ERM Ltd and
Humber Area Dredging Association (HADA)

Humber MAREA - Physical Processes Study: Assessment of Dredging Effects

Report R.1825

March 2012

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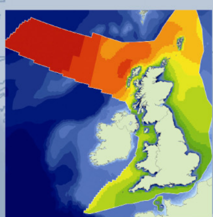


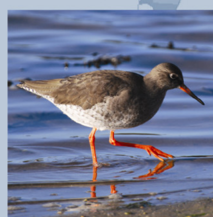

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Summary

The Humber Aggregates Dredging Association (HADA) has commissioned ERM Limited (ERM) to carry out a Marine Aggregate Regional Environmental Assessment (MAREA) for the Humber Region, which extends from Flamborough Head to Cromer and offshore to approximately 1º 26'E. The Humber MAREA is the fifth such study to be undertaken, with the others covering aggregate dredging within the Eastern English Channel, South Coast, Thames, and East Anglian regions. The MAREA will inform both the renewal process for existing licences and applications for dredging in new areas. There are 9 current production licence areas within the Humber area. Dredging is carried out in these by the following HADA companies: Tarmac Marine Dredging Ltd, Hanson Marine Aggregates Ltd, CEMEX UK Marine Ltd, Westminster Gravels Ltd and Van Oord Ltd. Additionally, there are a further six application areas.

A key element of the MAREA is an assessment of the effects of dredging on the physical environment, namely the hydrodynamic and sedimentary regime and consequential effects on the coast. ABP Marine Environmental Research Ltd (ABPmer) has been commissioned to undertake this study by ERM and HADA. The scope of this study is to determine the extent to which aggregate dredging carried out in the Humber Region has affected the natural hydrodynamic and sedimentary regimes and what further changes may occur in response to future dredging activities. Specifically, the impact assessment will consider the following:

- Changes to the tidal flows in response to past and future dredging;
- Changes to waves in response to past and future dredging; and
- Changes to sediment transport as a result of changes to the waves and tidal flows.

In order to be able to determine the effects of past and future aggregate dredging on the hydrodynamic and sedimentary regime it is necessary to develop an appropriate representation of the pre- and post-dredging bathymetry. For this investigation three separate bathymetric datasets have been produced:

- Pre-dredging - which provides a representation of bed levels across the licence areas prior to any aggregate extraction
- Present day - in which the bed levels within the licence areas reflect the dredging that has been carried out to date; and
- Future dredging - which shows the total bed level changes over a 15 year licence period, based on each company's maximum proposed dredging plans;

The bathymetric data used in this study has been compiled using data provided by the HADA members and from digital UK Hydrographic Office (UKHO) data supplied by Seazone Solutions Ltd. The data provided by HADA only covers the licence areas and not the surrounding seabed.

The two-dimensional software package MIKE 21 has been used in this study to determine the extent and magnitude of changes to the tidal flow and waves as a result of aggregate dredging. The modelling system was developed by the Danish Hydraulic Institute (DHI) Water & Environment for complex applications within oceanographic, coastal and estuarine environments. It is comprised of various modules enabling the simultaneous modelling of water levels, currents and waves. Two modules of the MIKE 21 FM (Flexible Mesh) model were applied here to resolve the key physical processes, as described below:

- The hydrodynamic module MIKE21 HD simulates the water levels variation and two-dimensional flows in the area of interest.
- The MIKE SW (Spectral Wave) model to represent both wave generation and transformation in the Humber and Greater Wash region.

The models were calibrated and validated using measured water level, flow and wave data obtained from BODC and Cefas. Extreme wave analysis was carried out using data obtained from the Met Office to determine the 1:200 year and 10:1 year wave conditions to be used in the study.

Changes in tidal currents and waves as a result of aggregate dredging have the potential to alter sediment transport rates and pathways both within the dredging areas and further afield. The extent and magnitude of sediment transport depends on a number of factors including the sediment type and morphology of the seabed, water depth and the natural variability in waves and tidal currents.

A desk based, empirical assessment of sediment mobility has been applied, rather than numerical modelling. This involves calculating the bed shear stress under currents and waves at key locations within the study area for each of the dredging scenarios and presenting this information alongside calculated theoretical sediment mobility thresholds for the different size fractions within the grain size distribution at each site. This enabled mobilisation events to be identified and demonstrated the extent to which changes in waves or tidal currents affect sediment mobility and hence the potential for sediment transport.

Tidal flow modelling results show an instantaneous snapshot of the current speeds and direction within the study area. Outputs from the flow model were obtained for four separate tidal conditions for each dredging scenario. These are:

- Peak flood - spring tide;
- Peak ebb - spring tide;
- Peak flood - neap tide; and
- Peak ebb - neap tide.

The current speeds and directions for the spring tide simulations produced greater effects than the neap tide simulations and the latter are not discussed in the present report. The figures show that the peak flood tidal currents flow in a southerly direction both along the Holderness and Lincolnshire coastlines and further offshore. Flows into The Wash are south-easterly and the tidal currents flow from east to west along the North Norfolk Coast. Peak flood flows increase in a southerly direction from less than 0.8m/s off Holderness to more than 1.6m/s at the mouth of the Humber and the entrance to The Wash. Nearshore current speeds rarely exceed 0.8m/s and off the North Norfolk coast, peak flood flows are less than 0.4m/s. Conversely peak ebb currents flow in a north easterly direction out of The Wash, easterly along the North Norfolk coast and northerly over the remainder of the study area. Flow speeds are similar to those experienced during the flood tide with the exception to the entrance to The Wash where peak ebb flows are smaller. Within the dredging areas themselves, peak flow speeds vary between 0.6m/s and 1.4m/s.

The differences between pre-dredging and present day tidal currents for peak flood and peak ebb show that with the exception of some very localised flow modifications of less than 0.1/s in Area 105, Area 440 and Area 481/1 the predicted changes to flow speeds are below the ± 0.02m/s threshold. It was concluded that cumulatively past aggregate dredging has not affected nearshore tidal currents or altered sediment transport within the Humber Region.

The proposed future dredging was predicted to affect tidal current speeds along the Spurn Peninsula and along a short section of the Lincolnshire coastline. In terms of absolute current speed the difference between the present day and future dredging scenarios is less than 0.02m/s within 1km of the coast. As the nearshore tidal currents are relatively small, this equates to a change of around 3%. However, even a 5% change is unlikely to be significant in terms of sediment mobility and changes to seabed features when the actual flow speeds change by less than 0.05m/s as is the case over much of the seabed between the dredging areas and the coast. Based on the available evidence it is concluded that the proposed future dredging would not change the flow regime sufficiently to cause an adverse effect on the coast or designated seabed features.

The 1:200 year return period wave was derived for four directional sectors, namely north-east, north, south-east and east. The Mike SW model was then used to simulate these waves at both high and low water on a spring tie for the three dredging scenarios: pre-dredging, present day and future.

Whilst the assessment showed that past dredging would have caused a change in wave heights, these were predominantly restricted to the immediate vicinity of the dredging areas. Based on the evidence from the numerical modelling study, it is concluded that cumulative effects of past dredging carried out in the Humber Region have not produced a measurable effect upon waves at the coast or over the majority of the study area.

The same modelling procedure and inputs scenarios were used to predict how proposed future dredging in the Humber Region might affect the 1:200 year wave conditions. Based on the results of the numerical modelling it is considered that cumulatively, the proposed future dredging within the Humber Region will not affect waves at the coast. Critically, in the context of impacts on coastal erosion and defences, the combination of extreme waves and high water levels did not produce measurable changes within 500m of the coast. Indeed over much of the study area, changes to the 1:200 year wave were below the 2% threshold or were highly localised within the dredging area and immediate vicinity for all combinations of incident wave direction and water level.

As a general rule, long-term seabed and coastal evolution is driven by moderate, frequently occurring events rather than the very extreme conditions described above. Therefore it is necessary to consider the effects of aggregate dredging on smaller, more frequent waves to establish whether and where changes to seabed features may occur. In order to represent this 'morphological wave' a 10:1 year wave was selected. The 10:1 year annual return period means that a wave of this size would be expected to occur up to ten times per year. Based on the results of the 1:200 year modelling, the north east incident wave angle was selected for this assessment as this produced the largest effects. The 10:1 year wave was simulated at MHWS and MLWS from this direction only for each of the three dredging scenarios.

For the past dredging scenario, the predicted changes to the 10:1 year waves at MHWS and MLWS showed that throughout the entire study area, no changes in excess of the ±2% threshold were predicted at either MHWS or MLWS for the 10:1 year waves. Consequently it is concluded that past dredging in the Humber Region is unlikely to have had a measurable effect on seabed morphology or wave driven sediment transport.

The predicted changes to the 10:1 year north easterly waves in response to the proposed future aggregate extraction showed that at MHWS the only changes that exceed the ±2% threshold are those resulting from dredging in Area 493 and very minor, localised changes in Areas 105 and at the southern tip of Area 448. The predicted changes emanating from Area 493 extend over 12km inshore from the dredging area with increases in wave height of up to 3% extending to the coast. In absolute terms this equates to a maximum difference of 3cm, which is within the natural variability of the wave itself.

The predicted changes at MLWS were again confined to a localised region within Area 105 (corresponding to the dredge zones) and in and around Area 493. As described previously the predicted changes are greater at low water than at high water due to the proportionally greater increase in total water depth. In this case, wave height increases of 15% were predicted to extend almost 2km from the dredging area, whilst a 5% increase was predicted to extend to the coast albeit over only a very small section of the frontage. However it is important to bear in mind that in absolute terms the predicted changes in wave height close to the coast are less than 0.1m, which is within the computational accuracy of the model.

UK Government guidance requires that all plans and projects should consider the possibility of such an increase in storminess and should carry out sensitivity tests to ensure that the proposed developments remain sustainable in the light of such changes. A further assessment of the effects of the proposed future dredging was carried out to establish whether the combined influence of higher sea level and larger waves would affect the original results.

For these sensitivity tests 1:200 year north easterly waves were increased in line with recent guidance (UKCP09) as shown below.

- Sea Level Rise:
  - SLR: =4mm/year;
  - Total for 19 years (2011 - 2030) which is 76mm (0.076m).

- Future Climate Change Scenario 1:
  - Wave: +5%;
  - Wave period: +2.5%; and
  - Wind : +5%.

- Future Climate Change Scenario 2:
  - Wave: +10%;
  - Wave period: +5%; and
  - Wind : +10%.

The numerical modelling output shows that for climate change scenario 1 (+5%) the predicted changes to the 1:200 year waves are similar in extent and magnitude to the future condition without climate change. This is most likely due to the increased water levels, which moderate the effects of the increased wave height. The predicted changes for climate change scenario 2 (+10%) were more widespread although the magnitude of change is similar to the original future dredging scenario. Critically, even with the larger waves and higher water levels the proposed dredging does not affect wave heights at the coast within the study area.

The potential in-combination impacts between aggregate dredging and offshore wind farms were considered. From this high level assessment, it was concluded that whilst there would be overlap between the footprints of certain OWFs and dredging areas, the overall 'in-combination' effects would be very minor and would not result in changes to waves or tidal currents either at the coast or in the vicinity of major seabed features.

Having assessed the effects of past and future dredging on tidal currents and waves, the changes were further interpreted within the context of seabed morphology and sediment transport. As the numerical modelling results showed that past dredging in the Humber Region has not resulted in large or widespread changes to either tidal flows or waves it was concluded that previous dredging would not have affected the morphology or sediment transport within the study area.

The sediment mobility assessment for future dredging focused on those areas for which large or widespread changes in waves and/or tidal currents were predicted, in conjunction with the various impact pathways identified in the baseline study. The key areas to be considered were:

- Zone 1: Inshore from Area 493 to the Lincolnshire coast;
- Zone 2: Inshore from Area 440 to Spurn Peninsula;
- Zone 3: Inshore from Area 440 to the north Lincolnshire coast; and
- Zone 4: Inshore from Area 107 to the North Norfolk coast.

The assessment concluded that the proposed future aggregate dredging would not affect wave or current induced sediment mobility anywhere outside the dredging areas themselves. The effects of dredging on combined wave and current induced seabed mobility were also examined and these also showed no change outside the licence area. This being the case, it is extremely unlikely that dredging would affect the existing sediment transport processes within the Humber Region.

Based on the evidence obtained from the numerical modelling, desk based studies and interpretation of the results, it is that neither the dredging carried out to date, nor the proposed future dredging in the Humber Region will not result in adverse effects on any of the physical processes receptors identified in the baseline assessment.

Abbreviations

%	percent(age)
‘	minute(s)
3D	Three-Dimensional
ABPmer	ABP Marine Environmental Research Ltd
ArcGIS	Geographical Information Software
BODC	British Oceanographic Data Centre
Cefas	Centre for Environment, Fisheries and Aquaculture Science
Cemex	Cemex UK Marine Ltd
CIRIA	Construction Industry Research and Information Association
CIS	Coastal Impact Study
cSAC	Candidate Special Area of Conservation
cm	centimetre(s)
DHI	Danish Hydraulic Institute
E	East
EIA	Environmental Impact Assessment
ERM	ERM Ltd
GIS	Geographic Information System
H	Wave height (m)
HADA	Humber Aggregates Dredging Association
Hanson	Hanson Aggregates Marine Ltd
Hs	Significant wave height
HW	High Water
km	Kilometre(s)
LW	Low Water
m	metre(s)
m/s	metres per second
MAREA	Marine Aggregate Regional Environmental Assessment
MarLIN	Marine Life Information Network
MEDIN	Marine Environmental Data and Information Network
MHWS	Mean High Water Springs
MIKE21	DHI Model
MLWS	Mean Low Water Springs
Mm	Million metre(s)
Mt	Million tonne(s)
N	North
n/a	Not applicable
NE	North East
NERC	Natural Environment Research Council
nm	Nautical Mile
N/m^2	Newtons per square metre
NW	North West
o	degree(s)
ODN	Ordnance Datum Newlyn
OWF	Offshore Wind Farm

POL	Proudman Oceanographic Laboratory
pSAC	Proposed Special Area of Conservation
Ramsar	The Convention on Wetlands (Ramsar, Iran, 1971)
RP	Return Period
RSPB	Royal Society for the Protection of Birds
s	second(s)
S	South
SAC	Special Area of Conservation
SE	South East
SLR	Sea Level Rise
SNS	Southern North Sea
SNSSTS2	Southern North Sea Sediment Transport Study(Phase2)
SPA	Special Protection Area
SSSI	Site of Specific Scientific Interest
SW	South West
SWAN	Simulating WAves Nearshore
TCE	The Crown Estate
TMD	Tarmac Marine Dredging Ltd
Tp	peak wave period (s)
UK	United Kingdom
UKHO	UK Hydrographic Office
W	West
Westminster	Westminster Gravels Ltd
WGS	World Geodetic System
Wp	wind speed (m/s)

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Contents

Appendices

Tables

Figures

1. Introduction

1.1 Background

The Humber Aggregates Dredging Association (HADA) has commissioned ERM Limited (ERM) to carry out a Marine Aggregate Regional Environmental Assessment (MAREA) for the Humber Region, which extends from Flamborough Head to Cromer and offshore to approximately 1º 26'E. The Humber MAREA is the fifth such study to be undertaken, with the others covering aggregate dredging within the Eastern English Channel, South Coast, Thames, and East Anglian regions. The MAREA will inform both the renewal process for existing licences and applications for dredging in new areas.

There are 9 current production licence areas within the Humber area. Dredging is carried out in these by the following HADA companies: Tarmac Marine Dredging Ltd, Hanson Marine Aggregates Ltd, CEMEX UK Marine Ltd, Westminster Gravels Ltd and Van Oord Ltd. Additionally, there are a further six application areas.

A key element of the MAREA is an assessment of the effects of dredging on the physical environment, namely the hydrodynamic and sedimentary regime and consequential effects on the coast. ABP Marine Environmental Research Ltd (ABPmer) has been commissioned to undertake this study by ERM and HADA. In order to establish an appropriate baseline, against which the effects of dredging may be assessed, a comprehensive characterisation of the study area has been produced. This is presented in ABPmer Report No 1820 (ABPmer, 2011) which accompanies this assessment. In addition to providing an overview of the contemporary hydrodynamic and sedimentary regimes, the report also includes a detailed description of the coastline and major seabed features and identifies the main impact pathways and receptors to be considered in this assessment.

1.2 Scope and Objectives

The principal questions to be answered by each of the MAREAs were defined by Cefas (2008). These are:

> *'Are the current levels of dredging environmentally acceptable and if so, can this be sustained along with dredging in new areas without causing significant environmental impacts?'*

The present assessment is solely concerned with the effects of dredging on physical processes, recognising that these are also the primary drivers for causing changes to other receptors. The scope of this study is therefore to determine the extent to which aggregate dredging carried out in the Humber Region has affected the natural hydrodynamic and sedimentary regimes and what further changes may occur in response to future dredging activities. Specifically, the impact assessment will consider the following:

- Changes to the tidal flows in response to past and future dredging;
- Changes to waves in response to past and future dredging; and
- Changes to sediment transport as a result of changes to the waves and tidal flows.

In addition to determining the extent to which dredging has impacted or potentially could impact upon the various physical processes receptors as defined in the baseline characterisation report, the outputs from this study will inform the other assessments being undertaken within the Humber MAREA.

1.3 Report Structure

The remainder of this report is structured as follows:

Section 2: Presents the study area and describes the historical and proposed future dredging activities. It also summarises the impact pathways and receptors to be considered in the assessment;

Section 3: Describes the sources of bathymetric data used in the study, the methods for integrating the data and discusses the natural variability of the bathymetry within the study area;

Section 4: Provides an overview of the physical processes and how they may be affected by dredging;

Section 5: Describes the numerical modelling undertaken for the study;

Section 6: Describes the method for assessing changes to sediment transport;

Section 7: Presents the results of the study a discussion of their significance;

Section 8: Discusses the potential effect of dredging on designated features; and

Section 9: Presents the conclusions drawn from the investigations.

2. Overview of the MAREA

2.1 The Study Area

The Humber MAREA study area extends from Flamborough Head in the North to Comer in the south and includes the open coastlines of Holderness, Lincolnshire, and North Norfolk (Figure 2.1). The offshore boundary is located at approximately 1º26'E. The study area boundaries have been selected on the assumption that the potential effects of dredging within the Humber Region will be confined within this area and the northern and southern boundaries also represent important process boundaries in terms of sediment transport.

2.2 Physical Processes Impact Pathways and Receptors

The baseline characterisation presented in ABPmer, 2011 sought to identify the receptors and impact pathways to be considered in the cumulative assessment of dredging effects. As described previously, the mechanisms by which aggregate dredging can change the hydrodynamic and sedimentary regime are:

I. Direct removal of the seabed material;
II. Changes to tidal current speeds and directions;
III. Changes to inshore wave height and direction; and
IV. Indirect changes to sediment transport rates and pathways as a result of the above.

From the coastal characterisation, it is clear that all three coastlines within the study area (Holderness, Lincolnshire and North Norfolk) are sensitive to changes in wave height and sediment supply. All the licence areas are located at least 12km from the nearest landfall. Based on the available evidence there are no direct interactions between these areas and the coast, but it is still necessary to determine whether any changes to the hydrodynamic or sedimentary regime in the dredging areas will propagate into the nearshore region. With this in mind, and based on the location of the licence areas, the following receptors and potential impact pathways were:

Table 2.1 Physical processes receptors and potential impact pathways

Receptor	Potential Impact Pathway
Holderness Coast	Changes to north easterly wave height and direction
Spurn Point	Changes to easterly wave height and direction
The Binks	Changes to northeast and easterly waves
	Interruptions to the southerly coastal & nearshore sediment transport pathway
Outer Humber Banks and North Lincolnshire Shore	Interruption of southerly sediment transport pathway across mouth of the Humber
Lincolnshire Beaches	Change in wave height at the coast
	Change in nearshore tidal currents
	Interruption of cross shore sediment transport processes
	Reduction in sheltering due to changes in nature or configuration of nearshore features such as banks, channels and overfalls.
North Norfolk Coast	Change in nearshore tidal currents
	Interruption in sediment transport pathways between Burnham Flats and North Norfolk coast.
Sandbanks and Other Bathymetric Features	Changes in sediment transport resulting from changes to the hydrodynamic regime.

2.3 Historic Aggregate Dredging Activity

Marine aggregates have been dredged from the Humber Region for many years. A review of dredging and disposal off the East Coast undertaken for the Southern North Sea Sediment Transport Study Phase 2 (HR Wallingford, 2002) indicates that an application for removing up to 0.6M tonnes/year from an area off the mouth of the Humber was submitted to The Crown Estate (TCE) as early as 1965.

The SNSSTS2 review goes on to say that prior to 1995 there was relatively little dredging activity in the Humber Region compared to other Regions. Since 1994 the volume of aggregate removed from the Humber Region has increased substantially. In addition to the generally higher demand from the construction industry, the increase in extraction was at least partly to fulfil the requirements of the Lincshore beach recharge scheme, which is described in the baseline characterisation.

There are currently 9 production licence areas within the study area. These are operated by Tarmac Marine Dredging Ltd, Cemex UK Marine Ltd, Hanson Aggregates Marine Ltd, Westminster Gravels Ltd and Van Oord Ltd. The active licences are shown in red on Figure 2.1 and are summarised in Table 2.2 below.

Table 2.2 Licence area statistics

Operator	Area No	Licence Start Date	Total Area (km^2)	Sediment Type
TMD	197	1968	29	Medium/coarse sand and fine/medium gravel
	481/1	2009	6	Medium coarse sand with some gravel
	481/2	2009	6	Medium coarse sand with some gravel
Cemex	102	1969	36	Cobbly gravel; sandy gravel and gravelly sand
	105	1976	166	Cobbly gravel; sandy gravel and gravelly sand
	107	1968		Gravelly sand and sand
Hanson	106/1	1982	4	Gravelly sand, sand and gravel (sand to the east)
	106/2	1982	3	Gravelly sand, sand and gravel (sand to the east)
	480	2009	10	Gravelly sand and sandy gravels
Westminster	440		53	Medium coarse sands
	441/1		13	Gravelly sand and sandy, shelly gravel
	441/2		34	Medium coarse gravelly sands and sandy gravel
Van Oord (with TMD)	481	2009	6	Medium coarse sand with some gravel

Summary statistics for the Humber Region are presented below. These are taken directly from information published on The Crown Estate website

- During 2008, 3.15 million tonnes of construction aggregate were dredged from a permitted licensed tonnage of 4.40 million. In addition, 0.45 million tonnes were specifically dredged for beach nourishment schemes; and
- Of the total marine aggregate dredged for construction from the Humber region, 1.02 million tonnes were landed at wharves in the North East, located on the Tyne, Tees and Humber Some 0.10 million tonnes were landed elsewhere in England, and 2.03 million tonnes were landed at wharves in mainland Europe (TCE, www.thecrown estate.co.uk).

2.3.1 Regional Statistics for 2008

- The licensed area in the Humber region was 454.62km^2;
- The total active dredging area within the Humber region during 2008 was 143.91km^2;
- Dredging took place within 24.03 km^2 (5.29 per cent) of the licensed area; and
- 90% of regional dredging effort took place from 9.00km^2.
- The area of seabed dredged in a single year ranged from 53.11km^2 in 1999 to 24.48km^2 in 2004.

2.3.2 Cumulative Footprint

- The total area of seabed dredged between 1998 and 2007 - the ten-year cumulative footprint - amounted to 103.30km².
- The area of new seabed dredged annually has reduced from 19.03km² in 1999 (35.83% of the total area) to 0.75km² in 2007 (3.05% of the total area).
- Over the full ten-year period (1998-2007), the average area of new seabed dredged each year was 5.60km², however during the most recent five-year period (2003-2007) this figure has reduced to 3.68km²/year.
- A total of 37.327 million tonnes of marine sand and gravel was dredged from TCE licence areas in the Humber region between 1998 and 2007.
- Averaged evenly across the cumulative footprint, this represents approximately 21.7cm of sediment depth removed across the area dredged.

