Appendix E3 – Geomorphological Assessment

Seagreen Wind Energy

July 2012

9V5268

Royal HaskoningDHV
Enhancing Society Together

DOCUMENT NO:

[A4MR-SEAG-Z-DEV260-ERP192]

DOCUMENT TITLE:

Seagreen Phase 1: Geomorphological Assessment

PROJECT NAME:

Round 3 Zone 2
Firth of Forth
Offshore Wind Farm Development

RESTRICTED COMMERCIAL

A1	20/04/2012	DRAFT for initial Seagreen review	JC	NC	
B1	05/05/2012	Final	DB	NC	
Revision	**Date**	**Description**	**Originator**	**Checked**	**Approved**

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1. Introduction

This document presents a desk based Historical Trend Analysis (HTA) and Expert Geomorphological Assessment (EGA) in relation to the potential environmental effects upon the physical environment associated with Seagreen's Phase 1 Offshore Wind Farm (OWF) and Export Cable Route (ECR) developments.

This assessment provides a summary of past morphological changes as part of a HTA of the study areas (see **Section 1.1** for definition of study areas). An historical perspective is essential for understanding the present seabed and coastline, particularly as a background to the proposed developments. The seabed and coast are naturally dynamic and should not be assumed to be stable or have remained in their present form for many years.

The seabed and coast being naturally dynamic are constantly readjusting to the changing physical drivers of waves, tides, sediment supply, wind and, more recently, human interference. Such dynamism, acting at a variety of temporal (centimetres to kilometres) and spatial (seconds to millennia) scales, makes the study and monitoring of coastal and seabed changes a challenging science.

It is imperative that the present and, if possible, the past rates and patterns of change should be known in order to effectively inform and establish the baseline environment, against which the magnitude of future change, both natural and anthropogenic, may be set.

The findings of the HTA are utilised to inform an EGA on the functioning of the study sites and thereby provide critical information for the wider EIA process, particularly the drafting of the Physical Environment section of the Phase 1 Environmental Statement.

On the basis of the understanding gained through this detailed study, the report considers the relationship between the proposed development and the surrounding seabed and coastline and implications of any potential changes upon sensitive receptors. These have been identified previously via a Source-Pathway-Receptor (SPR) model approach (Seagreen, 2011). The assessment approach has been agreed through consultation with Marine Scotland as being directly proportional to the level of environmental risk associated with the proposed development upon the physical environment and its key attributes (e.g. hydrodynamics, sediments, coastal geomorphology).

The report will feed into a wider assessment of other process based studies, including foundation scour assessments (Royal Haskoning, 2012).

1.1. Study site

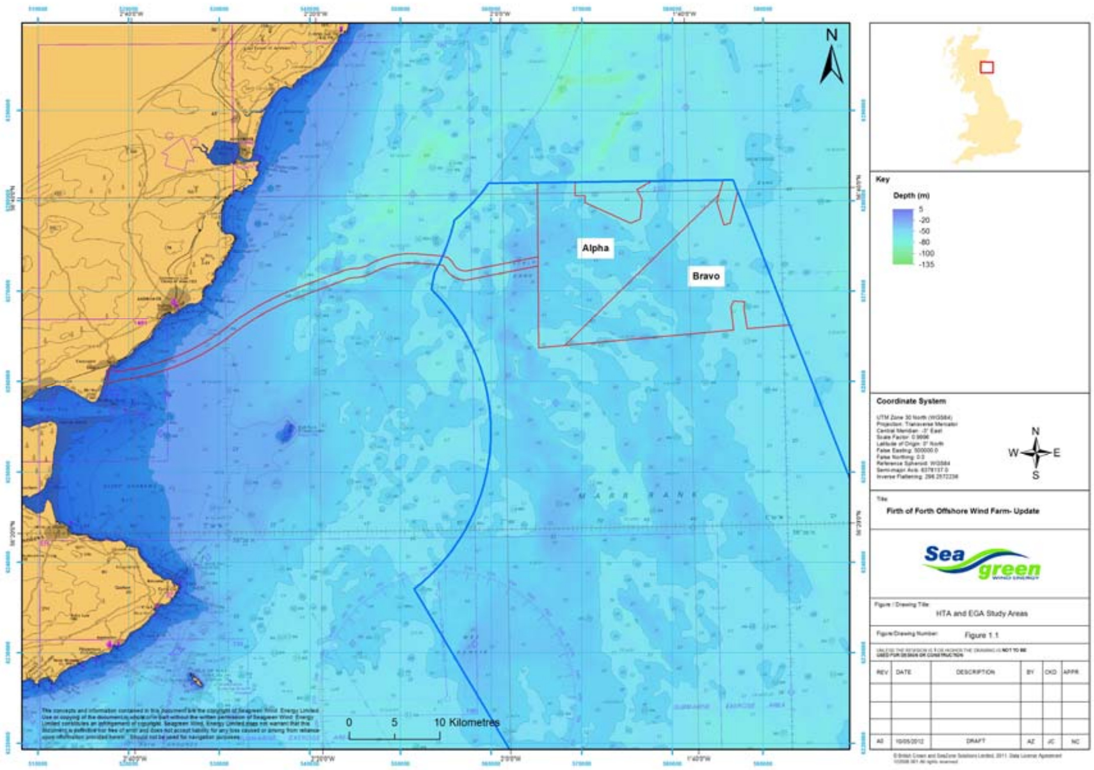
The purpose of the proposed Seagreen Phase 1 developments is to generate 1,075MW of energy from Seagreen Alpha and Bravo offshore wind farms and to link electricity production to the National Grid. The study area may therefore be considered as comprising three discrete elements (see **Figure 1.1**):

1. Phase 1 offshore development area;

2. Export Cable Route(s) (ECR); and,

3. Landfall at Carnoustie.

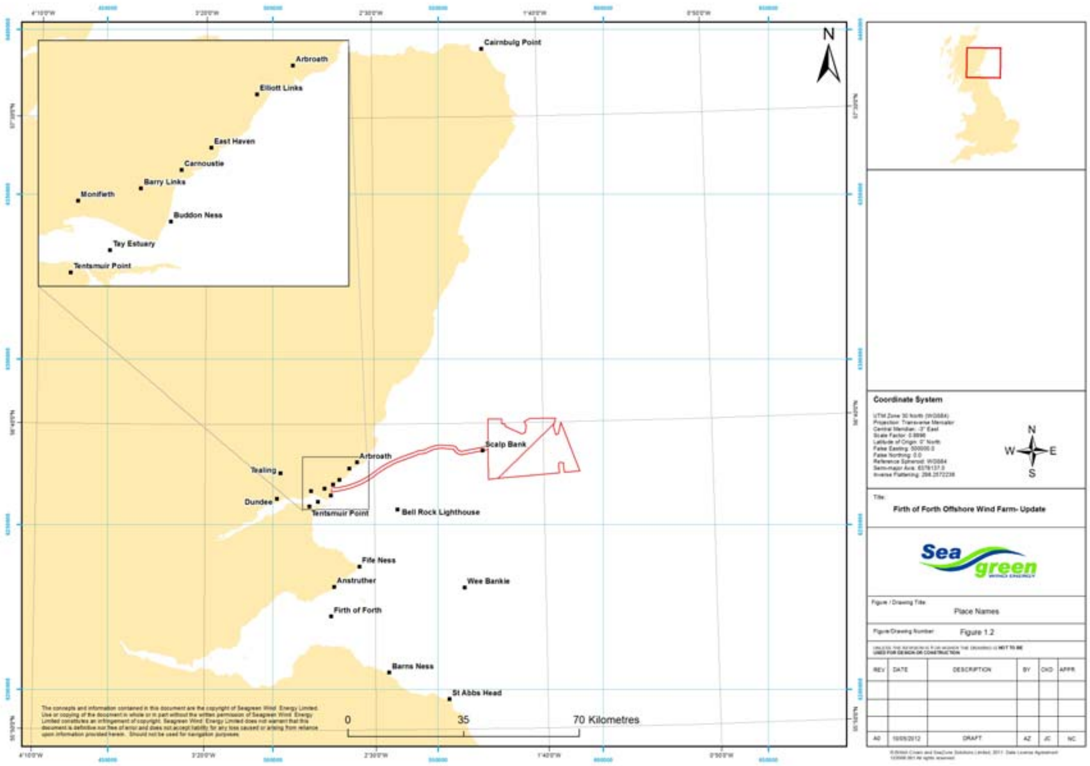
Figure 1.1 HTA and EGA Study Areas



The Phase 1 offshore wind farm development area comprises the development sites of Seagreen Alpha and Seagreen Bravo wind farms (see **Figure 1.1**). The ECR study area runs from the west-central boundary of Alpha prior to making landfall at Carnoustie. The coastal study area extends north from Buddon Ness, to include Carnoustie Bay and East Haven (see **Figure 1.2** for place names mentioned in text). The coastal study area includes all areas of the intertidal foreshore from Mean High Water Springs (MHWS) to Mean Low Water Springs (MLWS) that may be directly affected by the cable installation works. The offshore study area extends from the Round 3 Zone to MLWS.

In order to link electricity production from the coastal landfall site Seagreen is proposing to route underground export cables to the Tealing substation, approximately 20km inland. This work is assessed and presented in Seagreen's Phase 1 Onshore Grid Connection Works ES.

Figure 1.2 Place names mentioned in text



1.2. Previous and on-going studies

Reconstructing historical changes can be challenging and time consuming because the relevant evidence is often disparate and has to be collated from a range of sources. However, this is a critical first step in both the historic and geomorphological assessments, as it is within a historical context that future evolutionary trends of both seabed and coastal (i.e. intertidal) systems shall be assessed. It is thus useful to first establish what main studies have already been undertaken or are ongoing within the coastal and offshore study areas to minimise any unwanted repetition of work previously completed or ongoing.

Phase 1 offshore development area

Review of existing metocean information (HR Wallingford, 2009)

HR Wallingford (2009) in their review of existing metocean information with relation to the Firth of Forth and surrounding Scottish Territorial Waters (STW) provided a detailed review of the existing data sources in relation to:

1. Tidal regime, including tidal currents;
2. Wave regime;
3. Climate changes; and
4. Sediment regime.

HR Wallingford (2009) state 'numerous studies into water circulation in the Firth of Forth have been carried out…..the general pattern of the tide is southerly directed flood tide that moves along the eastern coastline…into the Firth of Forth, around Fife Ness. Across the mouth of the Firth, the flood tidal stream has a general east-south-east pattern, whilst the ebb tidal stream runs in a west-north-west direction'.

The wave regime in the proposed development can be regarded as a combination of swell waves moving into the area and locally generated wind waves. Swell wave conditions are dominated by waves generated from between 20^{o}N and 60^{o}N, with approximately 60% of swell conditions experienced from this sector. Since wind waves originate from meteorological forcing, the wave regime is highly episodic and exhibits strong seasonality. In locations with strong tidal flows, wave-current interactions and current refraction effects may also become important.

The majority of modern seabed sediments consist of substrates that are more than 10,000 years old and have been reworked by wave and tide generated currents to form large sand and gravel dominated areas. There are presently limited details to define type, concentration and variability of suspended sediment offshore of the Firth of Forth. However, the main sediment type for suspension is likely to be the finer fractions of sediment (e.g. mud, silt and fine sand) which are easier to mobilise within the water column.

HR Wallingford (2009) presents a conceptual understanding of the sediment regime within the wider Firth of Forth which is summarised herein:

- Wave-induced longshore transport dominates sediment movement in the Tay Estuary.

- There appears to be some movement of sand from the northeast into the Firth of Forth.

- There is no significant transport between the north and south shorelines of the Firth.

- Over much of the central North Sea, sand transport rates are relatively low as a result of lower tidal current speeds and increased water depths.

- Much of the seabed is covered by sheets of sand suggesting that hydrodynamic conditions are not sufficient to result in significant movement of sediment.

- The effects of sea-level rise, without supply of new sediments, will result in the deepening of sand banks relative to mean sea-level.

HR Wallingford (2009) conclude 'based on the present desk study, it is considered that there is already sufficient data to characterise the broad scale regime….The main data gap is represented by the need for greater and more detailed characterisation of site-specific conditions within the wind farm development areas'.

This data gap has been addressed by Seagreen's Phase 1 survey and assessment programme to support the Environmental Impact Assessment (EIA) process (see **Table 1.1**).

Table 1.1 Seagreen Phase 1 EIA survey and assessment programme

Title	Source	Year
Firth of Forth Offshore Wind Farm ECR: Geophysical survey	Osiris Projects	2011
Firth of Forth Offshore Wind Farm Development: Post survey report benthic services	IECS	2011
Firth of Forth Zone Development: Metocean survey	Fugro	2011
Round 3 Firth of Forth Phase 1 Preliminary Geological Report	Cathie Associates	2011
Round 3 Firth of Forth Phase 1 Export Cabling Routing Geotechnical Desk Study	Cathie Associates	2011
Geophysical Results Report Phase 1	GEMS	2010
UK Round 3 OWF Zone 2 Firth of Forth. Wave Height Spells for Survey Operability	Metoc	2010

Round 3 Sediment Gap Analyses (ABPmer (2009)

ABPmer (2009) in their work for The Crown Estate on Round 3 Sediment Gap Analysis stated that with regards to the Firth of Forth Zone that seabed mobility and migration of seabed features (megaripples and sand waves) was of low risk though the confidence in this risk rating was low.

ABPmer (2009) state that superficial sea bed sediments are predominantly coarse, typically composed of sand and gravel populations. Available literature indicates that the sea bed features within the Firth of Forth Zone are sand waves and mega ripples, indicative of a mobile regime (hydrodynamic and subsequent sediment transport). Due to the relatively benign nature of the tidal regime and the water depths, ABPmer (2009) suggest that the sediment transport within the Zone is under the predominant control of low-frequency high energy events (storms).

Export Cable Route (ECR)

It should be noted that the ECR comprises elements which are located in relatively deep water and are defined as open marine, while certain elements are also located within the relatively shallow inter- and sub-tidal areas.

There are no specific studies relating to the ECR *per se*. However, the review of existing metocean information by HR Wallingford (2009) provides a summary of the physical characteristics of the Phase 1 offshore development area of which some aspects are broadly applicable to the ECR. Furthermore, Ramsay & Brampton (2000) provide detailed information on Coastal Cells in Scotland which is directly applicable to those nearshore elements of the ECR and is set out in the proceeding sub-section: Landfall at Carnoustie; to which the reader is referred.

Landfall at Carnoustie

Angus Shoreline Management Plan (Angus Council, Undated)

Coastal Process Unit (CPU) 6 extends from Whiting Ness to West Haven and is the principal CPU of interest with regards to the work presented herein.

Shoreline changes at East Haven to the north of Carnoustie are shown in **Figure 1.3**. According to the SMP (Angus Council, Undated) the rate of coastal change along much of this frontage is not nearly as dynamic as along other sections of the Angus coastline, most likely due to the occurrence and protective effects of the shingle and cobble storm beach.

Figure 1.4 illustrates the average position of the Mean High Water mark relative to the present day position for each of the map editions used for the open coastline at East Haven. Considerable accretion has occurred within the bay since the first edition OS Map, which suggests that the MHWS line was up to 50m further landward than it is today. This pattern of accretion appears to have continued until around the 1970s. Subsequently, the position of the MHWS line has retreated by around 8m. To the south of East Haven as far as West Haven, there has been a similar pattern of accretion up until the early 1960s followed by a period of retreat to the present day.

Figure 1.3 Shoreline changes at East Haven

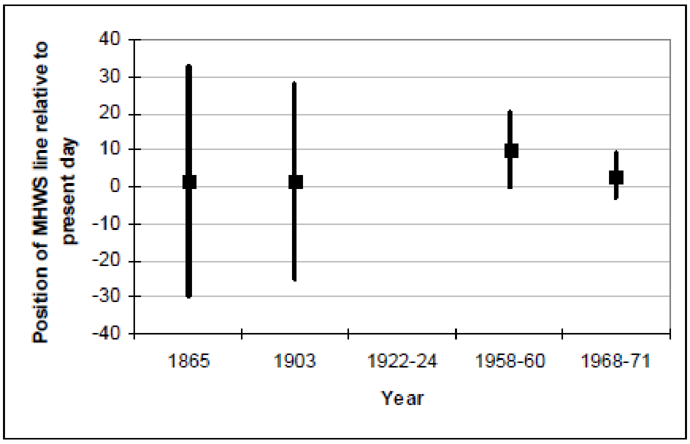
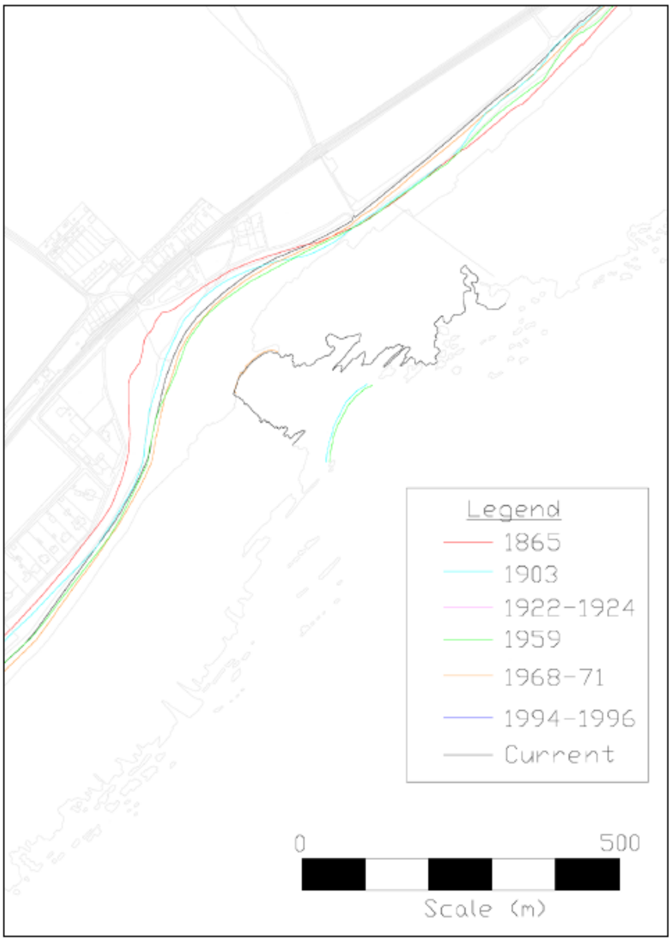


Figure 1.4 Historical shoreline changes at East Haven



Coastal cells in Scotland: Cell 2 – Fife Ness to Cairnbulg Point

Ramsay & Brampton (2000) provide detailed information on Coastal Cells in Scotland. Coastal cell reports set out:

Physical characteristics;

- Geology;
- Hydraulic processes;
- Littoral processes; and,
- Coastal defences.

The relevant information contained within the coastal cell report (Ramsay and Brampton, 2000) is presented within the corresponding section of the EGA (see **Section 4.3: Carnoustie**).

1.3. Summary

Phase 1 offshore development area

- Limited temporal data sets (2006-2010)
- Limited spatial coverage of data sets
- Data sets of varying resolution (gridded at 5 x 5mm and 20 x 20m)

Export Cable Route (ECR)

- Information relating to the ECR is notably sparse
- Little quantitative data on sediment transport rates or suspend sediment concentrations

Landfall at Carnoustie

- Detailed quantitative and qualitative data sets
- Extensive temporal (decades) and spatial (entire coastline) data coverage
- Highly dynamic coastline

1.4. Structure of this report

This report comprises 5 sections of which this introduction is **Section 1**. A brief method statement is provided to support understanding of the HTA and EGA in **Section 2**, which also outlines data sources utilised. Results of the Historical Trend Analysis (HTA) are presented in **Section 3**. The HTA provides an overview of the morphological development of the study site since the Holocene (approximately 10,000 years B.P.), prior to focussing on recent historical trends (approximately the last 162 years). **Section 4** presents the results from Expert Geomorphological Assessment (EGA). Both the HTA and EGA sections are concluded with a summary and discussion. **Section 5** presents the key findings of the work presented herein and its applicability to Seagreen's Phase 1 Environmental Impact Assessment (EIA) process.

2. Method statement

2.1. Historical Trend Analysis

The Historic Trend Analysis (HTA) involved a review of the past data and available records that relate to the Angus coastline set within the broader context of the Firth of Forth and northern North Sea. This HTA covered the period between 1703 and 2011 and considered both natural and anthropogenic changes within the area, which is particularly relevant in the context of morphological evolution. The HTA provides an analysis of the historic behaviours of the system; from such an analysis assessment can be made of potential future change.

The analysis made use of the following primary and secondary data sources (see **Table 2.1**).

Table 2.1 HTA Primary and Secondary Data Sources

Data	Year	Source	Coverage
Offshore – Phase 1 Area			
Bathymetry	2010	GEMS	Phase 1 area
Bathymetry	2006	UKHO	Regional seabed
Bathymetry	2006	Seazone	Regional seabed
Seabed substrate (backscatter and sidescan sonar)	2011	GEMS	Phase 1 area
Seabed substrate (benthic and sediment analysis)	2011	Envision	Phase 1 area
ECR			
Bathymetry	2011	Osiris	ECR
Bathymetry	2006	UKHO	Regional seabed
Seabed substrate (backscatter and sidescan sonar)	2011	Osiris	ECR
Seabed substrate (benthic and sediment analysis)	2011	Envision	ECR
Landfall			
Aerial photography	2000	Angus Council	Entire cost
Aerial photography	2004	Angus Council	Entire cost
Topographic survey	2012	Seagreen	Carnoustie landfall
OS 25 inch to the mile Forfar, Sheet 052.02	1865	Ordnance Survey	Dowrie Bitumen works
OS 25 inch to the mile Forfar, Sheet	1865	Ordnance Survey	Dowrie Bitumen works

Data	Year	Source	Coverage
052.06			
OS Popular edition, Scotland Sheet 58 - Arbroath & Montrose	1927	Ordnance Survey	Entire coast
OS One-Inch to the Mile, Sheet 049 1st ed.	1862	Ordnance Survey	Entire coast
OS One-inch 2nd edition, Scotland, Sheet 49 - Arbroath	1904	Ordnance Survey	Entire coast
Map of the Basin of the Tay, including the greater part of Perth Shire, Strathmore and the Braes of Angus or Forfar.	1850	National Archive	Entire coast
The Firth and River of Tay with all the Rocks, Sands, Shoals, &c., Surveyed by John Adair	1703	National Archive	Entire coast

Historical mapping aerial photography was compared to identify key changes in morphology through time. Desk based analysis and geomorphological interpretation were undertaken on the range of data available to understand the possible causes of change and determine future likely response on the basis of past behaviour.

