed	56 27.086	2 03.089	<3	
23/05/2012	13:35	124	bed	56 35.220	2 09.605	<3	
24/05/2012	07:40	86	bed	65 33.813	2 14.734	3	Springs; Mid ebb

10A.1.7 SEDIMENT TRANSPORT REGIME

10A.1.7.1 Introduction

Integration of information and data from the sources reviewed will provide an assessment of the baseline sediment transport regime across the Inch Cape Development Area. The chief questions that arise in relation to an assessment of the sediment transport regime across the Development Area include:

- Are the tidal currents at the Development Area sufficient to generate sediment transport?
  - If so, what is the percentage of time that current conditions exist which are sufficiently powerful to generate transport?
  - If so, what are the rates of suspension and bedload transport?
  - Are there asymmetries in transport which create a net transport direction? and
  - Are there differences in expected transport rate across the Development Area in relation to differing sediment types?

- Is the wave climate sufficient to generate sediment transport?
  - If so, what are the critical height-periods which do so, therefore when seasonally is transport expected to occur?
  - What is the percentage of time that wave conditions exist which are sufficiently powerful to generate transport
  - How variable across the Development Area is transport expected to be? and
  - How do wave and tide currents combine to generate sediment transport, and how important is this?

10A.1.7.2 Morphological Evidence for Sediment Transport

The presence of bedforms on the seabed provides indications as to the severity of sediment transport at the Development Area and also provide clues as to the predominant transport direction[s]. This information is useful, and supplements quantitative inferences made based upon particle size for the bed sediments. The seafloor at the Development Area comprises a thin veneer of sand and gravel, intermixed at shallower locations. The chief conclusions arising from consideration of the bed features information are as follows:

1. The geophysical survey is of insufficient resolution to determine whether the open sand plains (sand 'sheets'; cf. Pantin and Evans, 1984) are rippled or featureless;
2. The lack of a pervasive spatial coverage of megaripples across the open sand plains suggest relatively limited sediment movement in these areas; this is supported by the annotation in the geophysical survey reports of 'faint' megaripples in a few locations;
3. The location of numerous gravel deposits on the shallower areas suggest these might be regions of higher current flows and higher sediment transport; the geophysical survey classifies these areas a 'sandy GRAVEL' and if the geological classification terminology has been used correctly this suggest dominantly a gravel deposit within a minor sand content. This possibly indicates sand is winnowed away (i.e. suspension transport) by currents in these areas, a process which may be relic (i.e. it occurred in the past; Balson et al., 2002) or it may be occurring today;
4. The presence often of megarippled sand close to areas of higher gravel content and areas with mild slopes indicate that bottom flows are higher and sufficient to generate (bedload) sediment transport at these places;
5. The orientation of the crest-lines of megaripple fields is orthogonal to the principal tidal current axis, which suggests a tidally-related formation; however, lack of information on symmetry precludes assessment of net transport direction from these data;
6. The alignment of the crest-lines of megaripple fields is also orthogonal to the dominant wave direction, indicating they may also be wave-formed structures;
7. The presence of gravel ridges possibly indicates (intermittently) very high flows, although equally they may be stable relic structures.

This information can be used in conjunction with a more quantitative analysis, particularly using oceanographic data collected during the monitoring campaign, to provide a firm conceptual model of the sediment transport regime at the Development Area.

10A.1.7.3 Offshore Sediment Transport by Tides and Waves

Tidal Resuspension and Transport

As no near-bed digital time series measurements of suspended sediment concentration were collected during the oceanographic monitoring campaign, evaluation of whether the ambient tidal currents give rise to sediment resuspension is amenable only through a semi-theoretical analysis. For this purpose data from grain size analysis of bottom sediments is used (Table 10A.1.4) in conjunction with measured and modelled data from the oceanographic monitoring and from the FTMS.

Although seabed sediments contain a span of grain sizes it is customary to use the median grain size statistic (d_{50}) in sediment transport computations. Size analysis of bottom sediments (Table 10A.1.4) indicates that the bottom sediments are dominantly sandy, comprising grains within the range 250 to 50 μm (MEDIUM sand). A representative (Development Area average) median grain size is 320 μm, with a standard deviation of 67 μm. The ensuing seabed mobility assessment is performed for this specific sand fraction. GRAVEL size sediments are also present at locations on the seabed (Table 10A.1.4; Figure 10A.1.3/10A.1.4; most commonly on the shallower areas), and therefore some consideration is also given to the mobility of these sediments under the contemporary oceanographic regime. Where the gravel fraction forms the dominant component (i.e. is >50 per cent of the sample) the gravel tends to be quite coarse (>20 mm); however, where the sediments comprise slightly gravelly sands (which are more common) the gravel tends to be finer (between 2 and 20 mm).

An expression presented by Soulsby (1997) which includes $d_{50,}$ the acceleration due togravity, water and sediment density, and kinematic viscosity for seawater, can be used to determine whether the measured frictional bed stresses (denoted τ_0) generated by the tidal current velocities at the Development Area will generate sediment motion. Table 10A.1.16 summarises the d_{50} value for medium sand and for a representative (approximately median) gravel size (8 mm), and the associated critical value for τ_0[5]. In addition, column four in Table 10A.1.16 gives

5 The critical value for bed stress, denoted $\tau_{0crit.}$, is the *minimum* stress capable of generating sediment motion.

the ratio of u_*[6] to the grain settling velocity (ω_s), which forms a criterion for suspension of sediments[7]. The peak, tidally induced bed stress (≈ 0.37 N m^{-2}) has been used in this calculation.

Table 10A.1.16 Summary grain size and critical bed stress information for representative sediment types.

Sediment Type	d_{50} (mm)	$\tau_{0crit.}$ (N m^{-2})	u_*/ω_s
Medium sand	0.320	0.210	11.5
Gravel	8.00	6.930	----

The data indicate, for example, medium sand will be mobilised when the bed stress exerted by the tidal currents exceeds 0.210 N m^{-2}. Figure 10A.1.20 shows the time series of depth-averaged current velocity presented in Figure 10A.1.9 transformed into a bed stress time series. Superimposed on the time series are the critical bed stress values from Table 10A.1.6 (red lines) for the two representative sediment types (medium sand and 8 mm gravel). From this it is immediately apparent that gravel sediments are stable and never mobilised by the tidal currents; conversely, medium sand is mobilised *but only by the stronger Spring tides* (Figure 10A.1.21). Table 10A.1.17 summarises the proportion of time that the representative sediment types are mobilised by the currents for both Springs and Neaps, and for a year as a whole.