2.4 Proposed Future Dredging

In addition to the active licence areas in the Humber Region there are also a further six application areas for which production licences are being sought by HADA members. These are shown in green on Figure 2.1 and are summarised in Table 2.3 below.

Table 2.3 Licence application areas

Operator	Area No	Total Area (km²)	Sediment Type
TMD	493	12	Medium/coarse sand and fine/medium gravel
Cemex	448, 449	17/4	Sandy gravel and gravelly sand
Hanson	400/439	14/26	Gravelly sand, sand and gravel
Westminster	441/3	73	Fine sand at surface with underlying medium, coarse sand. Gravelly sand and sandy gravel.

In order to assess the combined impacts of both continued dredging in the active areas and extraction from these new sites, it is necessary to know the total depth of extraction over the whole licence period (typically 15 years). To provide the required information each HADA member has provided bathymetric data for their areas (both active and application), which represents bed levels following the maximum proposed extraction over the licence period. This and the other bathymetric datasets to be used in the study are discussed in Section 3.

3. Bathymetry

In order to be able to determine the effects of past and future aggregate dredging on the hydrodynamic and sedimentary regime it is necessary to develop an appropriate representation of the pre- and post-dredging bathymetry. Previously, Coastal Impact Studies for dredging licence applications assumed a uniform and deliberately exaggerated lowering of the seabed across the whole licence area. Whilst this approach represents an absolute worst case scenario it was not necessarily realistic. Improved numerical modelling techniques can represent more subtle changes in bed levels than previously, making the simulation of realistic dredging patterns more achievable. Additionally, the MAREAs are seeking to present the cumulative effects of dredging and this is best achieved using the more accurate bathymetric datasets, presented here. An overview of the bathymetry within the Humber MAREA region is presented in Figure 3.1.

For this investigation (and the previous MAREAs) three separate bathymetric datasets have been produced:

- Pre-dredging - which provides a representation of bed levels across the licence areas prior to any aggregate extraction (Figure 3.2);
- Present day - in which the bed levels within the licence areas reflect the dredging that has been carried out to date (Figure 3.3); and
- Future dredging - which shows the total bed level changes over a 15 year licence period, based on each company's maximum proposed dredging plans (Figure 3.4).

3.1 Sources of Bathymetric Data

The bathymetric data used in this study has been compiled using the data provided by the HADA members and from digital UK Hydrographic Office (UKHO) data supplied by Seazone Solutions Ltd. The data provided by HADA only covers the licence areas and not the surrounding seabed. The data was sourced as follows:

3.1.1 Pre-dredging

A number of the licence areas within the Humber Region date back to the 1960's, 1970's and early 1980's (Table 2.2) and HADA pre-dredging survey data was not available for these. The pre-dredging dataset was therefore compiled from a combination of published HO survey charts, more recent HADA datasets on un-dredged seabed and, in localities dredged, by carefully extrapolating bed levels, based on known total extraction volumes. This exercise was aided by the commonly flat and uniform natural bathymetry in and around the licence areas.

3.1.2 Present Day

This dataset was produced from the most recent available survey data held by the HADA members and Seazone.

3.1.3 Future Dredging

For the future bathymetry, the HADA members have sought to determine accurate bed level changes based on the known thickness and extent of the deposit and the maximum, cumulative extraction achievable within the licence period. In some cases the proposed depth changes represent removal of the entire resource, thereby testing a maximum extraction scenario. The future bathymetry represents both ongoing dredging in existing licence areas (including renewals) and anticipated extraction from the application areas.

3.1.4 Wider Study Area

For the remainder of the study area, i.e. outside of the aggregate dredging licences, a single bathymetric dataset has been used for all three scenarios. This data was obtained under licence from the UKHO (via Seazone Solutions Ltd). The study area has been represented in this way because even if it had been possible to obtain a complete and sufficiently detailed survey for the whole study area, for both the pre-dredging and present day scenarios, a similar dataset could not be produced for the future dredging scenario. Furthermore, using a single, consistent dataset for the wider study area means that only changes due to aggregate dredging are represented rather than the natural variability and inherent differences that would be apparent between bespoke seabed surveys undertaken at different times, using different survey techniques. The numerical model would not be able to differentiate between these changes and those resulting from aggregate dredging.

3.2 Method for Creating Combined Datasets

Having received the various bathymetric data from HADA and from Seazone, three integrated bathymetries were produced. A key requirement for HADA was that the data for the licence areas should be seamlessly integrated into the wider bathymetric sets to prevent 'steps' in the data that might artificially affect the waves or tidal flows. The following section provides a summary of the processes involved in bathymetry development; sources used and GIS processing employed. All bathymetries were developed in Esri ArcGIS 10 using WGS 1984 UTM31 datum projection.

3.2.1 Bathymetry Creation

The first stage of database development involved collecting appropriate data sources for the bathymetry of the areas.

3.2.1.1 Data sources

Datasets from various internal and dredging company sources were provided. These were transformed into a consistent format and were collated and synthesised using ArcGIS 10 processing techniques, which used the three-Dimensional (3D) Analyst extension.

3.2.1.2 GIS processing

Polygons of the relevant dredging areas were created and populated with ABPmer present day model bathymetry xyz point data. Dredging company present day bathymetry data were then overlaid onto the ABPmer model bathymetry and an assessment of the differences between the point depths was completed. All depth data were then combined into a 30m x 30m raster grid and interpolated in ArcGIS to produce a surface of the likely present day bathymetry for the Humber REA area.

The interpolated bathymetry surface was then displayed in 3D and interrogated in ArcScene, using the 3D Analyst extension to ensure quality. Any anomalous sharp angles were smoothed manually and the xyz data was then extracted to provide data suitable for the numerical modelling tasks. This process was repeated for the pre-dredge and future dredging bathymetry scenarios.

3.2.1.3 Metadata files

The raster and layer file metadata complies with the latest version of MEDIN Metadata Discovery Standard. The fields used in the standard are compliant with other international conventions such as INSPIRE, ISO19115, meaning that details can be transferred easily between organisations and queried by the MEDIN portal.

3.3 Review of Bathymetric Data

Following completion of the integrated bathymetries, these were reviewed by HADA members to ensure that the three different scenarios were correctly represented in each licence area. The three bathymetries were then inter-compared to demonstrate the change in bed level between the past and planned, future dredging respectively.

3.3.1 Difference Analysis

The differences between the pre-dredge and present day bathymetry is shown in Figure 3.5. The change in bed level is largely due to aggregate extraction but in some cases, small changes are observed in parts of the licence area where no dredging has taken place. This is either a result of natural bed level variations or is due to the interpolation of coarsely spaced soundings in old survey data. The differences between the present day and future dredging are shown in Figure 3.6. These indicate the areas of seabed both within existing licences and in the application areas, where future dredging will take place.

The future depth changes are a representation of the maximum off take during the licence period. In reality, the actual volumes extracted from each area by 2030 will depend on a number of factors including:

- The scale of applications (for both renewal of existing areas and new applications) in terms of maximum and annual extraction tonnages;
- The lead in time between the application and obtaining permission to dredge;
- The conditions that may be associated with any or all of the new licences granted; or
- The proportion of the permitted annual off take that actually takes place.

This means that whilst the bed levels depicted in the future bathymetry are an accurate representation of the seabed, this overestimates the amount of sediment removed from the Humber Region during the licence period. The depth changes presented in Figure 3.6 would yield a much larger volume of sand and gravel than would in reality be extracted from the study region, but at any given location, the maximum seabed lowering may be achieved.

3.3.2 Assumptions, Limitations and Uncertainties

Any data that is used to inform assessments of change should be subject to a thorough review in order to determine the validity of the conclusions that can be drawn from it. For example, apparent differences between two independently sourced surveys may result from real bathymetric change or may simply represent differences in datum or resolution between the two datasets.

In the present study, the ABPmer project team and HADA are satisfied that the three bathymetry datasets provide an accurate representation of the pre-dredging, present and future bed levels within the licence areas for the purposes of the modelling and that any anomalies resulting from the interpolation of widely spaced data points will not affect the performance of the numerical model.

It is important to note however that the datasets making up each regional bathymetry are not synchronous. For example, the data provided by HADA is based on surveys of individual licence areas that have not all been carried out during the same year, whilst the Seazone dataset is a combination of numerous surveys that have been carried out over many years. The Seazone data represents the best bathymetric information that covers the entire study area and is readily available to the MAREA.

3.4 Interpretation of Bathymetric Variability

Although the primary purpose of the three bathymetric datasets is to setup the numerical model, the data itself can also be examined further to assess the relative effects of the aggregate dredging against a background of natural bathymetric variability. It is a common misconception that dredging creates very deep, very broad depressions in an otherwise flat seabed. Whilst it is an accepted fact that the dredged depressions are permanent and are of sufficient size to alter both tidal flows and waves, the scale of the depressions are typically less than half a metre. The dredged depressions within all the licence areas do not exceed 6m deep and as described in the baseline characterisation (ABPmer, 2011) the bathymetry in the Humber Region is highly complex with large scale channel and sandbank features and smaller scale bedforms such as the Overfalls. Hence in the context of the surrounding seabed, the scale and extent of the dredged depressions is relatively insignificant.

4. Physical Processes

In this study, the physical environment is defined as the coast, the seabed and its sediments and the hydrodynamic and sedimentary regimes that act upon it. The baseline characterisation has provided an overview of the physical environment, but an understanding of how aggregate dredging might affect the different system components is necessary.

4.1 Tidal Currents

Tidal currents arise from the spatial differences in vertical water movements associated with the progression of the tidal wave. Tidal currents move in a rotational pattern and constrictions imposed on these currents by a shoaling seabed accelerate the flow, so that tidal currents are generally stronger close to the shore than in the open sea. This is particularly the case where the tide flows through narrow straits (e.g. the Dover Straits) or is funnelled into estuaries (e.g. the Bristol Channel and Severn Estuary). In shallow water, large volumes of sediment may potentially be transported by tidal currents alone, or more commonly, by a combination of currents and waves.

The change in bathymetry caused by aggregate extraction could potentially alter the magnitude and direction of tidal currents, both in the vicinity of the dredging area and further afield. Any such modification of the tidal currents may lead to a change in the rate and pattern of sediment transport, which could, for example, affect the integrity of reef features and their associated flora and fauna.

Research into the effects of aggregate dredging on physical processes carried out over many years has demonstrated that changes in tidal currents are typically very minor and localised (CIRIA, 1998). The depth changes associated with the majority of existing dredging operations are modest in relation to the pre-dredge water depth and therefore have little or no effect on current speeds. Numerical modelling studies have shown that tidal currents are generally reduced at either end of the dredged depressions, with modest increases in current speed along the edges (CIRIA, 1998).

There is no simple assessment for determining the significance of changes to tidal flows attributable to dredging with respect to the potential environmental damage such changes may cause. This judgement can only be made with detailed knowledge of the environmental or anthropogenic sensitivities in the areas within which the changes are predicted to occur.
For example, the Marine Life Information Network (MarLIN) suggests that '*The sensitivity of a species or community is an estimate of its intolerance to damage from an external factor and is determined by its biological and physical characteristics. Sensitivity must be assessed in response to a change in a specific environmental factor and to the magnitude, duration, or frequency of that change*'. In this specific biological context, MarLIN presents the following characterisation of tidal current strength.

- Very strong: >3m/s;
- Strong: 1.5-3m/s;
- Moderately strong: 0.5-1.5m/s;
- Weak: <0.5m/s;
- Very weak: Negligible.

MarLIN points out that many species and biotopes occur under a range of flow conditions. A prolonged change in current speeds of two or more categories is more likely to affect a range of species than if current speeds only change by one category. Even changing by one category represents major percentage change in current speed and the MarLIN guidance suggests that changes of just a few percent would be unlikely to cause a major impact on marine life. However, other interest features including sandbanks or anthropogenic features such as pipelines may be sensitive to small changes in tidal current speed. This will be an important consideration in interpreting the significance of changes to tidal flows within the present assessment.

4.2 Waves

Aggregate dredging causes a localised lowering of the seabed which has the potential to alter the way that waves propagate across the area. In deep water (>30m) modification to the waves is likely to be relatively minor, except in the immediate vicinity of the dredging area. These localised changes may only be of concern if there are interest features such as sandbanks, wrecks or submarine cables located near to the site. However, in shallow water (<30m), changes to the waves may be both larger and more widespread such that waves at the coast may be affected.

The wave propagation mechanisms that may be affected by dredging can be divided into two main categories as described in Sections 4.2.1 and 4.2.2 below.

4.2.1 Energy Conserving Processes

As waves travel into shallow water, the moving water particles begin to interact with the seabed and the resultant frictional drag modifies both the wave height and direction. When waves travel inshore with their crests orientated parallel to the isobaths the change in water depth gives rise to a reduction in the speed of propagation known as 'shoaling'. This is accompanied by an increase in wave height. In very shallow water rapid deceleration occurs, which leads to further increases in wave height and wave steepness until the wave eventually breaks.

Where waves approach isobaths obliquely, the variation in the speed of propagation along the wave crests also causes the waves to change direction. This process is known as refraction. Where the bathymetry is complex, refraction will lead to wave focus in some areas and a corresponding increase in wave height. In other areas, waves may diverge and reduce in height.

Where the change in depth between the surrounding seabed and the bottom of the dredged area is sufficiently large, then some of the wave energy can be reflected, even if the side slopes are very shallow. Partial reflection of the waves from aggregate dredging areas tends to occur only when the wave period is long, such as during storm conditions for example. Overall neither shoaling nor refraction alter the total wave energy flux but simply redistribute it over the sea surface.

Another process, wave diffraction, becomes important when there is a strong spatial variation in wave heights. Diffraction is a lateral transfer of wave energy, (i.e. along the direction of the wave crest), from areas of high to low wave heights. This process results in 'smoothing' of the changes in wave height and direction associated with the seabed features. Although more commonly associated with wave propagation around surface piercing structures such as harbour walls, diffraction also occurs landward of large seabed features, for example following the partial breaking of waves over a sandbank.

4.2.2 Energy Dissipating Processes

In addition to the energy conserving processes described above, there are a number of mechanisms that can alter the total energy flux as waves travel towards the coast. Some processes such as frictional drag at the seabed or partial breaking over the crest of a sandbank, will convert energy into turbulence. Others, such as sustained wind, will increase wave energy as it travels inshore.

In shallow water areas (<30m) the lowering of the seabed by aggregate dredging can reduce the energy dissipation that occurs as waves travel over the area. An example of this is where proposed dredging would remove or lower a mound or bank of sediment. If this natural feature pre-dredging causes the waves to break over the crest then post-dredge lowering will increase wave heights landwards. This influence could potentially extend as far as the coastline. As a result wave conditions within the dredging area will be different to those either side of it, although wave diffraction will then act to reduce this variation as the waves travel further inshore. Additionally, since most aggregate dredging areas are a considerable distance offshore, winds will continue to modify the waves as they travel over and past the deepened areas. In particular, wind action reduces the spatial variability in wave conditions (i.e. height, period and direction) as they travel away from the dredged area.

4.2.3 Sediment Transport

One of the main issues associated with aggregate dredging in the UK is the potential for detrimental effects on the coast and nearshore environment that may result from changes to the magnitude and direction of sediment transport. Sediment transport occurs when the friction generated by the combined effect of tidal and wave induced currents exceeds a critical value required to mobilise bed sediments of a given grain size. Depending on the value of additional friction, sediment grains may then be transported by the currents either in suspension or as bedload.

If dredging is carried out in water depths greater than around 20 m (in the UK), the sediments are unlikely to be mobile except under extreme wave and tidal conditions. Therefore, it is very unlikely that dredging in these depths will remove sediments that may ultimately supply beaches. However, aggregate dredging is locally carried out in water depths of less than 20 m in the Humber Region. There is therefore some potential that sediments in the vicinity of the dredging areas are mobile under moderate wave and tidal conditions, and possible that these may be may be linked to the littoral zone.

In addition to the direct removal of sediment, there is concern that the depressions created during dredging could 'intercept' and trap sediment travelling through the area and preventing it from reaching the coast or protected seabed features. When determining the extent to which dredging might impact upon sediment transport, it is also important to consider the natural variability of the seabed. For example, bedforms are generally used as an indicator of sediment transport rate and direction. Even where there is little or no evidence of sediment transport, natural depressions exist that are far larger than those created by dredging. Hence if these natural features do not interrupt the supply of sediment, it is argued that dredging is unlikely to have any measurable impact upon this process.

5. Numerical Modelling of Waves and Tides

5.1 Selection of a Suitable Numerical Model

The two-dimensional software package MIKE 21 has been used in this study to determine the extent and magnitude of changes to the tidal flow and waves as a result of aggregate dredging. The modelling system was developed by the Danish Hydraulic Institute (DHI) Water & Environment for complex applications within oceanographic, coastal and estuarine environments. It is comprised of various modules enabling the simultaneous modelling of water levels, currents and waves. Two modules of the MIKE 21 FM (Flexible Mesh) model were applied here to resolve the key physical processes, as described below:

- The hydrodynamic module MIKE21 HD simulates the water levels variation and two-dimensional flows in the area of interest.

- The previous MAREAs have applied the SWAN (Simulating WAves Nearshore) model to assess the effects of dredging on waves. Whilst ABPmer also has the facility to use this model, it was decided to use the MIKE SW (Spectral Wave) model to represent both wave generation and transformation in the Humber and Greater Wash region. The basis of this decision was that in using the MIKE 21 FM model to simulate changes to tidal flows it would be more efficient to apply the wave module of the same modelling suite. Furthermore the MIKE SW module is also constructed on a flexible grid, which means that the model can be resolved in more detail within the areas of interest, whilst remaining coarser offshore to minimise computational run times and thus maximise efficiency.

A comparison of the two models is presented in Appendix A to this report. Both are third generation wave models, which simulate the growth, decay and transformation of wind-generated waves and swell in offshore and coastal areas. The models represent the following processes acting on a complete directional wave spectrum:

- Wave growth by the action of wind;
- Non-linear wave-wave interaction;
- Dissipation due to white-capping;
- Dissipation due to bottom friction;
- Dissipation due to depth-induced wave breaking;
- Refraction and shoaling due to depth variations; and
- Wave-current interaction.

Either model is therefore appropriate to address the present questions. The models output wave predictions over the whole model domain producing colour contour plots of, for example, wave height. However, each run of the model is for specific driving conditions (offshore waves, winds, tidal state) and it is not practical in the present study to run the model to produce a complete long-term wave climate allowing for the full natural variation of all these parameters. Instead modelling has focussed on a range of representative wave conditions for a range of directions and tidal states, chosen to show the influences of bathymetric change on waves.

5.2 Model Configuration and Calibration

5.2.1 Mesh Design

The model is bound on its western and southern extents by the Lincolnshire and North Norfolk coasts respectively. The offshore limits are approximately 01°45'E and 54°06'N. Figure 5.1 shows the detail extents of the model.

Resolution across the model domain is variable. The model has been designed to provide a high resolution in the dredging and nearshore areas. In the offshore area the spatial resolution is around 5,000m while it increases to 200m within the dredging areas. The highest spatial resolution of 200m is sufficient to represent the detailed bathymetry of the dredging area. The model resolution is illustrated in Figure 5.2.

5.2.2 Bathymetry

Bathymetry data in the dredging areas was provided by HADA and from Seazone Solutions Ltd. The compiled dataset was incorporated into the model domain to a common reference level, Ordnance Datum Newlyn (ODN).

5.2.3 Boundary Conditions

For the MIKE21 HD model, the open boundaries apply time-varying water level conditions generated from the spherical grid North Sea model developed previously by ABPmer (ABPmer, 2005). To simplify the transfer of boundary conditions, the model has been aligned with the North Sea model grid with a northern boundary defined by latitude 54°06'N and the eastern boundary by longitude 01°45'E.

Time-series of wave data from the Met Office was acquired by ABPmer for the model calibration and validation. The offshore wave height, period and direction were applied along the offshore boundary of the models.

5.2.4 Model Calibration

Numerical models typically require significant amounts of data to assist with model calibration and validation. A description of these various datasets is provided below. A comprehensive calibration and validation report is presented in Appendix B.

Water level data were available from two tide gauges located at Immingham and Cromer (Figure 5.3). The tide gauge data were made freely available by the British Oceanographic Data Centre (BODC) as part of the function of the National Tidal and Sea Level Facility, hosted by the Proudman Oceanographic Laboratory (POL) and funded by the Environment Agency and the Natural Environment Research Council (NERC).

Tidal current data were selected from BODC mooring current meters within the area. The data records at five sites have been chosen based on their locations, durations and quality.

Measured wave data in 2007 from the WaveNet buoys located at Dowsing, North Well and West Silver Pit were used exclusively for the calibration and validation. These devices make use of modern technology and provide directional wave data. The data from the buoys are subject to rigorous quality checks and therefore considered to be the best available dataset for model calibration and validation purposes. The sites of observational data records for tides, currents and WaveNet buoys are displayed in Figure 5.3.

5.3 Selection of Input Conditions

Wave frequency tables were purchased from the United Kingdom Meteorological Office (Met Office). The data were extracted from the European Waters Wave model at the location 53.87N, 0.70E. The complete data set covers the period 06/1991 to 11/2008. Further analysis was carried out to provide 10 in 1, 1 in 1, 1 in 10, 1 in 50 and 1 in 200 year return period wave heights in eight directional sectors, as shown in Table 5.1.

Table 5.1 Wave conditions

Return Period (yr)	Significant Wave Height (HS) (m) by Directional Sector							
	N	NE	E	SE	S	SW	W	NW
0.1	4.26	3.24	3.14	3.00	2.92	2.78	2.84	3.27
1	4.91	4.60	4.00	3.79	3.70	3.61	3.78	4.06
10	5.53	5.93	4.77	4.56	4.41	4.36	4.58	4.78
50	5.95	6.85	5.26	5.09	4.87	4.83	5.07	5.24
200	6.30	7.62	5.65	5.54	5.24	5.20	5.45	5.62

Based on this analysis the most common wave directions (and those resulting in the largest waves are those arriving from the north, north-east, east and south-east sectors. This was also confirmed by data from the Cefas Wavenet buoys. The time-series of wave and wind data were used to create a synthetic relationship between wave height and wind speed in the model domain. The derived wave and wind conditions are given in Table 5.2.

Table 5.2 Applied wind and wave conditions

Dir.	Items	10:1	1:1	1:10	1:50	1:200
N	H	4.26	4.91	5.53	5.95	6.30
	Tp	9.40	10.0	10.8	10.9	11.5
	Wp	16.0	18.0	19.5	21.5	22.0
NE	H	3.24	4.60	5.93	6.85	7.62
	Tp	8.20	9.70	11.2	12.4	13.2
	Wp	12.0	15.0	19.8	22.8	25
E	H	3.14	4.00	4.77	5.26	5.65
	Tp	8.10	9.00	9.60	10.2	10.2
	Wp	13.0	15.5	18.5	20.8	21.5
SE	H	3.00	3.79	4.56	5.09	5.54
	Tp	7.60	8.50	9.20	9.60	10.2
	Wp	13.5	17.2	19.2	21.0	21.0

Note:
Hs: Significant wave height (m);
Tp: Peak wave period (s); and
Wp: Wind speed (m/s).

The offshore wave height, period and direction were applied along the offshore model boundary. A spatially uniform wind field was applied over the whole model domain. The wave model was run using a combination of wave, wind and water levels (High Water, Low Water).