Offshore

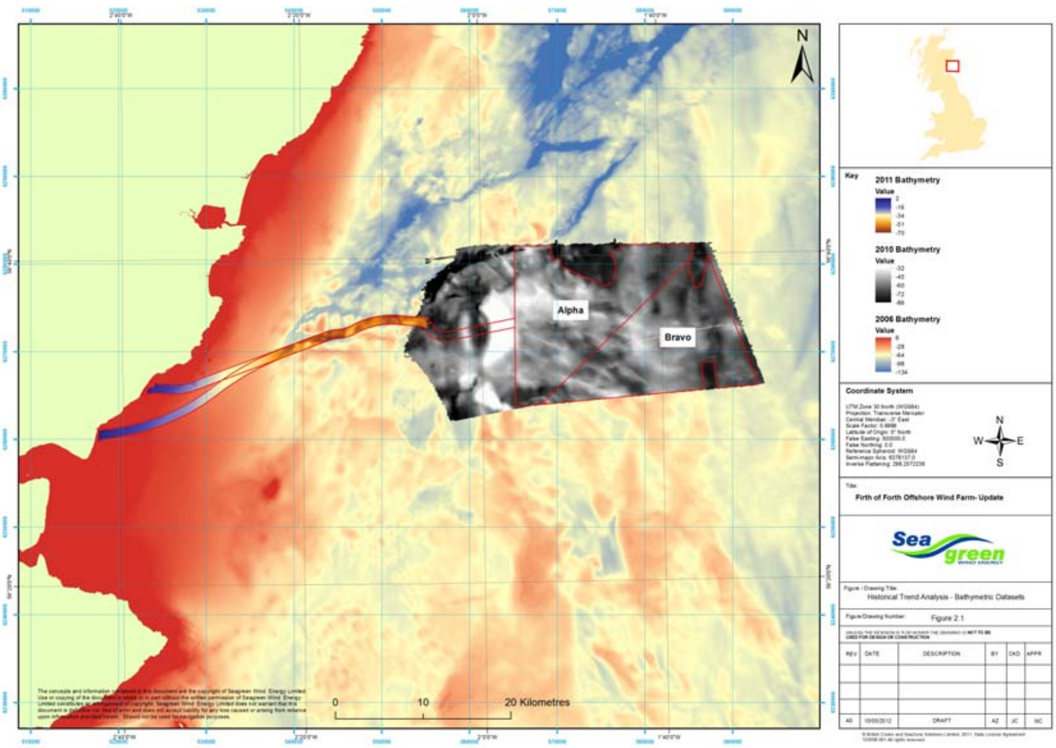
Analysis of bathymetric charts and data sets

Although charts covering the Firth of Forth and Northern North Sea exist back to the 16th century, it is only those published since the early 19th century that have sufficient spatial reference detail (e.g. grid references and projection information) and ground control points (structures located on maps that remain static through the time period considered, such as Bell Rock Lighthouse) for georectification, thereby enabling direct spatial comparison of features.

Bathymetry data sets were sourced from the UKHO and Seazone as pre-rectified digital charts and raster data sets. These were supplemented by site specific multibeam bathymetry, backscatter and side-scan sonar survey of the Phase 1 development area. **Table 2.1** and **Figure 2.1** present bathymetric data sets utilised in this study.

All depths were converted to metres relative to Ordnance Datum (OD) to enable direct comparison between charts. Due to the spatial extent of data coverage and the variable coverage of each chart, Regions of Interest (ROI) were defined to assist analysis. ROI were defined upon unique geomorphological and sedimentological characteristics (see **Section 2.3**).

Figure 2.1 Bathymetric data sets utilised in this study



The key data sets utilised within this study are temporally and spatially disparate. The most up to date data sets were acquired by Osiris (2011) on behalf of Seagreen and cover the ECR corridor from Carnoustie to the Phase 1 boundary. The Phase 1 data were acquired by GEMS (2010) and spatially extend to cover the entire Phase 1 area. All other bathymetric data out with these near-contemporary data sets has been acquired from Seazone (2006). All data analysis (e.g. volumetric changes) presented herein use the Seazone (2006) data as baseline data from which all subsequent changes are quantified. Therefore, changes within the ECR relate to the temporal period 2006 to 2011; Phase 1 area 2006 to 2010. For ease of comparison all results are presented as changes per year.

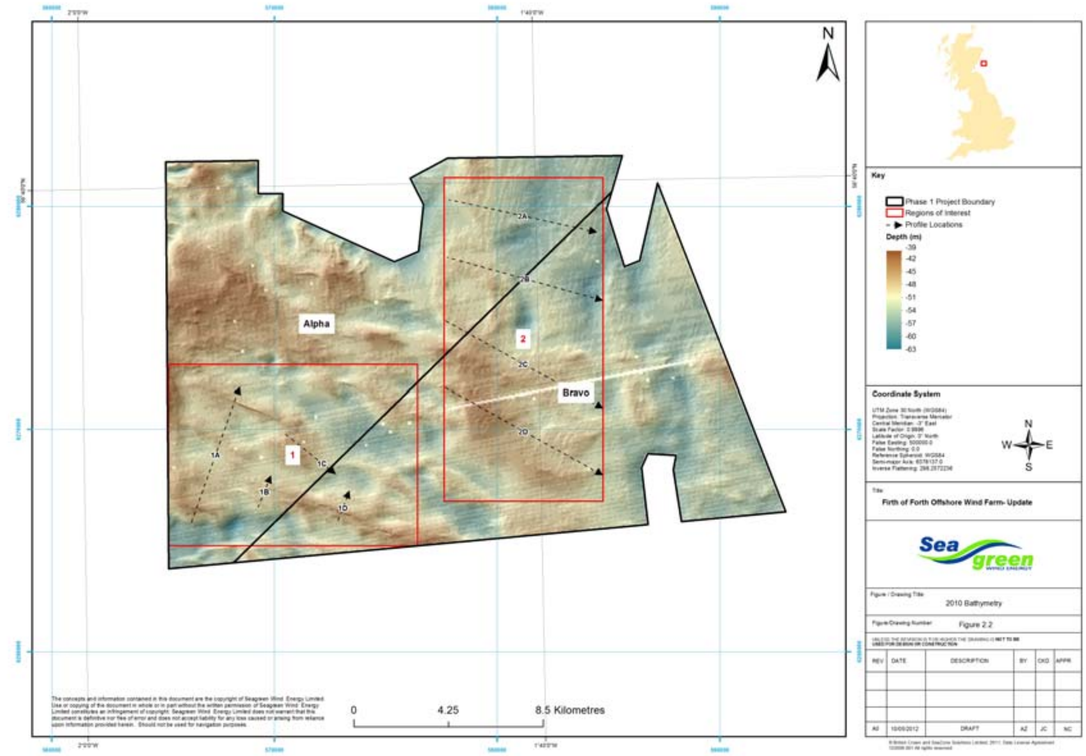
Analytical approach

Bathymetric surfaces were analysed to assess the patterns of change in seabed elevation. The broader patterns in seabed evolution were qualitatively assessed in terms of 3D morphological evolution using ArcGIS 9.2. Bathymetric change maps, which show a calculated depth change between successive surfaces, were also produced. Further analysis was achieved through standard descriptive statistics.

Seabed transects

One of the simplest and most effective ways of examining topographic or bathymetric change across complex morphologies is to reduce datasets to a series of 2D profiles or transects. Profiles can highlight shifts in the position of features. In the Phase 1 area, ROI and transects were established (see **Figure 2.2**). Transects 1A, 1B and 1D are orientated north-east to south-west, while Transects 1C, 2A, 2B, 2C and 2D are generally orientated north-west to south-east. Transect evolution plots are presented (see **Figures 3.4**, **3.5** and **3.7** to **3.10**) and discussed in **Section 3.2; Results; Offshore; Bathymetry**).

Figure 2.2 Phase 1 development area, ROIs and transect locations

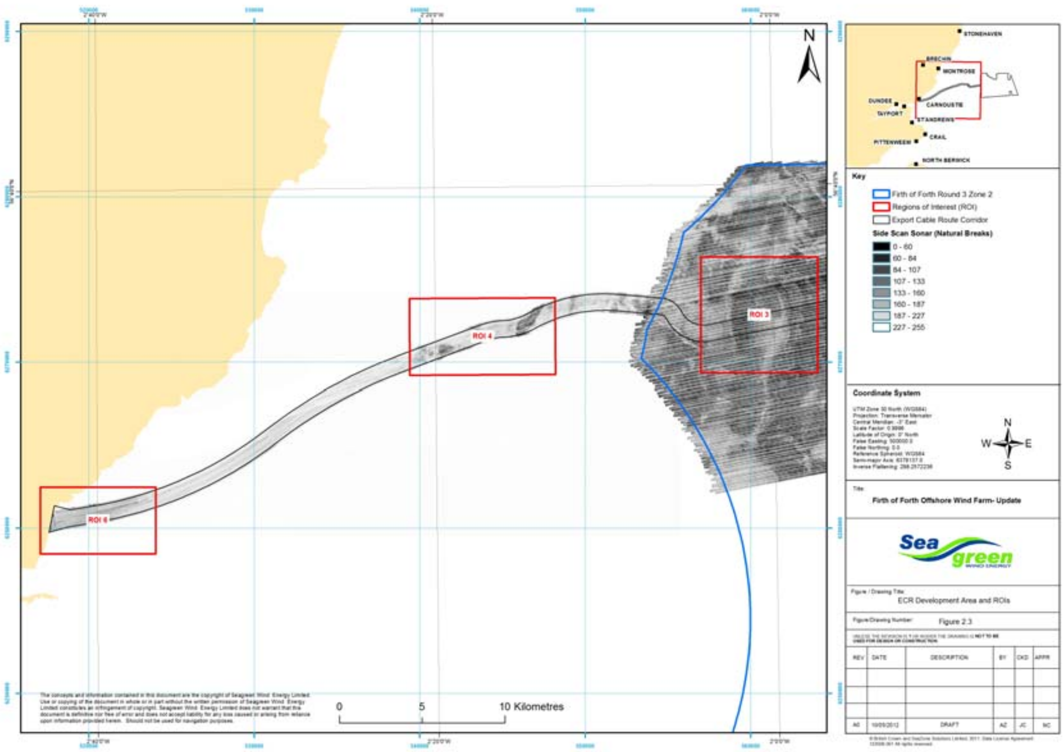


ECR

A similar approach to that adopted for the offshore was applied to the HTA for the ECR. The location of ROIs and transect evolution plots for the ECR (offshore and nearshore components) are presented in **Figure 2.3** and discussed in **Section 3.2; Results; ECR; Bathymetry**.

Due to the distance between the three ROIs of the ECR, results are presented for the offshore (ROI-3 and ROI-4) and nearshore (ROI-6) areas separately.

Figure 2.3 ECR development area, ROIs and transect locations



Landfall

<u>Analysis of aerial photography and historical maps</u>

Digital aerial photographs and historical maps were collated for the Carnoustie landfall (ROI-6) (see **Figure 2.3**) and assessed visually in the first instance to identify the direction and degree of change. As a discrete exercise, this is an appropriate approach toward this data and has been applied on previous mapping of habitats, for example, by English Nature (e.g. Burd, 1989).

Rectified aerial photographs were also assessed visually and utilised to obtain quantitative data from via interpolation within the GIS. Rectified and geo-referenced photography have a number of distinct advantages over hard-copy originals as:

- Rectification means that the photographs have been warped to reflect actual distances on the ground, without this process it should be recognised that a nonlinear distortion exits from the centre of the photograph and hence accurate quantification of distances (or levels) is not possible.
- Geo-referencing means the digital file is correctly adjusted to a known mapping co-ordinate system (OSGB).

Establishing changes in beach planform via time series map and aerial photography

Changes in coastal configuration can be detected by comparing sequential shoreline positions derived from aerial photography. This approach uses various analytical methods and equipment (GIS) to superimpose shorelines on a map and then to calculate rates of change both spatially and temporally. One way is to compare the earliest and most recent pairs of photos. This approach uses the longest span of years to determine an erosion or accretion rate. This ‘end point’ method can be a reliable proxy for predicting shoreline change in locations that have a steady erosion problem.

Another method, and the approach utilised herein, uses a time series of shoreline positions taken from a series of aerial photography (2000-2010). At any particular location, the horizontal position over time is used to calculate a linear regression or "best fit" to the data. This approach is favourable to reduce the influence of erosion and accretion cycles that may exist within a highly dynamic coastal environment.

2.2. Expert Geomorphological Assessment

Several techniques are available to investigate and predict the behaviour of seabed and coastal environments. Expert Geomorphological Assessment (EGA) is a technique which involves synthesising a range of data and integrating this with expert judgement to evaluate the current functional dynamics of a system and was applied to this study along with a HTA.

Data from a range of sources was compiled and analysed through both desk based review and Geographical Information System (GIS) interpolation. A combination of EGA and HTA allowed an evaluation of the geomorphological sensitivity of the seabed and coastal system within the study site in the context of the wider Angus coastline and the possible drivers of the evolution of the system to be identified. Following the EGA and HTA and taking account of local knowledge and that of other stakeholders, mitigation measures, where required, were developed.

2.3. Regions of Interest

As a consequence of the variable coverage of historic data sources and to provide direction to the EGA, Regions of Interest (ROI) were defined upon unique defining characteristics (e.g. location, geomorphology and sedimentology) as set out in **Table 2.2.** ROIs are presented graphically for the offshore (**Figure 3.1**), ECR and landfall areas (**Figures 3.9 and 3.15**).

Table 2.2 Phase 1 Regions of Interest (ROI)

Region of Interest	Location	Defining characteristics	Area (km^2)
Phase 1 Area			
ROI-1	Southwest Phase 1	Area of mixed seabed sediments with large sand bars (x 3) and megaripple field	90.998
ROI-2	East-central Phase 1	Area of active sediment transport indicated by the presence of extensive megaripple fields	103.600
Export Cable Route			
ROI-3	Western Scalp Bank	Area of exposed Quaternary deposits with little sediment cover. Highly variable bathymetry	49.494
ROI-4	Area of exposed Quaternary overlain with Holocene sediments	Distinct seabed features providing notable change in bathymetry and geotechnical properties	40.856
Landfall			
ROI-6	Carnoustie	Coastal landfall area at Carnoustie and including dune system of Barry Links	28.144

Seabed profiles were generated within the Phase 1 (Alpha and Bravo) and ECR areas. Transects were strategically placed within ROI to derive morphological characteristics of seabed features and to provide quantitative data to support the understanding of their conceptual development. Transect details are set out in **Table 2.3**.

Table 2.3 Phase 1 and ECR profile cross-sections

Region of Interest (ROI)	Defining characteristics	Length (m)
ROI-1		
1A	Orientated southwest to northeast and crossing 2 sand bar features	6,500
1B	Orientated southwest to northeast and crossing 2 sand bar features	1,600
1C	Orientated northwest to southeast and crossing 1 sand bar features	3,000
1D	Orientated southwest to northeast and crossing isolated megaripple field	1,600
ROI-2		
2A	Orientated west-northwest to east-southeast and crossing northern section of extensive megaripple field	7,000
2B	Orientated west-northwest to east-southeast and crossing north-central section of extensive megaripple field	7,250
2C	Orientated northwest to southeast and crossing south-central section of extensive megaripple field	8,000
2D	Orientated northwest to southeast and crossing southern section of extensive megaripple field	8,250
ROI-3		
3A	Orientated west-southwest to east-northeast and crossing northern section of the western perimeter of the Scalp Bank	7,250
3B	Orientated west-southwest to east-northeast and crossing central section of the western perimeter of the Scalp Bank	7,250
3C	Orientated west-southwest to east-northeast and crossing southern section of the western perimeter of the Scalp Bank	7,250
ROI-4		
4A	Orientated along centre line of ECR running offshore across an area of variable bathymetry	9,500
ROI-6		
6A	Orientated along centre line of ECR running offshore	6,500

3. Historical Trend Analysis

3.1. Introduction

The HTA has identified relevant studies that have previously been undertaken, or are ongoing, in the study area. This was to obtain the maximum possible benefit from previous work by reviewing their findings to provide an initial background context for the subsequent data analyses. It also considered the implications of such information in the context of the objectives that shaped the studies and subsequent reports. Importantly, the information was interpreted by applying EGA to help identify and focus further analytical work required to investigate and develop a fuller understanding of aspects on the coastal evolution.

3.2. Results

The study area was divided into 3 (1. Offshore; 2. ECR, and; 3. Landfall) each comprising a number of Regions of Interest (ROI) within which the historical behaviour of associated geomorphological features was explored. Results from the HTA are presented for these 3 study areas and their respective ROI in the following sections.

Offshore

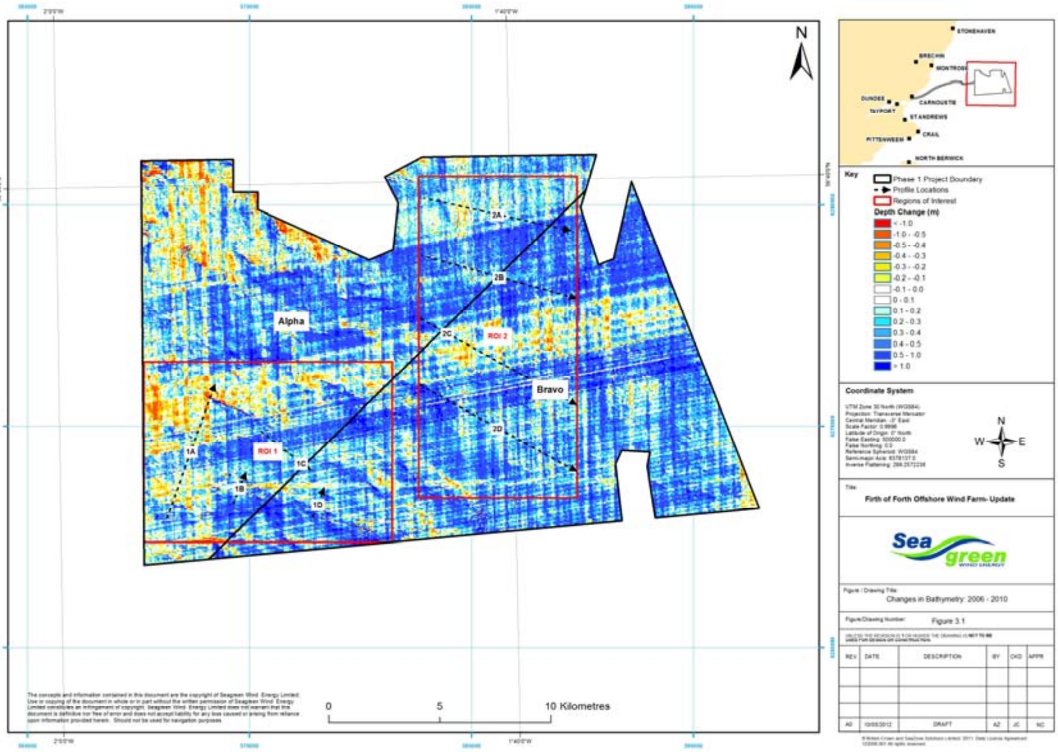
Bathymetry

The average seabed morphology, as determined by respective bathymetric data sets, highlights zones consistently deep or shallow. In combination with the depth range, the historical variability in seabed depth is well defined, irrespective of erosion vs. accretion (**Figure 3.1**). There are little to no areas that exhibit relatively little change in bathymetry over the analysed period (2006-2010), indicating that the entire seabed has, and continues, to evolve morphologically. However, these rates of change vary spatially from a low of ± 0.025m/yr to a maximum of 0.25± m/yr.

A general trend of erosion tends to dominate those areas to the west of the Phase 1 area. Large expanses of the upper centre are characterised by discrete stripped effect. This is interpreted as artefacts from data acquisition and post-acquisition processing.

Across the Phase 1 area, areas of relatively straight lines are observed as dark blue areas indicating deposition. These features are interpreted as sand bars which have been identified as part of the Phase 1 geophysical survey (GEMS, 2010) and are discussed in further detail in **Section 4: EGA.**

Figure 3.1 Cut/Fill raster bathymetric changes 2006-2010 for Phase 1 area



Calculation of rate of change in seabed depth is possible, and is most readily based on the assumption that site-specific changes are linear over time (e.g. Kemp & Brampton, 2007). The main patterns of net seabed change typically reflect the strength and direction of historical trends. Rates of vertical change within the Phase 1 area do not exceed ±0.25m/yr^{-1}.

Areas of increased deposition (dark blue in **Figures 3.2** and **3.3**) are spatially limited to known locations of mobile seabed features, such as sand waves and megaripples, and palaeochannels. The degree of seabed lowering along the Scalp Bank (to the northwest of **Figure 3.1**) is perhaps in response to tidal scouring, and is significantly enhanced to the west of Alpha as this area is within a region of notable bathymetric highs.

Geophysical surveys indicate the presence of a paleochannel across the centre of the Phase 1 area (see **Section 4.1**: EGA; Bathymetry), orientated northwest to southeast, which is partially infilled with Holocene sediments (GEMS, 2010). However, the feature is not discernible from the cut/fill analysis.

It is possible that the changes observed between the different bathymetric surveys, and hence result in cut/fill changes, may result from data acquisition and post-acquisition processing.

Figure 3.2 Cut/fill raster bathymetric changes (2006-2010) for offshore ROI-1

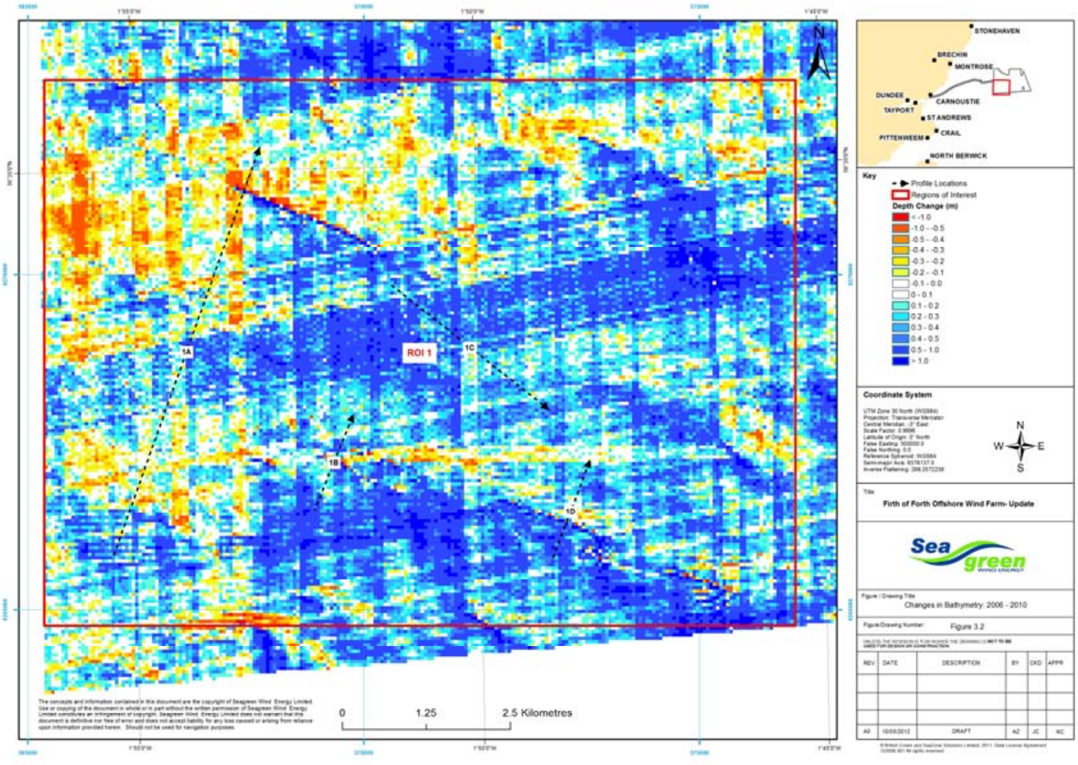
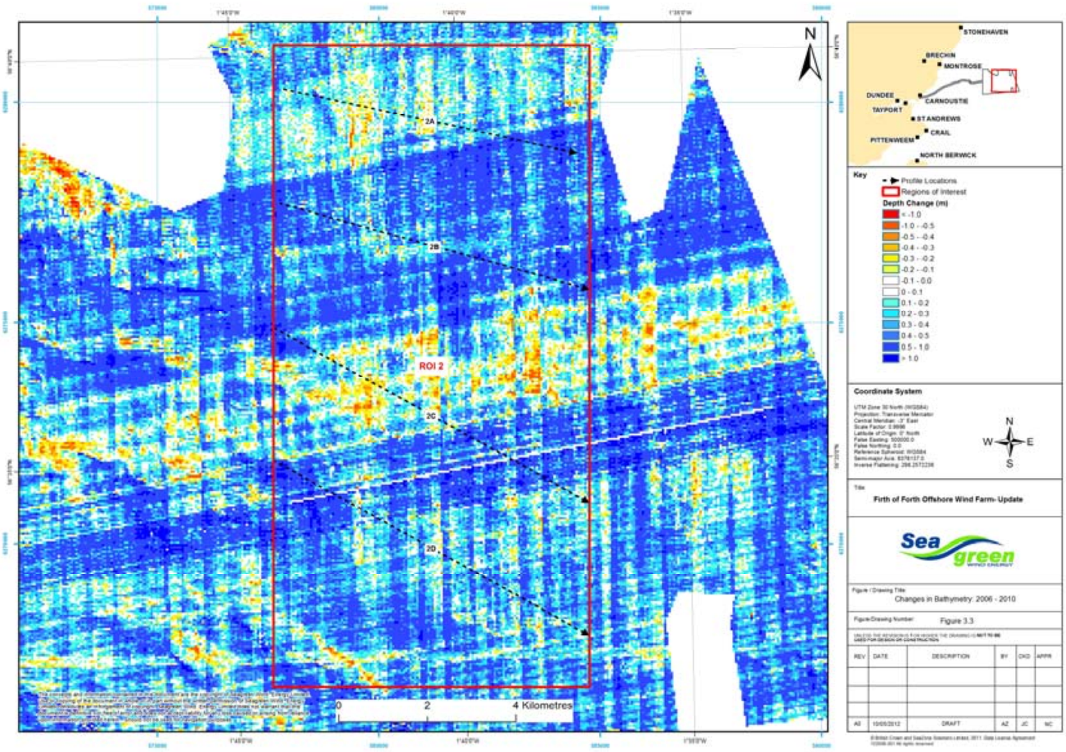