Table 10A.1.17 Percentage of the time by year, and by Spring and Neap tide, that bottoms sediments are mobilised by ambient tidal currents.

Sediment Type	Year	Spring	Neap
Medium sand	8.50%	35.68%	0.00%
Gravel	0.00%	0.00%	0.00%

6 $u_*=\sqrt{\{\tau_0/\rho_w\}}$; u_* is called the 'friction velocity' and has units of m s^{-1}; however, it is not a real velocity but a unit created for mathematical convenience.

7 For suspension to occur, and for suspended grains to remain in suspension, $u_* \geq \omega_s$ must be true.

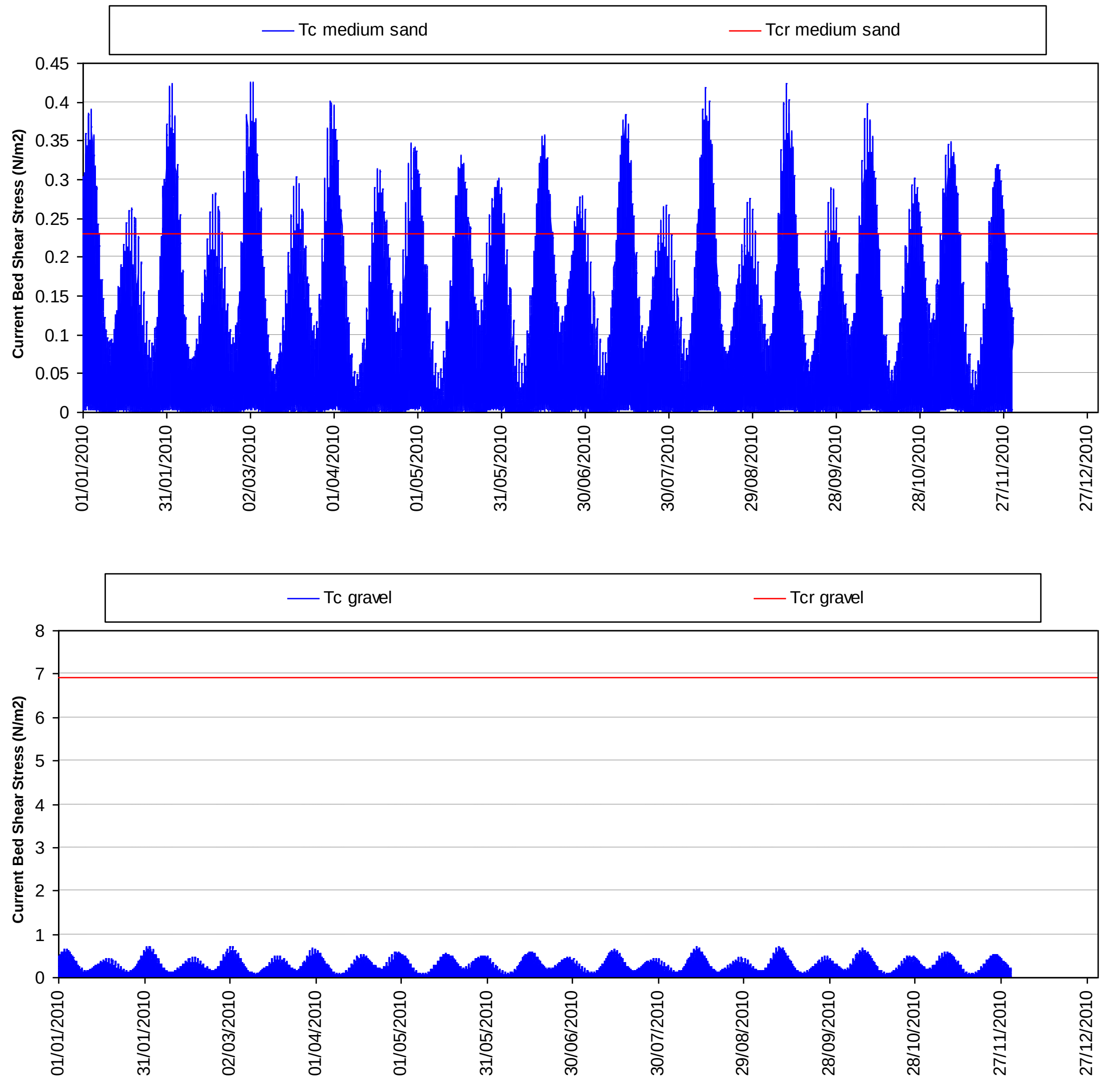


Figure 10A.1.20 Time series of current bed stress (blue lines) in relation to the critical bed stress values (red line) for medium sand (upper panel) and 8 mm gravel (lower panel).

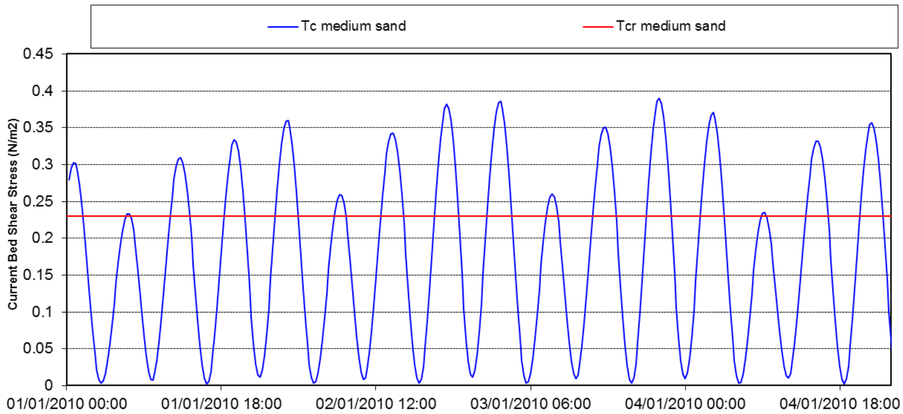


Figure 10A.1.21 Expanded time series of current bed stress (blue lines) in relation to the critical bed stress value for medium sand showing the relatively high 'elevation' of the critical bed stress value within the tidal frame i.e. the sediments are not in motion through the whole of the tidal cycle, only for part of it. Note also the asymmetry in subsequent Spring tide amplitudes which further reduces the periods of time medium sands are mobilised.