6. Sediment Transport

Changes in tidal currents and waves as a result of aggregate dredging have the potential to alter sediment transport rates and pathways both within the dredging areas and further afield. The extent and magnitude of sediment transport depends on a number of factors including the sediment type and morphology of the seabed, water depth and the natural variability in waves and tidal currents. The receptor and impact pathways identified in the baseline characterisation (ABPmer, 2011) and presented in Section 1 of the present report demonstrate the sensitivity of the coastlines within the study area to changes in sediment supply. Furthermore, Natural England has raised concerns about potential changes to sediment transport around sandbanks (Ian Reach, pers comm.).

For the previous MAREAs numerical modelling was used to predict changes to current induced sediment transport. However, modelling of this nature is subject to considerable uncertainty because of the large variations in tidal range and grain size that cannot be accurately represented within a regional scale study (HR Wallingford, 2010). For example, the previous MAREAs assumed a single sediment grain size across the whole study area and a larger than average tidal range.

In order to provide a simplified but more realistic picture of the potential changes to sediment movement as a result of aggregate dredging in the present study, it was decided to apply a desk based empirical approach rather than use numerical modelling. This involves calculating the bed shear stress under currents and waves at key locations within the study area for each of the dredging scenarios and presenting this information alongside calculated theoretical sediment mobility thresholds for the different size fractions within the grain size distribution at each site. This enabled mobilisation events to be identified and demonstrated the extent to which changes in waves or tidal currents affect sediment mobility and hence the potential for sediment transport.

To investigate the effect of changes in tidal current direction as a result of dredging, progressive vector analyses have been undertaken using current data obtained from the model. Spatial variation in residual flow and residual sediment displacement (i.e. the net advective pathway) is calculated as the net displacement of water only when current speeds are above the threshold for sediment mobility. Although the absolute magnitude of residual sediment displacement calculated in this way is not quantitatively meaningful, the net transport direction can be used together with the relative magnitude to draw a qualitative comparison between the different dredging scenarios.

Using these methods will not provide an indication of changes in sediment transport rates but will demonstrate where changes to the hydrodynamic regime are likely to have an effect on sediment movements in and around the dredging areas.

7. Presentation and Discussion of Results

The purpose of this study is to demonstrate how the aggregate dredging in the Humber region has affected the hydrodynamic and sedimentary regime in the past and what further changes might arise in response to proposed future dredging between now and 2030. To achieve this objective the MIKE numerical model has been used to simulate a range of different tidal flow and wave conditions as described in Section 5. The outputs from the modelling were subsequently used to infer changes to seabed mobility and sediment transport within the study area using the approach described in Section 6. A large number of model runs were carried out during the study and presenting them all in this report is not meaningful. The outputs presented in the following sections are intended to demonstrate the scenarios that produce the greatest effects along with others that show the changes under more common sea conditions.

Before presenting the results of the dredging affects assessment, it is helpful to first examine briefly the model confidence limits and the means by which change to hydrodynamic and sediment processes are assessed. As with all numerical models, it is possible to output and compare the results to a very high level of precision. However, such precision does not reflect the *accuracy* of the model's predictions as all such numerical tools are subject to limitations in computational calculations. This might for example result from an incomplete description of the relevant physics in the numerical model equations or something simpler such as numerical rounding errors. Typically models can only predict changes in waves or current speeds to around ±2% .Consequently, the modelling carried out for this study takes into account the inherent but small inaccuracies described above and changes smaller than 2% are not presented in the results. Values up to the ±2% the threshold should therefore be regarded as not significantly different from zero.

Diagrams showing the percentage change in flow speeds and significant wave height are used in this report to provide a helpful and informative means of presenting and describing the effects of aggregate dredging within the Humber Region . These diagrams are produced by comparing the predicted flow speed or wave height for the pre-dredging and present day bathymetries and for the present day and future bathymetries, and calculating the difference at each grid point within the model. This type of diagram is particularly useful in providing a rapid visual assessment of the extent of changes in flow speed and wave height within the study area. However, in order to place the abstract percentage changes into a clear perspective, the absolute changes in wave height are also presented. This enables the reader to appreciate the percentage changes in real terms, for example whether a 5% change in wave height equates to a difference of only 0.1m or perhaps as much as 1m, depending on the original height of the wave in question. As described previously the inherent small inaccuracies associated with the model mean that changes below a certain threshold are not reliably distinguishable from zero. For the absolute values, changes of less than 0.1m wave height and 0.02m/s flow speed are considered in this study to be within the confidence limits of the chosen model and are not shown as a difference. It is important to note, however, that in some cases a change of 2% or greater might be less than 0.1m in absolute terms and *vice versa*, which would result in a change in one figure but not in the other. This does not reflect an error in the model or presentation but is simply a function of the original size of the wave or magnitude of the current speed. For the purposes of this assessment, and to ensure consistency with the previous

MAREA reports, the diagrams showing percentage change are the primary source of information with the absolute changes included to provide a context for discussing the changes.

7.1 Tidal Currents

Tidal flow modelling results show an instantaneous snapshot of the current speeds and direction within the study area. Outputs from the flow model were obtained for four separate tidal conditions for each dredging scenario. These are:

- Peak flood - spring tide
- Peak ebb - spring tide
- Peak flood - neap tide
- Peak ebb - neap tide

The current speeds and directions for the spring tide simulations are shown in Figures 7.1 and 7.2. These produced greater effects than the neap tide simulations and the latter are not discussed further in the present report. The figures show that the peak flood tidal currents flow in a southerly direction both along the Holderness and Lincolnshire coastlines and further offshore. Flows into The Wash are south-easterly and the tidal currents flow from east to west along the North Norfolk Coast. Peak flood flows increase in a southerly direction from less than 0.8m/s off Holderness to more than 1.6m/s at the mouth of the Humber and the entrance to The Wash. Nearshore current speeds rarely exceed 0.8m/s and off the North Norfolk coast, peak flood flows are less than 0.4m/s. Conversely peak ebb currents flow in a north easterly direction out of The Wash, easterly along the North Norfolk coast and northerly over the remainder of the study area. Flow speeds are similar to those experienced during the flood tide with the exception to the entrance to The Wash where peak ebb flows are smaller. Within the dredging areas themselves, peak flow speeds vary between 0.6m/s and 1.4m/s.

The peak flood and ebb flows presented in Figures 7.1 and 7.2 do not appear to differ dramatically between the three dredging scenarios. In order to better demonstrate any changes in current speed, a series of difference plots have been created for pre-dredging to present day and present to future. The results for each scenario are discussed in the following sections.

7.1.1 Pre-dredging to Present Day

The differences between pre-dredging and present day tidal currents for peak flood and peak ebb are presented in Figures 7.3 and 7.4. These show that with the exception of some very localised flow modifications of less than 0.1/s in Area 105, Area 440 and Area 481/1 the predicted changes to flow speeds are below the ± 0.02m/s threshold. Therefore, for the reasons outlined above, it is concluded that cumulatively past aggregate dredging has not affected nearshore tidal currents or altered sediment transport within the Humber Region.

7.1.2 Future Dredging

The comparisons of peak flow speeds for the present day and future dredging scenario are presented in Figures 7.5 and 7.6. These show that over the dredged areas themselves, peak tidal currents are predicted to decrease as a result of the increased water depths. In all cases the reduction in flow speed is less than 0.2m/s and for the most part does not exceed 0.1m/s. In percentage terms this equates to decreases of between 2% and 20%. The magnitude of change appears to relate directly to the amount of seabed lowering with the largest changes corresponding to the deepest dredged depressions such as in Areas 105, 449 and 440 (Figure 3.5). In presenting these changes it is important to bear in mind that the future dredging scenario represents the maximum potential extraction over the whole licence period and that, whilst depth limits may be reached in some locations, the actual gross amount of seabed lowering may be considerably less.

Outside the dredged areas flows to the north and south are predicted to increase by up to 15% as a result of the larger tidal discharge through the deepened areas. The increased discharge entering and leaving the dredging areas causes current speeds to accelerate over the adjacent un-dredged areas. Increases in current speed of >5% are typically confined to within a few hundred metres of the dredging areas, with the exception of Area 493 where increases in peak flow speed of 10% are predicted to extend for more than 1km to the north on both the flood and the ebb tide. However, in absolute terms, this represents a difference of less than 0.1m/s compared to the present day.

To the east and west of the dredging areas, peak tidal currents are predicted to decrease on both the flood and ebb tide. In all cases the reduction in flow speed is less than 10% and typically changes of more than 5% are confined to within a few hundred metres of the licence area boundary. At all locations the absolute magnitude of change to tidal current speed is less than 0.1m/s. However, as shown in Figures 7.5 and 7.6 the proposed dredging in Areas 493, 448, 439 and 107 cause current speeds to decrease over several kilometres to the east or west of the licence areas. Although actual flow speeds (Figures 7.5a and 7.6a) are not predicted to change by more than 0.02m/s within 1km of the coast, Figure 7.5b shows that currents speeds are predicted to decrease by up to 3% along the Spurn Peninsula and between Saltfleet and Mablethorpe. Figure 7.6b shows similar changes although these do not quite extend to the coast due to the lower speeds and flow orientation of the ebb current. Both these frontages were highlighted in the Coastal Characterisation (ABPmer, 2011) as being sensitive to changes in the hydrodynamic and sedimentary regime and the implications of the changes in peak flow speed will require further consideration. Further widespread reductions in peak flood and ebb flow speed are predicted to the east of Area 107, although these are typically less than 5% lower than present day values.

7.1.3 Direction

In addition to the change in peak flow speed, changes in the tidal current direction have also been predicted as shown in Figures 7.7 and 7.8. These show that the maximum change in direction within the dredging areas is around 12º whilst outside, the maximum change is 10º. For the most part changes of >4º are confined to within a few hundred metres of the dredging areas. Clearly the direction of the flood and ebb flows is of great importance when considering sediment transport and although localised changes are unlikely to result in a widespread or long term shift in transport patterns the changes presented in Figures 7.7 and 7.8 will be considered further in Section 7.5.

7.1.4 Discussion of Changes to Tidal Flows

In evaluating the significance of the tidal current changes presented above it is necessary to consider the following:

- Generic changes in tidal strength;
- Changes in current speed at the coast and around large sedimentary features; and
- The implication of changes in current speed and direction for sediment transport.

In terms of the generic changes to tidal strength as described in Section 4.1, a prolonged change in current speed of two categories (e.g. from moderate to very strong) would be considered likely to have an adverse effect on marine life. For the future dredging scenario even the largest changes from the present day do not equate to a change in one tidal strength category. Furthermore the results presented provide a snapshot of peak flows at a single point in time and as such the predicted changes would not be prolonged. It is therefore considered unlikely that the predicted changes to tidal currents would have an adverse effect on marine life. However, it is not within the scope of the present study to make judgement about the effects on receptors, other than those specific to the physical environment and the significance of these changes on ecological receptors will be considered further elsewhere in the MAREA.

As described previously, the proposed future dredging is predicted to affect tidal current speeds along the Spurn Peninsula and along a short section of the Lincolnshire coastline. In terms of absolute current speed the difference between the present day and future dredging scenarios is less than 0.02m/s within 1km of the coast. As the nearshore tidal currents are relatively small, this equates to a change of around 3%. In presenting such changes it is important to bear in mind that all numerical modelling is subject to a degree of uncertainty and that very small changes to very small current speeds should be treated with caution. For example, tidal flows are subject to a degree of natural variability and peak current speeds may vary by a few percent on two days when the same tidal range occurs. As a result of this, changes of less than ±2% are not presented. However even a 5% change is unlikely to be significant in terms of sediment mobility and changes to seabed features when the actual flow speeds change by less than 0.05m/s as is the case over much of the seabed between the dredging areas and the coast.

The implications of the changes in tidal current speed on sediment transport will be discussed further in Section 7.5 to establish whether the proposed dredging could affect sediment supply to the coast or around key sedimentary features. Based on the evidence presented thus far it is concluded that the proposed future dredging would not change the flow regime sufficiently to cause an adverse effect on the coast or designated seabed features.

7.2 Waves

In a total of 5 different wave return periods were simulated in the present study (Section 5.9). The aim of this was to determine the potential worst case scenario in terms of potential changes to the nearshore wave climate as a result of dredging. For the previous MAREAs a 1:200 year return period was deemed to represent the worst case, particularly since this is also of relevance from a coastal defence perspective. In the present study the 1:200 year wave was also found to represent the worst case scenario. A more commonly occurring wave scenario of 10:1 years was also selected to demonstrate the effect of dredging on the morphology of the study region in and around the licence areas. The input conditions for the wave conditions presented previously in Section 5.9 are repeated here for the two relevant return periods.

Table 7.1 Wave input statistics

Dir.	Parameter	10:1 (yr)	1:200 (yr)
N	Hs(m)	4.26	6.30
	Tp (s)	9.40	11.5
	W (m/s)	16.0	22.0
NE	Hs(m)	3.24	7.62
	Tp (s)	8.20	13.2
	W (m/s)	12.0	25
E	Hs(m)	3.14	5.65
	Tp (s)	8.10	10.2
	W (m/s)	13.0	21.5
SE	Hs(m)	3.00	5.54
	Tp (s)	7.60	10.2
	W (m/s)	13.5	21.0

7.3 The Effects of Aggregate Dredging on Extreme (1:200 year) Wave Conditions

The 1:200 year return period wave was derived for each of the directional sectors described above. The Mike SW model was then used to simulate these waves at both high and low water on a spring tie for the three dredging scenarios: pre-dredging, present day and future, giving a total of 24 model runs. Not all of the results are presented here but Figures 7.9 to 7.11 provide examples of the outputs. These show the significant wave heights across the study area for the three dredging scenarios. The model outputs show waves from the northeast at MHWS. These figures demonstrate clearly the reduction in height as the waves move into shallow water. Close inshore, wave heights are also reduced as a result of interaction with the bed and eventual breaking. In addition to the general offshore - onshore reduction in wave height, more localised changes occur as the waves travel over sandbanks. The most obvious effects occur around Triton Knoll, Dudgeon Shoal and Race Bank although the changes to wave conditions are localised and wave heights commonly increase again inshore of the features. The inshore banks such as Inner Dowsing do not appear to provide any significant degree of shelter to the coast and the 1:200 year wave height along much of the study area coastline would be between 3m and 4m.

7.3.1 Presentation of Predicted Changes to Waves

The predicted changes to the 1:200 year waves for the directional sectors shown in Table 7.1 above are presented in Figures 7.12 to 7.27. These include simulations at both high and low water for past and future dredging scenarios. The differences are shown in terms of both absolute change in height and percentage change with the latter being the primary reference source for the MAREA as described in the introduction to Section 7. For the most part, the predicted changes result arise through interactions with the dredging areas and decrease in magnitude with increasing distance from the dredging area. A number of figures (primarily those showing % change) also show small, isolated differences that are not connected to the dredging areas. These tend to occur in areas where the bathymetry is very complex, over large intertidal areas or where wave heights are typically very small. These predicted changes have been carefully evaluated in the context of the natural environment and physical processes and are judged to be artefacts of the model calculations rather than real changes caused by the proposed dredging. This is particularly the case for changes within the Humber where the complex intertidal bathymetry is the estuary is not represented accurately, and where all estuarine processes are not included in the model (being outside the scope of the study). For these reasons the predicted changes to waves in the lee of Spurn Head should be disregarded. This is also the case for the more minor changes predicted in the Wash and at Donna Nook. It is noted also that frequently some degree of expert judgment is used when disregarding spurious numerical modelling results of this nature in this and other similar studies.

7.3.2 Effects of Past Dredging on Extreme Waves

Figures 7.12 and 7.13 show the predicted changes to waves from the north east between the pre-dredging and present day scenarios at MHWS and MLWS respectively. These show that changes above the 2% are restricted to Area 440. At MHWS the changes are highly localised and do not exceed 3% whilst at low water increases in wave height of up to 5% are predicted along the southern boundary of the dredging area. The greater increase in wave height is due to the proportionally greater water depth following dredging.

Figures 7.14 and 7.15 present the same results for waves from the south east. Again changes in excess of 2% are confined within Area 440 and the maximum difference between pre-dredging and present day is 5%. In this case, the predicted increases in wave height are to the south of the dredged area and area again highly localised. There is little difference between the predicted changes for MHWS and MLWS, which is most likely a function of the local seabed topography. Similar changes are predicted for waves from the north and east as shown in Figures 7.16 to 7.19. In all cases the predicted increases in wave height are less than 5% or 0.3m in absolute terms and are either contained within the licence area itself or extend only a few hundred metres beyond it.

Based on the evidence presented above, it is concluded that cumulative effects of past dredging carried out in the Humber Region has not produced a measurable effect upon waves at the coast or over the majority of the study area. The past dredging in Area 440 is predicted to have caused localised increases in wave height of up to 5% for all directional sectors that could at times extend more than 1km from the dredging area. However, given the complex bathymetry in this area, and the natural variability of the adjacent sandbanks which would also affect wave heights, it is unlikely that such small changes in wave height would ever be observable. In conclusion therefore dredging carried out in the Humber Region to date has not resulted in large changes to extreme waves either at the coast or elsewhere in the study area. It is also reasonable to assume that the various impact pathways described in Section 2 of this report would not have been affected by past dredging.

7.3.3 Effect of Future Dredging on Extreme Waves

The same modelling procedure and inputs scenarios were used to predict how proposed future dredging in the Humber Region might affect the 1:200 year wave conditions. An example of the model outputs is shown in Figure 7.11. As mentioned previously in Section 3.3 the total seabed lowering applied in the future dredging scenario represents the total amount of extraction that could take place by 2030. However, it is likely that the actual volumes removed during the licence period will be substantially less and the future dredging represents the absolute worst case scenario. It is therefore safe to assume that if the actual extraction is less than the maximum proposed then actual changes to the wave climate will be either the same or less than those predicted in the present study. The results of the numerical modelling for each directional sector are discussed below.

The predicted differences in 1:200 year waves from the north east (at MHWS) are presented in Figure 7.20. This shows that over much of the study area changes to the wave height are less than 2% or ± 0.1m and no changes greater than this threshold are predicted within 1km of the coast. In general any changes to the wave height are confined within the dredging areas, with the exception of Areas 493 and 448, which are discussed in more detail below.

Over much of Area 448 and some 6km to the south west, wave heights are predicted to decrease by around 3% or up to 0.2m. This is slightly unusual in that the larger water depths within a dredging area generally cause an increase in wave height both within the area and 'down wave' as a result of reduced energy dissipation. The bathymetry in this area is complex as the dredging are lies along the flanks of the natural deep New Sand Hole where the seabed shelves rapidly close to the southern boundary of Area 448. As the change in wave height is very small and does not extend either to the coast or over any key sedimentary features, this change is not considered to be important.

Within and adjacent to Area 493, which is located around 14km off the Lincolnshire coast increases in wave height of up to 15% are predicted. The larges changes are confined within a few hundred metres of the licence area but increases of 10% -3% (decreasing with distance from the dredging area) extend to almost 1km from the coast. This is due to the large depth changes in Area 493 as the other adjacent areas do not appear to affect waves beyond the boundary of the licence area. Critically, the proposed dredging in this area is not predicted to affect wave heights at the coast, which is the primary concern for such extreme waves at high water. However as the changes in wave height propagate a large distance inshore from the dredging area these results may require further consideration in the context of potential effects on the seabed morphology.

Changes to the 1:200 year north easterly waves at MLWS are shown in Figure 7.21. Over much of the study area there is little difference between this and the MHWS results. Minor increases are predicted to the south of the offshore dredging areas but these changes are highly localised and are not considered significant. The predicted decreases in wave height in and around Area 448 are much reduced compared to the MHWS results.

The largest changes are predicted for Area 493. Wave heights are predicted to increase by more than 25% compared to the present day within the dredging area and although changes of this magnitude are highly localised, increases of up to 10% or 0.3m are predicted to extend to within 2km of the coast. These changes are produced as a result of the large increase in water depth in Area 493. This bathymetry in this area was previously shallow and dissipated wave energy in the nearshore region as shown in Figure 7.10. Whilst it is unlikely that the predicted changes to the waves will result in any adverse effects on the coast, it will be necessary to consider these results further in the context of sediment transport and potential effects on nearshore seabed features.

Figures 7.22 and 7.23 show the predicted changes to the 1:200 year south easterly waves at MHWS and MLWS respectively. At MHWS predicted changes to the wave height are less than 2% over virtually the whole study area. As for north easterly waves, the largest change in Hs are predicted within and adjacent to Area 493. These are confined to within a few kilometres f the dredging area and the small, isolated areas of change adjacent to Donna Nook (Figure 7.22) and Mablethorpe (Figure 7.23) may be disregarded as computational anomalies. The extent and magnitude of change is greater at MLWS with increases in Hs of more than 25% predicted within Area 493. In all areas the changes in wave height are generally confined within a few kilometres of the dredging areas and it is considered that no adverse effects on the coast or major seabed features are likely.

The predicted changes to the 1:200 year waves from the north are presented in Figures 7.24 and 7.25. In common with other results the differences between present day and future dredging at MHWS are typically confined to the dredging areas or their immediate vicinity. Wave heights along a small stretch of the Lincolnshire frontage are predicted to increase by up to 3% (Figure 7.24) but in absolute terms this equates to an increase of less than 0.1m and is not therefore likely to produce an adverse effect at the coast. Figure 7.24 also highlights some apparent changes to the waves in the lee of Spurn Head. As described in Section 7.3.1, the model is not resolved to represent the complex estuarine processes and these predicted changes may be disregarded as computational artefacts.

The predicted changes at MLWS (Figure 7.25) are more widespread and greater in magnitude, particularly in and around Areas 493, 197 and 400 but these do not extend to the coast. Although changes of up to 10% are predicted this equates to an absolute increase of only 0.1 to 0.2m, which is unlikely to produce major effects on the seabed.

The predicted changes to waves from the east are presented in Figures 7.26 and 7.27. As for the other directional sectors changes to the waves are for the most part less than 2% at both MHWS and MLWS. Critically, this threshold is not exceeded anywhere along the coast. The largest and most widespread changes occur in and around Area 493, particularly at MLWS as a result of the proportionally large increase in total water depth as a result of dredging.

7.3.4 Discussion

Based on the results of the numerical modelling presented above it is considered that cumulatively, the proposed future dredging within the Humber Region will not affect waves at the coast. Critically, in the context of impacts on coastal erosion and defences, the combination of extreme waves and high water levels did not produce measurable changes within 500m of the coast. Indeed over much of the study area, changes to the 1:200 year wave were below the 2% threshold or were highly localised within the dredging area and immediate vicinity for all combinations of incident wave direction and water level.

The largest and most widespread changes in wave height were predicted to occur in response to the proposed dredging in Area 493. In the future dredging scenario, the seabed would be lowered by up to 6m by 2030 which, given the shallow present day water depths in this area represents a considerable increase in total water depth. Although the predicted wave heights do not extend to the coast, there is the potential that local wave-driven effects on the seabed and nearshore features could gradually propagate shoreward and ultimately lead to an impact on the coast. The most extensive effects were predicted for north easterly waves at low water and these will be considered further in the context of sediment transport and morphological change.

The 1:200 year wave condition applied in this study is by definition extremely rare and the expected duration of such an event would be very short (e.g. a few hours). Moreover it is highly unlikely that such a rare event would coincide with a very low tide level as severe storms in the Southern North Sea more often accompany surges, which typically raise water levels above normal tidal height (although negative surges, which considerably lower the water level also occur). Based on the modelling results, which predicted smaller changes at MHWS than at MLWS, a combined extreme wave and surge event would most likely moderate the effects of dredging inshore from Area 493. In addition, the infrequent occurrence and short duration of the 1:200 year event suggests that any effects on the morphology or sediment transport would be modest and short lived. Any potential effects on large seabed features would consequently be minor compared to longer-term natural variability. As described previously, the potential effects of dredging on more commonly occurring waves is of greater interest in the context of sediment transport and morphological change and this is discussed further in the following section.