Figure 3.3 Cut/fill raster bathymetric changes (2006-2010) for offshore ROI-2



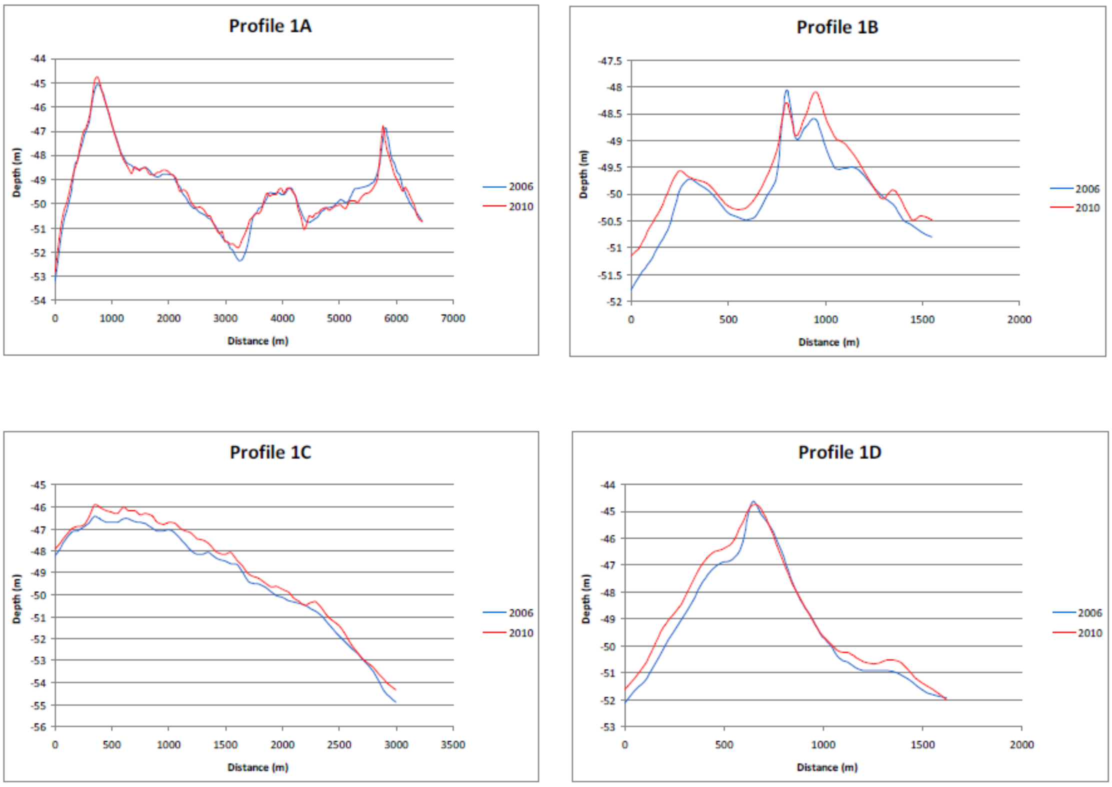
A series of seabed profiles (see **Figure 2.1**) have been extrapolated from the historical (2006) and near contemporary (2010) seabed data (see **Figures 3.4** (ROI-1) and **3.5** (ROI-2)). The results are presented and summarised in the following sections.

Although many of the smaller bedforms cannot be distinguished as a consequence of data resolution, the position of larger bedforms can be used to infer direction and rate of migration through time.

<u>Bedform migration</u>

A number of sand waves and megaripples are present across the Phase 1 development areas which tend to display a general orientation respective of their location, with relatively large-scale (100's of metres long) features (sand waves) within ROI-1 being orientated along a west-northwest to east-southeast axis. However, this broad-scale pattern is opposed within a small area of ROI-1, where megaripples are orientated along a south-southwest to north-northeast axis.

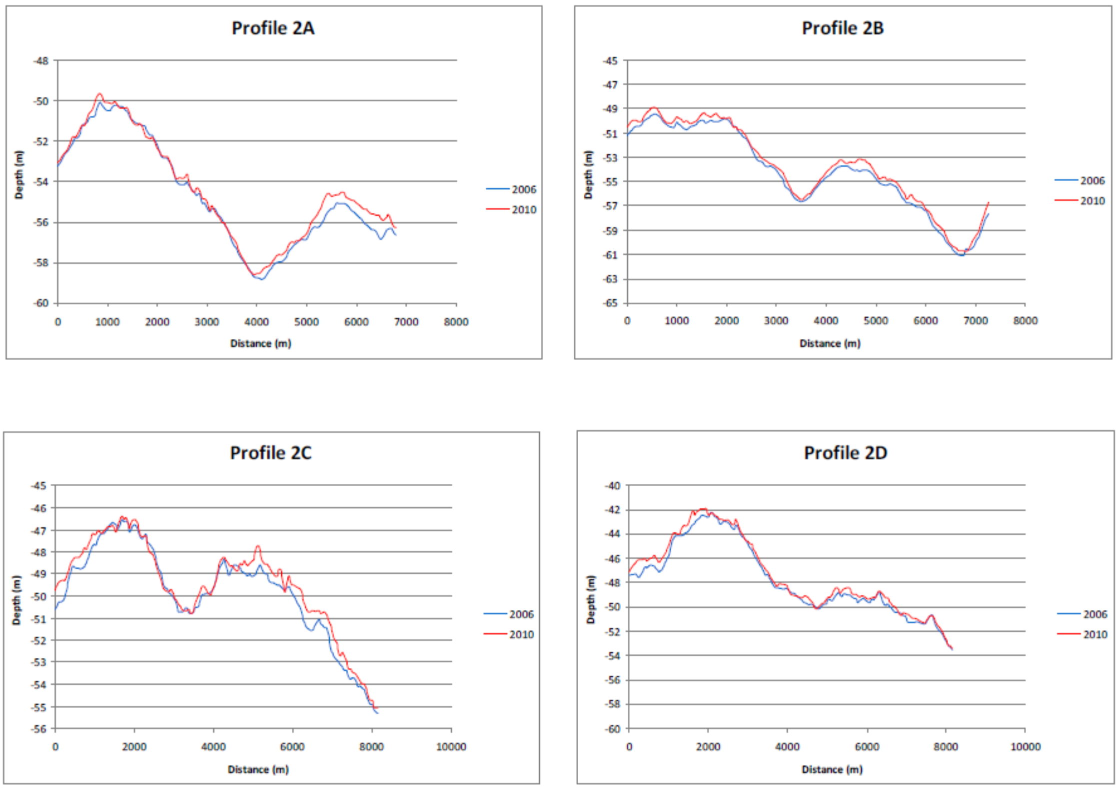
Figure 3.4 ROI-1 profile cross-section time series (2006-2010)



Three profiles (1A, 1B and 1D; see **Figure 3.4**.) have been extracted across the sand wave field and indicate morphological trends over the analysed period. The outline morphology of the seabed has shifted vertically between 2006 and 2010 indicating that the bedforms in this region are characteristic of an accreting environment. The degree to which accretion dominates is evidenced in all profiles within ROI-1 which display marked vertical shifts. In general, changes in bedform crest position and elevation are not observed, indicating that the bedforms have remained in position but have accreted vertically.

Four profiles (2A-2D; see **Figure 3.5**.) have been extracted from an extensive field of mobile bedforms which provide quantitative and qualitative data regarding their morphological trends. All bedforms analysed in Profiles 2A-2D indicate spatially consistent changes to their morphology, with small shifts in the lower flank profiles between 2006 and 2010, indicating that the bedforms in this region (ROI-2) are characteristic of an accreting environment. As with the bedforms of ROI-1, the degree to which accretion dominates mobility is evidenced in all profiles which display marked vertical shifts within their lower profiles. Changes in bedform crest position and elevation are not observed, indicating that the bedforms have remained in position but have accreted vertically.

Figure 3.5 ROI-2 profile cross-section time series (2006-2010)

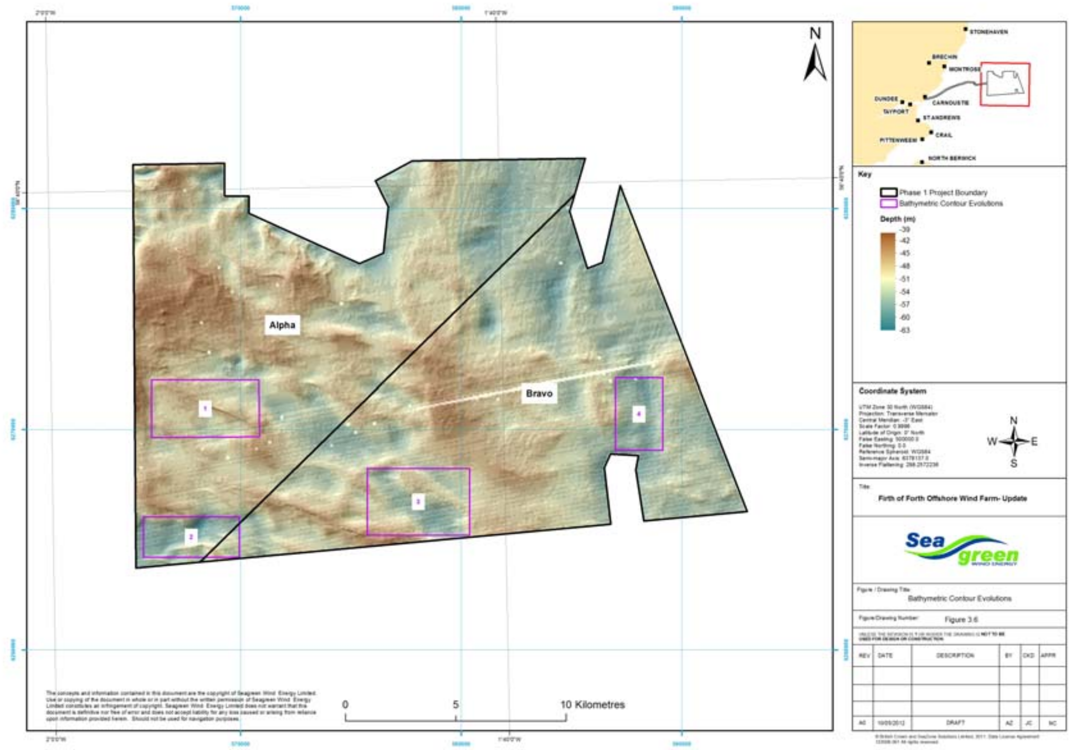


It is unclear from the charts whether sand waves and megaripples were present previously. However this is possible, given the somewhat hummocky seabed, but there is no doubt that the volume of material contained within the sand wave area has increased over the analysed period.

Contour analysis

Bathymetric Contour Evolution (BCE) provides a useful way to gain quantitative data on the rate of morphological evolution for features of interest. The technique has been applied to seabed features (sandbars and sand waves) within the Alpha and Bravo development areas (see **Figure 3.6**). Comparison of bathymetric contours provides spatial information on shifts in seabed features.

Figure 3.6 Bathymetric Contour Evolution (BCE) study locations



The BCE plots in **Figure 3.7** illustrate a gradual shift of a sandbar to the west or southwest. The southern extent of the sandbar crest, as delineated by the -46m contour, has accreted noticeably over the 4 year period (2006-2010), with the northern extent of the crest displayed a marked reduction in volume and a shift to the southwest. The -48 and -50m contours display a shift in morphology towards the southwest, with no noticeable sedimentary changes (i.e. accretion or erosion).

The BCE plots in **Figure 3.8** illustrate a gradual shift of a sandbar to the southwest into a trough with no noticeable shift in the flanks of the feature, as delineated by the -58 and -60m contours. The plotting of the bathymetric contours confirms a net south-westerly migration of the sandbar over the analysed period.

Figure 3.7 Bathymetric contour time series for seabed features in BCE-1

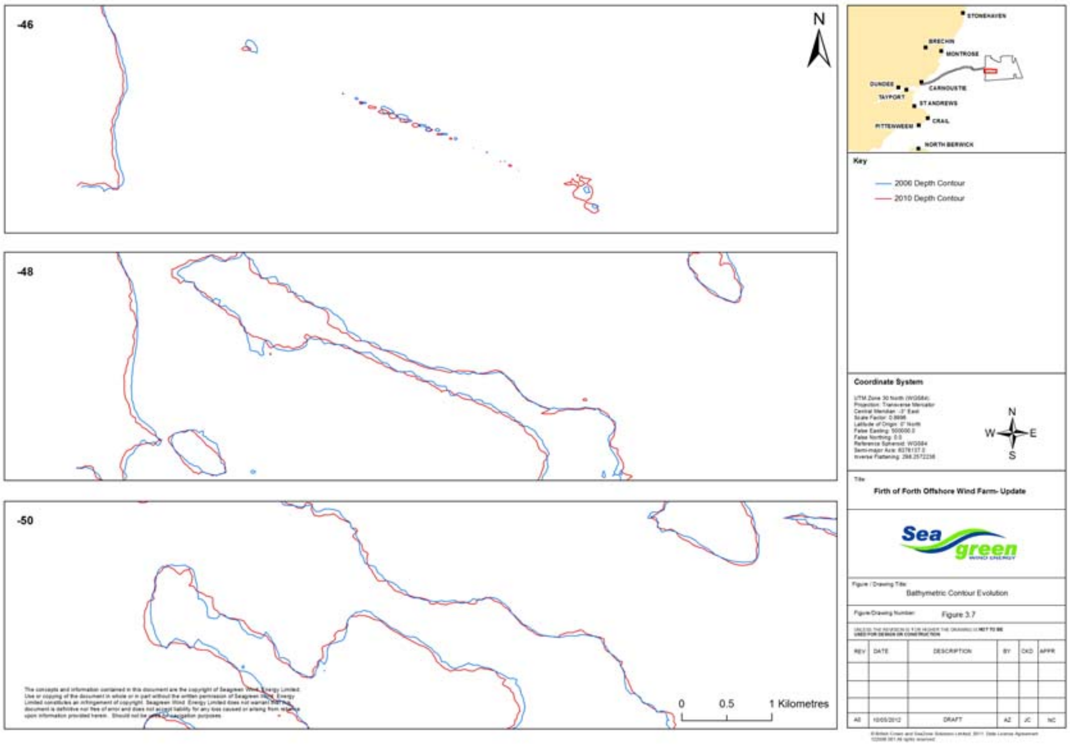


Figure 3.8 Bathymetric contour time series for seabed features in BCE-2

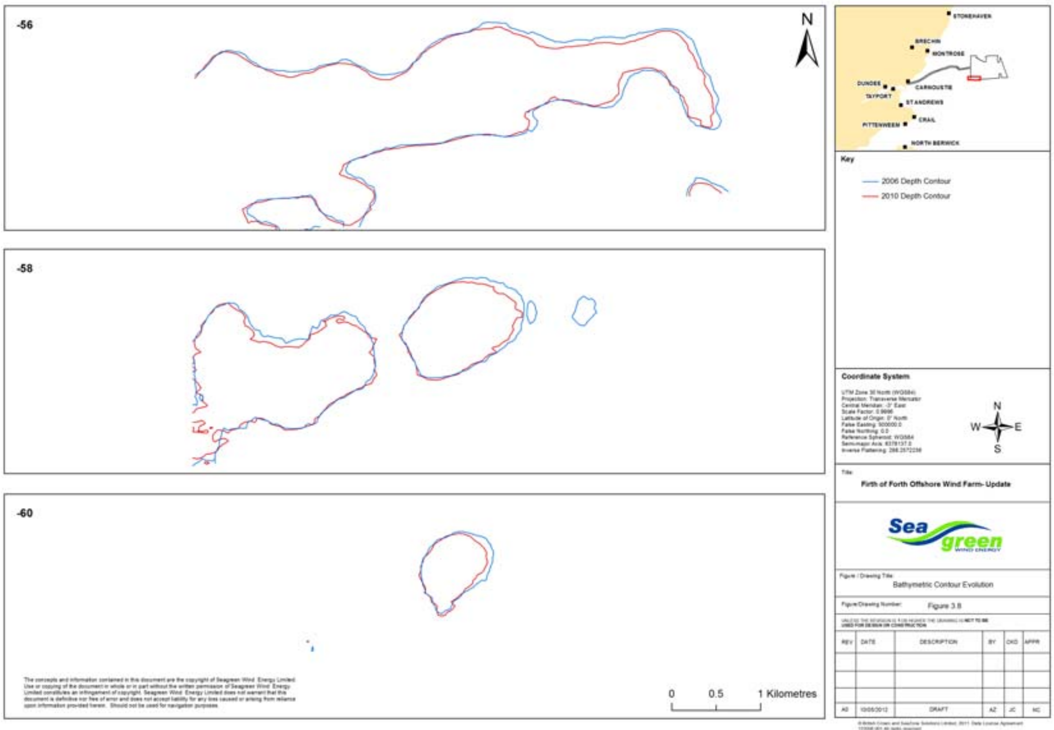


Figure 3.9 Bathymetric contour time series for seabed features in BCE-3

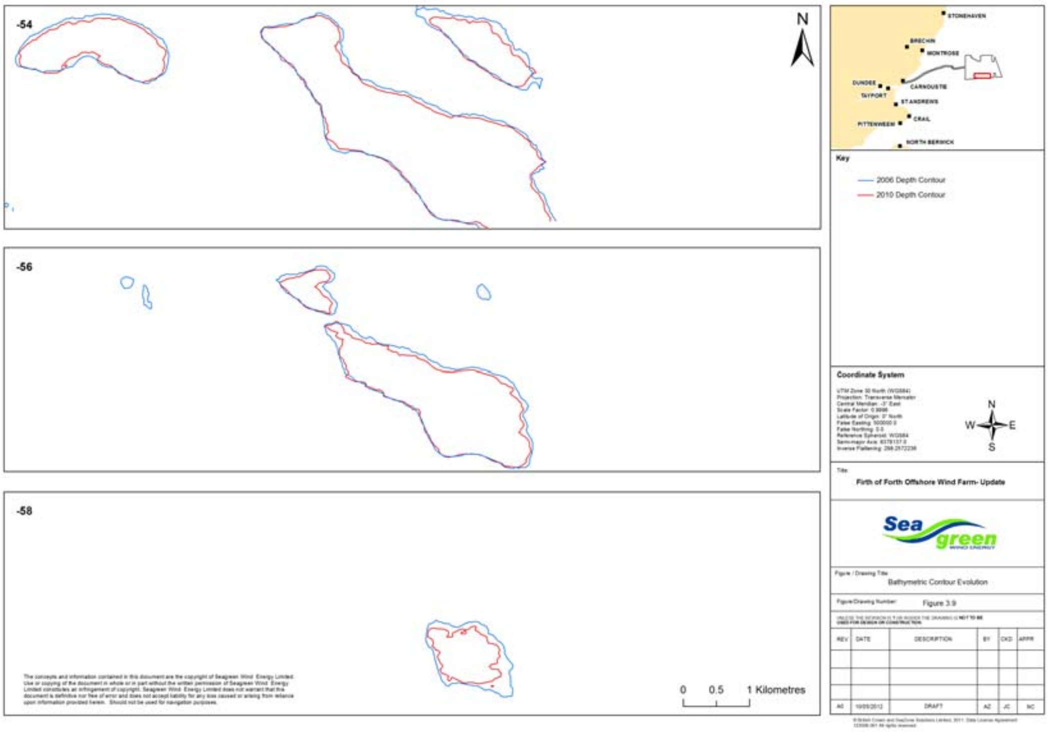
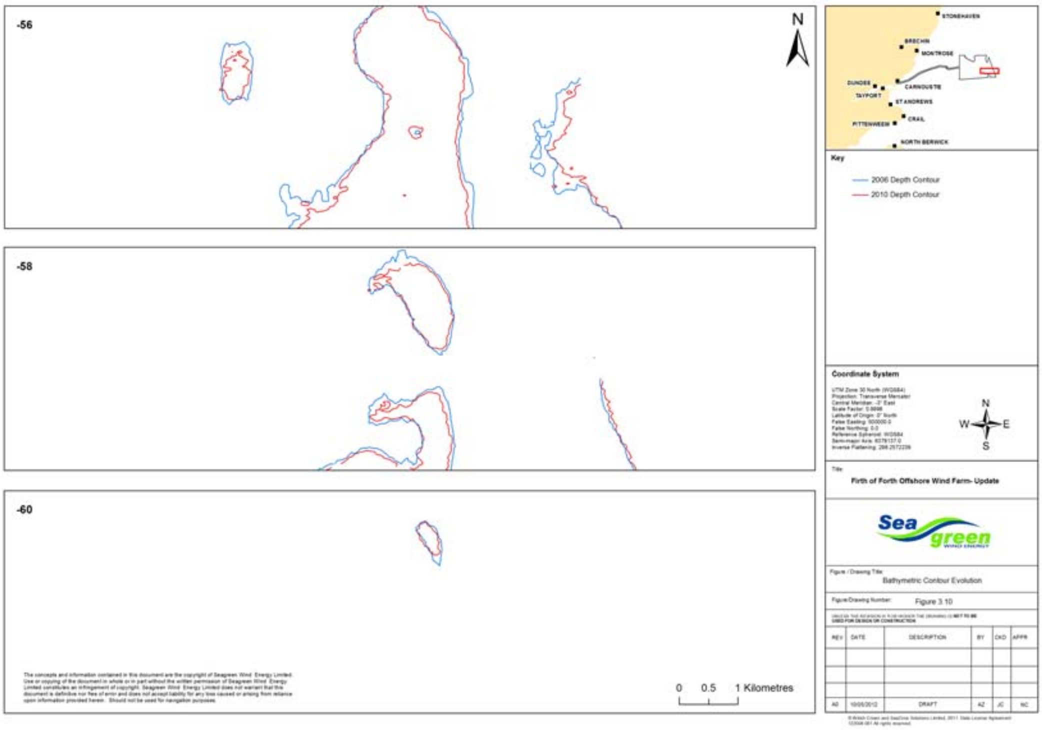


Figure 3.10 Bathymetric contour time series for seabed features in BCE-4

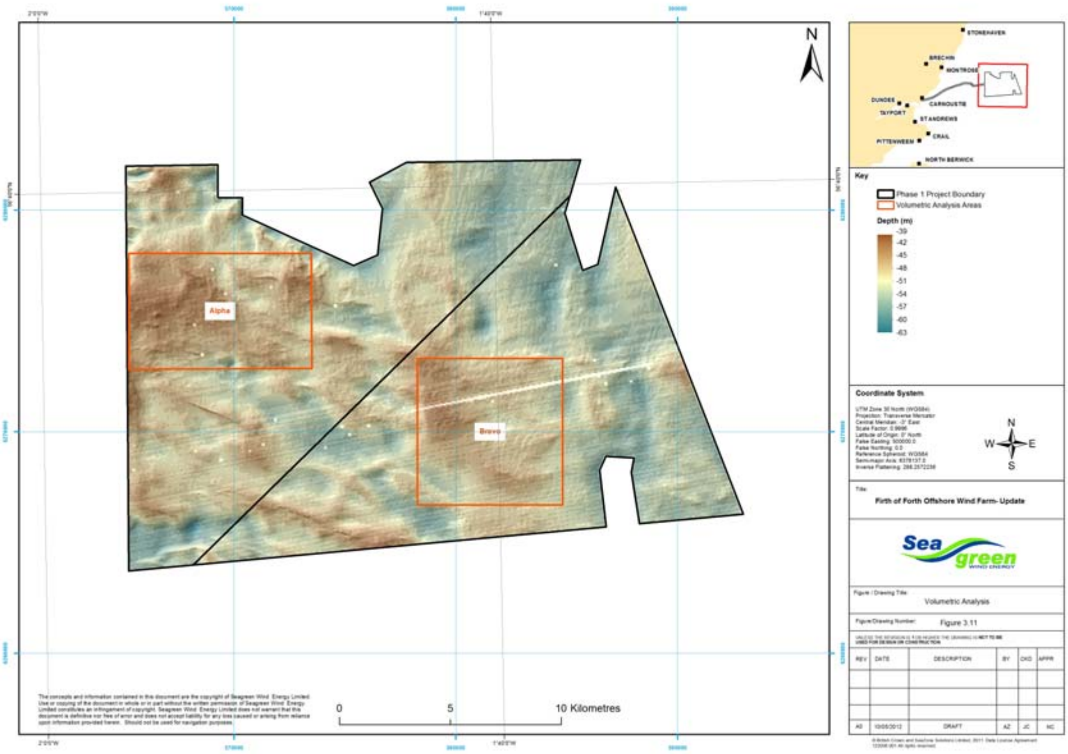


The BCE plots in **Figures 3.9** and **3.10** illustrate a gradual contraction of two seabed depressions over the analysed period; with the contraction more defined with increasing elevation from the seabed (i.e. -58m contour). Overall, the contours have remained relatively stable over the last 4 years.