The foregoing analysis can be up-scaled to indicate the degree of sediment mobilisation across the Development Area as a whole. Figure 10A.1.11 shows 50th and 90th percentile $\tau_{0current}$ data across the Development Area; the former indicates bed stress values which are not high enough to generate sediment mobilisation. However, the 90th percentile $\tau_{0current}$ bed stressvalues (0.178 – 0.316 N m^{-2})straddle the τ_{0crit} for medium sand indicating that flows approaching peak flows impart a bed stress which will generate some sediment transport for at least some of the time in the flood – ebb cycle. This is consistent with the above inferences based upon inspection of the collected oceanographic data. Further, with the exception of a small area in the north-west of the Development Area and along the southern periphery (deeper areas where the stress is lower) the distribution of bed stress is uniform across the Development Area, and therefore the stronger Spring tide currents would be expected to generate sediment transport across the majority of the Development Area.

The conclusions derived from the various lines of evidence above support the general inference from inspection of seabed morphological features (Section 7.2) of a largely stable bed under tidal currents; it concurs with the Development Area definition derived from biotope mapping (low energy, deep water [circalittoral] seabed environment) and it is consistent with very low sediment concentrations measured through direct water sampling (Section 6.2).

Seabed Mobility Classification

There is no universal framework which can be used to classify seabed regions in terms of mobility. Such a framework might include the following qualitative classifications to describe a seabed:

- Permanently immobile
- Slightly mobile
- Moderately mobile
- Highly mobile
- Permanently mobile

From the above analysis it is clear that medium sand is mobilised only by the stronger Spring tide currents and mobile for only 8.5 per cent of the year (Table 10A.1.17). Gravel size sediments are immobile under the contemporary current regime. On this basis, it would be appropriate to classify the seabed at the Inch Cape Development Area as 'slightly mobile' under tidal forcing.

Sediment Concentrations Under Currents

Where the bed stress exceeds the threshold bed stress for motion, sediment moves first as bedload (rolling, sliding, saltation) until flow stresses are sufficiently powerful to entrain sediments off the bed to be carried in suspension by the tidal flow. The metric u_*/ω_s is a useful guide as to whether bedload transport is likely to dominate in terms of time over suspension transport, or whether the sediments are likely to be lifted into suspension almost immediately after mobilisation. For medium sands u_*/ω_s=11.5 (Table 10A.1.16) and this indicates that the latter is likely to be the case. The general lack of megaripple features spatially across the Development Area in geophysical data sets points towards limited bedload transport and therefore supports this inference. Although data are limited, the maximum recorded suspended sediment concentration value (15 mg l^{-1}; Table 10A.1.15) indicates sediment in suspension very close to the seabed.

Entrainment of bed sediment into suspension gives rise to a near-bed pool of sediment (Table 10A.1.15). Anticipated concentrations at 1.0 m above the bed (the conventional height for instrument deployments to measure this parameter), computed using Smith and McLean (1977) with a power law vertical profile, range 14 – 24 mg l^{-1}. Although preferably these concentrations would derive from actual measurements, nonetheless these values are a guide to natural, tidally-induced suspension concentrations and agree reasonably well with the observed value of 15 mg l^{-1} (Table 10A.1.15). In reality the nearbed sediment concentrations are likely to vary temporally through the upper portion of the Spring tide curve when resuspension is active (see Figure 10A.1.21).

Wave-Induced Sediment Transport

The foregoing analysis indicates that bed sediments at the Inch Cape Development Area are mobilised during, and only during, the Spring tide phase. This analysis relates only to tidally-driven sediment transport, and thus is relevant only during periods when there are no or small waves such as during summer months. In shallow continental shelf environments waves, created by the wind blowing across the ocean surface, can also give rise to sediment transport if the energy associated with the wave is able to penetrate to the seabed. Penetration of wave energy to the seabed is a joint function of wave height and wave period. For the ensuing analysis, the depth of the seabed used is that at the oceanographic monitoring location (52 m) (i.e. equal approximately to the median/modal depth; Table 10A.1.3).

Wave period and height combine to generate a frictional bed stress at the seabed. In a similar approach to that adopted for the assessment of tidally driven sediment transport, a comparison can be performed of the range of stresses due to waves in relation to the minimum stress required to mobilise the bottom sediments.

Figure 10A.1.22 shows time series of bed stress (derived from transformation of the measured wave height and wave period data) for each of the representative sediment types (medium sand and gravel). From these time series it is immediately apparent that each of the sediment types are rarely mobilised by wave-induced currents. Wave action is relatively common during summer months, but waves typically are small (<1 m) with periods predominantly in the range 1 - 6 s (Figure 10A.1.15). The energy associated with these waves will not penetrate to the seabed. At a depth of 52 m the energy associated with the majority of winter waves (significant wave heights 2 to 5 m; period range ~ 5 – 7 s; Figure 10A.1.15) does penetrate to the seabed, however the stresses they exert on the bottom sediments are insufficient to generate sediment transport, even for fine sands.

The only time that wave-induced bed stresses are (were) sufficient to generate sediment transport (for medium sands, but not gravels) was during a storm event on 30.03.10 when significant wave conditions of 5.92 m significant height with a period of 8.05 s were recorded[8]. Inspection of the oceanographic monitoring data (Figure 10A.1.15) shows the waves during this period were from a direction of 047° i.e. from the northeast, which corresponds to the modal wave direction at the Development Area (Table 10A.1.12). These waves are long period swell waves. At a number of other locations within the time series e.g. 09.03.10, large period waves were recorded (T_z=8.52 m@19:59) but universally wave heights were low (0.76 m in this example) (see Figure 10A.1.15).