7.4 Effects of Dredging on ‘Morphological’ Waves

As a general rule, long-term seabed and coastal evolution is driven by moderate, frequently occurring events rather than the very extreme conditions described above. Therefore it is necessary to consider the effects of aggregate dredging on smaller, more frequent waves to establish whether and where changes to seabed features may occur.

The selected input conditions are presented in Table 7.3. The 10:1 year annual return period means that a wave of this size would be expected to occur up to ten times per year. Based on the results of the 1:200 year modelling, the north east incident wave angle was selected for this assessment as this produced the largest effects. The 10:1 year wave was simulated at MHWS and MLWS from this direction only for each of the three dredging scenarios and the results are presented in Figures 7.28 to 7.30. These show that the wave heights are much smaller than the 1:200 year wave and the more regular height contours indicate a lower degree of interaction with the offshore seabed and sandbank features. Along the coast, 10:1 year wave heights are typically between 1.5 and 2.5m.

7.4.1 Effects of Past Dredging on 10:1 Year Waves

The predicted changes to the 10:1 year waves at MHWS and MLWS are presented in Figures 7.31 and 7.32 respectively. Throughout the entire study area, no changes in excess of the ±2% threshold were predicted at either MHWS or MLWS for the 10:1 year waves. Consequently it is concluded that past dredging in the Humber Region is unlikely to have had a measurable effect on seabed morphology or wave driven sediment transport.

7.4.2 Effects of Future Dredging on 10:1 Year Waves

The predicted changes to the 10:1 year north easterly waves in response to the proposed future aggregate extraction are presented in Figures 7.33 and 7.34. At MHWS the only changes that exceed the ±2% threshold are those resulting from dredging in Area 493 and very minor, localised changes in Areas 105 and at the southern tip of Area 448. The two latter are not considered significant and will not be discussed further. However the predicted changes emanating from Area 493 extend over 12km inshore from the dredging area with increases in wave height of up to 3% extending to the coast. In absolute terms this equates to a maximum difference of 3cm, which is within the natural variability of the wave itself.

As shown in Figure 7.34, the predicted changes at MLWS are again confined to a localised region within Area 105 (corresponding to the dredge zones) and in and around Area 493. As described previously the predicted changes are greater at low water than at high water due to the proportionally greater increase in total water depth. In this case, wave height increases of 15% were predicted to extend almost 2km from the dredging area, whilst a 5% increase was predicted to extend to the coast albeit over only a very small section of the frontage. However it is important to bear in mind that in absolute terms the predicted changes in wave height close to the coast are less than 0.1m, which is within the computational accuracy of the model. Nonetheless, given the sensitivity of the Lincolnshire coastline and Spurn Point, and the importance of nearshore sediment transport pathways, the predicted changes to the 10:1 year waves will be considered further within the context seabed mobility and morphological change.

7.5 Sensitivity Tests

7.5.1 Climate Change

As global warming occurs, mean sea level increases as sea water expands and as fresh water is released from melting ice masses. An increase in the frequency and intensity of severe storm events is also possible in a warming climate. UK Government guidance requires that all plans and projects should consider the possibility of such an increase in storminess and should carry out sensitivity tests to ensure that the proposed developments remain sustainable in the light of such changes. Consequently, it was decided that a further assessment of the effects of the proposed future dredging would be carried out to establish whether the combined influence of higher sea level and larger waves would affect the original results.

For these sensitivity tests 1:200 year north easterly waves were increased in line with recent guidance (UKCP09) as shown below.

- Sea Level Rise:
  - SLR =4mm/year; and
  - Total for 19 years (2011 - 2030) which is 76mm (0.076m).

- Future Climate Change Scenario 1:
  - Wave: +5%;
  - Wave period: +2.5%; and
  - Wind : +5%.

- Future Climate Change Scenario 2:
  - Wave: +10%;
  - Wave period: +5%; and
  - Wind : +10%.

Table 7.2 Wind and wave conditions for climate change sensitivity tests

Dir.	Items	Future Scenario	Future Climate Change Scenario 1	Future Climate Change Scenario 2
NE	Hs (m)	7.62	8.0	8.4
	Tp (s)	13.2	13.5	13.9
	Wp (m/s)	25	26.3	27.5

As the primary purpose of these sensitivity tests was to determine whether there would be any changes in wave conditions at the coast, the results are only presented for MHWS, which has been increased to reflect sea level rise of 4mm/year.

Figures 7.35 and 7.36 show the 1:200 year NE wave height for climate change Scenarios 1 and 2 respectively. As with the previous results, difference plots have been produced to demonstrate the change in wave height between present day and future dredging. Figure 7.35 shows that for climate change scenario 1 (+5%) the predicted changes to the 1:200 year waves are similar in extent and magnitude to the future condition without climate change. This is most likely due to the increased water levels, which moderate the effects of the increased wave height. As shown in Figure 7.36 the predicted changes for climate change scenario 2 (+10%) are more widespread although the magnitude of change is similar to the original future dredging scenario. Critically, even with the larger waves and higher water levels the proposed dredging does not affect wave heights at the coast within the study area.

7.6 In-Combination Effects

Aggregates are just one of a number of marine resources that are exploited in the Humber Region. These activities along with a number of 'other sea uses' that affect the physical environment were described in the baseline characterisation (ABPmer, 2011) and are listed below.

- Maintenance dredging;
- Offshore disposal;

- Commercial fishing;
- Coastal defences;
- Offshore wind farms; and
- Cables and pipelines

Based upon the information presented in the baseline review, it was concluded that of the above, only offshore wind farms are likely to produce 'in-combination' effects with aggregate dredging and therefore the others will not be discussed further within the present study.

7.6.1 Offshore Wind farms

As described in the baseline characterisation, there are a total of 10 offshore wind farms (OWF) within the study area, of which 2 are operational and the remainder are either under construction or still awaiting consent. Several offshore wind farm sites are located near to aggregate licence areas and in particular, the Triton Knoll and Docking Shoal developments lie adjacent to Areas 440 and 107 respectively.

Wind farms are known to affect the waves and tidal currents in the lee of the array and in the same way as marine aggregates, are subject to detailed physical processes impact assessments as part of the consenting process. Consequently the 'footprint' of effect for a number of the proposed wind farms has been established through numerical modelling, although as not all of this information is within the public domain it is not possible to present the data directly. Instead a high level evaluation of the potential interactions between the OWFs and future aggregate dredging has been carried out.

7.6.2 Effects of Offshore Wind Farms and Aggregate Dredging on Tidal Currents

As shown in Section 7.2 aggregate dredging typically reduces tidal flow velocity over the dredging area and increases it on either side. The results from the present modelling study show that changes to the tidal currents are largely restricted to the licence area and the immediate vicinity with only very minor changes in flow speed extending more than a few hundred metres away from the licence boundary.

Numerical modelling of the combined effects of the Race Bank, Docking Shoal and Triton Knoll Wind farms predicted changes to spring tidal current speed (both increases and decreases) of up to 0.2m/s within the arrays and immediately outside the boundary. Elsewhere changes of 0.02m/s were predicted to extend as far as the North Norfolk and Lincolnshire coastline.

Given the fairly broad extent of the wind farm footprint with respect to flow speed changes, there is almost certain to be some overlap with the flow speed changes due to aggregate dredging, particularly around Areas 440 and 107. However, as the wind farms are predicted to cause both increases and decreases in flow speed at the same location, at different states of the tide, and given that the magnitude of change outside both the wind farm and the dredging areas is very small, the net combined effect of the two developments is unlikely to be distinguishable from the natural flow variability.

7.6.3 Effects of Offshore Wind Farms and Aggregate Dredging on Waves

Numerical modelling of the combined effects of several OWFs on waves show that wave heights would be reduced both within the arrays and in the lee. The extent of the disturbance is typically dependent on the size of the array, the foundation type and the spacing between turbines. Whilst there may be some overlap between areas of disturbance from both the wind farms and dredging this would only occur during N and NE waves. Additionally, whilst the OWFs are predicted to reduce wave heights, the modelling results presented in Section 7 show that aggregate dredging commonly increases wave heights downwind of the dredging areas. Consequently the two activities would counteract each other, thereby moderating what are in any case minor changes to the waves.

7.6.4 Summary

Based on the high level consideration of potential interactions between OWFs and aggregate dredging presented above, it is concluded that whilst there would be overlap between the footprints of certain OWFs and dredging areas, the overall 'in-combination' effects would be very minor and would not result in changes to waves or tidal currents either at the coast or in the vicinity of major seabed features. Nevertheless as this conclusion is based entirely on 'expert judgement', the findings are qualitative, rather than quantitative and further consideration of this issue may be required as part of any future EIAs.

7.7 Sediment Transport

Having assessed the effects of past and future dredging on tidal currents and waves, it is necessary to further interpret these changes within the context of seabed morphology and sediment transport. This will involve revisiting the impact pathways identified in the baseline characterisation and applying the methods described in Section 6 to determine whether the various physical process receptors may be affected by the predicted changes to the hydrodynamic regime.

As discussed in Sections 7.1 to 7.3 the numerical modelling results showed that past dredging in the Humber Region has not resulted in large or widespread changes to either tidal flows or waves. Consequently, it was concluded that previous dredging would not have affected the morphology or sediment transport within the study area and hence the effects of this past dredging will not be considered further in this assessment.

The predicted changes to tidal currents and waves are for the most part confined within the dredging areas and their immediate vicinity. Therefore it is not necessary to consider changes to sediment transport and seabed morphology over the entire study area. Rather, this assessment will focus on those areas for which large or widespread changes in waves and/or tidal currents were predicted, in conjunction with the various impact pathways described in Section 2.2 of this report. The key areas to be considered are:

- Zone 1: Inshore from Area 493 to the Lincolnshire coast;
- Zone 2: Inshore from Area 440 to Spurn Peninsula;

- Zone 3: Inshore from Area 440 to the north Lincolnshire coast; and
- Zone 4: Inshore from Area 107 to the North Norfolk coast.

In order to put these changes into context, it is necessary to characterise the seabed within each of the four zones listed above.

7.7.1 Zone 1 Inshore from Area 493 to the Lincolnshire Coast

This zone has been selected on the basis that the proposed future dredging in Areas 493 and 197 produced the largest and most widespread changes to both tidal currents and more particularly waves. The main reason for these changes is that the present day seabed within Application Area 493 is relatively shallow and has been shown to reduce inshore wave heights (Figure 7.9). The proposed future dredging would lower bed levels by up to 6m, which represents a proportionally large increase in total water depth. The changes to tidal flows and waves do not necessarily translate directly into changes in sediment movement and it is therefore important to determine how the hydrodynamics interact with the nearshore seabed features.

7.7.1.1 Characterisation of the seabed

The sand beach along the Lincolnshire coast shelves relatively steeply to a depth of - 8mODN some 500m from the shore. No changes to the waves or tidal currents were predicted this close to the coast, which is in any event seawards of the beach toe along this frontage. The beach profile at Mablethorpe, presented in the baseline characterisation (ABPmer 2011) also shows a large bathymetric feature 1km from the shore. This is will provide shelter from wave action. Further offshore, the seabed slopes gently and is covered by a thin veneer of sand. The complex of Overfalls off Lincolnshire consists of mounds of sand, gravel and glacial till with isolated fields of sandwaves. These shoals affect both the tidal currents and waves. Elsewhere the seabed is gently undulating and is covered with sands and sandy gravels alongside areas of exposed till. The seabed features in this area appear stable from their smooth profiles and low surface gradients although isolated bedforms which may be active are superimposed on the sandy gravel seabed of the Overfalls.

In order to calculate the bed shear stress and hence infer potential changes to sediment mobility as a result of the proposed future dredging it is necessary to determine the local sediment grain size. Despite having no seabed samples from the inshore areas, TMD's high resolution shallow seismic and side scan sonar data over Protector Overfalls and within Area 493 displays an identical signature to that further inshore and in addition this data is complemented by seabed samples consisting of sandy gravel. It is thus considered that the sediment grain size is similar between the two areas. Further information on the sediment distribution was obtained from BGS charts and Admiralty Charts for the area.

7.7.1.2 Current induced seabed mobility

Using the sediment samples and seismic information obtained for Area 493, a theoretical grain size distribution has been calculated for a number of locations inshore of the dredging areas. This information was then used along with current data from the model to calculate bed shear stress over a typical spring tide at Points B and E on Figure 7.39. The variability of bed shear stress at these locations is shown for both the present and future dredging scenarios (Figures 7.40 and 7.41). The graphs also show the critical bed shear stress required to mobilise the different grain size fractions found on the bed at this location. Figure 7.40 indicates that during spring tides fine sand is mobile most of the time whilst coarse sand is mobilised during periods of peak flow speed. Critically, the two graphs are almost identical, which demonstrates that the predicted changes to tidal currents do not greatly affect the bed shear stress and consequently bed shear stress inshore from the dredging areas. Figure 7.41 shows that within Area 197 bed shear stress for the future dredging scenario is predicted to decrease in comparison with the present day scenario. This would result in a slight reduction in the mobility of very coarse sand but as this size fraction is only currently mobile during peak flood and peak ebb, this change is unlikely to have a significant effect on sediment transport. Additionally, the bed shear stress has been calculated for a specific location, for which a reduction in flow speed was predicted. Elsewhere in the immediate vicinity, both increases and decreases in current speed were predicted and as such any changes in sediment transport are likely to be highly localised.

Progressive vector analysis has also been carried out at these locations. As shown in Figure 7.42 the present and future tidal residuals at Point B are identical, indicating that despite a change in current direction the net potential transport direction would not be affected. Whilst the progressive vectors at Point E show a slight change in potential transport direction, this is unlikely to result in a widespread alteration in transport direction given the variability in flow speeds and consequently seabed mobility in the immediate vicinity.

7.7.1.3 Wave induced seabed mobility

The wave induced bed shear stress for the present and future dredging scenarios has been calculated along a transect between dredging Area 493 and the Lincolnshire coast as shown in Figure 7.39. The changes are shown in Table 7.3 a and b below. Graphs have been produced for 10:1 year waves at both high and low water and these are presented in Figure 7.43. As for the tidal current plots the graphs also show the critical bed shear stress required to move the different sediment size fractions that are found on the bed at these locations. The plots show that over the dredging areas themselves, (Points a1 and b1) the bed shear stress for the future dredging scenario is reduced compared to present day values at both low and high water. This is due to the increased water depth at the site combined with relatively small waves. Further inshore the future bed shear stress is increased slightly compared to present day values although this does not result in significant change in bed mobility.

Table 7.3a Comparison of wave induced bed shear stress at high water (Site 1)

Location	D_{50} (µm)	Present					Future				
		Water Depth	Hs (m)	T(s)	Dir (o)	τ_w N/m^2	Water Depth	Hs (m)	T(s)	Dir (o)	τ_w N/m^2
a	500	10.5	2.43	5.36	46	1.95	14.5	2.41	5.21	47	0.79
b	500	12.3	2.39	5.31	44	1.32	15.1	2.38	5.16	47	0.66
c	500	15.7	2.20	4.96	47	0.43	15.7	2.30	5.03	47	0.49
d	400	15	2.16	4.84	47	0.38	15.1	2.24	4.93	47	0.44
e	400	15	2.10	4.73	47	0.32	15	2.16	4.81	47	0.37
f	400	10	1.98	4.66	50	1.00	10	2.02	4.73	50	1.09

Table 7.3b Comparison of wave induced bed shear stress at low water (Site 1)

Location	D_{50} (µm)	Present					Future				
		Water Depth	Hs (m)	T(s)	Dir (o)	τ_w N/m^2	Water Depth	Hs (m)	T(s)	Dir (o)	τ_w N/m^2
a	500	5.3	1.68	4.73	47	2.95	9.3	1.78	4.59	48	1.10
b	500	7	1.54	4.42	38	1.50	9.90	1.74	4.48	46	0.84
c	500	10.5	1.45	3.82	45	0.24	10.5	1.66	4.16	47	0.48
d	400	9.9	1.50	3.74	45	0.25	9.9	1.63	3.95	47	0.40
e	400	9.8	1.50	3.65	46	0.22	9.8	1.59	3.80	47	0.31
f	400	4.8	1.31	3.58	50	1.49	4.8	1.36	3.75	50	1.72

7.7.1.4 Summary

Based on the available evidence and the further analysis of the model data presented above, it is considered unlikely that proposed future dredging in the licence areas off the Lincolnshire coast, and particularly area 493, will produce a measurable or permanent change in sediment mobility or seabed morphology in the inshore areas or at the coast.

7.7.2 Zone 2 Inshore From Area 448 to the Spurn Peninsula

This has been selected on the basis of the potential impact of changes to waves and currents inshore from New Sand Hole on the sediment transport pathway between Holderness and Lincolnshire.

7.7.2.1 Characterisation of the seabed

The seabed slopes quite steeply from the beach along the Spurn Peninsula to around 400m offshore where there is a clear reduction in the seabed gradient, which is likely to indicate the beach toe. Thereafter the seabed is relatively flat but dips gently until New Sand Hole is reached 10km offshore. The increase of water depth from 6m at the beach toe to just 12m at over 10km offshore represents a gradient of only 1 in 1600 over the gravelly veneers and glacial till forming the seabed offshore from Spurn. The seabed in New Sand Hole descends from 12m water depth at the lip of the feature to over 40m at the base. New Sand Hole is around 1.5km wide at the lip with infilling gravelly sands typically 5m thick at the base.

7.7.2.2 Current induced seabed mobility

A theoretical grain size distribution at a point inshore of Area 448 and a point within Area 105 (Points C and F on Figure 7.39) has been calculated based on available information from BGS sediment charts and the more detailed survey data collected for the present study. This has been used to inform calculations of current induced bed shear stress as described above. The variability of bed shear stress is shown for both the present and future dredging scenarios (Figure 7.44 and 7.45). The graphs also show the critical bed shear stress required to mobilise the different grain size fractions found on the bed at this location. Based on the plots shown in Figure 7.44, it is clear that there is very little difference in the current induced bed shear stress for the future dredging scenario compared to the present day case. Progressive vector analysis carried out at this location (Figure 7.42) also showed no change in the net potential transport direction (for a spring tide).

As shown in Figure 7.45 the bed shear stress within Area 105 is relatively large compared to other locations (including Point C) such that the mobility threshold for gravel is exceeded at certain times during spring tides. Point F corresponds to a location outside the dredging area, for which increases in flow speed were predicted and this is reflected in the bed shear stress calculations, which also show a slight increase compared to present day values. As the differences in bed shear stress between the future and present day scenario is small, there is unlikely to be a residual effect on sediment transport in this area. Progressive vector analysis at Point F shows a change in net potential sediment movement. However, as this location is relatively far offshore and the original vector was not orientated towards the coast, it is unlikely that the coastal transport pathways between Holderness and Lincolnshire would be affected. It is also important to bear in mind that the vectors are calculated at a point and are not indicative of sediment transport over a wider area.

7.7.2.3 Wave induced seabed mobility

The wave induced bed shear stress for the present and future dredging scenarios has been calculated along a transect between dredging Area 448 and the Spurn Peninsula as shown in Figure 7.39. The changes are shown in Tables 7.4 a and b below. Graphs have been produced for 10:1 year waves at both high and low water and these are presented in Figure 7.46. As for the tidal current plots the graphs also show the critical bed shear stress required to move the different sediment size fractions that are found on the bed at these locations. The plots show that over the dredging areas themselves, the bed shear stress for the future dredging scenario is reduced compared to present day values at both low and high water. This is due to the increased water depth at the site combined with relatively small waves. Further inshore there is no apparent difference between the present day and future dredging scenarios.

Table 7.4a Comparison of wave induced bed shear stress at high water (Site 2)

Location	D_{50} (µm)	Present					Future				
		Water Depth	Hs (m)	T(s)	Dir (o)	τ_w N/m^2	Water Depth	Hs (m)	T(s)	Dir (o)	τ_w N/m^2
a	500	22.7	2.70	5.41	42	0.22	23.89	2.71	5.41	40	0.17
b	300	24.3	2.62	5.29	44	0.10	29.8	2.62	5.28	44	0.03
c	500	19.4	2.66	5.39	44	0.40	19.4	2.67	5.39	45	0.40
d	500	19.4	2.61	5.34	44	0.37	19.4	2.63	5.36	45	0.38
e	500	15.6	2.50	5.26	47	0.70	15.6	2.51	5.27	47	0.71
f	500	10.4	2.26	5.21	53	1.70	10.4	2.26	5.23	53	1.72

Table 7.4b Comparison of wave induced bed shear stress at low water (Site 2)

Location	D_{50} (µm)	Present					Future				
		Water Depth	Hs (m)	T(s)	Dir (o)	τ_w N/m^2	Water Depth	Hs (m)	T(s)	Dir (o)	τ_w N/m^2
a	500	17.5	2.36	5.04	38	0.34	18.7	2.37	5.04	37	0.26
b	300	19.1	2.27	4.87	43	0.13	24.6	2.26	4.85	43	0.03
c	500	14.2	2.34	5.06	43	0.72	14.2	2.34	5.05	44	0.71
d	500	14.2	2.25	4.98	44	0.64	14.7	2.27	5.00	44	0.66
e	500	10.4	2.08	4.89	48	1.28	10.4	2.09	4.92	49	1.31
f	500	5.2	1.67	4.80	58	3.08	5.2	1.68	4.82	58	3.10

7.7.2.4 Summary

Based on the available evidence and the further analysis of the model data presented above, it is considered unlikely that proposed future dredging in the licence Areas off the Spurn Peninsula will produce a measurable or permanent change in sediment mobility inshore. There is therefore good evidence that the sediment transport pathway between Holderness and the Lincolnshire coast will be unaffected by the proposed dredging.

7.7.3 Zone 3 Inshore from Area 448 to the North Lincolnshire Coast

This profile has been selected on the basis of the small but widespread changes in wave height within and inshore from Area 448. No changes to the tidal currents were predicted in the modelling and therefore the changes to current induced bed shear stress and sediment mobility have not been assessed in this instance.

7.7.3.1 Characterisation of the seabed

The intertidal and nearshore flats of Donna Nook and Haile Sand extend offshore at a low angle for almost 1km. The seabed then shelves abruptly at around 1.2km, which is likely to indicate the beach toe. Thereafter the seabed dips gently seawards, reaching 10 m water depth some 7km offshore, at a gradient of only 1 in 700. The seaward margin of the coastal sand flats is sharply defined against the underlying glacial till. Till is exposed at the seabed over much of the rest of the profile until the south-westerly slope of New Sand Hole is reached 13km offshore. The infill of New Sand Hole thickens from the flanks into the base of the feature and consists of sands and gravelly sands, merging with sandwaves lying at the base. The bedforms display well defined crests 8m high in 30m of water.

7.7.3.2 Wave induced seabed mobility

The wave induced bed shear stress for the present and future dredging scenarios has been calculated along a transect between dredging Area 448 and the Spurn Peninsula as shown in Figure 7.39. The changes are shown in Table 7.5 a and b below. Graphs have been produced for 10:1 year waves at both high and low water and these are presented in Figure 7.47. The graphs also show the critical bed shear stress required to move the different sediment size fractions that are found on the bed at these locations. Within the dredging areas the bed shear stress is typically low due to the larger water depths at the site (>20m for the present day scenario) and the bed shear stress for the future dredging scenario is slightly reduced compared to present day values at both low and high water. Further inshore there is no apparent difference between the present day and future dredging scenarios.