<u>Volumetric changes</u>

To calculate volumetric changes, the volume of seabed above a selected contour was extracted from the gridded dataset. To ensure that results were comparable the spatial extent of analysis was set to a polygon of known extent (see **Figure 3.11**).

Figure 3.11 Location of Alpha and Bravo volumetric change polygons



The volumes are presented in **Table 3.1**. Change volumes are calculated relative to the baseline data of 2006.

Table 3.1 Volumetric changes for Alpha and Bravo

Contour (m below MSL)	2006 (m^3)	2010 (m^3)	Change (m^3)
Alpha			
-50	150,482,423	160,292,668	9,810,245
-45	24,818,472	27,785,914	2,967,442
-40	382	3,452	3,070
Bravo			
-55	234,131,347	248,538,060	14,406,713
-50	59,620,086	68,411,080	8,790,994
-45	3,341,999	4,486,147	1,144,148

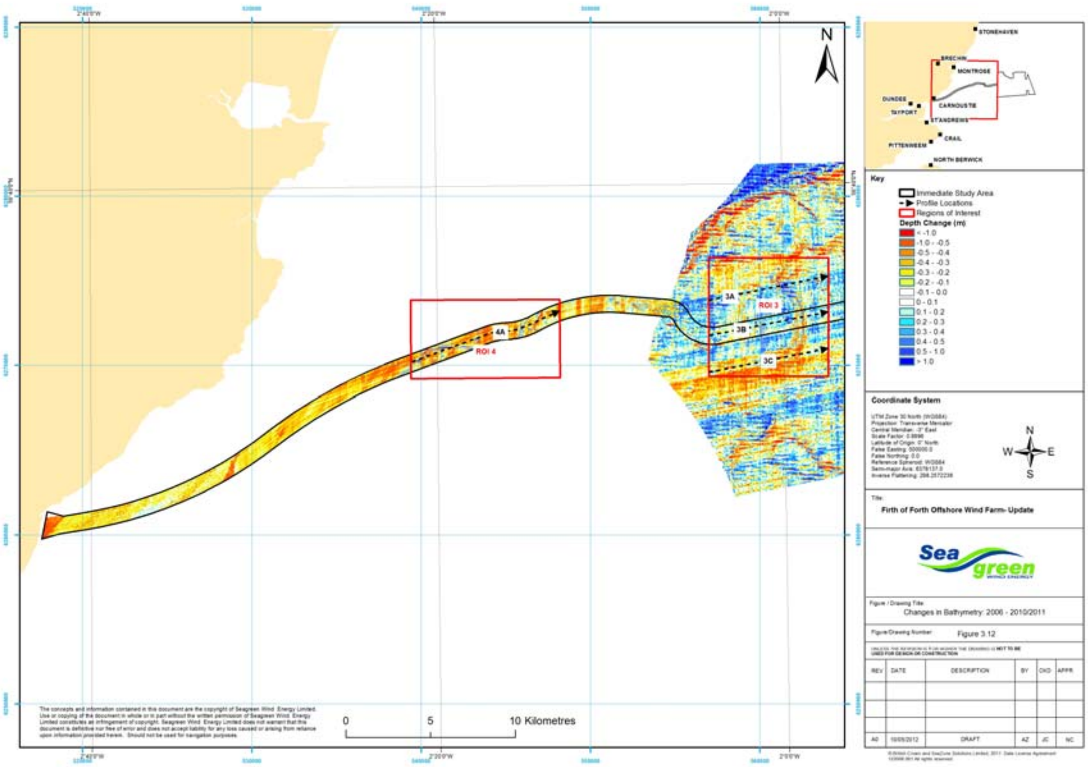
The volume analysis indicates a general pattern of seabed accretion across the spatial extent of the Alpha and Bravo volumetric change polygons over the analysed period (2006-2010). Volumetric change analysis may be interpreted as indicating broadly the sedimentary trend within each analysed area.

ECR

Bathymetry (ECR: ROI-3 and ROI-4)

The average seabed morphology, as determined by respective bathymetric data sets, highlights only a few areas that exhibit relatively small scale (≤0.02m/year) change in bathymetry over the analysed period (2006-2010 for the Phase 1 area and 2006-2011 for the ECR), indicating that the entire seabed has, and continues, to evolve morphologically (see **Figure 3.12**). However, these rates of change vary spatially from a low of 0 to a maximum of ±0.25± m/yr.

Figure 3.12 Cut/Fill raster bathymetric changes 2006-2010 and 2011 for Phase 1 and ECR area respectively



A general trend of erosion tends to dominate within the ECR corridor, being especially pronounced in close proximity to the shoreline. Areas to the northwest of the Phase 1 area tend to be characterised by marked accretion in bathymetric lows. As highlighted prior (see **Section 3.2: Results: Offshore; Bathymetry**), the Phase 1 bathymetric changes are characterised by discrete stripped effect. This is interpreted as artefacts from data acquisition and post-acquisition processing.

Areas of increased deposition (dark blue in **Figures 3.13** and **3.14**) are spatially limited to bathymetric lows, with a small area occurring on the lower margin of the Scalp Bank being attributable to bedform accretion and/or migration. The degree of seabed lowering along the Scalp Bank (to the northern and southern western perimeter of **Figure 3.13**) is perhaps in response to tidal scouring, and is significantly enhanced to the west of Alpha as this area is within a region of notable bathymetric highs.

Figure 3.13 Cut/fill raster bathymetric changes (2006-2010) for ECR ROI-3

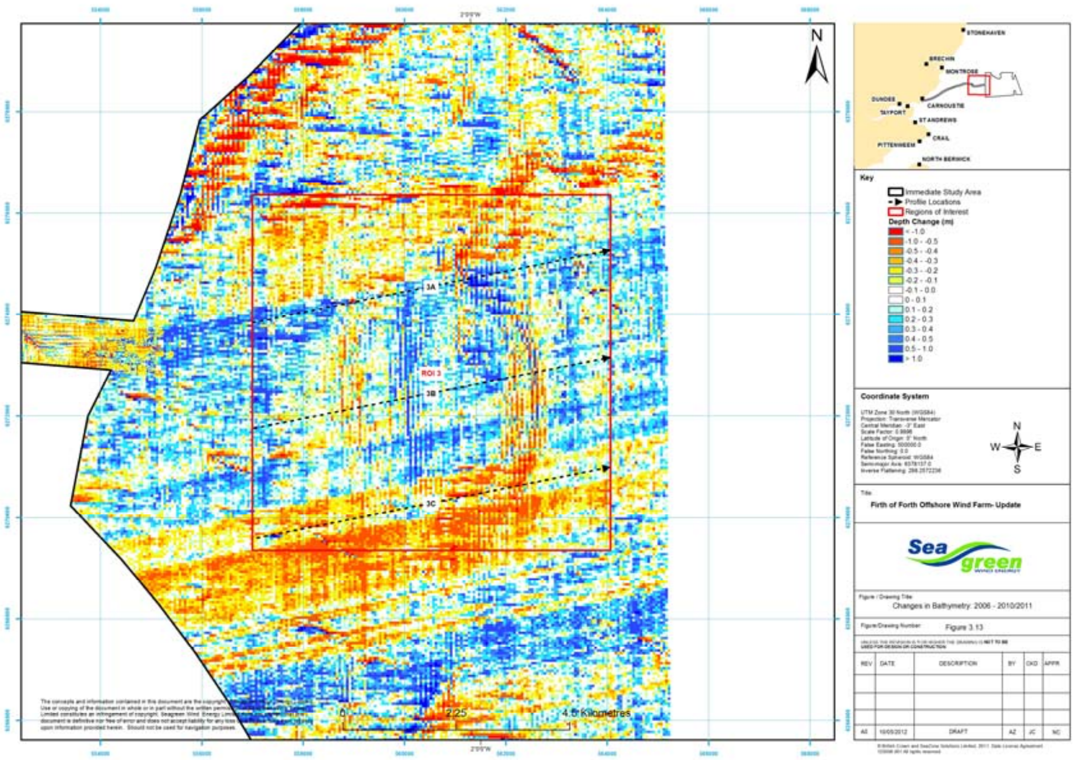
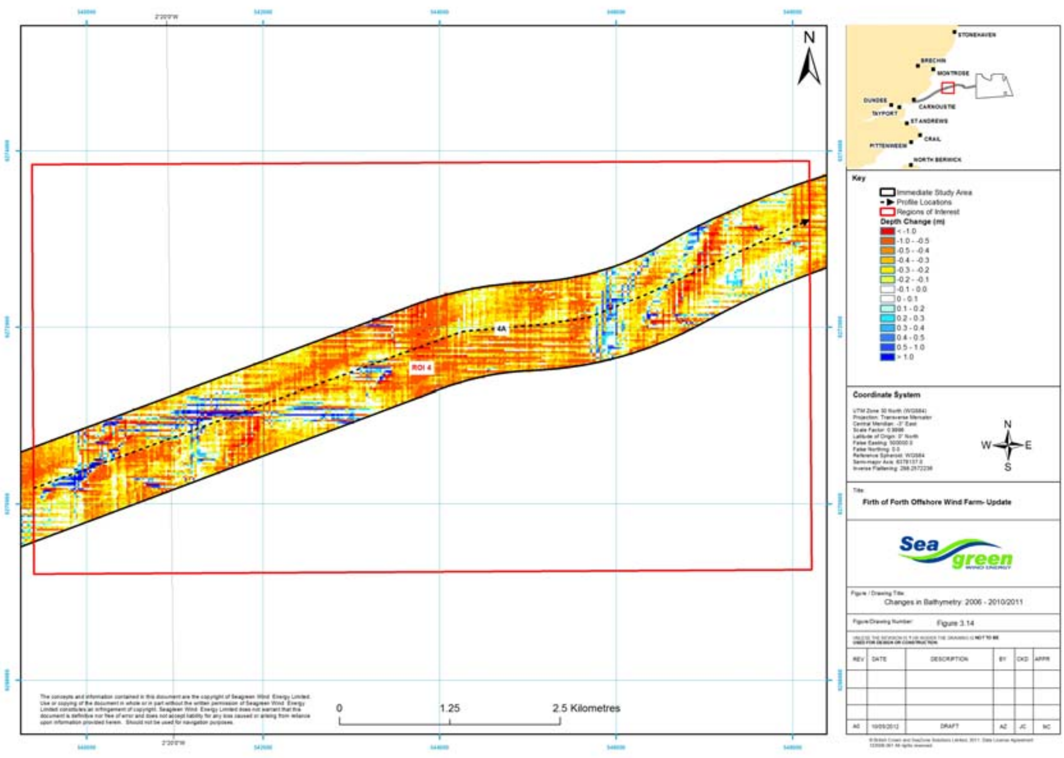


Figure 3.14 Cut/fill raster bathymetric changes (2006-2011) for ECR ROI-4

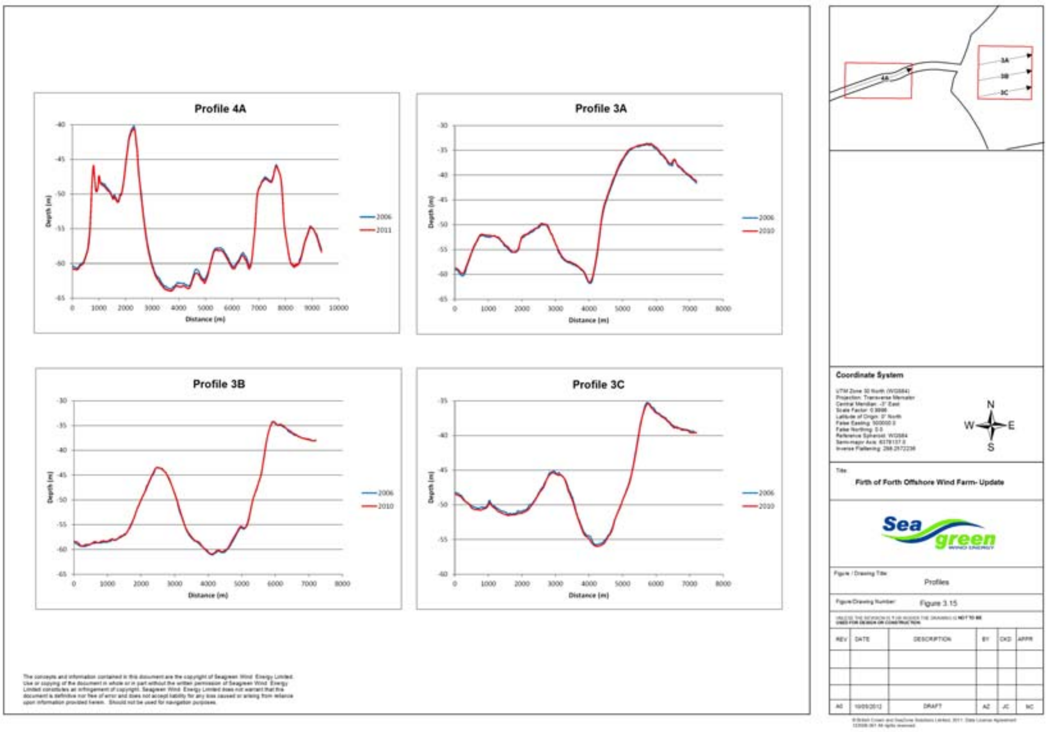


Bedform migration (ECR: ROI-3 and ROI-4)

No notable mobile bedforms have been documented within the ECR corridor. Three profiles (3A, 3B and 3C; see **Figure 3.13** for location and **3.15** for detail.) have been extracted from ROI-3 and indicate morphological trends over the analysed period. All profiles show little to no change in the bathymetric expression of the seabed over the analysed period, with the exception of some lowering of the seabed within bathymetric depressions along Profile 3C (see **Figure 3.15**).

As with the profiles within ROI-3, ROI-4 profile 4A shows little to no change in the bathymetric expression of the seabed over the analysed period, with the exception of some lowering of the seabed on bathymetric elevations (see **Figure 3.15**).

Figure 3.15 ROI-3 and 4 profile cross-section time series (2006-2010/11)



Contour analysis (ECR: ROI-3 and ROI-4)

BCE were generated for ROI-3 and ROI-4 (see **Figure 3.12** for locations). The technique has been applied to the seabed within the ECR ROIs (see **Figure 3.16** and **3.17**). Comparison of bathymetric contours provides spatial information on shifts in seabed features.

Figure 3.16 Bathymetric contour time series for seabed features in BCE-5

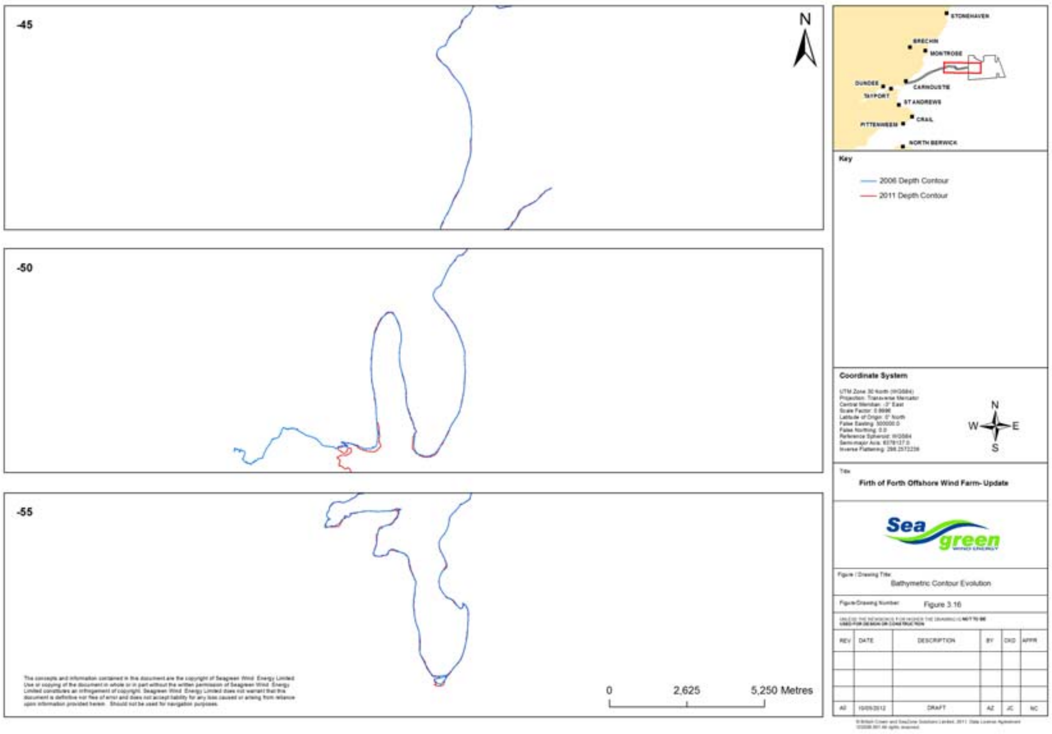
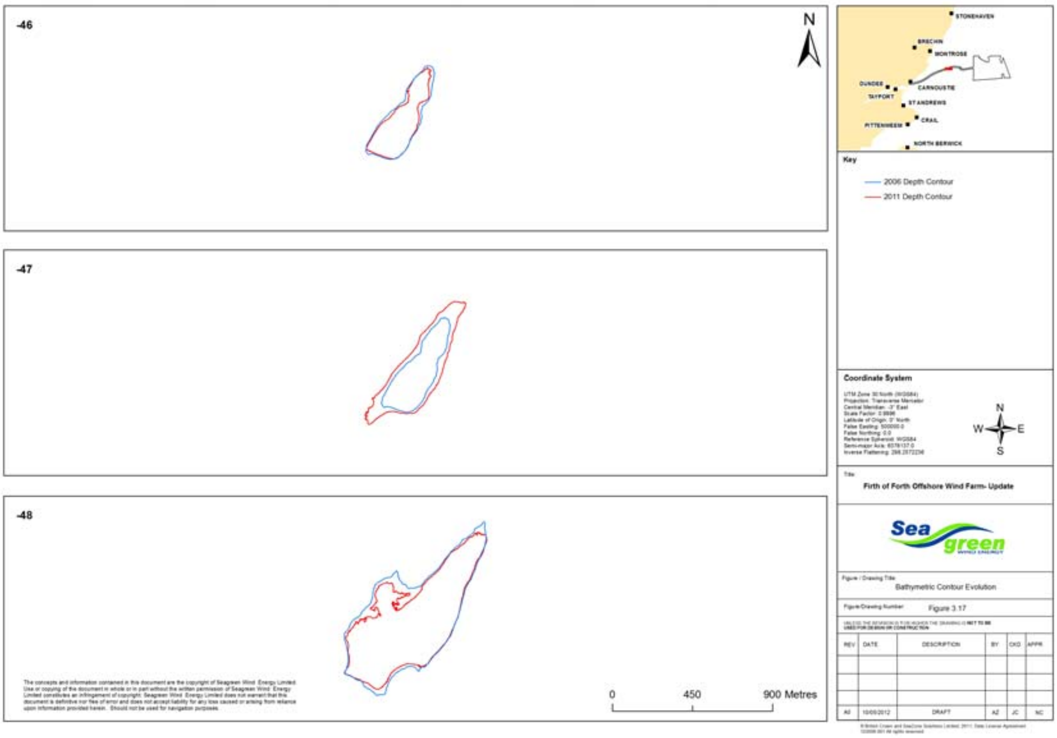


Figure 3.17 Bathymetric contour time series for seabed features in BCE-6



The BCE plots in **Figure 3.16** illustrate no change in the nature of the Scalp Bank over the analysed period (2006-2010). Overall, the contours have remained stable over the last 4 years.

The BCE plots in **Figure 3.17** provide an indication of the seabed evolution for an area of bathymetric high in the centre of ROI-4 with the pattern of change dependent upon the bathymetric elevation. Figure 3.14 displays a relatively small decrease in surface area, as expressed by the -46m contour. However, at -47m the feature displays an increase in surface area which is notably of greater extent on its northeast and southwest sides (parallel to the shore normal tidal currents).

Volumetric changes (ECR: ROI-3 and ROI-4)

The volume analysis (**Table 3.2**) indicates a general pattern of seabed accretion across the spatial extent of ROI-3 (2006-2010). Volumetric change analysis may be interpreted as indicating a sedimentary trend of accretion within ROI-3. This trend is in contrast to ROI-4, which indicates a strong sedimentary trend towards erosion.