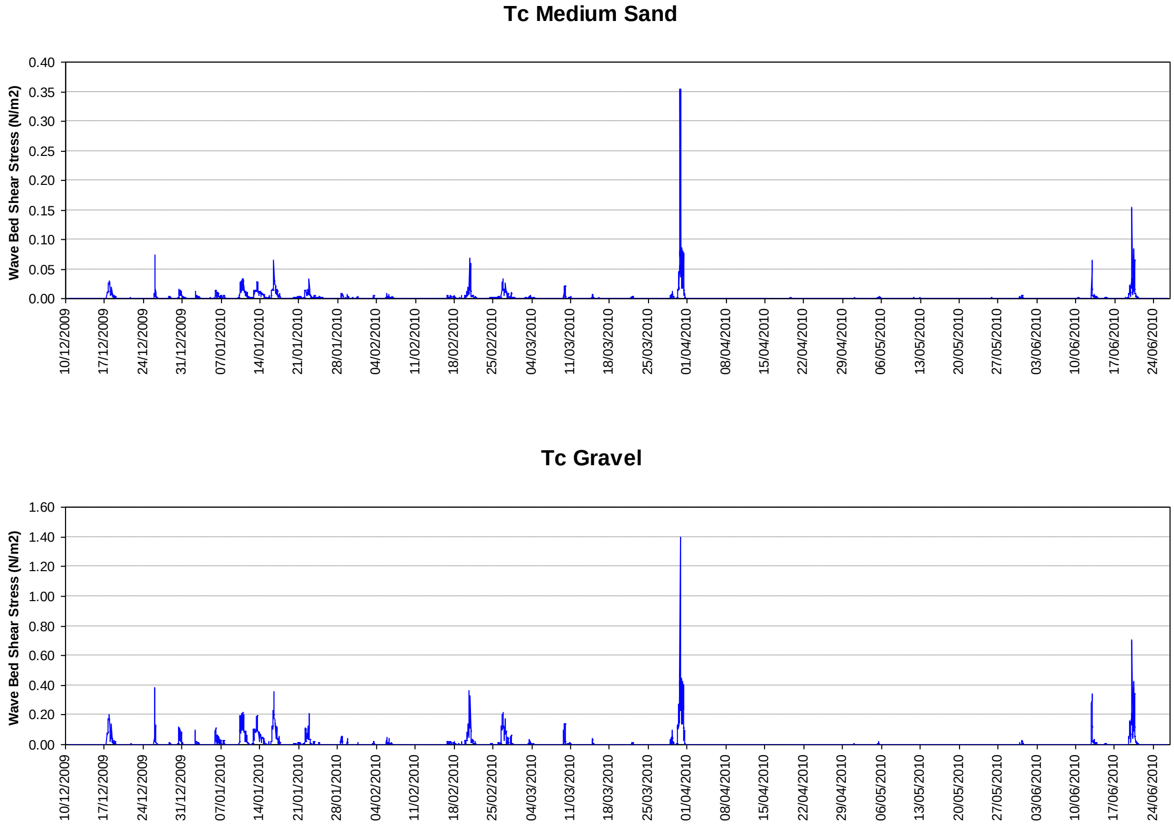


Figure 10A.1.22 Time series of wave induced current bed stress (blue lines) for fine sand (upper panel), medium sand (top panel) and 8 mm gravel (lower panel); τ_{0crit}.for medium sand is 0.210 N m^{-2}, for 8 mm gravel 6.930 N m^{-2}. The stress values correspond to a water depth of 52 m.

---

8 This discussion is restricted to water depths of ~52 m; it is however of interest to learn that this wave would not mobilise gravel sediments at the shallower central region of the site (water depths ~43-44 m). A wave in excess of 11 m with T_z=8 s would be necessary to generate gravel motion at this depth.

Table 10A.1.18 presents bed stress data for medium sand in relation to both wave height and wave period. This representation is useful in determining the sub-spectrum of wave periods and heights which will mobilise bottom sediments. It is clear from this that waves above 2 m in height are necessary for transport but that wave period is a far more important factor governing energy penetration to the bed. For mobilisation to occur in general, large waves (>5 m) with periods in excess of 8 s are required (smaller waves can generate sediment transport only if they have much longer periods). The mean and modal wave periods are, respectively, 4.55 s and 4.82 s, and given a mean significant wave height of 1.3 m from the observational data (Figure 10A.1.15) it is expected that transport occurs for only a very small proportion of the time for sand size sediments. A frequency analysis of the wave climate at the Inch Cape Development Area made using the FTMS shows that only 1 per cent of waves have a significant height in excess of 5.5 m and a period in excess of 8 – 8.5 s (Figure 10A.1.16; Figure 10A.1.17), and only the upper five percent or less of waves generate stresses capable of mobilising the sand sediments (Figure 10A.1.18). Since large wave conditions (Hm0 > 5.5 m) with periods > 8 s occur once in every 10 years or less (Table 10A.1.9) it can be concluded that wave driven sediment transport may occur but only highly infrequently.

Table 10A.1.18 Wave-induced bed stresses over medium sand in relation to wave period and wave height. The coloured shaded areas indicate when transport due to waves will occur.

Wave Height (m)	Wave Period (T_z)						
	5	6	7	8	9	12	14
	Medium Sand ($\tau_{0crit.}$=0.230 N m^{-2})						
6	0.000	0.003	0.023	0.391	0.632	1.235	1.551
5	0.000	0.003	0.017	0.065	0.465	0.902	1.129
4	0.000	0.002	0.012	0.045	0.320	0.616	0.767
3	0.000	0.001	0.008	0.029	0.199	0.378	0.468
2	0.000	0.001	0.005	0.016	0.103	0.191	0.235

The foregoing analysis can be up-scaled to indicate the degree of sediment mobilisation across the Development Area as a whole. Figure 10A.A.18 shows four percentile wave bed stress data (τ_{0wave}) across the Development Area; and these show that when wave energy can penetrate to the seabed (refer to the limiting conditions in Table 10A.1.18), sediments (medium sands) across almost the entire Development Area will be mobilised. In addition, wave-induced stresses are consistently higher over the central, shallower ridge area, and therefore the rate of resuspension and transport would be expected to be greater.

Seabed Mobility Classification

Likewise for the classification of tidally-driven sediment transport, there is no universal framework which can be used to classify seabed regions in terms of mobility under wave forcing. A similar scheme to that proposed for the tidal transport can be used:

- Permanently immobile
- Slightly mobile
- Moderately mobile
- Highly mobile
- Permanently mobile

From the foregoing analysis it is clear that gravel sediments are permanently immobile on the seabed year round. Both fine and medium sands can be mobilised by wave action but waves in excess of ~ 5 m only, and with periods in excess of 8 – 9 s only, are capable of generating sediment transport. Such conditions occur only rarely across the Development Area, and only during the winter period (i.e. half the year). It would thus be appropriate to classify the seabed at the Inch Cape Development Area under wave forcing as 'permanently immobile' during the summer months and 'slightly mobile' during winter months.

Sediment Concentrations Under Waves

Oscillatory motions associated with the passage of waves over the seabed can, if the above criteria are met, entrain bottom sediments into the water column. Unlike tidal currents, there is little net advective component to this process, and hence waves are commonly regarded as effective 'stirring' agents of the seabed. Anticipated concentrations up to 294 mg l^{-1} are predicted at 0.1 m above the bed for Hm0=6.0 m and T_z=9 s (using the method of Nielson, 1992).

Sediment Transport by Waves and Tides in Combination

In most coastal and shelf seas around the UK both waves and currents play important roles in the mobilisation and transport of bottom sediments. Tides are a regular, predictable phenomenon throughout the year whereas waves are stochastic and occur only on occasion. As demonstrated not all waves will penetrate down to exert influence on bottom currents. However, where energy can penetrate to the bottom boundary layer (see Table 10A.1.18) at the Inch Cape Development Area then the wave energy (orbital currents) will add to the stress exerted by the tidal current; for a given wave the magnitude of the stress coupling, and the resultant drag on the seabed, will vary depending on the phase of the tide (Spring, Neap, intermediate) and this interaction is also non-linear. Transport rates are expected to at their greatest following superposition of the larger/longer waves at peak Springs, largely during the winter period.