Table 7.5a Comparison of wave induced bed shear stress at high water (Site 3)

Location	D_{50} (µm)	Present					Future				
		Water Depth	Hs (m)	T(s)	Dir (o)	τ_w N/m²	Water Depth	Hs (m)	T(s)	Dir (o)	τ_w N/m²
a	500	26.2	2.83	5.57	42	0.14	28.6	2.89	5.64	44	0.11
b	500	26.4	2.69	5.39	42	0.10	30.3	2.68	5.37	41	0.04
c	500	23	2.56	5.23	42	0.14	28.5	2.54	5.19	43	0.04
d	500	17.3	2.41	5.09	43	0.39	17.3	2.37	5.02	44	0.35
e	500	12.3	2.26	5.03	44	1.03	12.3	2.23	4.98	44	0.98
f	250	6.9	1.78	4.72	51	1.52	6.9	1.78	4.70	51	1.50

Table 7.5b Comparison of wave induced bed shear stress at high water (Site 3)

Location	D_{50} (µm)	Present					Future				
		Water Depth	Hs (m)	T(s)	Dir (o)	τ_w N/m²	Water Depth	Hs (m)	T(s)	Dir (o)	τ_w N/m²
a	500	21	2.55	5.30	40	0.24	23.4	2.62	5.39	43	0.17
b	500	21.2	2.37	5.01	39	0.14	25.1	2.35	4.98	39	0.05
c	500	17.8	2.17	4.75	40	0.19	23.3	2.15	4.71	41	0.04
d	500	12.1	1.94	4.55	40	0.57	12.1	1.89	4.47	41	0.51
e	500	7.1	1.66	4.45	41	1.69	7.1	1.63	4.39	41	1.62
f	250	1.70	0.44	3.31	67	1.00	1.70	0.44	3.28	67	0.99

7.7.3.3 Summary

Based on the available evidence and the further analysis of the model data presented above, it is considered unlikely that proposed future dredging in the licence Areas off the Spurn Peninsula will produce a measurable or permanent change in sediment mobility inshore. There is therefore good evidence to suggest that the sediment supply to the Lincolnshire coast will be unaffected by the proposed dredging.

7.7.4 Zone 4 Inshore from Area 107 to the North Norfolk Coast

This profile has been selected on the basis of predicted tidal current changes across Docking Shoal and Burnham Flats and the potential impact pathway between Burnham Flats and the North Norfolk Coast.

7.7.4.1 Characterisation of the seabed

Moving seaward from the coast, the nearshore slope dips to 8m depth in Brancaster Road, then rises gradually to Burnham Flats over 3km offshore. Burnham Flats is a sheet of sands and gravelly sands 4-6m thick on till, thickening further towards Docking Shoal at 18km offshore. Bedforms are common on the sheet and these display crests orientated north-northwest to south-southeast. Within Area 107 there are larger bedforms of around 3-4m in height. The seabed north from the coast remains shallow, only dipping into substantially deeper water at 26.5km offshore. Large sandwaves with sharply defined crests characterise dredging area 481 at the northern limit of Docking Shoal. These display northwest to southeast trending crests and southerly orientated lee faces.

7.7.4.2 Current induced seabed mobility

A theoretical grain size distribution points inshore of Area 107 and within the dredging area itself (Points A and D on Figure 7.39) has been calculated based on available information from BGS sediment charts and the more detailed survey data collected for the present study. This has been used to inform calculations of current induced bed shear stress as described above. The variability of bed shear stress is shown for both the present and future dredging scenarios (Figures 7.48 and 7.49). The graphs also show the critical bed shear stress required to mobilise the different grain size fractions found on the bed at this location. The plots show that the current induced bed shear stress in this area is typically low although coarse sand would be mobile during much of the spring tide. Based on the plots shown in Figure 7.48, it is clear that there is virtually no difference in the current induced bed shear stress for the future dredging scenario compared to the present day case. Progressive vector analysis carried out at this location (Figure 7.42) also showed no change in the net potential transport direction (for a spring tide).

The present day bed shear stress within Area 107 (Figure 7.49) is sufficient to mobilise very coarse sands during peak flow conditions. For the future dredging scenario, peak flow speeds and consequently bed shear stress are predicted to decrease compared to the present day. As shown in Figure 7.49, the reduced bed shear stress could affect the mobility of very coarse sands at certain times but overall the general seabed mobility and sediment transport will be unaffected by the proposed dredging. Progressive vector analysis carried out at this location (Figure 7.42) also showed no change in the net potential transport direction (for a spring tide).

7.7.4.3 Wave induced seabed mobility

The wave induced bed shear stress for the present and future dredging scenarios has been calculated along a transect between dredging Area 107 and the North Norfolk Coast as shown in Figure 7.39. The changes are shown in Table 7.6 a and b below. Graphs have been produced for 10:1 year waves at both high and low water and these are presented in Figure 7.50. As for the tidal current plots the graphs also show the critical bed shear stress required to move the different sediment size fractions that are found on the bed at these locations. The plots show that over the dredging areas themselves the bed shear stress is typically very low due to the large water depth compared to the wave height. There is no difference between the future dredging scenario and the present day at either high or low water. Further inshore the water depths are very shallow but as the waves are also very small as a result of energy dissipation across Burnham flats the resultant bed shear stress is also fairly low. There is no apparent difference between the present day and future dredging scenarios.

Table 7.6a Comparison of wave induced bed shear stress at high water (Site 4)

Location	D_{50} (µm)	Present					Future				
		Water Depth	Hs (m)	T(s)	Dir (o)	τ_w N/m^2	Water Depth	Hs (m)	T(s)	Dir (o)	τ_w N/m^2
a	300	25.3	2.29	4.86	41	0.03	25.3	2.24	4.80	42	0.02
b	300	20.3	2.13	4.74	41	0.07	24.5	2.13	4.73	41	0.02
c	300	11.1	2.02	4.68	40	0.68	11.1	2.01	4.67	40	0.68
d	300	8.3	1.80	4.57	39	1.12	8.3	1.79	4.56	39	1.11
e	300	8.0	1.60	4.32	39	0.88	8.0	1.60	4.30	40	0.87
f	300	8.0	1.45	3.78	41	0.47	8.0	1.45	3.78	41	0.47

Table 7.6b Comparison of wave induced bed shear stress at low water (Site 4)

Location	D_{50} (µm)	Present					Future				
		Water Depth	Hs (m)	T(s)	Dir (o)	τ_w N/m²	Water Depth	Hs (m)	T(s)	Dir (o)	τ_w N/m²
a	300	20.1	1.81	4.06	36	0.01	20.1	1.77	4.01	36	0.01
b	300	15.1	1.53	3.74	31	0.02	19.3	1.52	3.74	31	0.00
c	300	5.9	1.38	3.46	37	0.77	5.9	1.37	3.44	38	0.75
d	300	3.1	0.87	2.91	41	1.12	3.1	0.87	2.90	43	1.11
e	300	2.8	0.66	2.02	47	0.25	2.8	0.66	2.02	47	0.25
f	300	2.8	0.67	2.07	50	0.29	2.8	0.67	2.07	50	0.29

7.7.4.4 Summary

Based on the further analysis of the model data presented above, there is good evidence to suggest that the proposed dredging in Area 107 will produce no measurable or permanent change in sediment mobility inshore. It is concluded that neither the Burnham Flats and Docking Shoal sandbanks, nor the sediment supply to the North Norfolk coast from offshore would be affected by the proposed future dredging.

7.7.5 Combined Sediment Mobility

In addition to determining the effects of dredging on seabed mobility due to waves and tidal currents in isolation, potential changes to total sediment mobility (i.e. that arising from the bed shear stress exerted by waves and currents combined) have also been assessed.

7.7.5.1 Spatial extent of changes to combined bed shear stress

To enable the calculation of changes to seabed sediment mobility under the combined effects of waves and tidal currents, it is necessary to determine the extent of changes to bed shear stress. Given the inherent complexities associated with the calculation and representation of combined bed shear stress, defining a theoretical 'worst case scenario' is not straightforward. For the purposes of this assessment the scenario to be tested will comprise a 10:1 year wave from the NE with peak flood tidal currents. These parameters were selected because they combine to produce a worst case set of circumstances. The NE wave is the largest for the chosen return period and furthermore this wave direction is almost the same as that of the peak flood current. This means that the bed shear stress generated by the wave and current will be additive, (rather than opposing if the wave and current directions were different) and therefore produces the largest combined stress on the bed. The probability of this wave condition coinciding with peak current speeds is small and hence the combined shear stress will be commonly less than predicted here.

To determine the extent of changes to the combined shear stress, the wave and flow models have been run for the present day and future dredging scenarios. The outputs have been subject to further analysis based upon standard empirical techniques (Soulsby, 1997) to demonstrate the spatial extent of changes. The analyses have been carried out for a range of sediment sizes from medium to very coarse-grained sand. The different grain-size fractions are considered because the sediment size affects bed roughness, which is a key factor in the calculation of bed shear stress. The sediment sizes are considered independently as the model does not permit the representation of variable, poorly sorted seabed sediments. Results show changes between present day and future dredging scenarios in terms of absolute values in N/m^2 and percentages relative to the present day bathymetry (Figures 7.51 to 7.53). It should be noted that the results show changes to bed shear stress and not sediment mobility. The effects of the proposed future dredging on combined wave/current sediment mobility have been subject to further analysis and are discussed in Section 7.7.5.2.

The results presented in Figures 7.51 to 7.53 demonstrate that for all sediment sizes, changes to the combined bed shear stress (both positive and negative) are confined to within the licence areas and their immediate vicinities. The most widespread effects are predicted inshore of Areas 197 and 493 although the magnitude of these changes is relatively small and the changes do not extend to the coast. Changes in absolute values outside all the licence areas range from -0.5 to + 0.5 N/m^2, which is in all cases less than 10% of present day values. As described above, those areas for which changes in combined shear stress have been predicted have been subject to more detailed, location specific analysis to determine how the proposed future dredging would affect combined sediment mobility.

7.7.5.2 Effects of proposed future dredging on combined sediment mobility

This assessment has considered the total effects on seabed mobility of the modelled tidal currents combined with a 10:1 year NE wave condition. The total bed shear stress has been calculated using standard empirical techniques (Soulsby, 1997). Due to the inherent complexities of representing non-linear processes, it has been necessary to make a number of simplifications and assumptions, as described below.

In order to be conservative, it has been assumed that the 10:1 year wave condition occurs throughout the tidal cycle. This obviously results in an over estimation of the total bed shear stress as waves are episodic and would not occur continuously in this way.

The wave height in shallow water varies with water depth and therefore with tidal state. As described in the previous section, the waves were found to exert the least and greatest influence on bed shear stress at high water and low water respectively. For the purposes of the present assessment the 10:1 year wave heights at LW and HW have been used as the representative wave conditions and have both been applied throughout the tidal cycle. Whilst this does not provide a realistic representation of wave behaviour through a whole tidal cycle it ensures that the minimum and maximum bed shear stress values are captured and that the actual bed shear stress at any time will be between these values.

Data has been extracted from the numerical model at three locations (b, d, and f) on each of the transects (1 - 4) shown in Figure 7.39b. These locations were chosen to represent the combined bed shear stress within the licence areas and to demonstrate the extent of any changes closer inshore. The results of the combined seabed mobility assessment are presented in Figures 7.54 to 7.57 and are described in more detail below.

7.7.5.3 Zone 1 inshore from Area 493 to the Lincolnshire Coast

As shown in Figure 7.54 the total peak bed shear stress is reduced by up to 0.5N/m^2. In terms of actual seabed mobility, the graph for location b1 at the boundary of the licence area shows only a slight reduction in the mobility for very coarse sand (in terms of the percentage of the tidal cycle for which this size fraction is mobile). However, given that at this location very coarse sand is predicted to be mobilised during at least half the tidal cycle during both the baseline and post dredging scenarios the reduction in combined bed shear stress is unlikely to result in a measurable change to sediment transport processes. The mobility of other sediment size fractions is unaffected by the proposed dredging.

Inshore from the licence area there is virtually no change in total bed shear stress and hence sediment mobility. This shows that the cumulative effects of dredging on combined wave and current induced seabed mobility are limited to within the licence area boundaries and do not extend to the coast.

7.7.5.4 Zones 2 and 3 inshore from Area 448 to Spurn and the Lincolnshire Coast

The results of the bed shear stress calculations for these zones are presented in Figures 7.55 and 7.56. These show a similar pattern of change to Zone 1 with a reduction in total bed shear stress within the licence area (locations b2 and b3) and little or no change further inshore. Overall, the seabed mobility either within or inshore from this cluster of licence areas is not expected to change as a result of the proposed future dredging.

7.7.5.5 Zone 4 inshore from Area 107 to the North Norfolk Coast

As shown in Figure 7.57 the total bed shear stress within Area 107 is predicted to decrease compared to the baseline and at certain times during the spring tidal cycle coarse sand would no longer be mobilised. However, the threshold of motion for this size fraction is still frequently exceeded and it is concluded that the dredging would not significantly affect sediment transport through this area. Closer inshore, the total bed shear stress and hence sediment mobility are not predicted to change relative to baseline values.

7.7.5.6 Summary

Having examined the cumulative effects of aggregate dredging on combined wave and current induced sediment mobility at a number of locations the results show that in spite of a slight reduction in the mobility of coarser sediments within the licence areas (in terms of persentage mobility during the spring tidal cycle), overall seabed mobility would be unaffected. It is also important to note that the assessment of combined sediment mobility was conservative in that it assumed a 10:1 year wave event continued throughout a spring tidal cycle. Therefore it is concluded that the proposed dredging would not affect the contemporary sediment transport regime either within the licence areas or closer inshore.

8. Effects on Designated Features

A large number of protected sites have been established within the Humber MAREA study area including both national and international designations. This reflects the level of ecological diversity across the region, including the seabed, the coast, estuaries and wetlands; many of which support populations of internationally important species. Sites within the study area which are protected by European and national designations were described in the baseline characterisation (ABPmer, 2011). These included five SACs, one Candidate SAC, five SPAs and four Ramsar sites along with numerous coastal SSSIs. Of particular interest to the present study is the Inner Dowsing, Race Bank and North Ridge cSAC, which has been scheduled for designation to provide protection for the important, permanently submerged sandbanks and biogenic *Sabellaria spinulosa* reefs, which are found in the area. As shown in Figure 8.1 a number of existing licence areas and application areas lie either within or adjacent to the cSAC boundary and it is therefore necessary to demonstrate that the predicted changes to the waves and currents will not have a detrimental effect on the interest features. This issue will be covered in more detail elsewhere in the MAREA but a high level overview is provided here, which will inform the subsequent assessment.

The results of the wave and tidal modelling studies presented in Section 7 show that apart from some minor flow speed variations (<0.05m/s) near the north western boundary, the cSAC features would be unaffected by the proposed dredging. Furthermore, as the predicted changes to waves do not extend to the coast, it is concluded that none of the coastal designations would be affected by the proposed dredging either.

9. Conclusions

The overall aim of this study was to provide a regional scale assessment of the cumulative impacts of past and future aggregate dredging, which will inform both the renewal process for existing licences and applications for dredging in new areas. The study has used a combination of state-of-the-art numerical modelling, established analytical techniques and expert judgement to determine the effect of all previous and proposed future dredging on waves, tidal currents and sediment mobility. The principal conclusions are presented below.

9.1 Past Dredging

The modelling carried out to examine the effects of previous dredging showed that the total extraction to data has had a negligible effect on the most extreme wave events considered. Changes to the tidal currents were largely restricted to a single licence area and these were confined to within the area itself or to the immediate vicinity. No interactions between dredging areas were identified for either waves or tidal currents and it is concluded that previous dredging in the Humber Region has not affected waves or tidal currents along the coast or around the major sedimentary features within the study area.

9.2 Future Dredging

The numerical modelling showed that over much of the study area the waves and tidal currents would be unaffected by the proposed future dredging. Critically no changes in tidal currents of significance to sediment mobility were predicted at the coast even for the most extreme conditions tested. For the most part the predicted changes to wave heights were restricted to within the dredging areas and the immediate vicinity. Under certain scenarios changes to waves were predicted to extend from dredging areas situated closest to the shore to the coast. However, the absolute magnitude of change was of the order of a few centimetres, which is almost certainly within the natural variability of the wave in question. Furthermore the length of coastline affected was less than 100m and it was therefore concluded that the wave changes would not produce an adverse effect on the coast. More detailed analysis was carried out for those areas for which larger or more widespread changes were predicted to determine whether modifications the waves or tidal currents would affect seabed morphology or sediment transport. This showed that even for the largest changes in wave height there would be little or no difference in seabed mobility compared to the present situation. Consequently it is concluded that the proposed future dredging in the Humber Region will not result in adverse effects on any of the physical processes receptors identified in the baseline assessment.

10. References

ABPmer 2005. Humber Strategy Implementation Study Model Design and Calibration. ABP Marine Environmental Research Ltd, Report No. R.1143.

ABPmer, 2011. Humber MAREA: Physical Processes Study - Baseline Characterisation. ABP Marine Environmental Research Ltd, Report No. R.1820

Cefas, 2008. Regional Environmental Assessment: A Framework for the Marine Minerals Sector. Centre for Environment, Fisheries and Aquaculture Scienc19pp

CIRIA. 1998. Regional seabed sediment studies and assessment of marine aggregate dredging. Construction Industry Research and Information Association, C505.

HR Wallingford, 2002. Southern North Sea Sediment Transport Study, Phase 2. Report produced for Great Yarmouth Borough Council by HR Wallingford, CEFAS/UEA, Posford Haskoning and Dr Brian D'Olier. HR Wallingford Report EX 4526.

HR Wallingford, 2010. Thames Estuary Dredging Association MAREA: Tidal Flows and Sediment Transport Study.

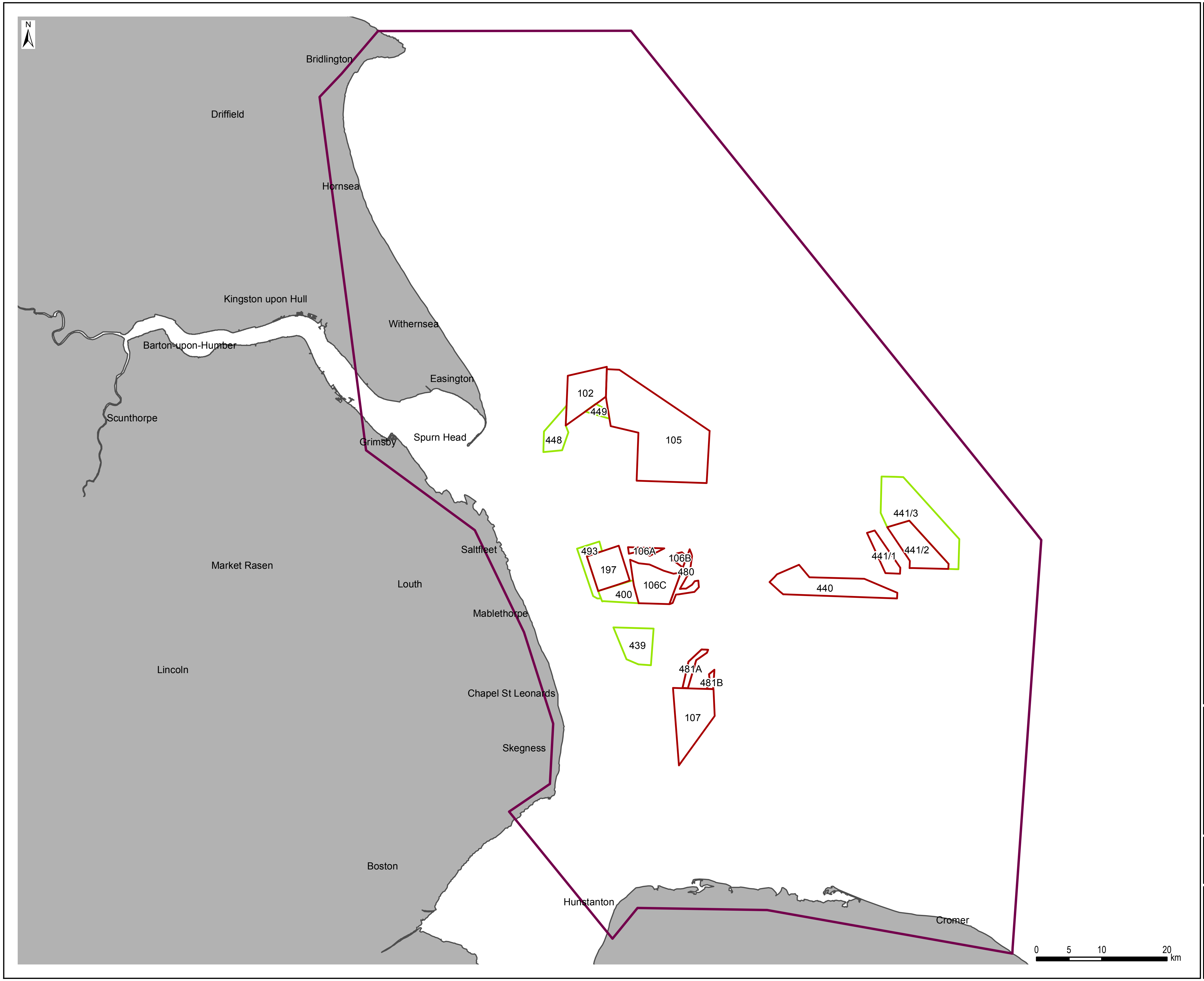
INSPIRE, 2009 rev. Metadata Implementing Rules: Technical Guidelines based on EN ISO 19115 and EN ISO 19119 - European Commission Joint Research Centre, MD_IR_and_ISO_20090218, Revised 2009.

Moeini & Etemad-Shahidi, 2007. Application of two numerical models for wave hindcasting in Lake Erie. Applied Ocean Research, Volume 29, Issue 3, July 2007, Pages 137-145.

Soulsby, R. L. 1997. Dynamics of Marine Sands. Thomas Telford.