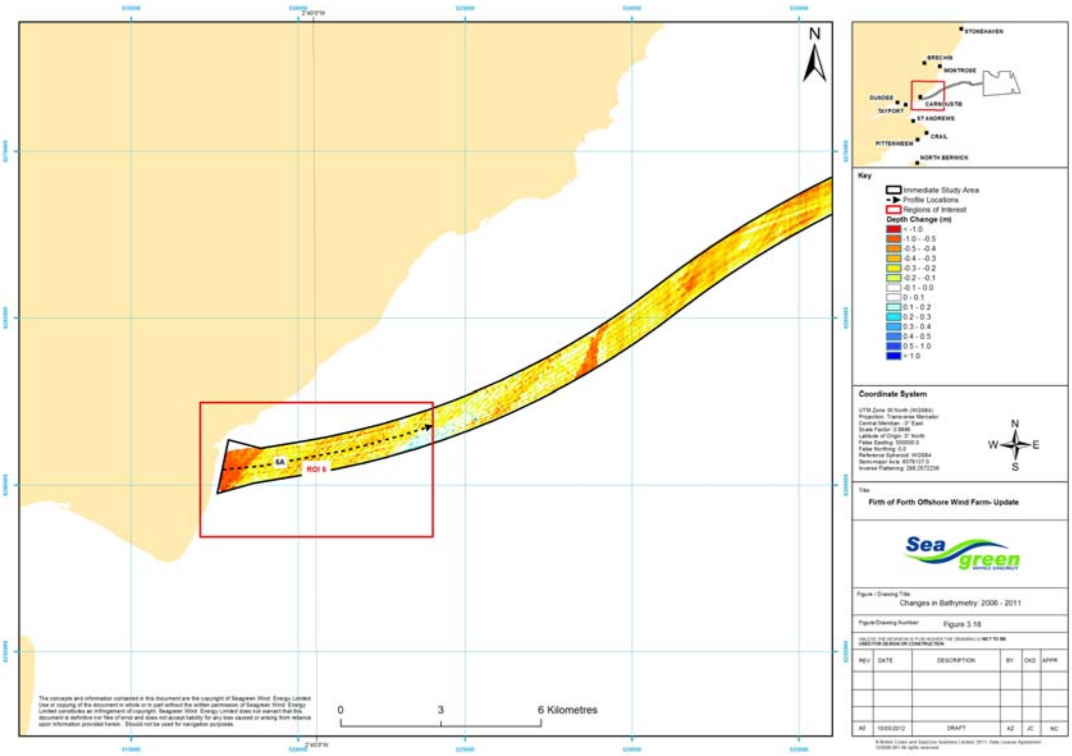
Table 3.2 Volumetric changes for ROI-3 and ROI-4

Contour (m below MSL)	2006 (m^3)	2010 (m^3)	Change (m^3)
ROI-3			
-45	1,065,825	1,084,277	18,451
-55	20,006,254	21,549,507	1,543,253
-65	81,788,651	89,451,163	7,662,513
ROI-4			
-40	5,449,891	5,279,665	-170,225
-50	26,319,942	24,804,398	-1,515,544
-60	65,940,801	62,590,258	-3,350,543

Bathymetry (ECR: ROI-6)

Changes in seabed morphology, as determined by the cut/fill raster (**Figure 3.18**) derived from the bathymetric data sets, highlights a broad general pattern of lowered seabed bathymetry over the analysed period. This trend is particularly pronounced toward the nearshore at Carnoustie where the pattern of seabed lowering increases.

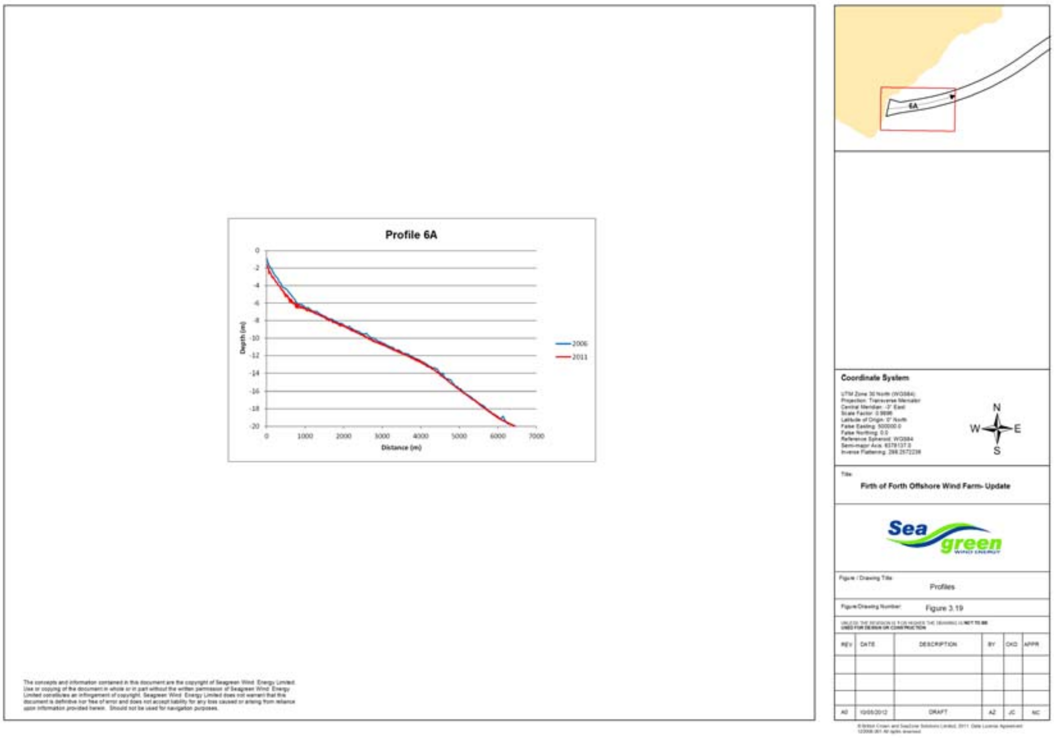
Figure 3.18 Cut/Fill raster bathymetric changes 2006-2010/11 for Phase 1 and ECR area respectively



Seabed profiles (ECR: ROI-6)

No mobile bedforms have been noted within the ECR corridor nearshore. **Figure 3.16** presents seabed changes for a centre line location for the ROI-6 time series (2006-2010/11). As highlighted previously in **Figure 3.18**, the pattern of seabed lowering is pronounced on the approach Carnoustie (**Figure 3.19**), with notable seabed lowering occurring within the final kilometre on approach to landfall.

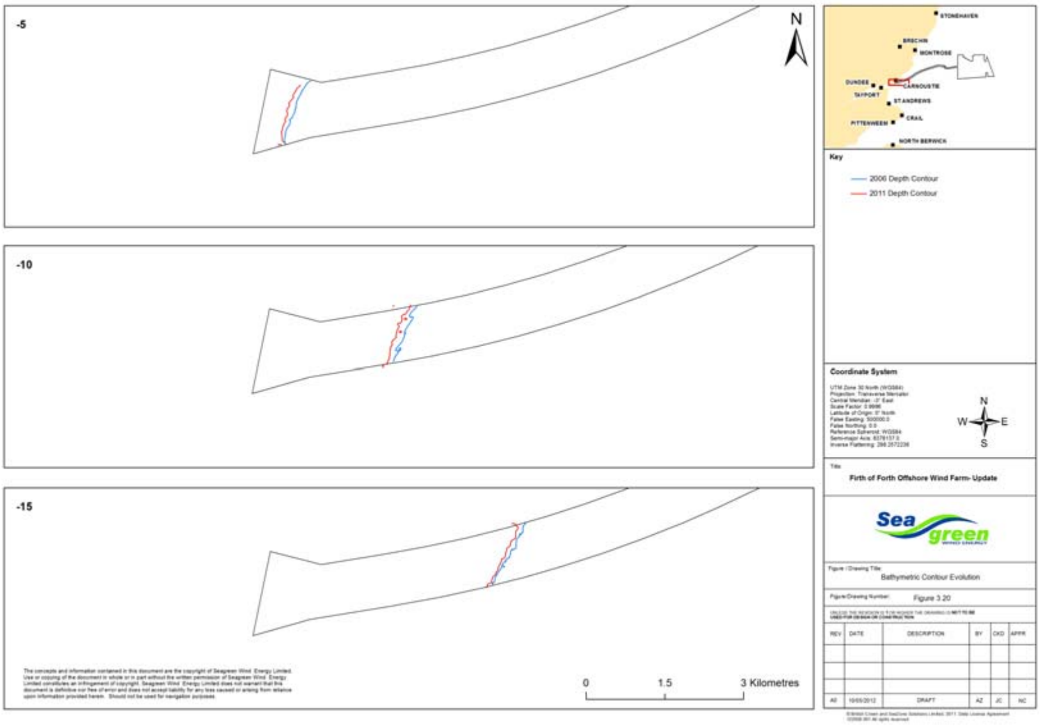
Figure 3.19 ROI-6 profile cross-section time series (2006-2010/11)



Contour analysis (Offshore: ROI-6)

A BCE (8) was generated for ROI-6 (see **Figure 2.3** and **3.15** for location). Comparison of the -5m, -10m and -15m bathymetric contours provides spatial information on changes to these features (**Figure 3.20**). In all instances there is a marked shift landward of these contours over the analysed period (2006-2010/11). This landward shift is particularly marked for the -5m contour, indicating a steepening of the nearshore profile at this location. This is supported by Figure 3.16 which illustrates a marked seabed lowering for the seabed profile within the first kilometre offshore from Carnoustie.

Figure 3.20 Bathymetric contour time series for seabed features in BCE-8



Volumetric changes (Offshore: ROI-6)

Table 3.3 Volumetric changes for ROI-6

Contour (m below MSL)	2006 (m^3)	2011 (m^3)	Change (m^3)
ROI-6			
-5	222,741	86,352	-136,390
-10	3,975,088	3,003,744	-971,344
-20	26,761,433	25,125,883	-1,635,550

The volume analysis (**Table 3.3**) indicates a general pattern of seabed erosion across the spatial extent of ROI-6 (2006-2010/11).

Landfall

Scottish Natural Heritage (2011) reviewed various techniques available for monitoring the physical changes associated with beach and dune systems in Scotland and developed a standard methodology for monitoring such changes in the future. The preferred techniques were applied to three selected beach and dune sites, of which Barry Links is of significance to the work presented herein, as it at the Carnoustie landfall.

The recommended methodology proposed by SNH (2011) is based on the use of digital photography. SNH (2011) however emphasised that historical maps have a vital role to play, especially in identifying large-scale changes over long time periods and so setting the context for detailed recent changes. However, maps remain selective in the information that they portray and cannot match the geomorphological detail carried by photography that is, by its very nature, non-selective in its data-capture.

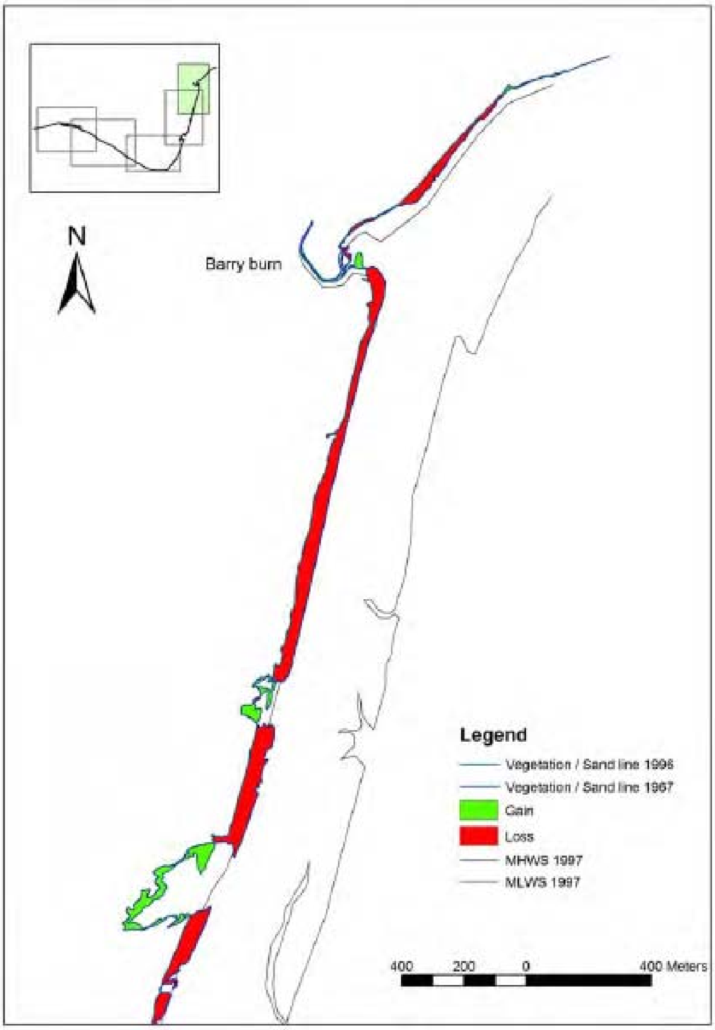
SNH (2011) provide a detailed presentation of Barry Links under the headings:

1. General setting;
2. Beach and coastal edge;
3. Dunes and links;
4. Historical changes to the beaches and dunes;
5. Recreation and landuse; and,
6. Management recommendations.

A summary of the key findings of the work concluded by SNH (2011) in relation to historical changes to the beaches and dunes is presented here. A more detailed analysis of the work and how it relates to EGA is presented in **Section 4**, to which the reader is referred.

SNH (2011) state ‘although the general shape of Buddon Ness has changed very little over at least the last 200 years, local evidence indicates that the Ness itself has undergone considerable fluctuation. The largest changes to Barry Links occur along the east sands and include a general landward translation of the shoreline, the effects of erosion protection measures and the continued adjustment and stabilisation of two large blowouts. There is an apparent shoreline recession along this eastern section of up to 55m, mainly caused by pre-defence recession. **Figure 3.21** presents the planimetric changes at the mouth of the Barry Burn over the period 1967-1996.

Figure 3.21 Planimetric changes at the mouth of the Barry Burn, 1967-1996



Erosion of this section of coast over the last three decades has moved the shoreline landwards by an average of 26m along a length of 2.84km of shore (net areal loss = 74,245m^2, shore-normal erosion: maximum 51m). In terms of the future management of the foreshore and dunes, SNH (2011) states a 'focus on mitigation of the damage already caused to the functionality of the site. Thus, it seems logical to recommend that no further armouring of the upper foreshore and dune toe be allowed.

4. Expert Geomorphological Assessment

4.1. Physical Environment: Offshore Wind Farms and Export Cable Route

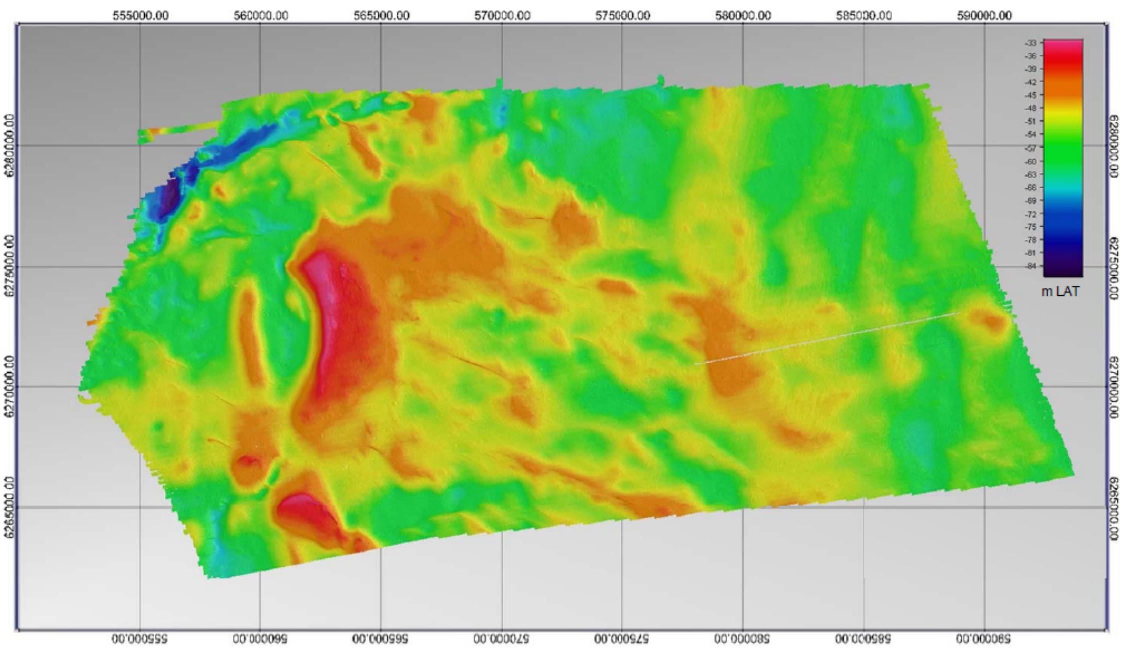
Bathymetry

Phase 1 Area

The maximum depth across the site (86.2m Lowest Astronomical Tide (LAT)) is observed towards the northwest of the Phase 1 area where a relatively deep channel cuts into the surrounding seafloor. The channel is orientated northeast to southwest. The shallowest areas were identified along the north-south orientated Scalp Bank to the west of the Phase 1 area. The majority of the Phase 1 area is within 40m – 60m LAT. An overview of bathymetry is presented in **Figure 4.1**.

There are limited areas of steeply sloping seabed associated with the channel feature but the majority of the site can be characterised as having a slightly sloping gradient (0 to 5%), though in areas of mobile bedforms (i.e. megaripples) localised slope gradients (<11.9^{o}) exceed these values (GEMS, 2010).

Figure 4.1 Phase 1 bathymetry



Source: GEMS Phase 1 Geophysical Survey 2010.

Export cable route

Depths along the ECR corridor range from 3.0m above LAT to approximately 69.0m below LAT in close proximity to the Phase 1 area. Along the nearshore section of the ECR the pattern of bathymetric change is reflected by the presence of a series of bathymetric depressions and broad, steeply sided (<2.6°) bathymetric mounds. It should be noted that steeper gradients are expected as a consequence of survey lines crossing the mounds obliquely.

Geology and geomorphology

Phase 1 Area

The Holocene and Quaternary geological sequence across the Phase 1 is presented in **Table 4.1**. The geology in the survey area is complex with a well-defined boundary between bedrock and Quaternary sediments in the east and the west. The bedrock typically comprises Triassic strata over the majority of the Phase 1 area and is noted to comprise undifferentiated sedimentary strata. Carboniferous strata occur in the southwest edge of the site only (Cathie Associates, 2010).

During the Quaternary several glacial episodes and subsequent climatic ameliorations resulted in the deposition of highly variable sequence of glacially derived formations. The offshore Quaternary sequences generally form cyclical depositional patterns marked by glacio-lacustrine and glacio-marine conditions prevalent during inter-glacial periods. Quaternary deposits from the upper Pleistocene and early Holocene present across the Phase 1 area comprise the Marr Bank, Wee Bankie and Aberdeen Ground Formations (see **Table 4.1**).

Subsequent to Quaternary glacial cycles, the Holocene transgression resulted in the extensive reworking of the Quaternary deposits and their subsequent deposition as near contemporary (Holocene) seabed sediments comprising both terrigenous and biogenic constituents.

Table 4.1 Geological sequence within the Phase 1 area

Stratigraphy	Depth (metres BSB)	Properties	Predicted Soils
Undifferentiated Holocene	Generally less than 0.5m thick	Superficial sediments: thin veneer of sediments generally less than 0.5m thick and locally absent.	Sand, slightly gravelly sand, gravelly sand and also some small patches of sandy gravel.
	Up to 35m to base of formation	Forth Formation: occurs as blanket deposit or infills depositional hollows on the surface of the Wee Bankie Moraine, or late Weiselian channels. Internal erosion surfaces common. Mainly amorphous; some well-layered sediments in north and west.	Sand (fine grained, well to poorly sorted, soft to firm, olive to grey brown, with lithic pebbles, shells and shell fragments in variable amounts) and some possible mud/silt towards its base. Fluviomarine.

Stratigraphy	Depth (metres BSB)	Properties	Predicted Soils
		Present across most of the site.	
Wee Bankie Formation	Up to 63m to base of formation	Sheet-like deposit on rugged bedrock topography. Covers most of west of area; grades into Marr Bank Formation. Generally <20m thick, up to 40m thick in some places.	Boulder clay (hard, dark grey to red-brown, gravelly, angular to rounded clasts) with thin interbedded sand and pebbly sand. Basal till.
Marr Bank Formation	0 to 38m to base of formation	Sheet-like deposit on flat basal surface. Covers most of east of area; grades into Wee Bankie Formation.	Sand (fine grained, poor to well sorted, soft to firm, grey to red-brown with abundant lithic granules) and pebbles. Locally silty. Glaciomarine.

Export cable route

The solid geology beneath the ECR corridors comprises a thick sequence of sandstones, siltstones and mudstones of Lower (Emsian) and Upper (Famennian) Devonian ages. To the east, these Devonian rocks are, in turn, overlain by undifferentiated Permo-Triassic rocks.

The solid geological units are in turn overlain by Pleistocene deposits of Quaternary age, comprising variable materials ranging from soft clayey silts/silty clays of the Forth Formation to possibly hard gravelly clays/clayey gravels of the Wee Bankie Formation. The soft clayey silts/silty clays can be up to 40m thick and are more prevalent in the western sections of the ECR, whereas the hard gravelly clays/clayey gravels are thought to represent glacial tills and are generally present throughout the area, reaching thicknesses of up to 40m in places.

These Quaternary deposits are frequently overlain by very thin finer-grained surface sediments, generally less than 2.0m thick. These materials comprise gravelly sands/sandy gravels or clayey gravelly sands, which may exhibit very little variation in character with the underlying Quaternary strata.

Seabed substrate

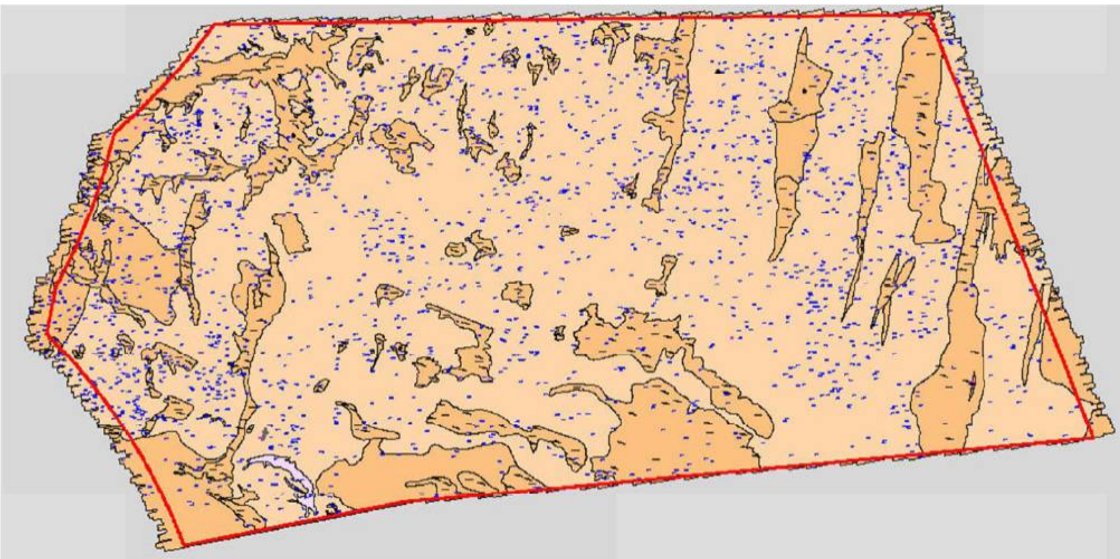
Phase 1 Area

Sea bed sediments have been classified by GEMS (2010) using an adapted Folk classification and are interpreted to consist of gravelly sand and slightly gravelly sand across the entire area. Three main features were identified which are indicative of active sediment transport (see **Figure 4.2**): megaripples, sand waves and boulder fields (see Table 4.2 for definition of terms). All these features are characteristic of active sediment transport zones, the most regularly occurring being megaripples. **Figure 4.2** presents the spatial distribution of these features across the Phase 1 area.

Table 4.2 Seabed features

Terminology	Definition
Ripple	Undulations (<0.5m λ) produced by fluid movement (waves and currents) over sediments
Megaripple	Undulations (0.5m to 25m λ) produced by fluid movement (waves and currents) over sediments
Sand wave	Undulations (>25m λ) produced by fluid movement (waves and currents) over sediments

Figure 4.2 First draft seabed substrate map



The GEMS report (2010) and relevant BGS charts (1986) identify that the majority of the site is subject to sediment transportation, with the dominant tidal flow pattern approximately parallel to the coastline in a north-northeast to south-southwest direction. According to GEMS (2010) currents (near bed flows) are strong enough to move and potentially erode medium sand grade material. These flows may display spatial and temporal variation in strength as the isolated boulders are representative of a lag deposit from the active erosion and subsequent transportation of the Quaternary sedimentary units (e.g. till).