Inspection of the wave+current stress data (Figure 10A.1.19) shows that 'average' wave+current conditions cannot mobilise sediments at the Development Area but the upper 5 – 10 per cent of occurring wave+current conditions exert stresses at the seabed which are of a sufficient magnitude to mobilise medium sands across the entire Development Area, but not (8 mm) gravels. In other words $\tau_{0wc} > \tau_{0crit.}$ during the most energetic marine conditions (a superposition of a storm event and a Spring tide). During the most energetic conditions greater rates of transport and resuspension would be expected in the shallower regions in the Development Area centre and to the north of the Development Area.

Figure 10A.1.23 makes use of the data from Figure 10A.1.19 together with grain size statistics and information on the statistical frequency of occurrence of specific wave heights and periods from the FTMS 10 year model data to illustrate, specifically, the *proportion of time that stresses* *due to both waves and currents in combination exceed the critical entrainment stress for the sediments*. This can be thought of as a 'mobility index'.

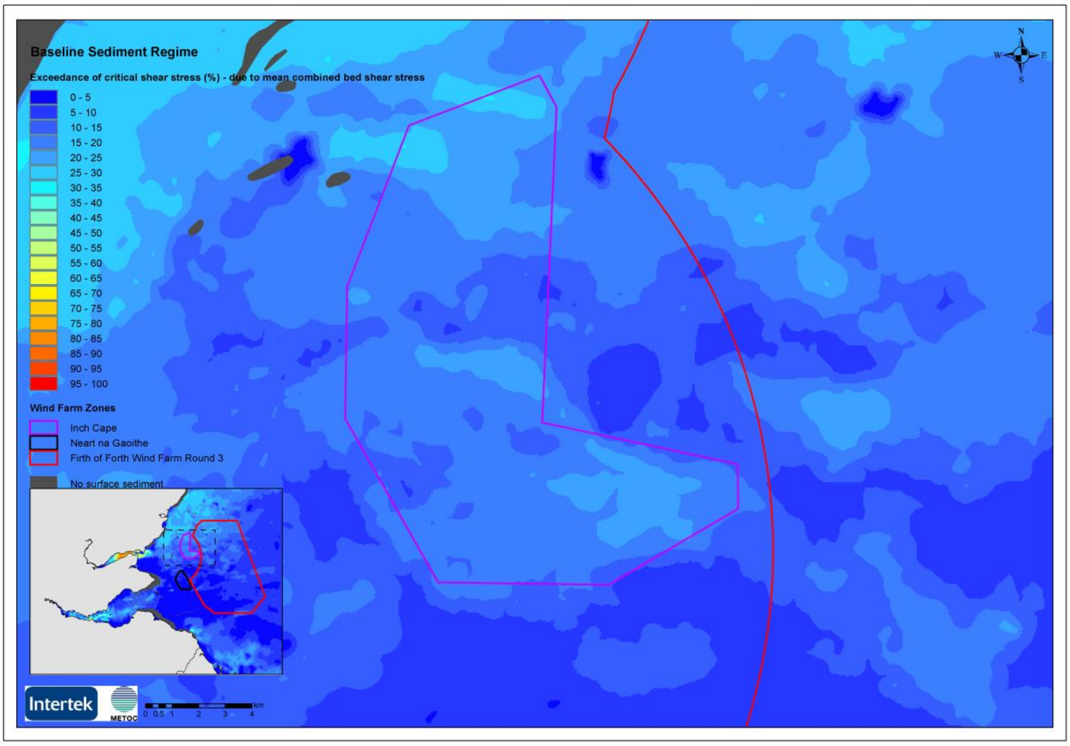


Figure 10A.1.23 The proportion of time that bed stresses due to both waves and currents in combination exceed the critical entrainment stress for the sediments at the Development Area. The time frame for this scenario is a nominal 10 year period. Source: FTMS.

Representing the information in this way facilitates the same summary description of the general Development Area stability on the basis of the frequency of sediment mobilisation as undertaken for currents and waves separately (e.g. Table 10A.1.17). For instance, if combined stress is greater than the critical value[s] for bottom sediments for much of the time (e.g. >75 per cent of the time), then clearly the inference would be that the Development Area is highly dynamic and sediment transport would be a prevalent and recurrent feature of the Development Area (which might therefore be expected to exhibit morphological features related to sediment transport e.g. megaripples and dunes).

This analysis indicates that over the shallower areas of the Development Area (the two sandbank areas to the north-west, the central ridge (ca. 43 m), and areas within the south eastern corner) the mobility index is 25 – 30 per cent. By implication the proportion of time that stresses due to both waves and currents in combination exceed the critical entrainment stress for all the deeper zones of the Development Area is less than this value; large areas of the Development Area, particularly those in the south, west and northwest have a have a mobility index of 15 – 20 per cent, and there are very few areas with index values less than this.

Since sediment mobilisation is a complex function of water depth, wave energy penetration, sediment type and bed roughness it is not possible to deduce an over-arching explanation for the pattern observed. However, in general terms there would seem to an underlying bathymetry control on sediment distributions with areas with a higher mobility index correspond to the shallower areas, which are also commonly areas of coarser sediments (gravels; Figure 10A.1.4) as well as megaripple formations (Figure 10A.1.3). The broader sand plains, for example in the south western area of the Development Area centred on 49 m/50 m, dominate areas of lower frequency of mobilisation. The at best moderate sorting of the medium sand fraction and the lack of pervasive megaripple cover in these areas also supports a bed which is subjected to super-critical bed stress and periodically resuspended, but only for a fraction of the time.

<u>Seabed Mobility Classification</u>

Likewise for the classification of tidal- and wave-driven sediment transport, there is no universal framework which can be used to classify seabed regions in terms of mobility under combined wave-current forcing. A similar scheme to that proposed previously can be used:

- Permanently immobile
- Slightly mobile
- Moderately mobile
- Highly mobile
- Permanently mobile

From the foregoing analysis it is clear that (8 mm) gravel sediments are permanently immobile on the seabed year round, even under large storm events. For an assessment of mobility under combined wave-currents, it is necessary to consider seasonal effects. In the absence of wave action or for low heights i.e. during the summer, there is a weak tidal transport during Spring tides only. It would thus be appropriate to classify the seabed at the Inch Cape Development Area under combined wave-current forcing as per the tide-only situation i.e. 'slightly mobile' during the summer months. Superposition of significant waves, during the winter period, increases the percentage of time (up to 30 per cent) that near-bed currents are sufficiently powerful to mobilise bottom sediments, as well as generating greater rates of transport. It would thus be appropriate to classify the seabed at the Inch Cape Development Area under combined wave-current forcing as 'moderately mobile' during winter months (tidally and wave driven).