The Crown Estate. www.thecrownestate.co.uk

Figures



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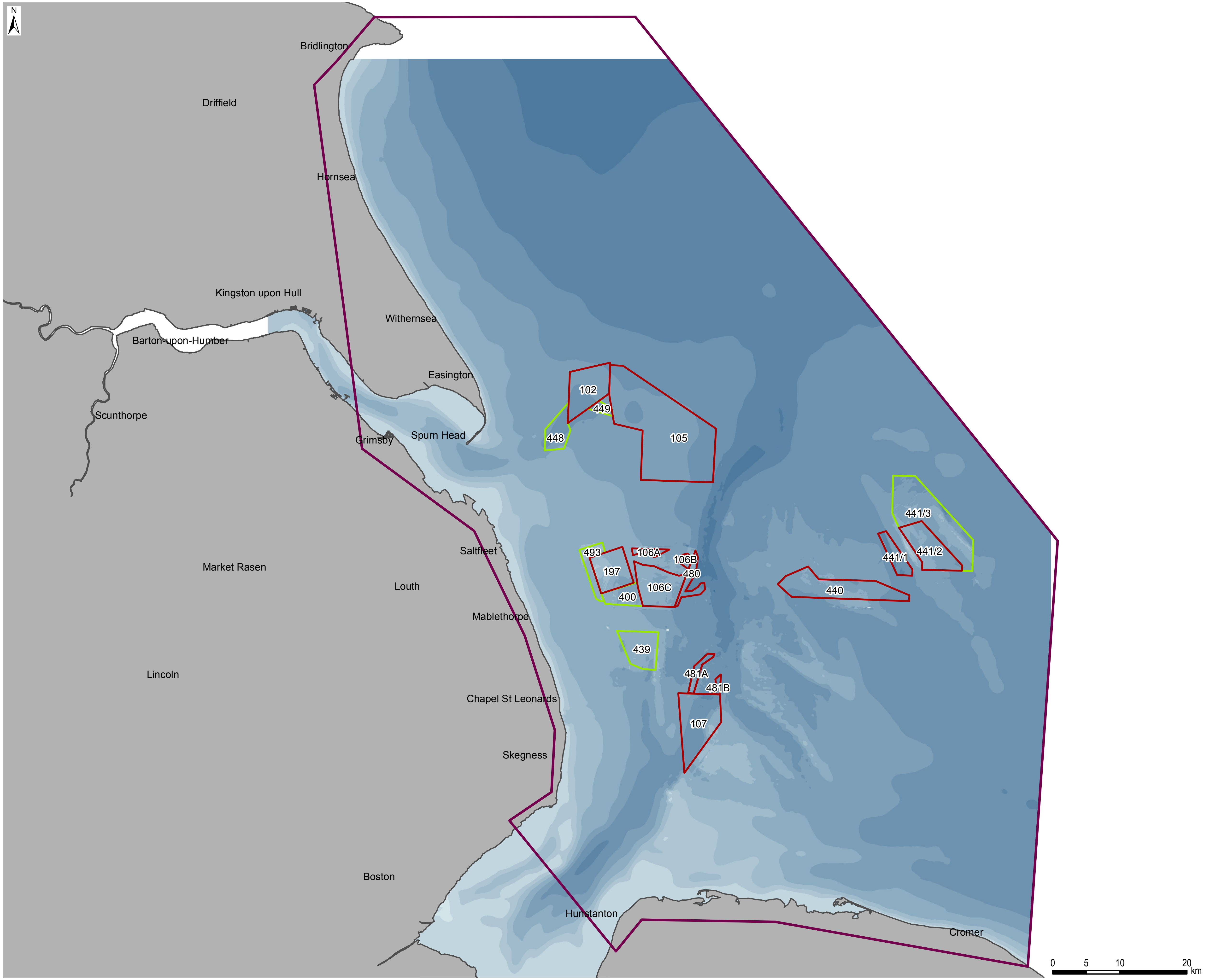
Humber MAREA Study Area and Licence Areas

Figure 2.1



MAREA Study Area
Licence Area
Application Area
Present Day Bathymetry
m-CD
>100
-70--100
-50--70
-30--50
-30--20
-15--20
-10--15
-7--10
-5--7
-2--5
0--2

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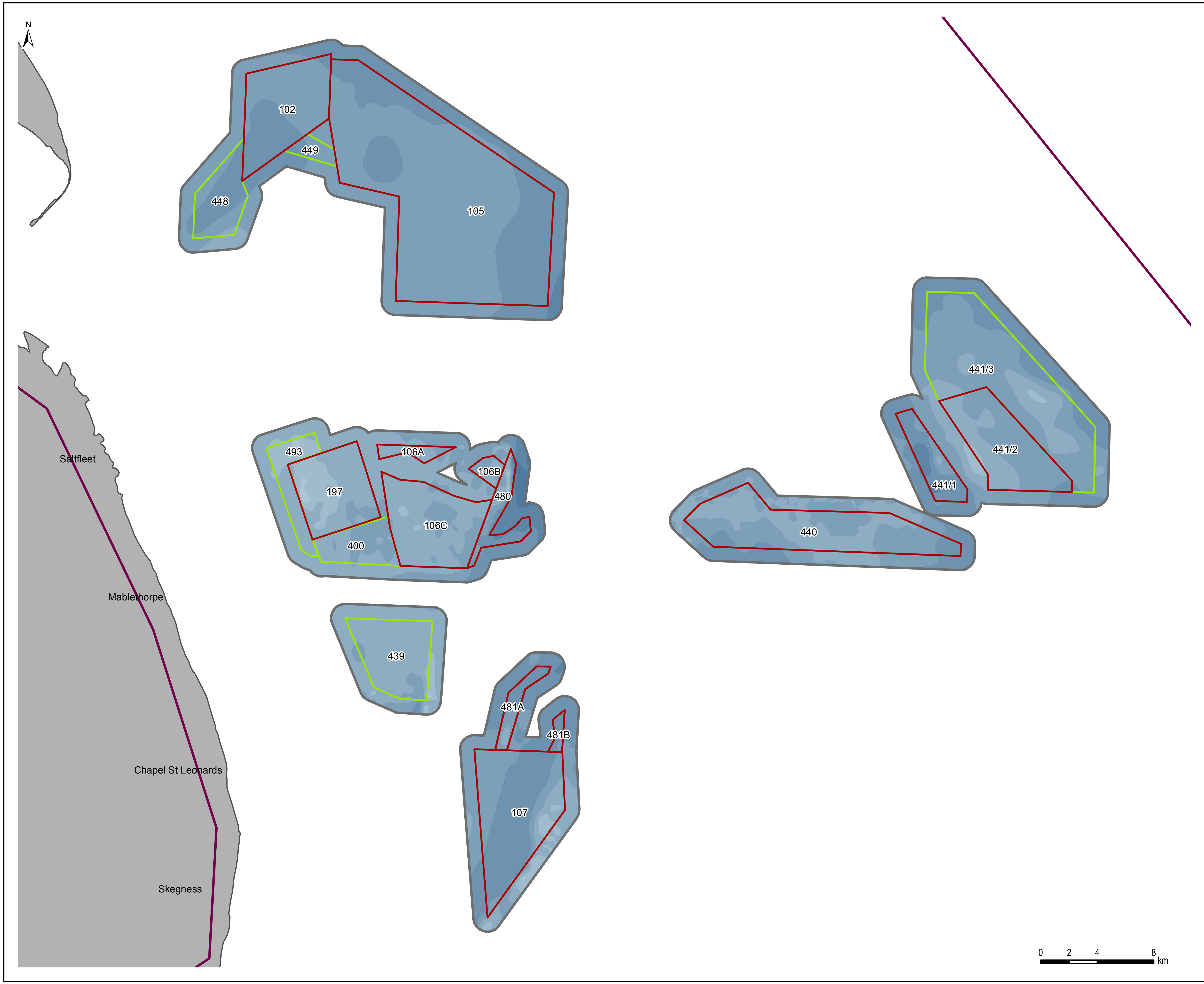
Bathymetry

Figure 3.1



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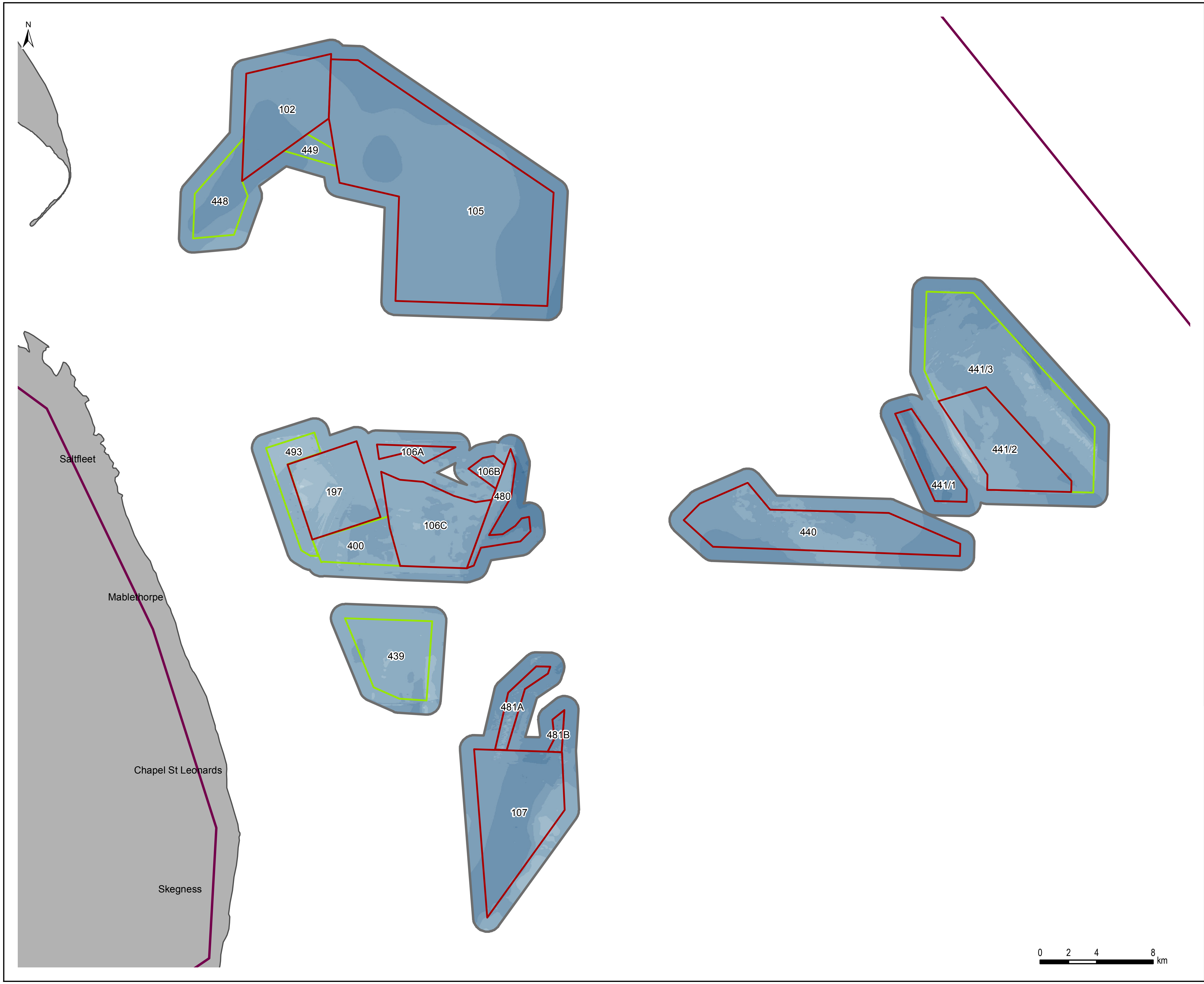
Pre-dredging Bathymetry

Figure 3.2



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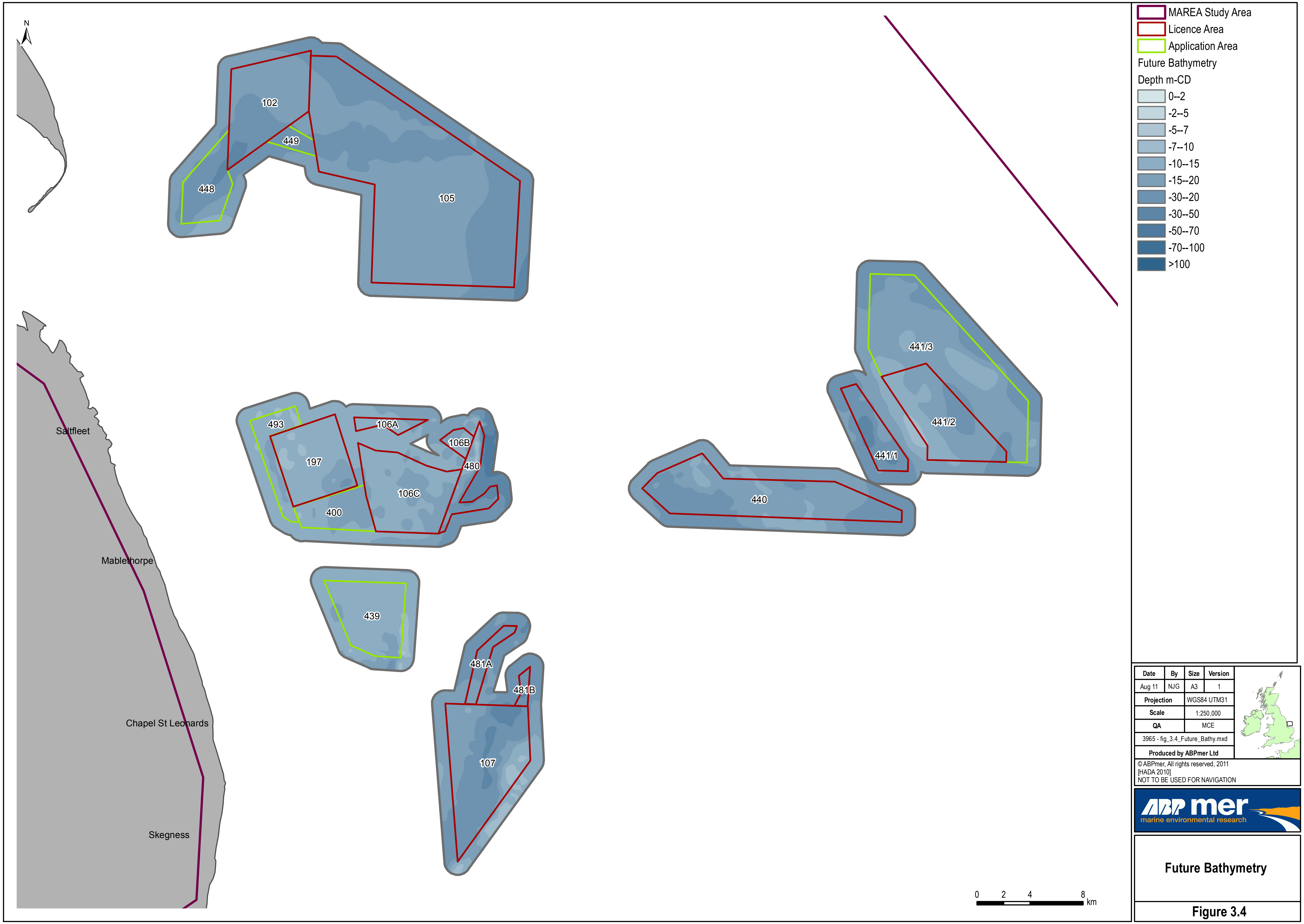
Present Day Bathymetry

Figure 3.3



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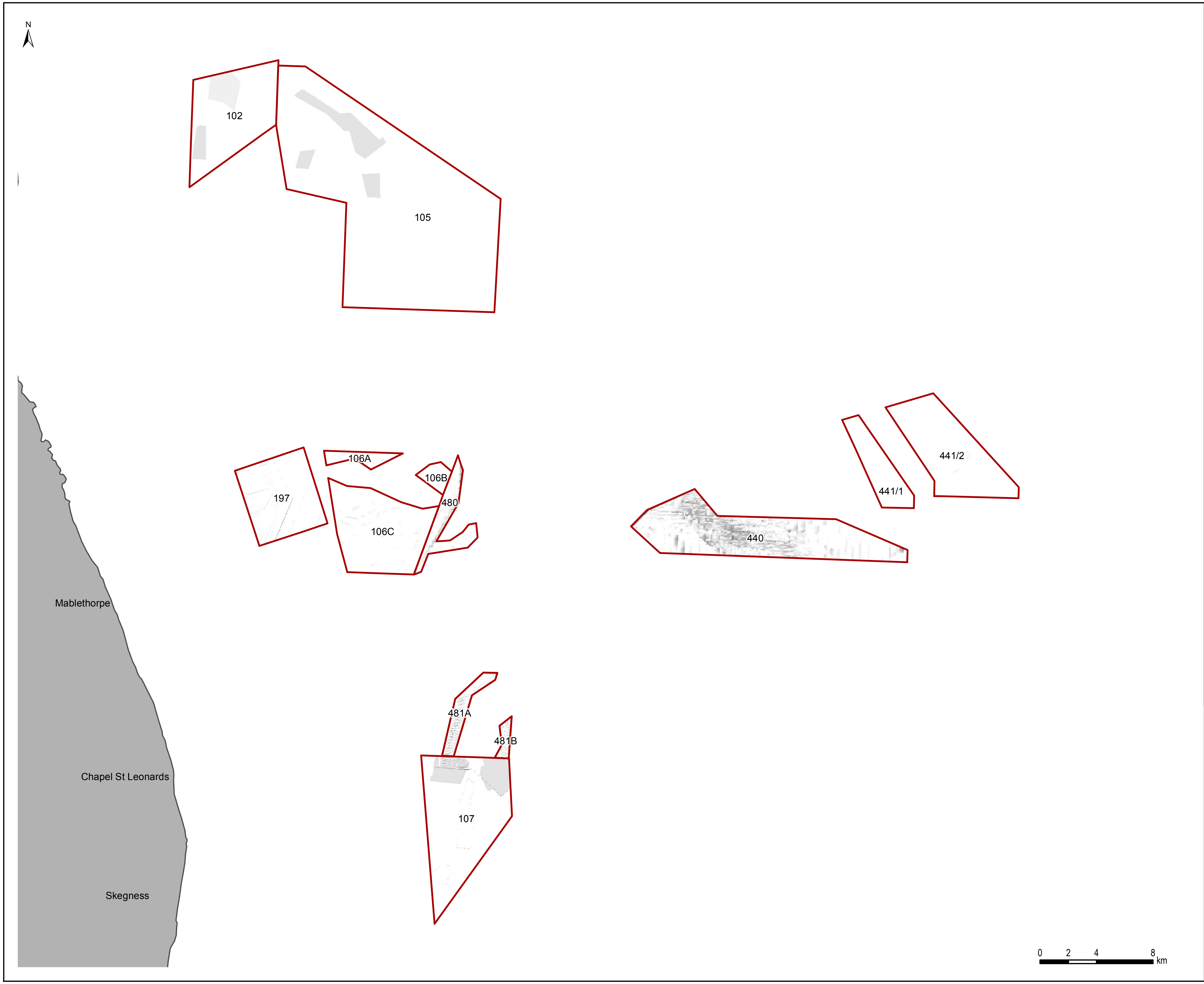
Future Bathymetry

Figure 3.4



Licence Area

Predredge to Present Day Bathymetry Depth Change (m)

<0.2
0.2-0.5
0.5-1
1-1.5
1.5-2
2-2.5
2.5-3
3-3.5
3.5-4
4-4.5
4.5-5
5-5.5
5.5-6
6-6.5
6.5-7

Date	By	Size	Version
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Projection		WGS84 UTM31	
Scale		1:250,000	
QA		NMW	

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Produced by ABPmer Ltd

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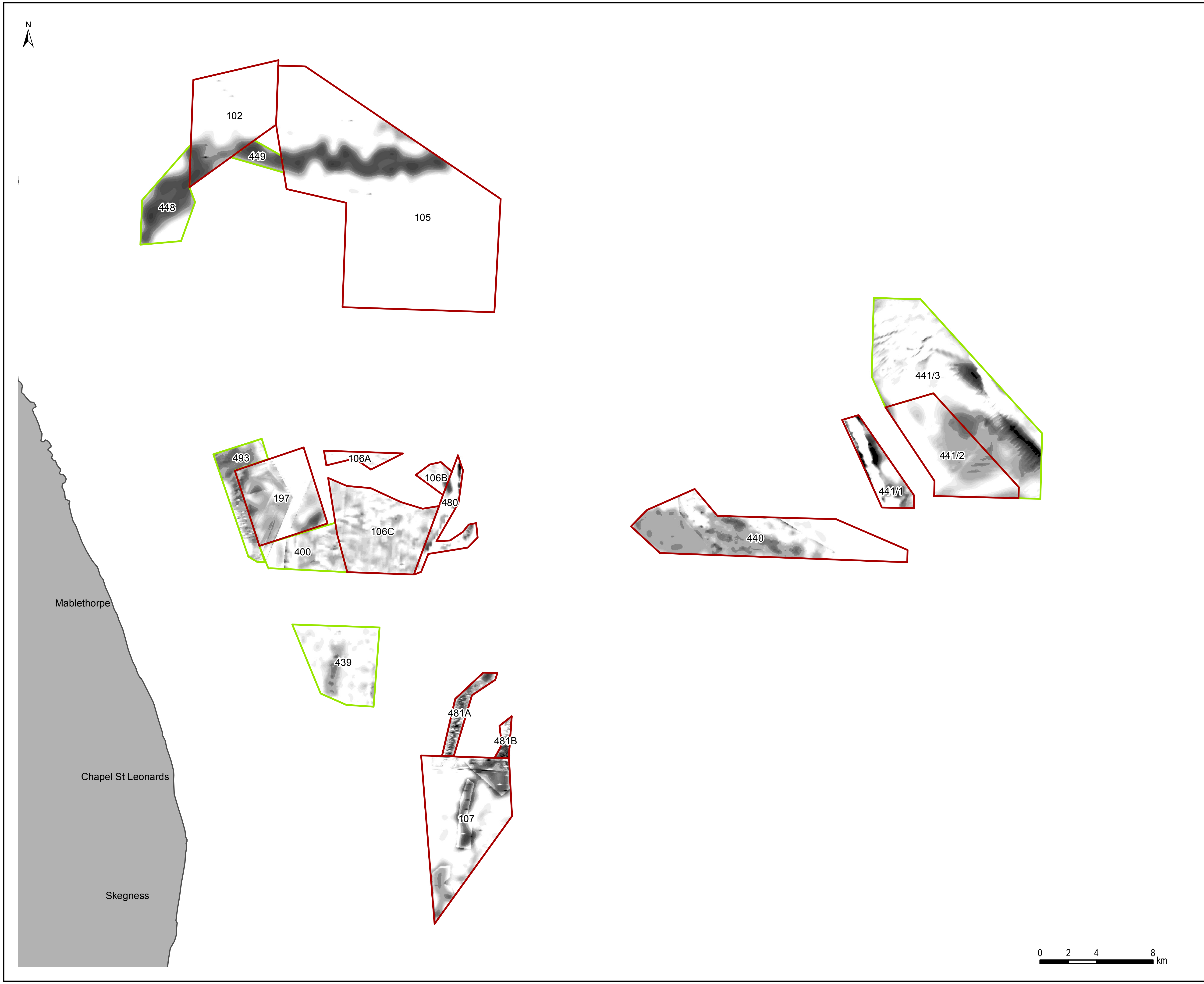
Predredge to Present Day Difference Plot

Figure 3.5



Licence Area
Application Area
Present Day to Future Bathymetry Depth Change (m)

- <0.2
- 0.2-0.5
- 0.5-1
- 1-1.5
- 1.5-2
- 2-2.5
- 2.5-3
- 3-3.5
- 3.5-4
- 4-4.5
- 4.5-5
- 5-5.5
- 5.5-6
- 6-6.5
- 6.5-7

Date	By	Size	Version
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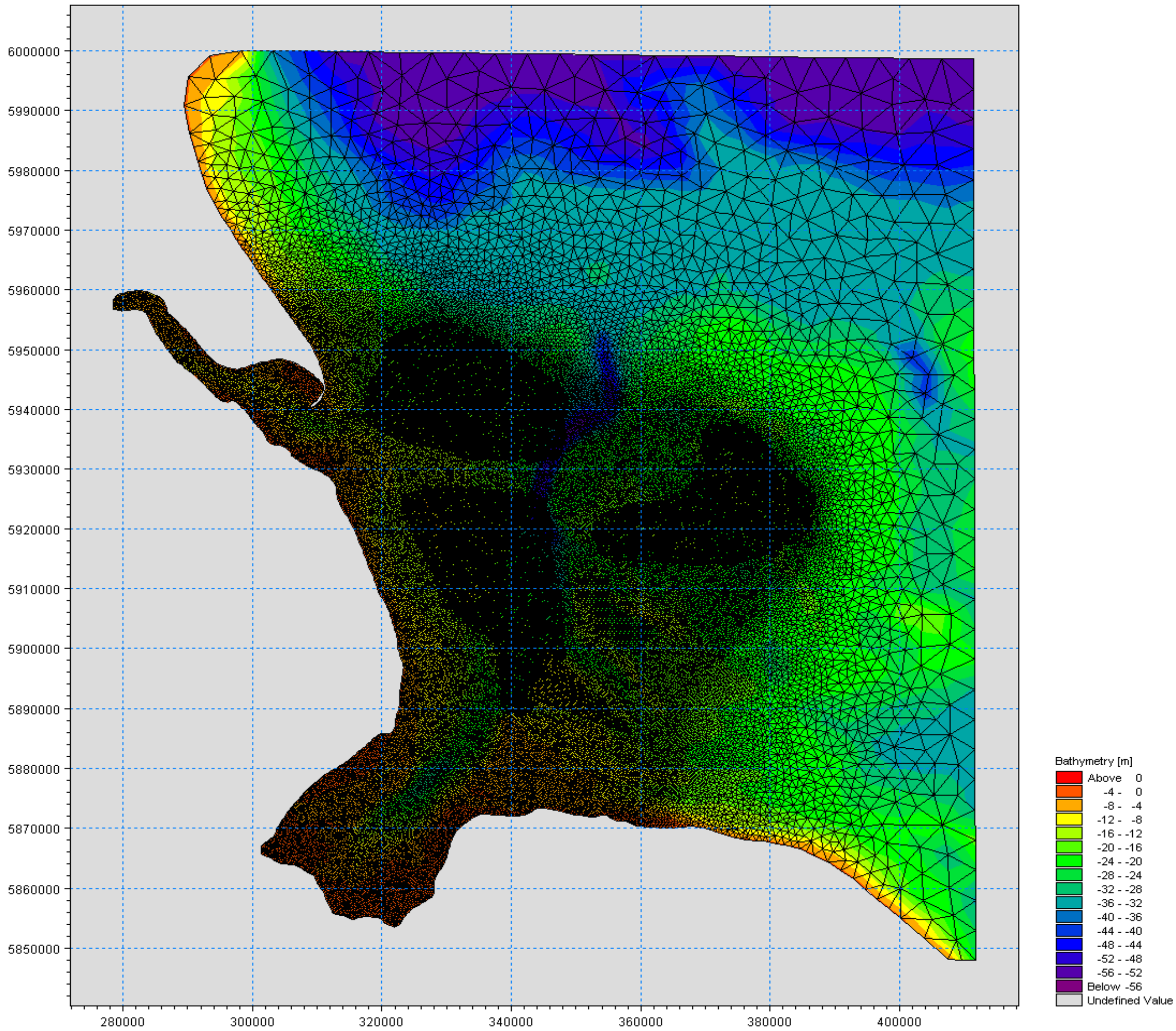
Present Day to Future Difference Plot