The three main seabed features from which proxy information on active sediment transport zones can be inferred are:

Meggaripples (generally less than 0.5m in height) predominantly covering slightly gravelly sand are the predominant seabed features across most of the site. Their crests are orientated perpendicular to the shoreline (WNW to ESE), suggesting sediment movement is parallel to the coast The bedforms are in general symmetrical, suggesting that sediment does not have one dominant direction of flow, but rather moves tidally parallel to the coast. There is a slight change in the build up of sediment either side of the Scalp Bank in the mid-west, with sediment build up to the south of bedforms (megaripples) west of the bank; suggesting northward dominant flow, and to the north of bedforms (megaripples) east of the bank; suggesting southward dominant flow. However, this is not conclusive.

There are large isolated **sand waves** in the western area, with approximately the same orientation as the megaripples. The sand waves reach up to 10m in height from the sea bed.

Boulders, thought to be of glacial origin, are prevalent across the area, especially in northern and central parts, either as isolated boulders or clustered within boulder fields. Boulders are also present in southern areas, but these are not as large as those in northern and central parts.

Recently completed surveys and currently ongoing analysis (IECS, 2011) have indicated extensive deposits of coarse sand and lag deposits **Plate 4.1** and **4.2** illustrate seabed substrates typical of large expanses of the seabed within the Phase 1 area. **Plate 4.1** illustrates a rippled seabed comprising coarse sand with occasional gravel. **Plate 4.2** illustrates a mixed clast seabed type, comprising a lag gravel and pebble on coarse sands.

Plate 4.1 Coarse sand rippled seabed type

Source: IECS DDV image, site V9, west of Scalp Bank, 62.3m depth

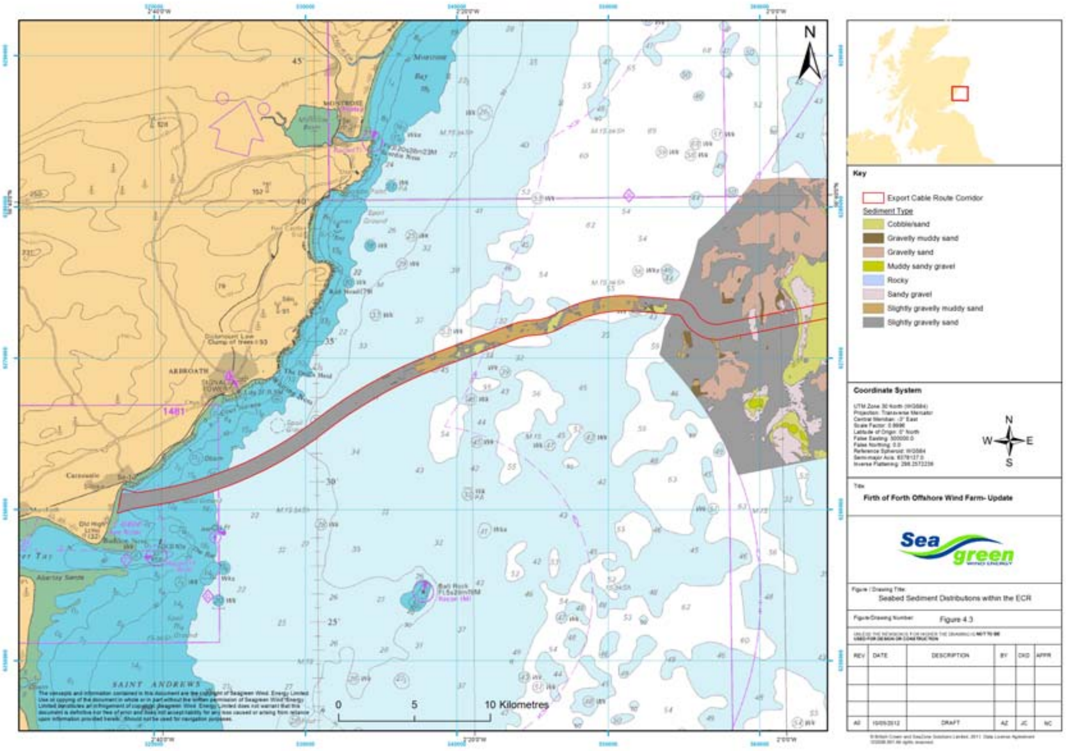
Plate 4.2 Mixed clast lag on coarse sand

Source: IECS DDV image, site V24, east of Scalp Bank, 44.5m depth

<u>Export cable route</u>

Geophysical data indicate that variable, generally finely granular sediments are present at seabed level across much of the ECR, with occasional patches of outcropping rock present in the extreme northern section (see **Figure 4.3**). These sediments are interpreted as ranging from very silty fine to coarse grained sands, with variable shell content, to coarser grained sandy gravels, with occasional cobbles and (generally small) boulders (Osiris, 2011).

Figure 4.3 Seabed sediment distributions within the ECR corridor



The seabed is characterised by gentle gradients (maximum 2.5^{o}), comprising mainly fine or silty fine sands. However, the gradient steepens (≤9.5^{o}) towards bathymetric depressions which are typically marked as a series of gravelly ridges (Osiris, 2011). Some irregular rock outcrops lay just to the north of the corridor suggesting that the finely granular sediment cover is relatively thin in that area.

Irregular patches of coarser grained sands are also present across the Southern Route as are some large areas of sandy gravels and occasional small boulders. Osiris Projects (2011) interprets this as the result of a thinning of the Holocene sands/Forth Formation deposits, relating to a shallowing of the underlying glacial deposits. It is likely that these coarser grained materials are representative of strata of the underlying Wee Bankie Formation. These patches of coarse grained sediments exhibit a degree of bathymetric relief, attaining elevations up to 20m above the surrounding seabed, with the finer grained materials between the coarser patches with mobile megaripples.

The interpreted Wee Bankie sediments outcrop along the Southern Route centre line at numerous locations. Many of these ‘outcrops’ again exhibit some bathymetric relief, and are flanked by irregular areas of megaripples. As with previous features, megaripples are orientated approximately northwest-southeast, and attain elevations up to 0.4m high and have average wavelengths between 6 and 15m.

4.2. Physical Processes: Offshore Wind Farm and Export Cable Route

Table 4.3 presents data sources that have been used to inform the characterisation of Physical Processes for both the Phase 1 area and the ECR.

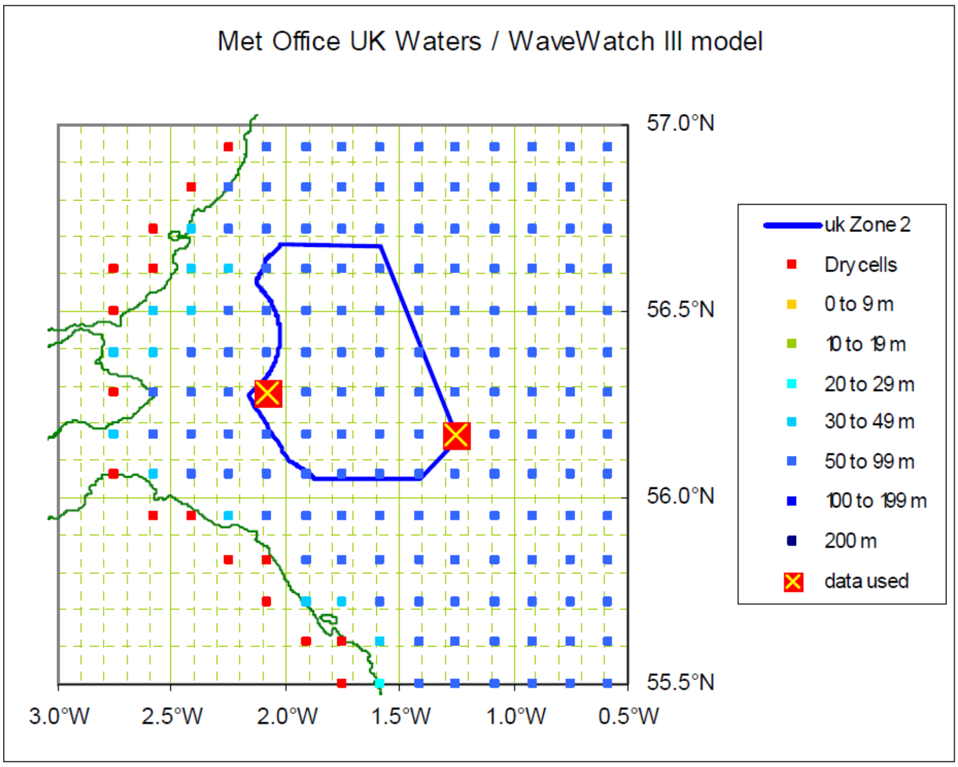
Table 4.3 Data sources reviewed to inform SPR model

Data source	Author	Year
Seagreen Winter Metocean Survey: Phase 1 Interim Report	Partrac	2012
Seagreen Metocean Campaign: Progress Report	Fugro	2012
10 year Met Office wave analysis for the Firth of Forth Zone	Royal Haskoning	2011
Firth of Forth OWF Phase 1 – Metocean criteria for conceptual design	Metoc	2011
Seagreen Position Paper: Coastal and Seabed Impact Assessment	Seagreen	2011a
UK Round 3 OWF Zone 2 Firth of Forth. Wave Height Spells for Survey Operability	Metoc	2010
Firth of Forth and Tay Developers Group, Collaborative Oceangraphic Survey, Specification and Design. Work Package 1. Review of existing information.	HR Wallingford	2009
Coastal Cells in Scotland: Cell 2 – Fife Ness to Cairnbulg Point	SNH	2000
Angus Shoreline Management Plan (SMP)	Angus Council	Unknown

Wind and waves

Royal Haskoning (2011a) provided an analysis of Met Office forecast data at two grid points of 56.17°N 1.25°W (referred as East Point) and 56.28°N 2.08°W (referred as West Point) within the Zone (see **Figure 4.4**). The data covers a ten year temporal period from June 2000 to February 2010. The analysed and presented data includes wind (wind speed and direction), sea wave, swell and resultant wave (wave height, period and direction). Significant wave height (Hs) is >6.7m and 8.7m for 1 year and 50 year return period waves averaged from all sectors respectively. Swell conditions tend to be dominated by waves generated from north and north-eastern sectors

Figure 4.4 Met Office forecast data locations



Wind conditions at West Point are influenced by the Firth of Forth corridor leading to clearer predominance of south-westerly wind (**Figure 4.5**). The East Point displays more of a spread of wind directions across the south to western sectors. The wind climate is predominantly offshore. **Figure 4.6** presents the offshore sea wave climate for the East and West Points. The influence of land is more clearly defined than for the wind climate. In general for the area the sea wave rose plots show three dominant directions for sea waves, in the descending order of south-westerly, southerly and northerly waves. These predominant wave approaches do not impact upon any coastal receptors within the vicinity of the potential Export Cable Route landfall.

Figure 4.7 suggests that the swell wave environment is dominated by swell waves incident from the north and north-eastern sectors. Both north-easterly and south-easterly swell waves may interact with STW sites within the wider study area. The resultant waves illustrate three dominant directions in a descending order of north-easterly, south-easterly and south-westerly (**Figure 4.8**).

While strong winds can occur throughout the North Sea, wave heights vary greatly due to fetch limitations and water depth effects. Waves in the Northern North Sea can be generated either by local winds or from remote wind systems (swell waves).

Figure 4.5 Wind environment

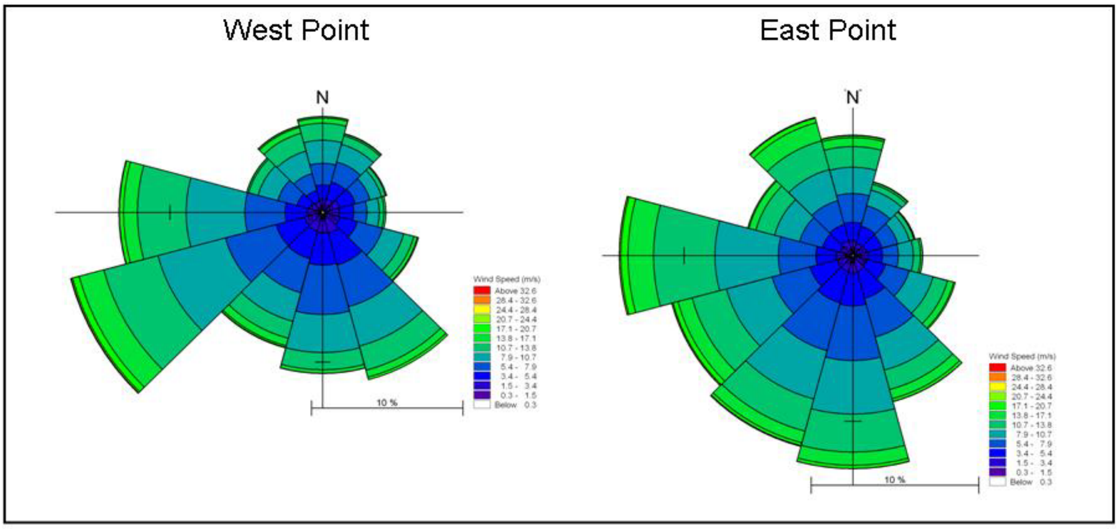


Figure 4.6 Sea wave environment

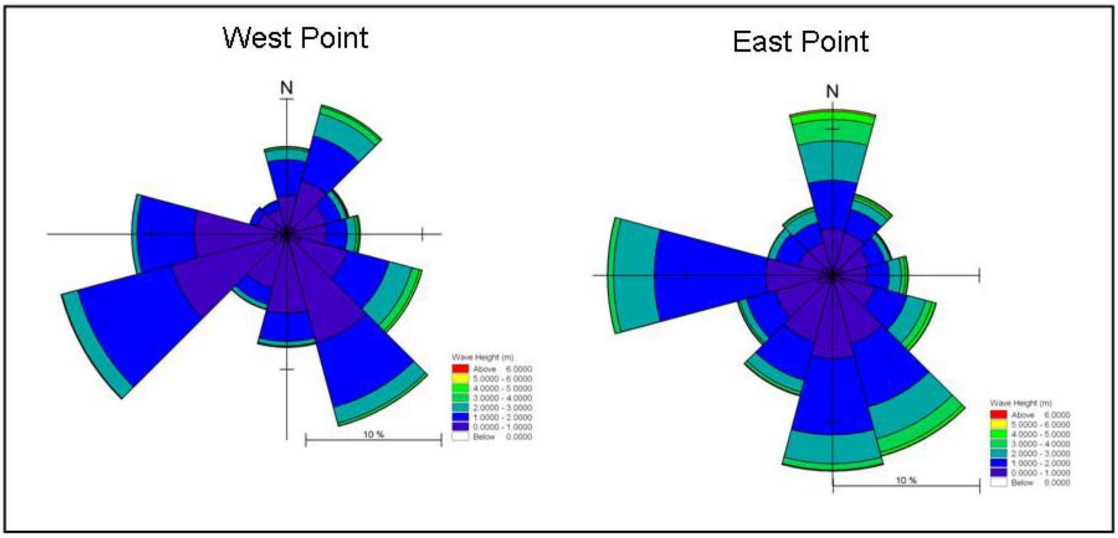


Figure 4.7 Swell wave environment

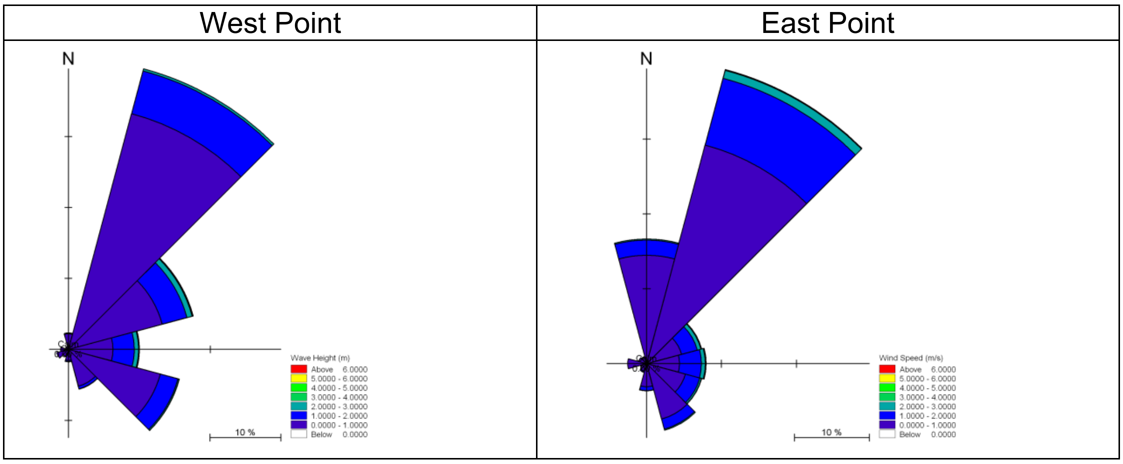
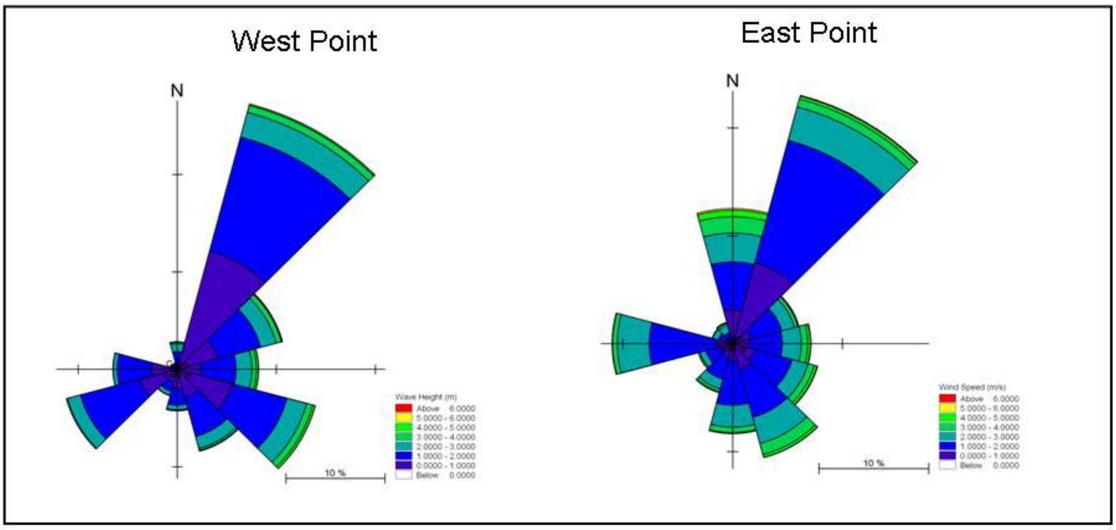
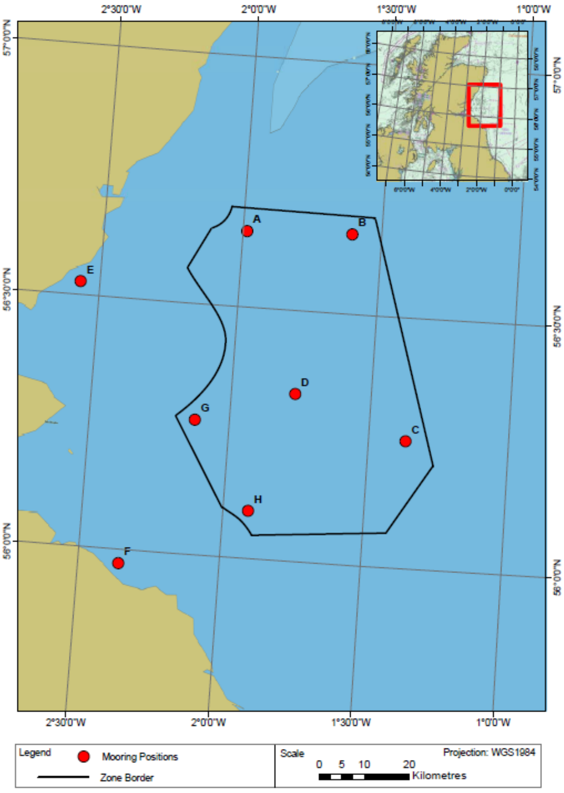


Figure 4.8 Resultant wave climate



Fugro (2012) provide a near contemporary record of metocean conditions as recorded from a series of met buoys within the wider study area (see **Figure 4.9**).

Figure 4.9 Seagreen Metocean Deployments



A summary of wave parameters for the Zone and ECRs, as recorded during the metocean deployment (Fugro, 2012), is presented in **Table 4.4.**

Table 4.4 Summary of wave parameter statistics

Site	Parameter	Max	Mean	Direction at time of Max
A	Hs (m)	4.6	0.9	212
	Hmax (m)	7.2	1.4	215
	Tp (s)	14.3	5.9	052
	Tz (s)	8.5	4.3	028
C	Hs (m)	5.0	2.0	236
	Hmax (m)	9.2	1.3	244
	Tp (s)	20.0	7.2	071
	Tz (s)	9.9	4.8	017
E	Hs (m)	4.0	0.6	201
	Hmax (m)	7.1	1.0	201
	Tp (s)	14.1	4.9	080
	Tz (s)	6.6	3.2	096
F	Hs (m)	1.9	0.6	-
	Hmax (m)	3.1	0.9	-
	Tp (s)	15.2	6.9	-
	Tz (s)	7.5	3.7	-
H	Hs (m)	3.9	0.9	248
	Hmax (m)	7.1	1.4	248
	Tp (s)	14.9	6.4	042
	Tz (s)	8.7	3.7	012

The highest significant wave height recorded during the metocean deployment was 5.0m recorded on the 23rd May 2011 at 7.10pm at Site C. Although the maximum wave height was recorded in May, mean significant wave height was greatest between December and March which were generated by regular winter storms (Fugro 2012).

Comparisons of Site A, C and H show that wave conditions at the three sites were very similar from March to June 2011. Sites E and F experience strong sheltering, due to their coastal location and as such do not correlate as well with Site C. Site F experienced no increase in waves during the 23rd May 2011 since the waves were from the south-west. Wave heights were generally lower throughout the deployment at Sites E and F, but were subject to sheltering from predominant wave direction when the de-correlation between sites increased. Waves were predominantly from the north or east due to the sheltering of all sites from the west and to a lesser extent the south. However wave directions during the 23rd May 2011 storm event were from the south-west, therefore, offshore.

Tides and tidal currents

Figure 4.9 presents the location of Seagreen metocean deployments across the Firth of Forth. A summary of tidal current statistics for the Zone as recorded during the metocean deployment is presented in **Table 4.5**.

Table 4.5 Summary of tidal current statistics

Site	Depth (m bmsl)	Height (m asb)	Speed		Direction at Max
			Max	Mean	
A - AWAC	10.5	43.0	0.91	0.35	029
A - ADCP	45.25	8.25	0.74	0.28	017
B	8.8	52.7	0.88	0.32	196
C	7.3	50.7	0.72	0.26	000
D	8.1	46.7	0.77	0.29	006
E	6.3	19.0	0.76	0.29	064
F	6.5	23.0	0.68	0.21	-
G	9.8	44.7	0.72	0.26	001
H	10.0	43.0	0.76	0.23	136

The strongest current flows were observed at the two most northerly sites, A and B. Site A recorded the maximum of 0.91 m/s on 18 April 2011 during a period of spring tides that correlated with the maximum water level at most sites. Current speeds decreased slightly at the other sites with maxima ranging from 0.68 m/s to 0.77 m/s. Directions varied little between sites. Sites A and B were characterised by current directions along a NNE to SSW axis (see **Figure 4.10**.), while Sites C, D and G were characterised with a tidal axis of N to S (see **Figure 4.11**). Site E and Site H had axes parallel to their respective nearby coastlines, which were NE to SW at Site E and NW to SE at Site H. The directions at Site F were deemed invalid and are not discussed further.