Sediment Concentrations under Waves and Tides in Combination

Superposition of wave action on the regular tidal variation creates increased stress at the seabed which can lift bottoms sediment into suspension. The foregoing analysis shows that during summer months wave action does not penetrate to the seabed, and therefore near-bed sediment concentrations will reflect those due to tidal resuspension only. In the absence of any measurements of near-bed sediment concentrations, estimates of typical concentrations are available from a semi-theoretical analysis, which give concentrations in the range 14 – 24 mg l^{-1}, and limited direct measurements from *ad hoc* water sampling (maximum 15 mg l^{-1}; Table 10A.1.15).

During winter months superposition of wave action on the regular tidal variation gives rise to enhanced bed stress. The FTMS indicates that approximately the most energetic upper 10 per cent of (mean) winter conditions would mobilise bottom sediments, and that worst case (peak) wave current stresses exceed substantially the critical entrainment stress of bottom sediments (τ_{0crit}= 0.210 N m^{-2}; τ_{0wc} = 1.780 – 3.16 N m^{-2}). Although derived from an entirely theoretical assessment, calculation of the concentration @0.1 m above the bed under the largest winter wave measured (Hm0 = 6.24 m; T_z = 9.04 s; See Table 10A.1.8) coincident with a storm surge peak Spring tide (u = 1.05 m s^{-1}; mean τ_{0wc}=1.844 N m^{-2}) using the method of Soulsby (1995) DATA 13 gives some indication of representative winter sediment concentrations. This analysis gives a concentration of 81 mg l^{-1}[9]. Note the resuspended sediment will be largely contained within the wave boundary layer, which is a very thin layer adjacent to the sea bed, but subject to transport along the tidal axis by the currents.

9 Note the author of this method (see Soulsby, 1997) states: "many aspects of sediment response and suspension under combined waves and currents are still poorly understood, so results should be treated with caution". Preferably, real measurements are used to underpin this assessment.

10A.1.7.4 Net Sediment Transport Direction

The foregoing analysis indicates a net directional sediment transport for material transported as bedload in the direction of the flood tidal axis (SSW; Figure 10A.1.12). The tidal asymmetry will also drive a net flux of suspended sediments towards this direction. From a single point source, a continued net transport would eventually lead to exhaustion of supply. However, as sediment is transported out of the Development Area to the SSW, similar sedimentary material will likely be brought into the Development Area from the NNE.

The net flux is not envisaged to be great principally because current induced sediment transport occurs for only a limited period (only during Spring tides, and only during the upper stages of the tide; see Figure 10A.1.21) and sediments are mobilised only by very infrequent, very high energy events. Further, peak currents during consecutive Spring tides themselves are not equal through time and this generally reduces transport durations further. The worst case scenario i.e. when residual transport will be at a maximum, will be when storm events stir up the bottom sediments as strong Spring tidal currents transport the sediments in suspension south-southeastwards.

10A.1.7.5 Bed Level (Morphological) Change

Sediment transport over extended timeframes gives rise to natural changes in bed level i.e. the depth of the sediment-water interface. Changes occur as a result of differential erosion and deposition of sediments across the Development Area and, not surprisingly, the largest changes are found following storm events. Information on the magnitude bed level changes around the UK coastline is extremely rare, and such information is amenable only through recurrent bathymetric survey[10], or highly sophisticated 4D, coupled hydrodynamic-geomorphological models.

Natural changes in bed level are important for foundation structures as they are key to understanding local scour processes (which also change bed level, locally) and classifying these in relation to natural changes which might occur. It is not possible from the oceanographic data collected to discern the magnitude of bed level change across the Development Area. However,

10 Some information is available on this from submerged scour sensors attached to marine structures. This is because not only do they measures the dimensions of any scour pit but extend outwards to measure also unaffected seabed.

any changes are not envisaged to be large, certainly through most of the year, on account of an overall low mobility of the sandy surficial sediments and immobility of coarser gravel lags. Singular winter storm events may induce some degree of morphological change across the non-gravel regions, but wave periods in excess of 10 s would be required and these do not have a high frequency of occurrence (see Section 7.3.3).

10A.1.7.6 Shoreline Processes

The Inch Cape Development Area is located some 15 km offshore from the south Angus coastline and offshore east off the Fife coastline. An overview of shoreline processes has been provided within accompanying Regional Baseline Assessment report, and a far more detailed summary is given as a series of coastal sub-cell/management unit reports within the Angus Shoreline Management Plan[11]. A summary only is presented here.

Geological processes operating at the shoreline are a function of coastal geology and geomorphology, shoreline orientation, tidal regime and exposure to wave action. The Angus coast comprises a range of differing hard rock and soft sediment regions which creates a coast of variable stability. Offshore of Montrose, the flood and ebb tides are rectilinear, flowing parallel with the coast in a south-west and north east direction respectively. Peak spring flows are 0.6 – 0.7 m s^{-1} with peak neap flows 0.3 – 0.4 m s^{-1} (Table 10A.1.8). Whilst these tides, especially in shallower inshore regions are capable of generating sediment movement, the shore-parallel alignment precludes any significant shoreward transport of offshore sediments and the uniformity of the offshore bathymetry supports this foundation. Present day erosion and accretion tends to be due to the re-distribution of existing beach and hinterland sediments both along the coast, and between the beach and nearshore zone, and this appears to be largely wave-driven (although at some places e.g. Montrose strong inshore currents can move sediment suspended by surf).

The Angus coastline experiences a wave climate with two components: wind waves and swell waves. Wind waves are generated by winds blowing from a variety of directions, whereas swell is generated from two main directions:

11 http://www.angus.gov.uk/ac/documents/roads/SMP/default.html

- Storm activity within the southern North Sea can result in swell off the Angus coastline from a direction of between about 120°N to 140°N.
- Storm activity in the North Atlantic with the resulting swell waves propagating into the North Sea and approaching the Angus coastline from between about 10°N to 50°N.