Figure 3.6



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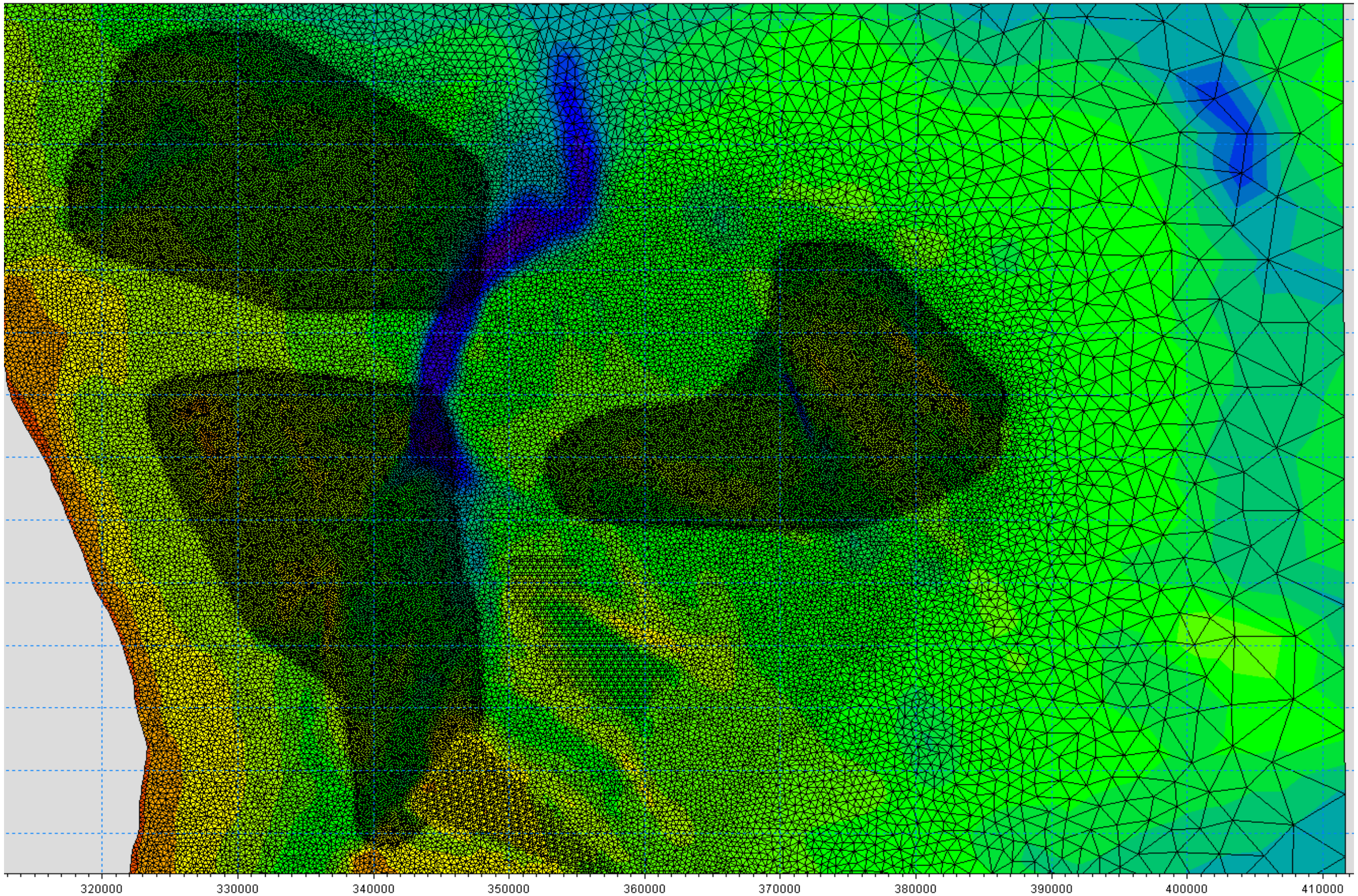
Model Domain

Figure 5.1



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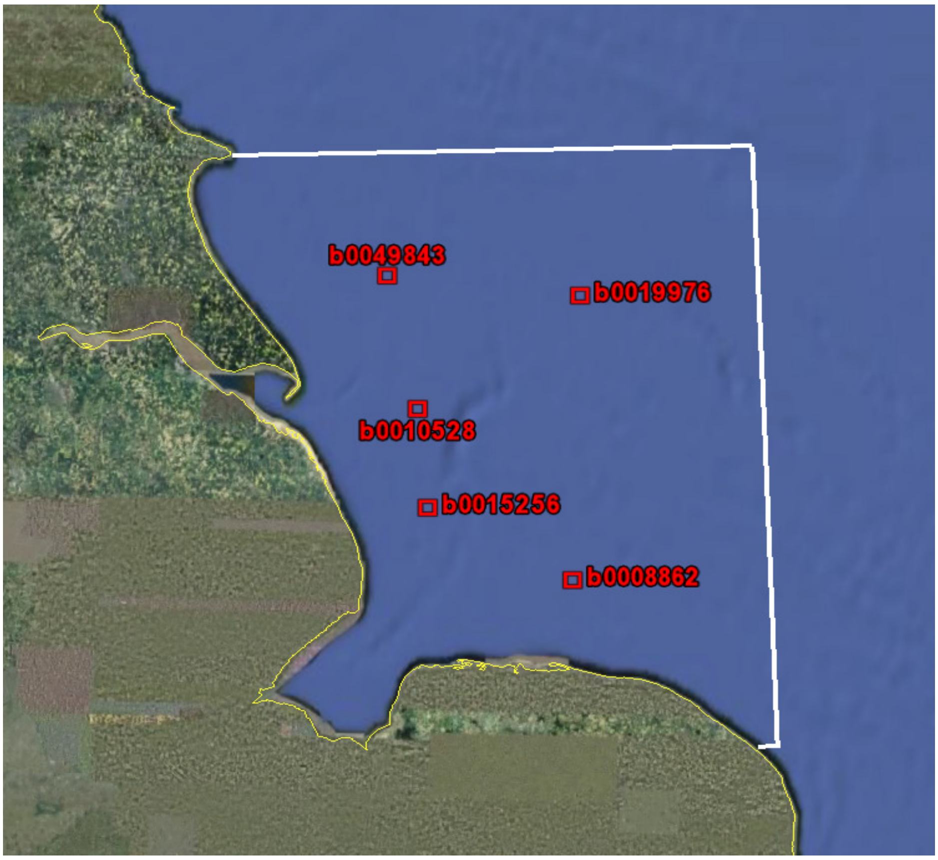
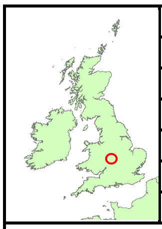
Mesh Resolution

Figure 5.2





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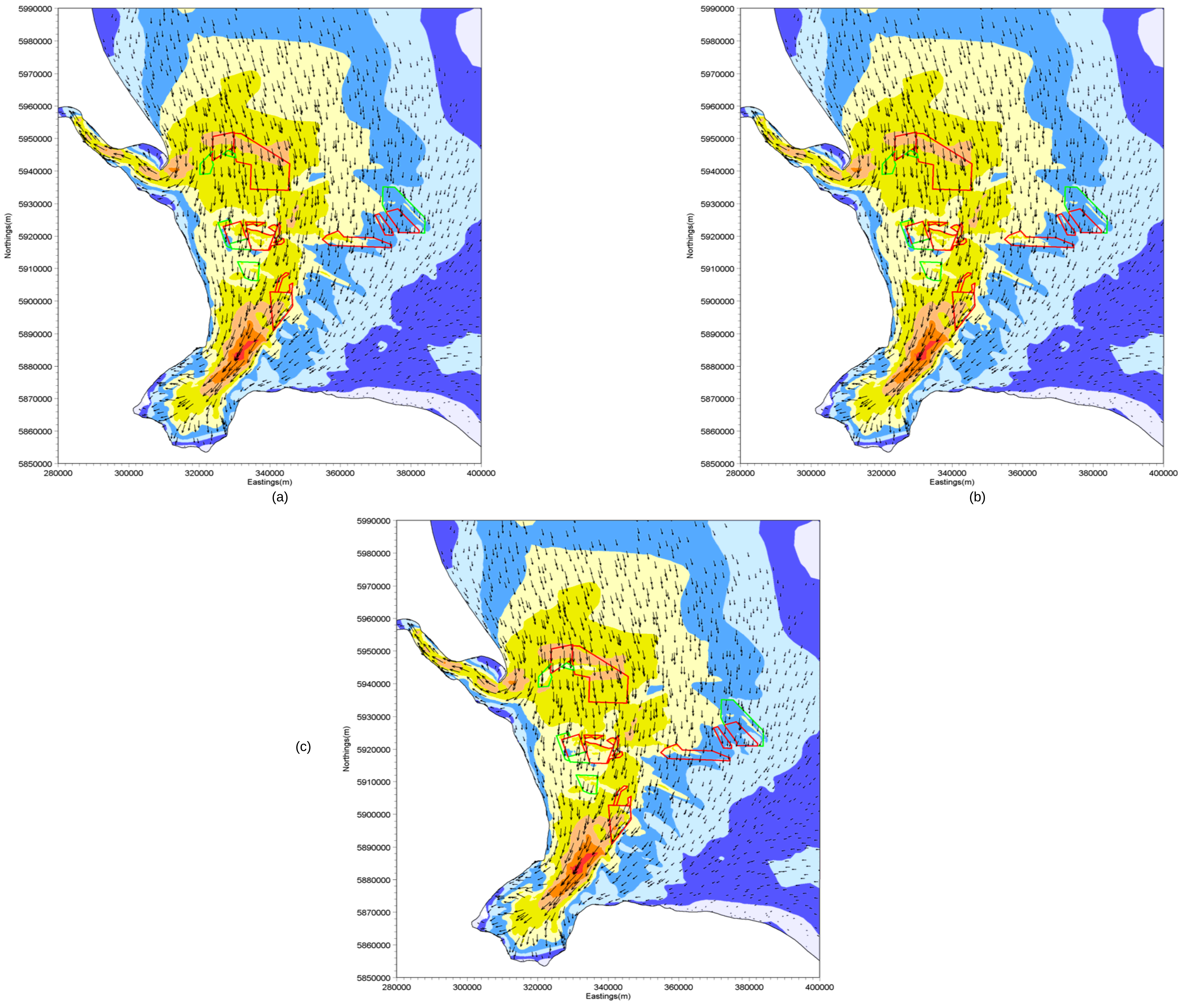
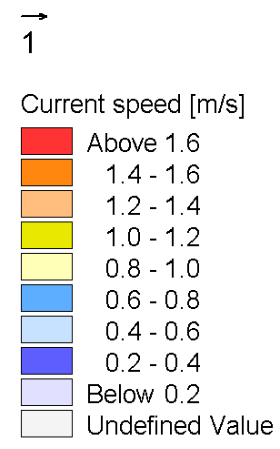
Sources of Calibration Data for Water Levels and Currents

Figure 5.3





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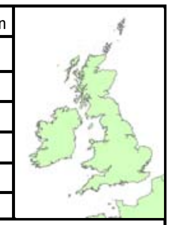

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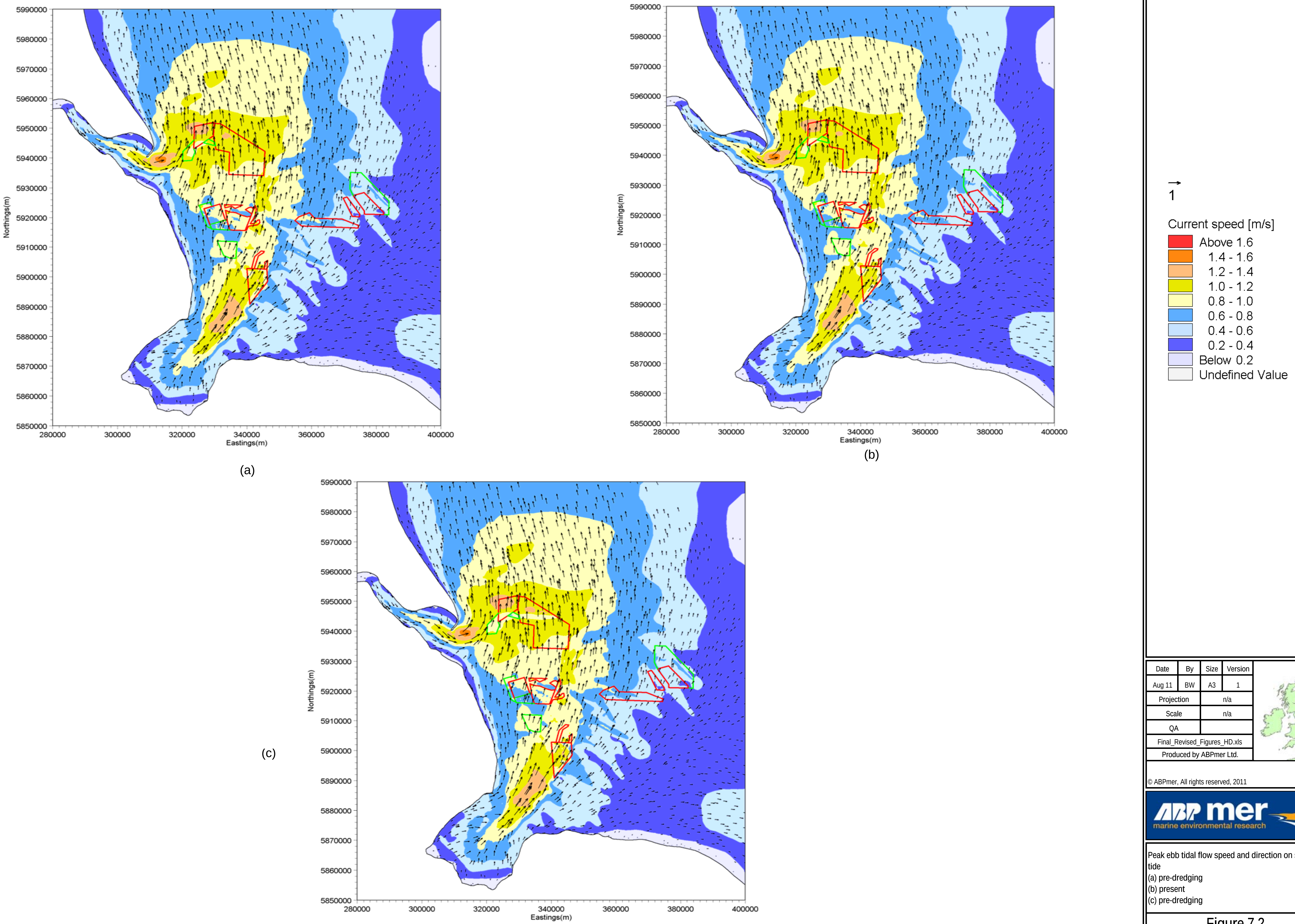
Peak flood tidal flow speed and direction on spring tide
(a) pre-dredging
(b) present
(c) future

Figure 7.1



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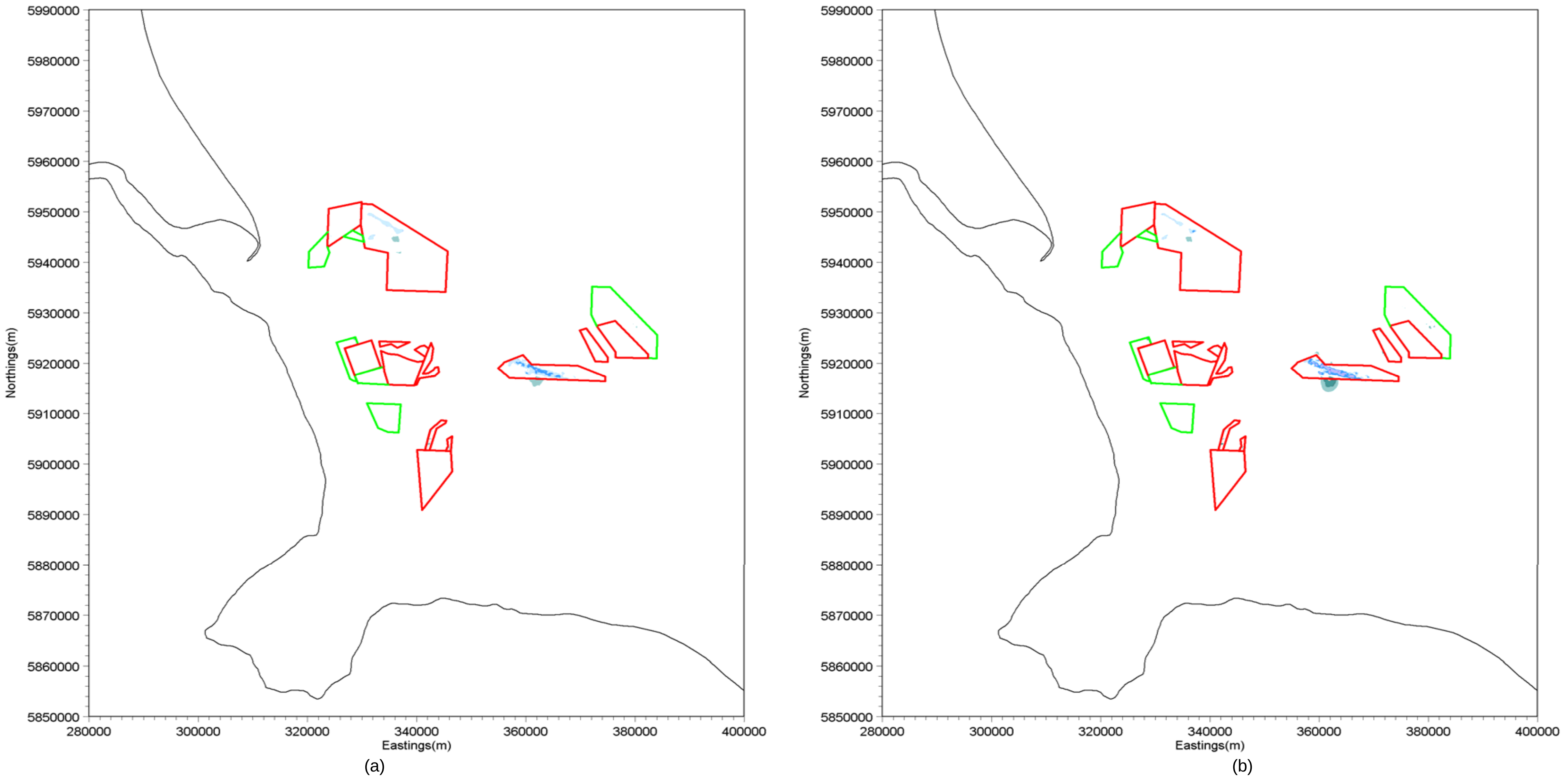
Peak ebb tidal flow speed and direction on spring tide
(a) pre-dredging
(b) present
(c) pre-dredging

Figure 7.2



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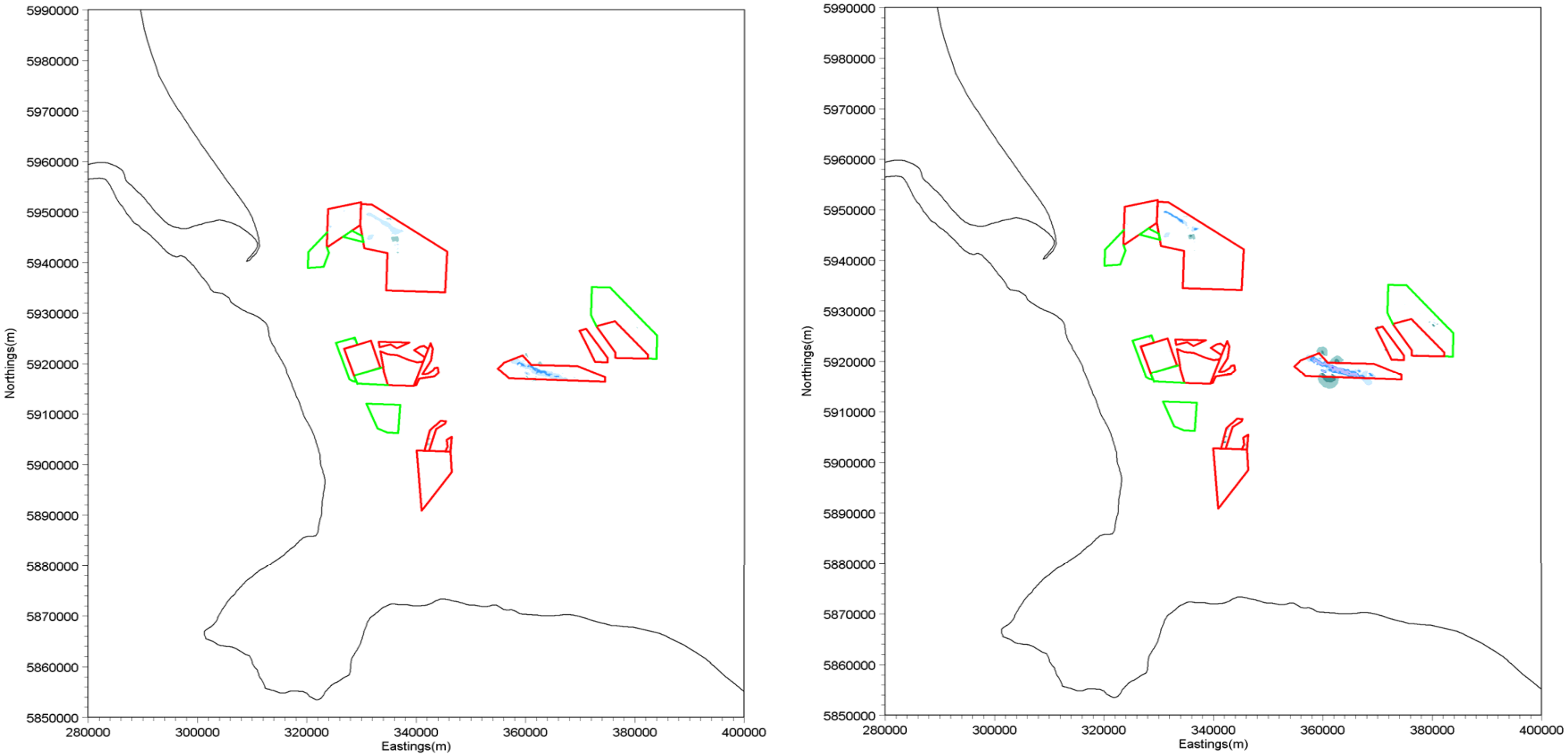
Change in peak flood flow speed on spring tide (present minus pre-dredging)
(a) absolute values (b) percentages