Figure 4.10 14 day ADCP record from Site A

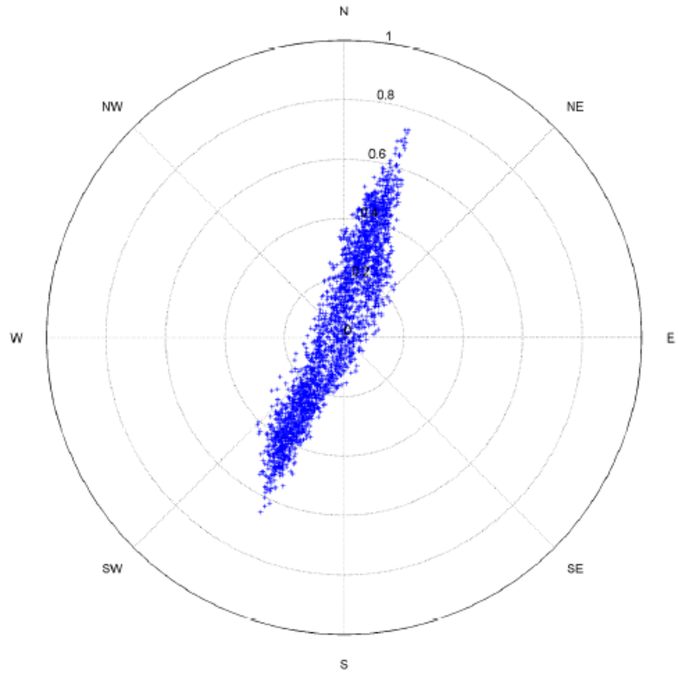
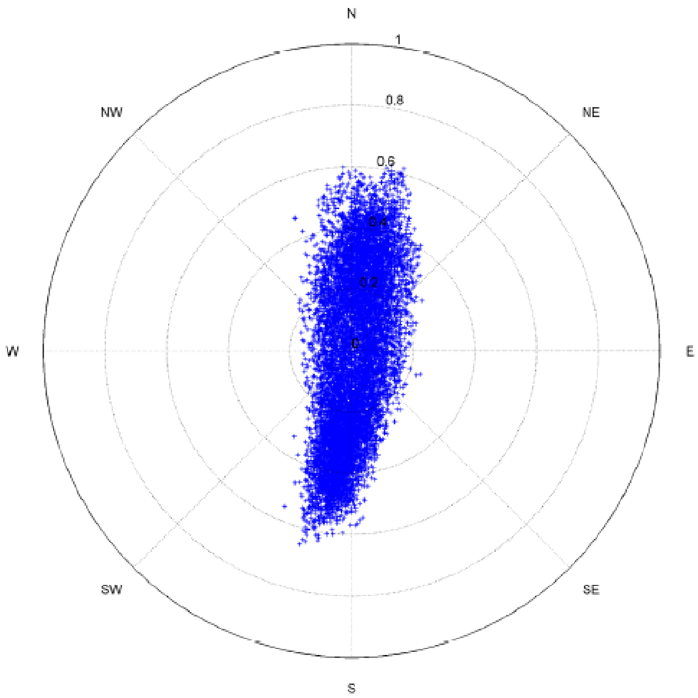


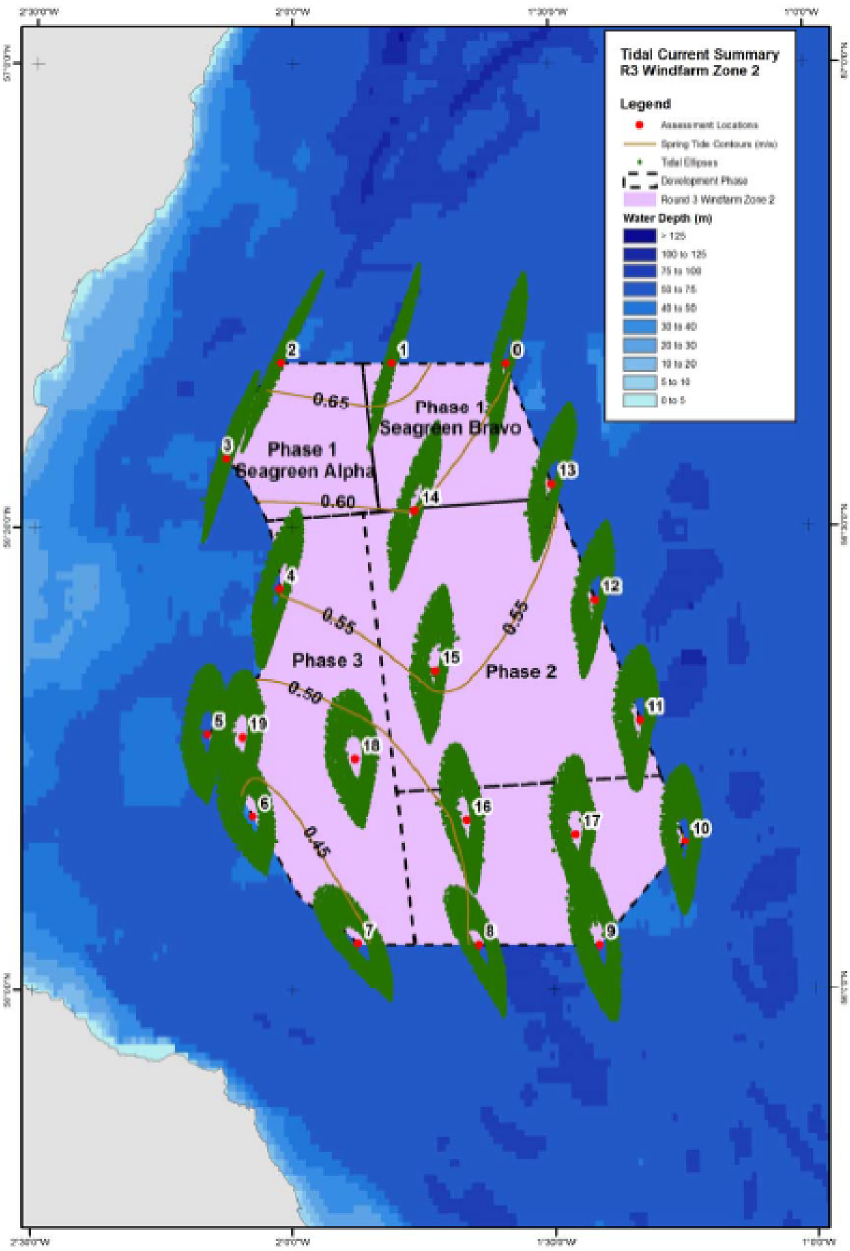
Figure 4.11 14 day ADCP record from Site C



The current is tidal at all sites and as such the strongest currents are associated with spring tides. The largest non-tidal component is wind driven currents but these are only seen to cause significant deviation from predicted tidal currents during strong storm events, such as that on 23 May 2011.

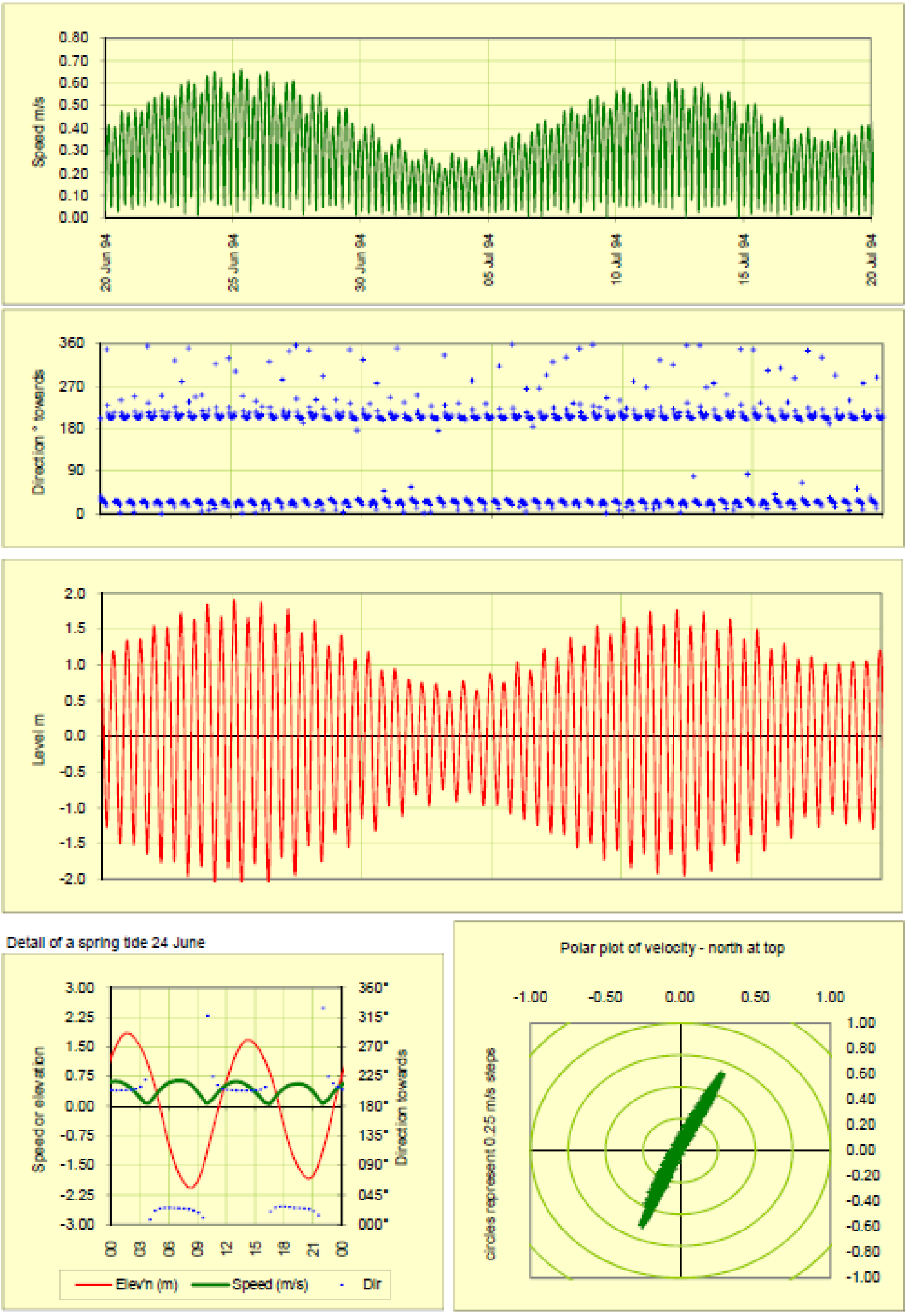
The spatial variation of tidal currents in relation to the Zone is presented in **Figure 4.12.** The data is derived from Metoc's hydrodynamic (HD) model (Metoc, 2011) and illustrates the shore parallel nature of tidal currents (depth-averaged) which are particularly notable by the their ellipse shape within the Phase 1 area, being more pronounced towards the coastline than further offshore. As presented in **Figure 4.12** tidal current speeds are marginally lower to the east of the Zone.

Figure 4.12 Spatial variation of tidal current (depth-averaged) across the Zone



Metoc (2011) provide a summary of hydrodynamic conditions and extreme events for the Firth of Forth Zone, detailing tidal characteristics and current speeds across the Zone. **Figure 4.13** presents a one month tidal current speed record, tidal current vector, mean water level, detail of a spring tide and a polar plot of tidal current velocity for the northwest of the Zone.

Figure 4.13 Tide and tidal current characteristics for the northwest of the Phase 1 area



HR Wallingford (2009) has stated that tidal current velocities can reach 1.2m/s within the Tay estuary. At Rosyth, within the Firth of Forth estuary, typical peak flood velocities are in the range of 0.4 to 0.7m/s and 0.7 to 1.1m/s on the ebb. Seaward of the estuaries, the tidal flows are typically weaker. This is demonstrated at points 5, 6, 18 and 19 in **Figure 4.12**.

The pattern of tidal elevations across the Outer Forth (including the Round 3 Zone) is governed by a southerly directed flood tide that moves down along the eastern coastline of Scotland into the Firth of Forth around Fife Ness (HR Wallingford, 2009). This is supported by the metocean campaign which indicated reciprocal flood and ebb tidal currents (see **Figures 4.10 and 4.11**). The main peak flood tide occurs approximately 2 hours before HW, with the main peak ebb tide occurring approximately 4 hours after HW.

Water levels

Water level maxima observed during the metocean deployment are interpreted to result from two different phenomena depending on the presented data (Fugro, 2012). Water level maxima at Sites A, E and F were the result of a storm surge on 4 February 2011 that produced residual water levels of 1.4 m above predicted tidal elevations, at all three sites. Maxima at all other sites were caused by spring tides on 19 February 2011.

Suspended sediments

Results from the water sampling carried out at four stations in the Firth of Forth during March and June 2011 show TSS to be low (**Table 4.7**). The majority of the samples had TSS of <5mg/l with a maximum reading during March of 18 mg/l (Site H, bottom, 30 and 90 minutes). Site E was noted to have generally higher results during March than the other sites; however the results for samples collected in June showed no difference to the other sites. Sediments at Site E were noted to be classified as very fine sand which could contribute to the higher TSS; however this was not apparent in June when sediment samples collected were noted to be coarse silt.

Table 4.7 Total Suspended Solids (mg/l), March and June 2011

Site	Time (mins)	March					June				
		0	30	60	90	120	0	30	60	90	120
A	Top	10	<5	<5	<5	<5	<5	<5	<5	<5	<5
	Middle	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
	Bottom	8	<5	5	6	<5	<5	<5	<5	<5	<5
E	Top	5	6	7	11	10	8	<5	<5	<5	<5
	Middle	6	8	10	10	11	<5	6	<5	<5	<5
	Bottom	11	10	11	10	11	<5	<5	<5	<5	<5
F	Top	7	6	7	<5	5	<5	<5	<5	<5	<5
	Middle	<5	5	<5	5	5	<5	<5	<5	6	<5
	Bottom	<5	5	5	5	<5	<5	<5	<5	<5	<5
H	Top	5	<5	<5	<5	<5	<5	<5	<5	<5	<5
	Middle	<5	<5	<5	10	<5	<5	<5	<5	<5	<5
	Bottom	6	18	<5	18	<5	6	<5	<5	<5	6

Although all values are low, a slight increase in TSS is observed in March. This distinction is more evident at Sites E and H. The turbidity values observed at Sites A and E support these results with higher values being observed at Site E.

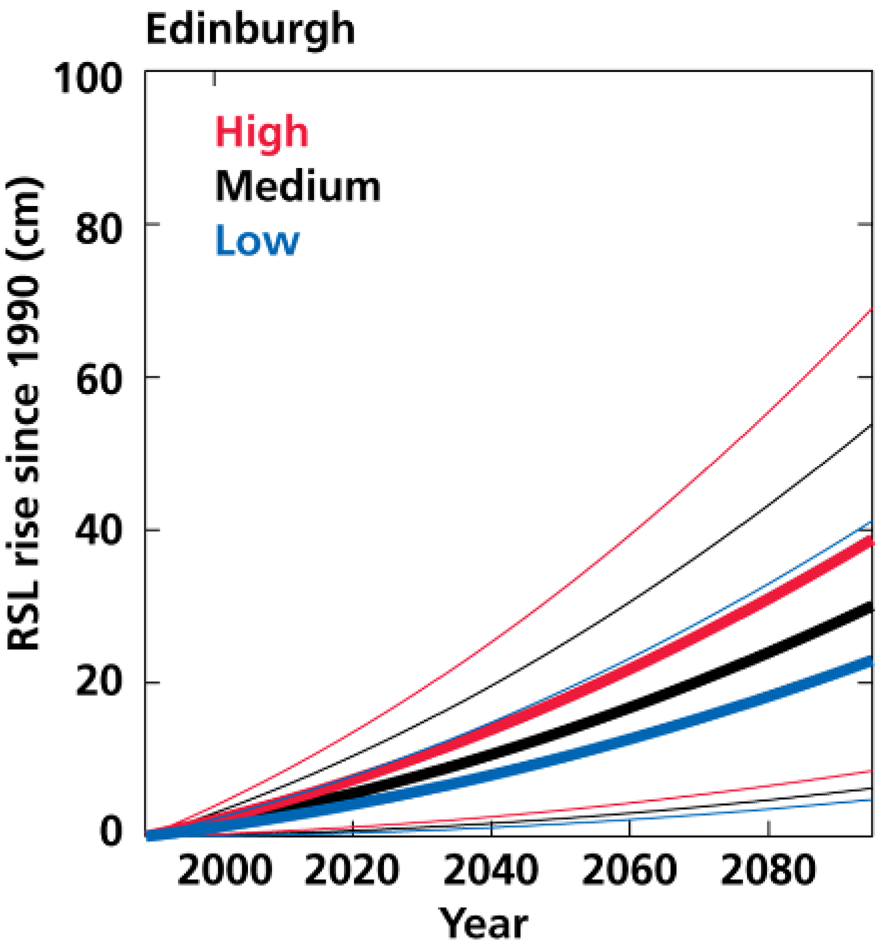
Valid turbidity data were recorded by the Site A and Site E AWACs from January 2011 to March 2011, and the Site A from December 2010 to June 2011. The highest values were recorded at Site E where the maximum measureable value of 500 NTU occurred many times but always during periods of persistent, large easterly waves. Turbidity at Site E was generally higher than at Site A, where the two instruments record very similar values throughout. At Site A the tidal currents are the predominant driver of turbidity with a clear spring-neap cycle and a semi-diurnal fluctuation observed throughout both datasets.

Sea-level rise and surges

Superimposed on tidal behaviour are surges and sea-level rise. Surges can result in variation to tidal water levels above or below the predicted tidal level. Over longer time periods (e.g. decades) mean sea-level varies and hence the baseline datum is not stationary. Over relatively short temporal periods (e.g. months to a small number of years) the tidal signal can be regarded as varying relative to the datum of MSL. However, over longer temporal periods (e.g. beyond the duration of the 18.6 year lunar nodal cycle) MSL varies in response to sea-level rise. Hence the datum of MSL is non-stationary. Future sea-level rise results from the net effect of global change to sea-level and local changes to land levels due to post-glacial isostatic readjustment (rebound or subsidence).

Global warming is predicted to increase pressure on the coastline due to increased storminess and rising sea levels from thermal expansion of seawater and melting of far-field glaciers. The UK Climate Projections 2009 (UKCIP09) has provided estimates for each decade of relative sea level changes with respect to 1990 levels. Central estimate values and 5th and 95th percentile limits of the range of uncertainty for three emissions scenarios (high, medium and low) are provided in **Figure 4.14** for Edinburgh. Central values for absolute sea level rise indicate between 29.8cm (low) and 45.6cm (high) by the end of the 21st century.

Figure 4.14 Future sea-level rise curves for Edinburgh



Source: http://ukclimateprojections.defra.gov.uk/images/stories/marine_pdfs/UKP09_Marine_report.pdf

The implications of sea-level rise over the coming century require consideration for Seagreen's development, particularly with respect to ensuring that any nearshore development components are 'future-proofed'. The UKCIP (2009) provides a detailed review of increased probability of storm generated surges as a result of climate change. UKCIP09 state 'confidence in the Met Office/Proudman Oceanographic Laboratory (POL) models to simulate the present day regime of extreme storm surges has improved from previous assessments in 2002. Around the UK the size of surge expected to occur on average about once in 50 years is projected to increase by less than 0.9 mm year (not including relative mean sea level change) over the 21st century. In most locations this trend cannot be clearly distinguished from natural variability'.

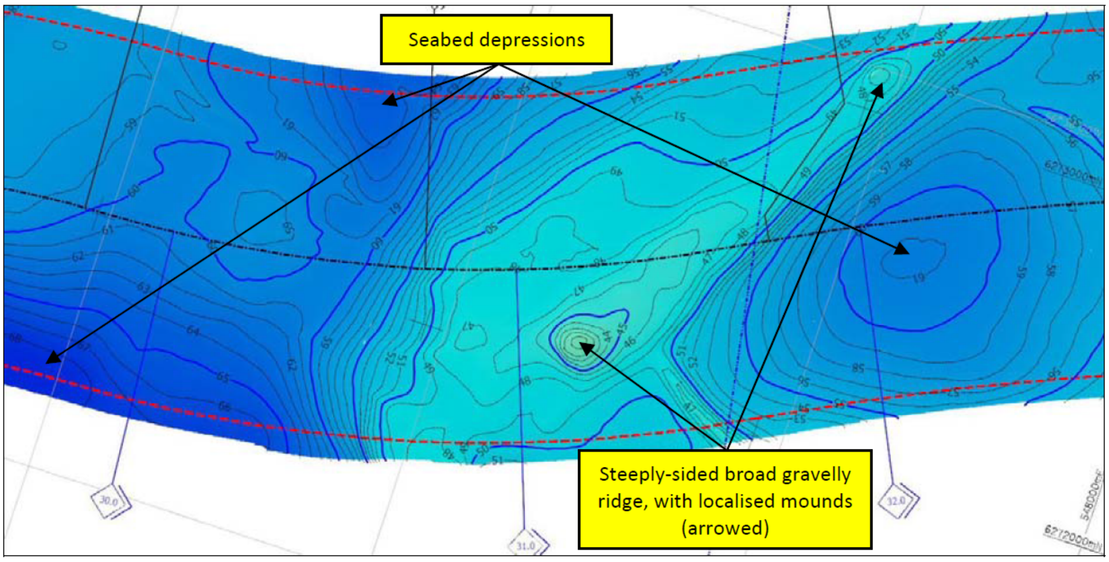
4.3. Carnoustie

Bathymetry

Seabed levels along the Carnoustie ECR corridor range from 3.0m close to the shore to approximately 69.0m in the extreme north of the combined corridor, approximately 36km offshore. The nearshore seabed dips gently to the east-southeast (ESE) across a relatively flat sandy seabed, from 1.0m to 3.0m below, at an average gradient of 0.6°. The gradual dip of the seabed decreases gradually until 20km offshore where water depths attain 42.0m. At approximately this point, the very gentle seabed gradient begins to gradually steepen as a seabed depression is approached, with water depths approaching 60.0m. This bathymetric depression is located between 23 and 24.5km offshore. Seaward of 24km seabed levels begin to shallow again to the ENE with the eastern edge of the seabed depression marked by a series of gravelly ridges (broad, steeply sided (<2.6°) bathymetric mounds) (see **Figure 4.15**).

Seabed levels within the central section of the approach to Carnoustie undulate between 39.0m below LAT and 69.0m below LAT, as the route crosses a series of frequently broad, steeply-sided (≤2.6°) ridges or mounds of gravelly sands/sandy gravels.

Figure 4.15 Bathymetric mounds and depressions characteristic of the ECR approach to Carnoustie (30-32km)



Geology and geomorphology

The Barry Links dune system has developed on the triangular foreland of Buddon Ness (see **Plate 4.3**). Although Barry Links contains representative examples of many beach and dune landforms, the main geomorphological interest centres on a series of exceptionally well-developed parabolic dunes and on the foreland growth as a result of sea-level changes on coastal development. Well-developed parabolic dunes are relatively rare in the Scottish coastal dune environment, with the parabolic dunes of Barry Links being unique in their pronounced V-shaped form. The parabolic dunes are now almost completely vegetated and stabilised, with the exception of a large dune, now utilised by the MoD as a firing range.

Plate 4.3 Oblique aerial photo of Buddon Ness from the south

The pattern of dune forms on Barry Links displays an unusual degree of regularity on account of two distinctive morphological attributes. First, the measured length-to-width ratios and, second, the orientation of the long axes of the dunes is remarkably uniform. The 238º orientation of the Barry parabolic dunes suggests that they have migrated in the past from the SW to NE towards the eastern coastline (Landsberg, 1956) although it is also clear that the eastern shoreline has undergone varying amounts of westwards migration.