These waves can drive alongshore sediment transport in opposite directions within the same sub-cell e.g. various studies (Ferentinos and McManus, 1981) have shown that although the swell waves contain generally higher energy, due to their direction from the north-east and the shoreline orientation, swell from this direction undergoes significant refraction before reaching the Angus coastline, dissipating much of the wave energy[12]. This does not occur for waves generated from the S-E quadrant and consequently storms with winds from the east or south-east (occurring for ~10 – 15 per cent of the time based upon Figure 10A.1.13) are responsible for most of the episodic erosion along the south Angus coast.

Numerous instances of shoreline change can be correlated with short to medium term fluctuations in the wave climate; indeed, the classic seasonal onshore/offshore movement of beach material (with winter storms tending to pull beach levels down and move sand offshore and summer waves moving the sediment back onshore) is seen at many locations along the Angus coast. The problems of erosion at Carnoustie which started in the late 1970s, at a similar time as erosion started to become an issue at Montrose, Monifieth and to a lesser extent at Lunan Bay and the coastline between Arbroath and Carnoustie, are thought to be related to an increase in south easterly wave conditions and a decrease in north-easterly wave conditions (which also reduced sediment supply). Although both direct and indirect impacts on the coastal zone can be due to human activities, these observations indicate the prevalence of natural forcing as a governing agent for coastal morphological change, and the complex interactions between sediment supply and wave and tidal processes. There are additional natural forcings which can modify coastal wave processes, and these include rises in mean sea level due to climate change and changes in storminess also, perhaps, due to climate change (Street *et al.*, 2009). The numerous factors mean that deciphering absolute cause and effect is difficult, and this is important in any assessment of potential anthropogenic impact (through modification of the coastal wave climate) on shoreline processes and stability e.g. due to offshore wind farm construction.

---

12 These waves can, however, generate strong southward directed longshore currents.

A useful quantitative metric which is due to, and therefore reflects, wave action at the shoreline is the shoreline profile i.e. the gradient of the beach surface between the high and low water marks. Such data is useful in indicating the magnitude and rate of erosion-deposition and to derive beach volume changes in beach volumes, and it can be usefully correlated with metocean events to establish principal causative mechanisms which drive coastal change. At present monitoring of the Angus coast is carried out by Angus Council Roads Department at the varying spatial and temporal intervals. This data has not been made available to this study.

10A.1.7.7 Contaminant Mobilisation and Transport

It is clear that any sediment-associated contamination (metals, TBT etc.) has the potential to be mobilised, albeit infrequently by both tidal and wave currents, at the Development Area. This potential rises substantially where seabed structures exist, due to amplification of the nearbed currents around the foundation. Once brought into suspension the tidal currents are able to laterally transport the contamination across and potentially to transport it outwith the Development Area. The transport distance and geographical fate is a function of the absolute tidal current magnitude and direction for coarser sediments, and also the excursion distance and residual current magnitude and direction for finer sediments. No assessment can be made directly since there is no seabed sediment quality data at present. It is the understanding that such data will be collected, and an analysis of the fate of any mobilised particulate contamination for both baseline and construction scenarios can be completed at a later date.

10A.1.7.8 Summary of Coastal Processes Regime

The following provides a general summary of the coastal processes regime for the Inch Cape Development Area.

- The water depths across the Development Area range from approximately 35.5 m to 63.3 m. The Development Area forms a broad oval plain centred on a depth of ~49 m with a shallower region in the centre (depths ~43 – 44 m); deeper regions (depths ~53 – 54 m) in pockets across the area, especially in the south-eastern region, and the deepest waters (to 63 m) are found around the Development Area periphery.
- Except for two sandbank areas in the northwest, and a generally shallower bank in the Development Area centre, the seabed topography displays no dramatic geomorphological features and seabed slopes are everywhere low.

- Surficial sediments form a relatively (0 – 0.5 m thick) thin veneer and are characterised dominantly by MEDIUM sand (distributed across the Development Area, including in deeper areas), with generally a minor mud fraction and a variable gravel component. Where gravel is present in minor amounts it is generally very fine to fine (2 – 8 mm), whereas in richer gravel deposits particle sizes can range up to ~20 – 30 mm, or even greater in isolated pockets.
- The vertical profile of Quaternary sediments comprises contemporary sands/gravels, over interbedded sand and silt overlying stiff, hard (boulder) clay.
- Bed features (megarippples) are not found extensively across the Development Area; they are frequently faintly discernible on open plain areas and are often associated with shallower, gravel-rich areas. This suggests the Development Area is not highly dynamic. Crestlines of megaripples are oriented normal to the principal tidal axis.
- Fine sand and medium sand are transported by the tidal currents but only during Spring tides and only higher in the tidal frame (i.e. not continuously through Spring tides); the Development Area can be classified as 'slightly mobile' during summer months when wave action is negligible.
- Storm conditions with significant waves in excess of 5.5 m and a period in excess of 8 – 8.5 s *only* are predicted to mobilise sediments across the Development Area, and such conditions have a return period of > 1 in 10 years. However, in combination with tidal currents, winter storms, on average, mobilise bottom sands for of 15 – 20 per cent, of the time within any year, and this percentage increases over the shallower regions. The Development Area can therefore be classified as 'moderately mobile' during winter months. Gravel sediments are immobile under the contemporary oceanographic regime, even on the shallower regions.
- The Development Area receives waves most frequently from a north-north easterly direction (22.5°); (zero-crossing) wave periods range from ~2 to 9 seconds and significant heights up to ~ 6.24 m were recorded by *in situ* instrumentation. Waves also arrive from both the south-eastern and south-western quadrants but form only a minor component of the wave direction spectrum.
- Wave breaking does not occur at the Development Area (but might occur under very extreme marine conditions).
- Fair-weather suspended sediment concentrations (nominally due to tidal resuspension) are very low (< 15 mg l^{-1}).

- Large scale vertical changes in bed level are not expected to characterise the Development Area.
- A net directional (suspended) sediment transport in the direction of the flood tidal axis (S – SSW) exists, but residual tidal transport of suspended fine sediments is not judged to be significant on an annual basis.
- Tidal excursion during Spring tides have the potential to transport very low settling velocity material outwith the Development Area to 7.2 km (North) and 8.7 km (South)
- Fluvial inputs of freshwater to the Development Area are small in relation to the tidal (marine) volume. Concentrations of suspended sediment in fluvial discharges are low and therefore input of fluvial sediments is negligible.
- Shoreline sediment transport is dominantly due to wave action, by waves from the southeast. Information is available on shoreline sediment transport processes via regional Shoreline Management Plan.