Some breaks in the orderly dune pattern occur at the southern and eastern margins of the foreland, where some of the parabolic dunes have intersected the present coastline. The convergence of the parabolic dunes with the coastal dune ridges in the east and at Buddon Ness has resulted in the production of high relief and complex dune topography. Isolated SW-NE trending elongated dune ridges suggest truncation by coastal erosion.

The dune system at Barry Links also contains well-developed active dunes that exhibit a range of different controls. A series of long, narrow, well-vegetated coast-parallel dune ridges back the estuarine (south-facing) beach. The coastal dunes are

5-11m high at Buddon Ness and decrease in height westwards to 1-2m near Buddon Burn. The topography of this coastal dune system is complex. Towards the western end of the shoreline for a distance of c. 2km there are three clearly defined subparallel dune ridges, whereas further east the dune ridges are characterised by old blowouts and associated re-depositional dunes. Close to the point of Buddon Ness, the mature dunes are fronted by a narrow line of active and accreting dunes. The single coastal dune ridge along the North Sea (east-facing) coast has a more varied morphology.

Two 4.5km long sand beaches converge at Buddon Ness at the eastern tip of the foreland, each a sandy strip running along the base of a prominent dune ridge of varying height. The intertidal area on the estuary side is slightly narrower than the beach on the seaward and eastern side. Some 500m east of Buddon Ness, and trending towards the north, there is a series of subtidal and intertidal sand bars called Gaa Sands. The east flank of Gaa Sands is truncated along a straight west-east line by the main channel of the Tay.

Barry Links is also designated as a Site of Special Scientific Interest (SSSI) and is a Geological Conservation Review (GCR) site for the excellence of its coastal geomorphology. It supports a wide variety of natural habitats and is of international importance for its ecology, grassland and wet/dry heathland and both fixed and mobile dunes.

Buddon Ness probably developed in association with the Tentsmuir foreland on the south side of the Firth of Tay. Since the mid- Holocene, the Buddon area has been isostatically uplifted by about 8m, so that relative sea level has fallen. Since isostatic uplift in the area is currently about 1.0mma$_{-1}$, and general sea-level rise is c. 1.0mm/yr^{-1}, the Buddon coastline is probably now more or less static (Dawson et al., 2000).

According to SNH (2011) Barry Links can be conveniently subdivided into 3 geomorphological/sedimentological units: the east sands from Carnoustie beach to Buddon Ness, the area of the Ness itself, and the western sands from the Ness to Monifieth. The east sands are composed of medium grade, non-calcareous sand (D50=0.24mm) with occasional patches of gravel. At the eastern extremity of the site, the foreshore at Carnoustie is a low-gradient sandy beach backed by a variety of erosion protection structures including some experimental concrete mats and discontinuous intertidal rip-rap breakwaters. To the west of this beach, the northern 4km of the eastern sands of Barry Links is a low-gradient east-facing beach c. 300m wide at low tide and is characterised by several shore-parallel intertidal sand bars with intervening pools and runnels which are deflected southwards and extend the entire length of the foreshore as far as Buddon Ness.

Hydrodynamics

Waves

East of the mouth of the river Tay, the dominant wave conditions approach from between 20°N and 60°N. However, extreme wave conditions (>4m) can be experienced from the entire eastern sector (0° to 180°). Numerical modelling of the offshore wave climate, presented within Angus Council's Shoreline Management Plan, has shown that storm wave conditions can occur from any direction where fetch length extends into the North Sea

The offshore wave climate, both total sea and significant wave height for return periods of 1-100 years, have been reported on by Ramsay & Brampton, (2000a and b) for coastal cells to the north and south of Fife Ness respectively. The predicted wave climates were derived from the Met Office Wave Model and are stated to be representative of the general offshore wave climate i.e. they do not represent one particular location (see **Table 4.8**: Total sea maximum and significant offshore wave heights).

Table 4.8 Total sea maximum and significant offshore wave heights

Return period (years)	Total sea maximum wave height (m)	Significant wave height (m)
1	6.23	3.56
10	7.62	4.49
100	8.95	5.36

Source: SNH, 2000

As offshore waves transfer from the deep water of the offshore (e.g. Phase 1 OWF) to shallower water (e.g. ECR and landfall location) a number of important modifications result due to interactions of offshore deep water waves with the seabed, with the resultant modifications producing shallow water waves. These physical 'wave transformation' interactions include:

- Shoaling and refraction (due to both depth and current interactions with the wave)
- Energy loss due to breaking
- Energy loss due to bottom friction
- Momentum and mass transport effect

Analysis of the wave regime during the Seagreen metocean campaign provides site specific information for the ECR corridor on approach to Carnoustie (see Site E in **Figure 4.8**). The AWAC at Site E recorded wave data from 15th December, 2011, 14:11 to 1st March, 2012, during which time a total sea maximum wave height of 7.52m was recorded on the 3rd of January 2012, with significant wave height being

4.16 over the analysed period (Partrac, 2012). Partrac (2012) in their analysis of wave data state the largest waves are incident from between 90° and 135° (east to southeast).

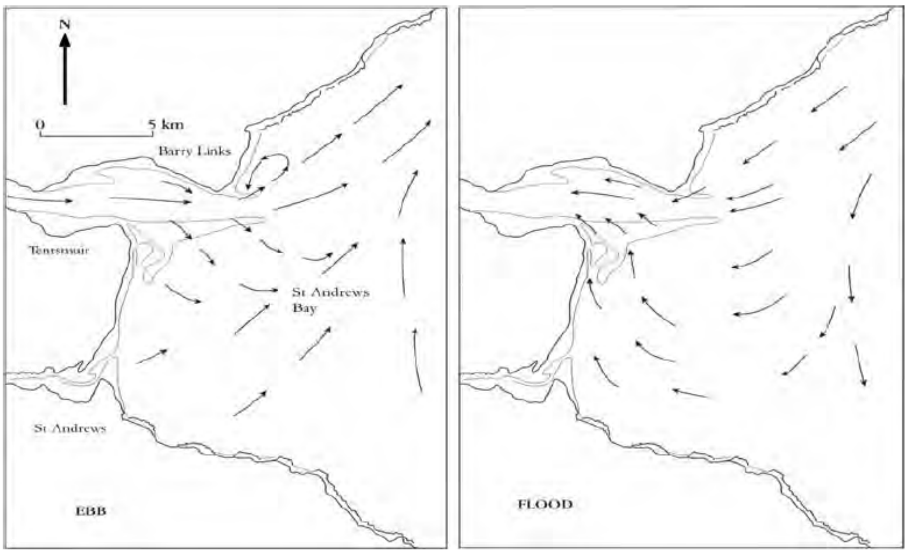
Tides

Tidal range varies spatially along the coast in response to the interaction of incident tidal energy, bathymetry and coastal planform, and orientation. Tidal range along the eastern Scottish shoreline, to the west of the Zone, is 4.6m at Dundee, 4.8m at Anstruther (Ramsay & Brampton 2000b) and 4.5m at Dunbar (Ramsay & Brampton 2000a).

Because Carnoustie is located close to a major port and estuary, there is a substantial amount of research concerning tidal conditions in the Tay that bears upon the intertidal sediment transport regime and thus the geomorphology at Barry Links. The Tay entrance experiences a spring tidal range of 4.4m and spring tidal flows exceeding $1.2m/s^{-1}$.

The flood flows south along the shore east of Buddon Links and divides into two streams, one flowing westwards into the Tay Estuary and the other forming an offshore clockwise rotation before moving into St. Andrews Bay to move north towards the south bank of the Tay (HR Wallingford, 1997) (**Figure 4.16**). The ebb flows eastwards out of the Tay and is deflected to the north over the Gaa Sands by the open coast northward ebb. This forms an anticlockwise eddy sweeping back onto the east shore of Buddon Ness from the north (Ferrentinos & McManus, 1981). Thus on both flood and ebb, tidal currents sweep sediment south along the east of Barry Links towards Buddon Ness, whereas the stronger ebb sweeps sediments from the west towards Buddon Ness.

Figure 4.16 Flood and ebb tidal pattern within the Regional Study Area

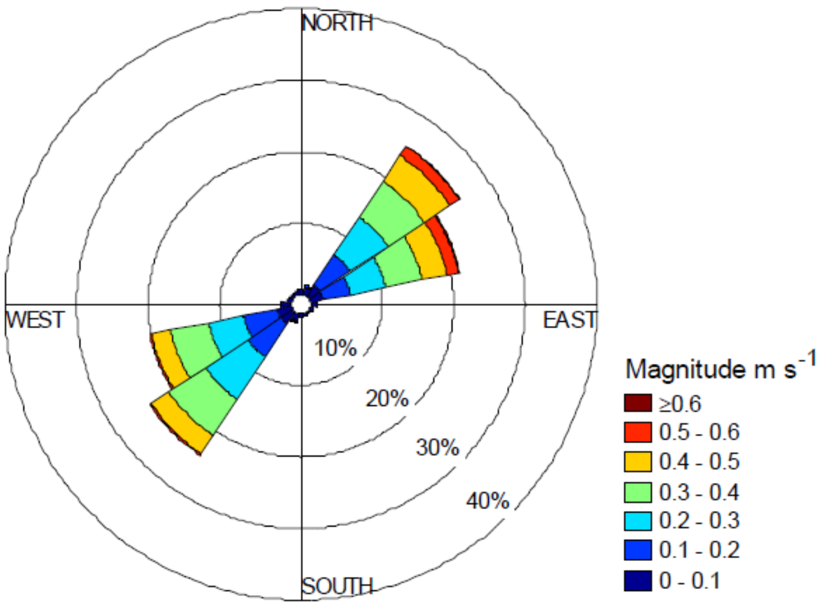


Taken from SNH (2011).

Original source: Ferentinos and McManus (1981

Tidal current data retrieved over the period 15th December 2011 to the 1st March 2012 show a consistent variation in both magnitude and direction throughout the water column and this is correlated with the tidal phase. However, the predominant current direction is along a northeast to southwest axis (Partrac, 2012). Current direction is presented for the whole deployment in **Figure 4.17**; which shows variation through the spring-neap cycle and slight ebb dominance (with stronger magnitudes seen on an ebbing tide).

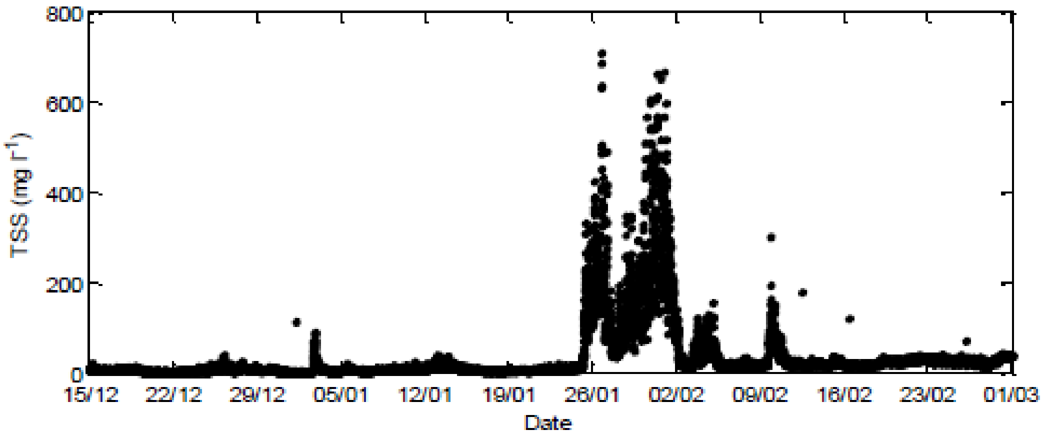
Figure 4.17 Rose diagram of depth averaged tidal current velocity for Site E



Suspended sediments

Turbidity data were recorded from 15th December, 2011 to 1st March, 2012 at Site E (see **Figure 4.18**) (Partrac, 2012). Suspended sediment data recorded over the deployment show a strong correlation to the wave climate with the highest TSS values coinciding with the storm events observed at the end of January. Tidal variation is also seen to have an effect on suspended solids with a cyclical variation of ~5-10 mg l^{-1} during times of low wave heights. The minimum recorded TSS value was recorded on the 2nd January 2012 at 2mg/l. The maximum recorded value occurred on the 27th January 2012 at 709mg/l. The mean TSS concentration over the analysed period was 34mg/l.

Figure 4.18 Total suspended sediments (TSS) (mg/l) for Site E



Coastal (littoral) processes and Sediment dynamics

Within the coastal and nearshore environment, physical processes are driven by a complex variety of wind and wave, tides and tidal currents and, to varying degrees, estuarine / fluvial forcing with the latter dependent upon the coastal / estuarine setting. The nearshore bathymetry is shallow and characterised by shore-parallel sand bars, with the extensive intertidal sand banks of Gaa Sands, lying to the east of Buddon Ness, being submerged during most of the tidal cycle. Offshore in the Firth of Tay entrance, the seabed consists mainly of sands except in the centre of the estuary itself where gravel occurs (Barne et al, 1997).

As a result of both waves and tides, the Tay entrance is characterised by a complex interchange of sediment and, although local variability exists, the resultant net longshore sediment transport direction is from the north onto the eastern coast of Buddon Ness and from the east onto the southern coast of the Ness (HR Wallingford, 1997). The net longshore drift of beach material within Carnoustie Bay is north to south, with the rate of coastal retreat slowing notably to the north of Carnoustie, due to the geological character of the coastline, with coastal erosion being limited to episodic (storm) events.

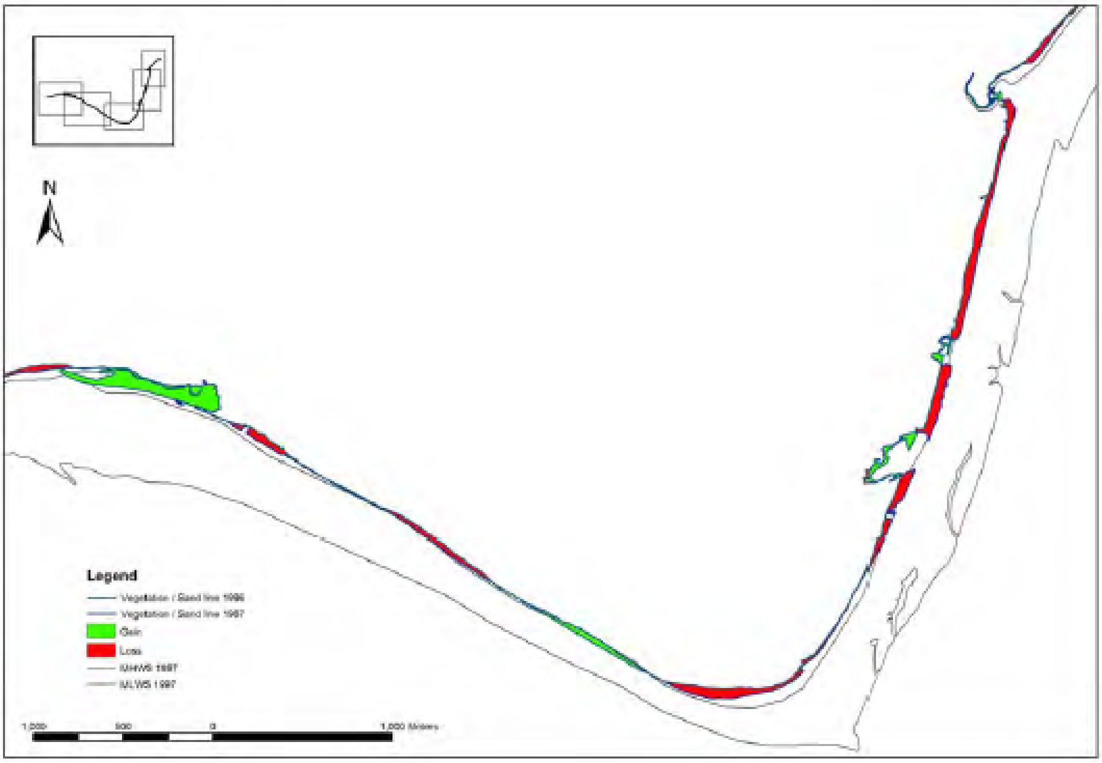
There is a high potential input of beach material into the active coastal system through reworking (erosion), though this is limited (SNH, 2000). Fluvial input from the River Tay is unlikely to be significant with much of the material being deposited on the intertidal sand banks found within the Tay estuary, or being deposited further offshore. Outside of the Tay estuary, i.e. on the open coast, longshore sediment transport is wave dominated and therefore northward dominated.

Changes to beach planform

Although the general shape of Buddon Ness has changed very little over at least the last 200 years (Steers, 1973), local evidence indicates that the Ness itself has undergone considerable fluctuation.

Using a Digital Terrain Model (DTM) for Barry Links, SNH (2011) compared the elevation data with 1967 aerial photography and identified significant changes in the location and boundary of bare sand areas/vegetation (**Figure 4.19**), particularly at the mouths of the Barry and Buddon Burns and along the east sands. The general pattern of change shown on **Figure 4.19** shows the eastern flank of Barry Links to be erosional over this time period with some minor healing of large parabolic dunes that had become re-activated by coastal truncation of their advancing faces.

Figure 4.19 Overview of morphological change at Barry Links



Coastal erosion of this shore has caused relatively rapid retreat along most of its length. This coast has a recent history of severe erosion and the dune face is recorded to have retreated up to 10m in one year (Wright 1981). In response to the erosion, coastal protection works along the northernmost 3.5km stretch of the coastline have effectively halted erosion of the coastal edge. 0.5km of protective gabions and boulder rip-rap were emplaced in 1978, extending from Carnoustie to the northern limit of the MoD range, just beyond the exit of Barry Burn. On account of a perceived erosional threat to the MoD firing ranges, the boulder rip-rap was further extended in 1992/3 from Barry Burn south along a 3km stretch of the east side of Buddon Ness and up to the full frontal dune height of 7-10m (ASH Consulting Group, 1994) (**Plate 4.4**).

Plate 4.4 Erosional bight to the south of the MoD protected shoreline

Source: SNH, 2011

As a result of the coastal protection works, the eastern sands now exist only as intertidal sand, with the upper beach above HWST being entirely boulder rip-rap which now replaces the crest of the backing dune and its landward slope (see **Plate 4.4**).

The rip-rap ends close to where one of the large parabolic dunes intersects with the coast. At this point, the coastline curves inland in an erosional bight by about 50m before slowly coming back into alignment with the overall coastal orientation of the eastern sands. As a result, the intertidal beach here is wide with a low gradient and several intertidal bars.

At the eastern flank of Buddon Ness itself, the beach becomes markedly steeper (7-8º) and narrower. The high dunes backing the Ness itself are now undercut and the remains of coastal protection structures (concrete blocks, originally tank traps, laid down to protect the toe of the dune at the Ness) now lie on the intertidal, having been by-passed by HWST. At this point, the orientation of the dune ridges lies at a high angle to the shore and testifies to truncation and ongoing and long-term erosion. However, the intertidal area at the Ness remains wide and still feeds sand to the dunes. As a result, there are local areas of infill and dune building, albeit with an undercut toe in places. The Ness thus appears to be highly dynamic with active erosion and deposition occurring as tide and wave conditions change.

West of Buddon Ness, on the Tay Estuary coast, the west beach is about 200m wide (but widens to the west towards Monifieth) and lacks some of the morphological variety of the North Sea coast. The backshore is more steeply sloping than the east beach and fronts a foredune that has both actively accreting and eroding sections. One such accreting section, south of the disused lighthouses, lies a few hundred metres to the east of the Ness and is characterised by rapid sand deposition and several shore-parallel dune ridges.

At the western limit of the site, Buddon Burn has experienced significant modification as it enters the beach. The burn's mouth has been deflected to the west and flows shore parallel for c. 1km behind a low spit capped in the east by embryo and fore dunes. Where the burn meets the coast before it is deflected west, a low area is characterised by marshy ground obscured by dense stands of reeds. Seaward of this poorly drained area lies a series of young, low dune ridges. Immediately to the east of the marshy area lies a series of buildings. Their seaward side has been protected by concrete ramps sloping down to an old channel whose orientation indicates that it once exited through the beach to the north.

Subsequently, deflection to the east has occurred and this is now reflected in the geomorphology of the extending intertidal spit and can be quantified in comparisons between the 1965 and 1990 photography (see SNH, 2011).

The amount of erosion of the coastal edge generally appears to increase to the west and wartime bunkers, once sited atop the dunes, now lie on the foreshore outside the site towards Monifieth. Beyond this to the west, erosion of the backshore and beach has resulted in a derelict shore with tipped builders' rubble and foundry waste being exposed by erosion. Further west, an extensive groyne-field extends towards the beach at Barnhill and the Dichty Burn. As a result of these structures, any potential for substantial sand supply from these areas to feed east towards the beaches at Barry Links has been all but removed.

Figure 3.18 presented an overview of change at Barry Links. However, significant local changes are concealed within the general pattern. Erosion of this section of coast over the last three decades has moved the shoreline landwards by an average of 26m along a length of 2.84km of shore (net areal loss = 74,245m^2, shore-normal erosion: maximum 51m). The MoD response to this erosion was to clad the coastline with a massive rip-rap scheme in 1992/3 and this has halted the recession of the coastal edge. However, immediately downdrift of the protected area, a 50-m wide erosional bight has now developed (**Plate 4.4**). As yet, no undermining of the rip-rap appears to have occurred but ASH Consulting Group (1994) noted that increased scouring of the toe had led to substantial lowering of the backshore.

The Barry Burn area of the east sands was subject to extensive shore protection and landscaping work in late 1970s that resulted in significant adjustments to the burn mouth. The gross morphological changes include straightening of the mouth and extension of both banks of the burn. Some loss of shoreline towards the Carnoustie

Yacht Club has since occurred, with the vegetated coastal edge moving up to 30m landwards. The largest changes to Barry Links occur along the east sands and include a general landward translation of the shoreline, the effects of erosion protection measures and the continued adjustment and stabilisation of two large blowouts. There is an apparent shoreline recession along this eastern section of up to 55m, mainly caused by pre-defence recession. However the actual displacement of the shoreline is less, due to the construction of the rip-rap and the subsequent location of the new vegetation line to the landward of that of the previously unmanaged shoreline (<5m) and thus reflecting the area occupied by the rip-rap and the overwash area.

5. Conclusions

5.1. Historic Trend Analysis

Phase 1 offshore development area

- General trend of accretion across the Phase 1 area
- Sand waves and megaripples are present but their mobility is limited

Export Cable Route(s) (ECR)

- Centre of ECR corridor characterised by erosional trend
- Seaward end of ECR corridor characterised by accretion
- No notable mobile bedforms documented within the ECR corridor

Landfall at Carnoustie

- Nearshore 1km at landfall characterised by erosion and over-steepening of seabed profile
- Between 1967 and 1996 the Carnoustie landfall coast moved landwards by an average of 26m (~0.9m/year)

5.2. Expert Geomorphological Assessment

Phase 1 offshore development area

- Seabed sediments are predominantly gravelly sand covered in part by sand waves and megaripples
- Waves approach mainly from the northeast sector and a maximum significant wave height of 4.6m was measured
- Tidal currents flow along a north-northwest to south-southeast axis with a maximum recorded velocity of 0.91m/s
- Measured suspended sediment concentrations (March and June 2011) are low, ranging from less than 5mg/l to a maximum of 10mg/l

Export Cable Route(s) (ECR)

- Seabed sediments vary from silty sands to sandy gravels with occasional outcrops of the underlying formations
- Measurements of waves, tidal currents and suspended sediment concentrations are absent along most of the ECR

Landfall at Carnoustie

- The Carnoustie landfall comprises a sandy beach backed by a wide dune system.
- Sediment is driven south along the Carnoustie coastline by the predominant waves from the northeast sector
- 100-year extreme wave heights in the nearshore zone (850m from the coast) reach 3.8m from the southeast

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