10A.1.8 REFERENCES

- Balls, P. W. 1992. Nutrient behaviour in two contrasting Scottish estuaries, the Forth and the Tay. OceanologicaActa 15 261-277.
- Balson, P., Butcher, A., Holmes, R., Johnson, H., Lewis, M. and Musson, R. 2002. SEA2 & 3 Technical Report 008 Rev1 Geology. Downloadable from http://www.offshore-sea.org.uk/consultations/SEA_3/TR_SEA3_Geology.pdf.49pp.
- Blott, S.J., and Pye, K. 2001. GRADISTAT: a grain size distribution and statistics package for the analysis of unconsolidated sediments. Earth Surf. Process. Landforms 26, 1237–1248 (2001).
- Cheshire, M., Fannin, N.G.T., and Thomson, M.E., Solid Geology, 1:250,000 series, Tay Forth, Sheet 56°N-04°W, 1986; UTM070SF ISBN 0751813834.
- Envision 2011. Data Analysis and Design of Sampling Programme for Inch Cape. 2010-1039-SERL-Inch Cape Report v1. 23pp.
- Ferentinos, G. and McManus, J. 1981. Nearshore processes and shoreline development in St Andrews Bay, Scotland, U.K. In Holocene Marine Sedimentation in the North Sea Basin (eds S.-D. Nio, R.T.E. Schuttenhelm and TJ.C.E. van Weering), Special Publication of the International Association of Sedimentologists, No. 5, Blackwell Scientific Publications, Oxford, pp. 161–71.
- Folk, R.L. 1954. The distinction between grain size and mineral composition in sedimentary rock nomenclature. Journal of Geology 62 (4), 344-359.
- Fugro 2011. Geotechnical Survey. J11099 – 1 September 2011, Geotechnical Report – Field Data.
- Gatliff, R.W., Richards, P.C., Smith, K., Graham, C.C., McCormac, M., Smith, N.J.P., Long, L., Cameron, T.D.J., Evans, D., Stevenson, A.G., Bulat, J. and Ritchie, J.D. 1994. The geology of the Central North Sea. British Geological Survey offshore regional report, HMSO, London. ISBN 0118845047.
- Graham, A., 1986 Sea Bed Sediments, 1:250,000 series, Tay Forth, Sheet 56°N-04°W, 1986; UTM070SS ISBN 0751813869.
- http://www.dundee.ac.uk/crsem/TEF/review.htm.
- http://www.angus.gov.uk/ac/documents/roads/SMP/default.html.
- http://cmis.eastlothian.gov.uk/CMISWebPublic/Binary.ashx?Document=4117.
- http://fifedirect.org.uk/minisites/index.cfm?fuseaction=page.display&siteID=C03E446A-0241-A6A5-7462DD169B215841&pageid=C040877C-B767-3F71-8454BE5167C5BC58.

- Holmes, R. 1977. Quaternary deposits of the Central North Sea. 5. The Quaternary geology of the UK sector of the North Sea between 56 and 55° N. Report of the Institute of Geological Sciences, No.77/1.4.
- Holmes, R., Jeffrey, D. H., Ruckley, N. A., Wingfield, R. T. R. 1993. Quaternary geology around the United Kingdom (North Sheet). 1:1 000 000. (Edinburgh: British Geological Survey.).
- Holmes, R., Bulat, J., Henni, P., Holt, J., James, C., Kenyon, N., Leslie, A., Long, D., Musson, R., Pearson, S. and Stewart, H. 2004. DTI Strategic Environmental Assessment Area 5 (SEA5): Seabed and superficial geology and processes. British Geological Survey Report CR/04/064N.
- HR Wallingford 2009. Firth of Forth and Tay Developers Group, Collaborative Oceanographic Survey, Specification and Design. Work Package 1: Review of Existing Information. Technical Note DER4539/01. 17 September 2010.
- IXSEA 2011 Report of Survey to SENERGY On Behalf Of SeaEnergy Renewable. Site Survey Inchcape Volume Survey Results. JN3508 JN3508. 41 pp.
- iXSurvey Ltd 2011. Report of Survey for Senergy S&G on behalf of SeaEnergy Renewables. Site Survey – Inchcape, Volume 1 – Survey Results. JN3508.
- McCave, I.N. 1971. Sandwaves in the North Sea off the coast of Holland. Marine Geology, 10, p. 199-225.
- McManus, J. 1986. Land-derived sediment and solute transport to the Forth and Tay Estuaries. Journal of the Geological Society 143: 927-934.
- McManus, J., Diez, J. J., Duck, R. W., Escobar, V. A., Anderson, J. M., Esteban, V. and Paz, R. 1993. Comparison of Scottish firths and Spanish rias. Bulletin of the International Association of Engineering Geology. 47: 127-132.
- Nielson, P. 1982. Coastal Bottom Boundary Layers and Sediment Transport. Word Scientific Publishing. Singappore. Advanced Series on Ocean Engineering, Vol. 4.
- Pantin, H. 1981. The seabed sediments around the UK. BGS Research Report SB/90/1. 47pp.
- Pantin, H.M., and Evans, C.D.R. 1984. The Quaternary history of the central and southwestern Celtic Sea. Marine Geology 57, 259–293.
- Partrac 2011. P1127.05.14.D001s03 - Forth and Tay Final Data Report - SeaEnergy Renewables.
- Physe 2011. R485_Inch Cape Metocean Criteria Vo1 D1 (3). 25 pp.

- Ramsay, D.L. and Brampton, A.H., 2000a. RSM 143 Coastal Cells in Scotland Cell 1.
- Ramsay, D.L. and Brampton, A.H., 2000b. RSM 144 Coastal Cells in Scotland Cell 2.
- Smith, J., and McLean, S.R. 1977. Spatially averaged flow over a wavy surface. J Geophys. Res., 82(12), 1735-46.
- SEPA 2000. Water Quality in the Forth Estuary 1980 – 1999 Report TW 07/00 July 2000.
- Soulsby, R.L. 1995. Bed shear stresses due to combined waves and currents. In Advances in Coastal Morphodynamics, Ed., Stive, M.J.F., et al, pp4-20-4-23. Delft Hydraulics, Netherlands.
- Soulsy, R.L. 1997. Dynamics of Marine Sands. Telford. 121 pp.
- Street, R., Steynor, A., Bowyer, P. & Humphrey, K. 2009. Delivering and using the UK Climate Projections 2009. Weather 64 (9), 227–231.
- Stoker, S.J. 1987. Quaternary Geology, 1:250,000 series. Tay Forth, Sheet 56°N-04°W, UTM070Q ISBN 0751813885.
- UKHO Admiralty Chart 1407 Montrose to Berwick-upon-Tweed.
- UK Admiralty Co-tidal and Co-Range Charts around the British Isles (1994-1996). 2009 In: Admiralty Charts (2008). Document Reference 1027005 (BODC Identifier 375).