Figure 7.3



(a) (b)

Change in Flow Speed [m/s]

Above	0.25
0.20 -	0.25
0.15 -	0.20
0.10 -	0.15
0.05 -	0.10
0.02 -	0.05
-0.02 -	0.02
-0.05 -	-0.02
-0.10 -	-0.05
-0.15 -	-0.10
-0.20 -	-0.15
-0.25 -	-0.20
Below	-0.25
Undefined Value	

Change in Flow Speed [%]

Above	20
15 -	20
10 -	15
5 -	10
3 -	5
2 -	3
-2 -	2
-3 -	-2
-5 -	-3
-10 -	-5
-15 -	-10
-20 -	-15
Below	-20
Undefined Value	

Date	By	Size	Version
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QA			

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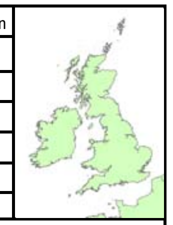

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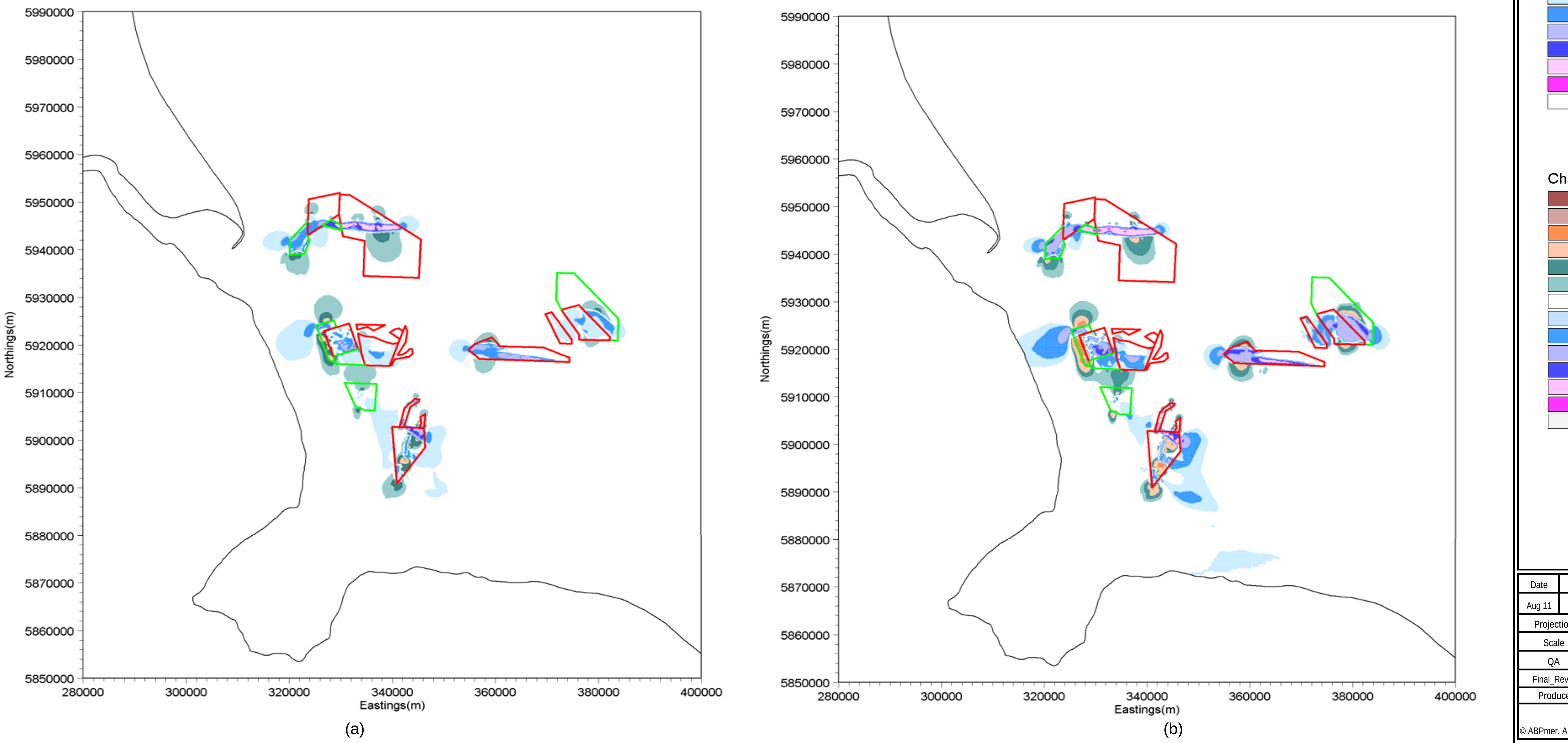
Change in peak ebb flow speed on spring tide (present minus pre-dredging)
(a) absolute values (b) percentages

Figure 7.4



Change in Flow Speed [m/s]

- Above 0.25
- 0.20 - 0.25
- 0.15 - 0.20
- 0.10 - 0.15
- 0.05 - 0.10
- 0.02 - 0.05
- -0.02 - 0.02
- -0.05 - -0.02
- -0.10 - -0.05
- -0.15 - -0.10
- -0.20 - -0.15
- -0.25 - -0.20
- Below -0.25
- Undefined Value

Change in Flow Speed [%]

- Above 20
- 15 - 20
- 10 - 15
- 5 - 10
- 3 - 5
- 2 - 3
- -2 - 2
- -3 - -2
- -5 - -3
- -10 - -5
- -15 - -10
- -20 - -15
- Below -20
- Undefined Value

Date	By	Size	Version
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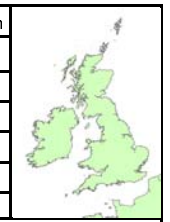
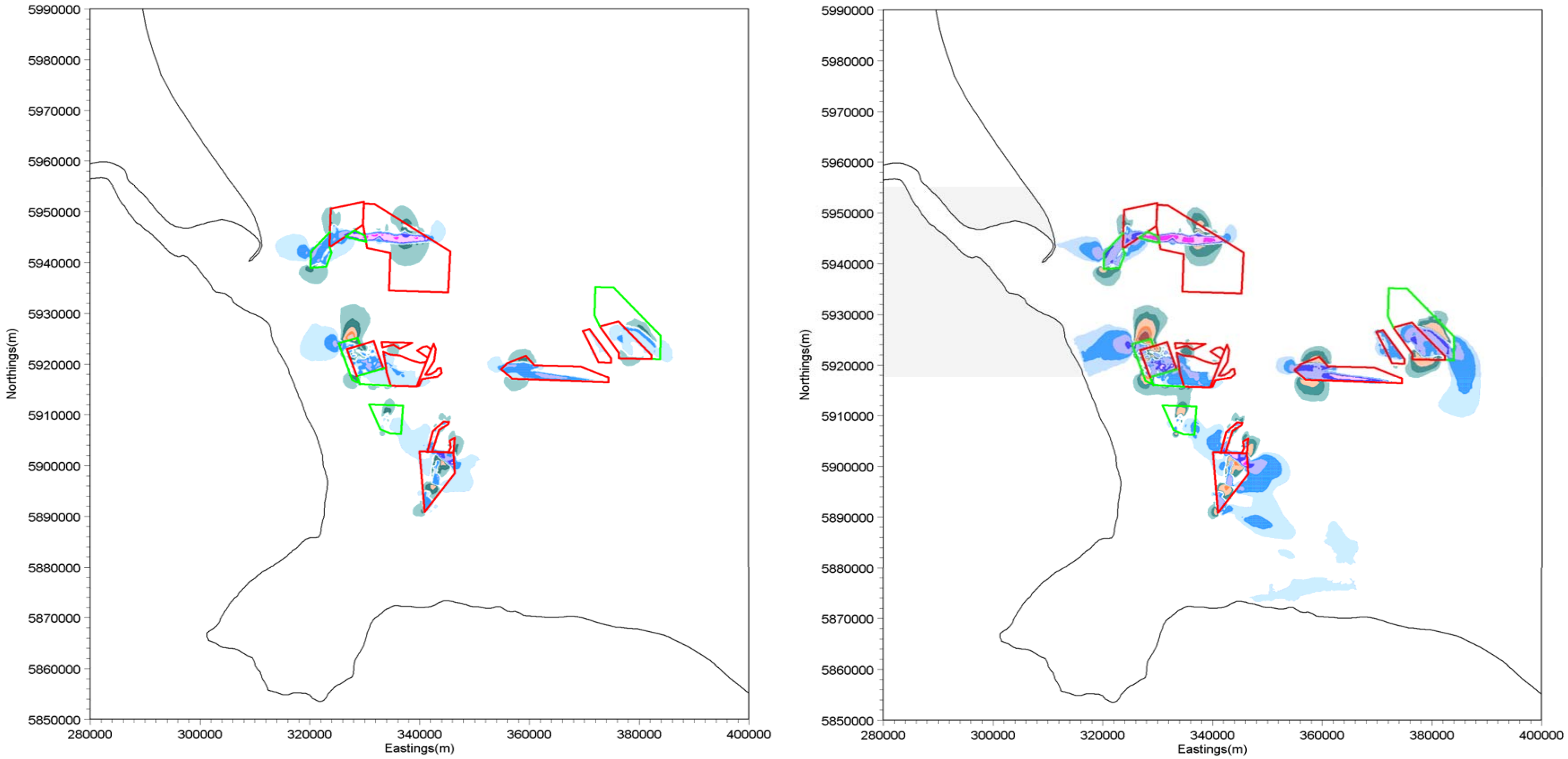


Change in peak flood flow speed on spring tide (future minus present)
(a) absolute values (b) percentages

Figure 7.5



(a) (b)

Change in Flow Speed [m/s]

- Above 0.25
- 0.20 - 0.25
- 0.15 - 0.20
- 0.10 - 0.15
- 0.05 - 0.10
- 0.02 - 0.05
- -0.02 - 0.02
- -0.05 - -0.02
- -0.10 - -0.05
- -0.15 - -0.10
- -0.20 - -0.15
- -0.25 - -0.20
- Below -0.25
- Undefined Value

Change in Flow Speed [%]

- Above 20
- 15 - 20
- 10 - 15
- 5 - 10
- 3 - 5
- 2 - 3
- -2 - 2
- -3 - -2
- -5 - -3
- -10 - -5
- -15 - -10
- -20 - -15
- Below -20
- Undefined Value

Date	By	Size	Version
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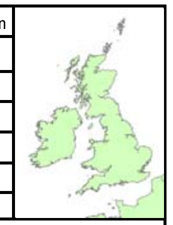

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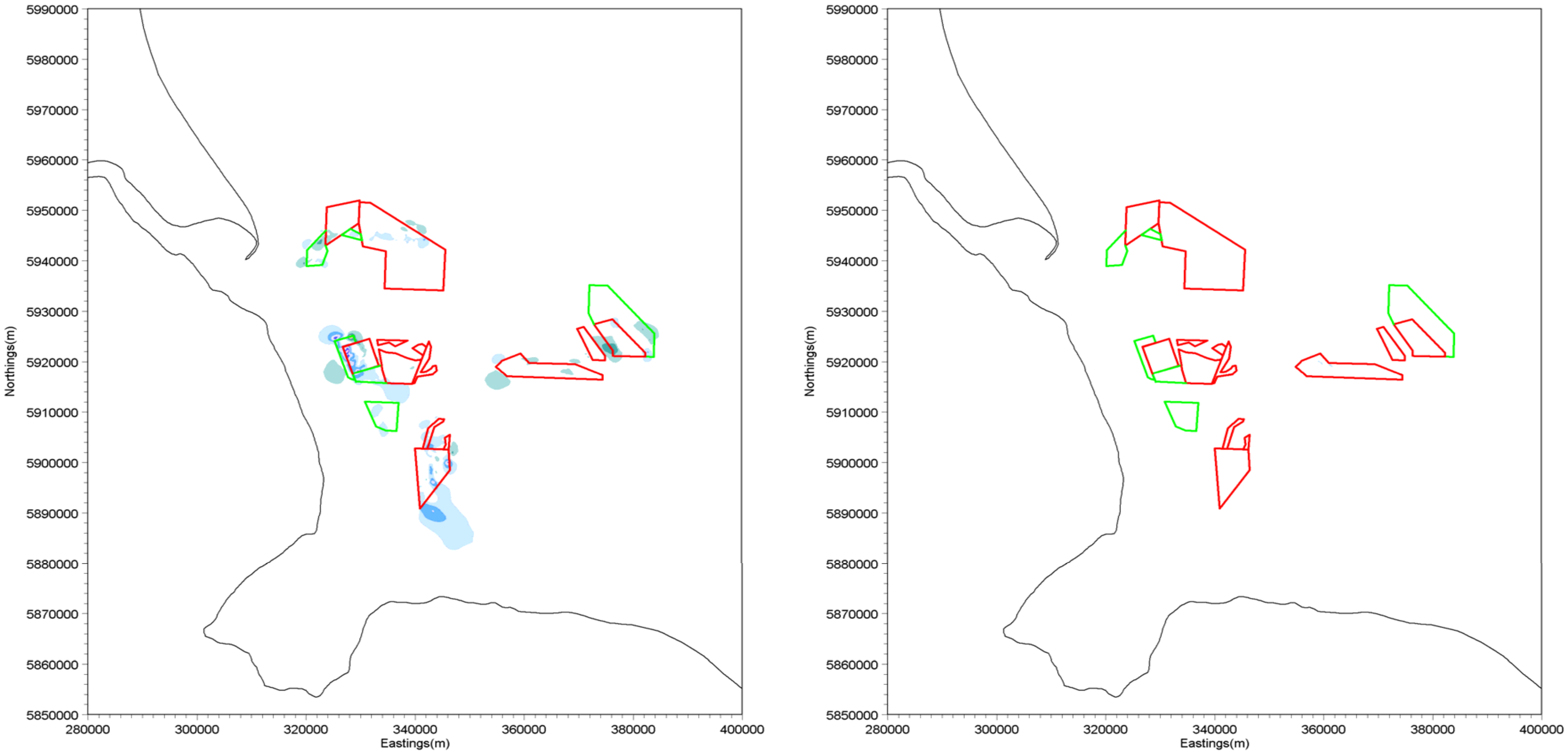
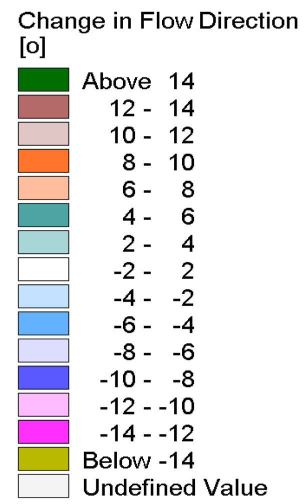
Change in peak ebb flow speed on spring tide (future minus present)
(a) absolute values (b) percentages

Figure 7.6



(a)

(b)



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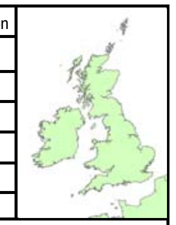

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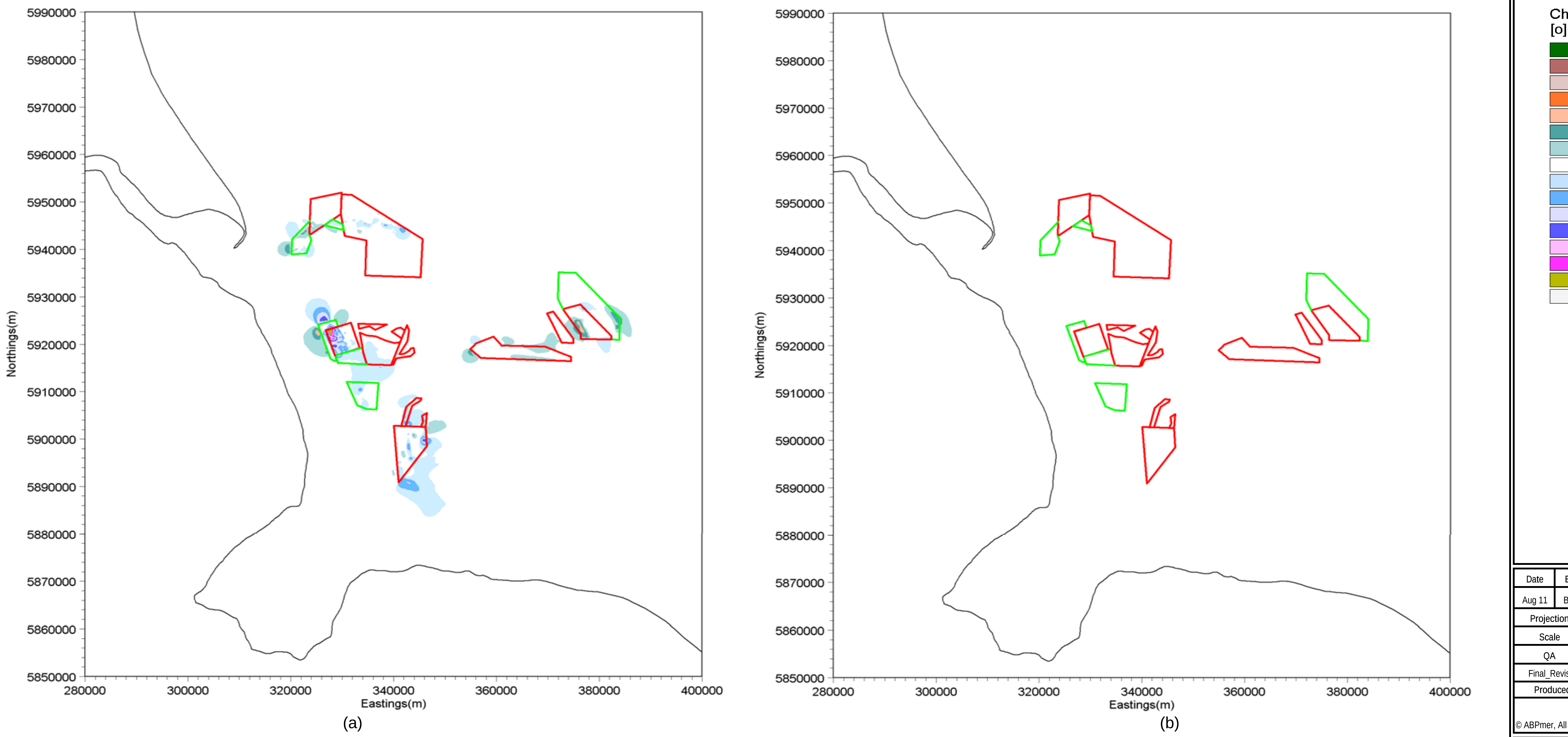
Change in peak flood flow direction on spring tide
(a) future minus present
(b) present minus pre-dredging

Figure 7.7



Change in Flow Direction [o]

Above	14
12 -	14
10 -	12
8 -	10
6 -	8
4 -	6
2 -	4
-2 -	2
-4 -	-2
-6 -	-4
-8 -	-6
-10 -	-8
-12 -	-10
-14 -	-12
Below	-14
Undefined Value	

Date	By	Size	Version
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Projection		n/a	
Scale		n/a	
QA			
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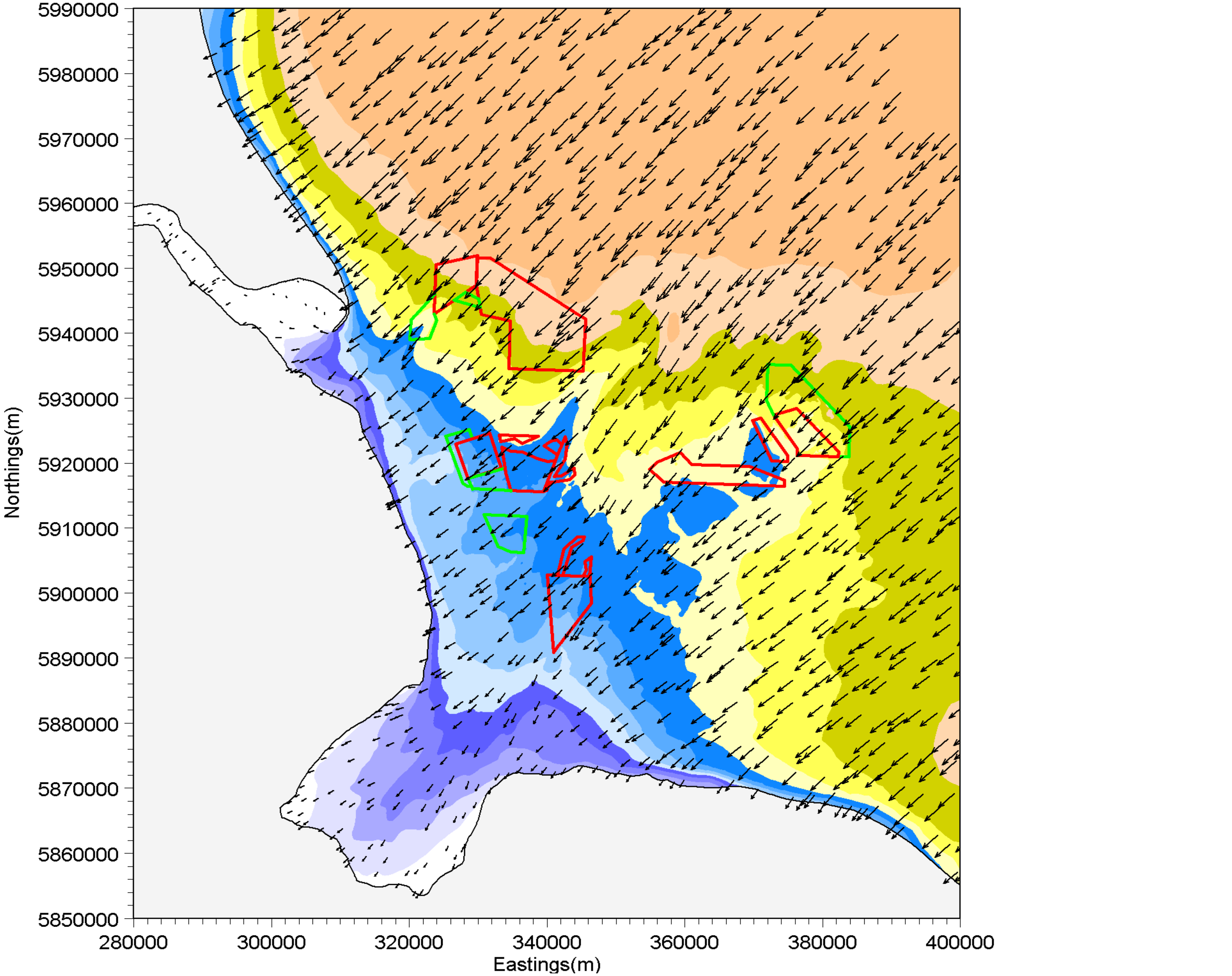
Change in peak ebb Flow direction on spring tide
(a) future minus present
(b) present minus pre-dredging

Figure 7.8



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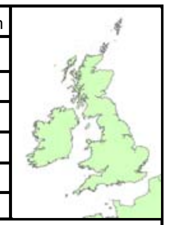

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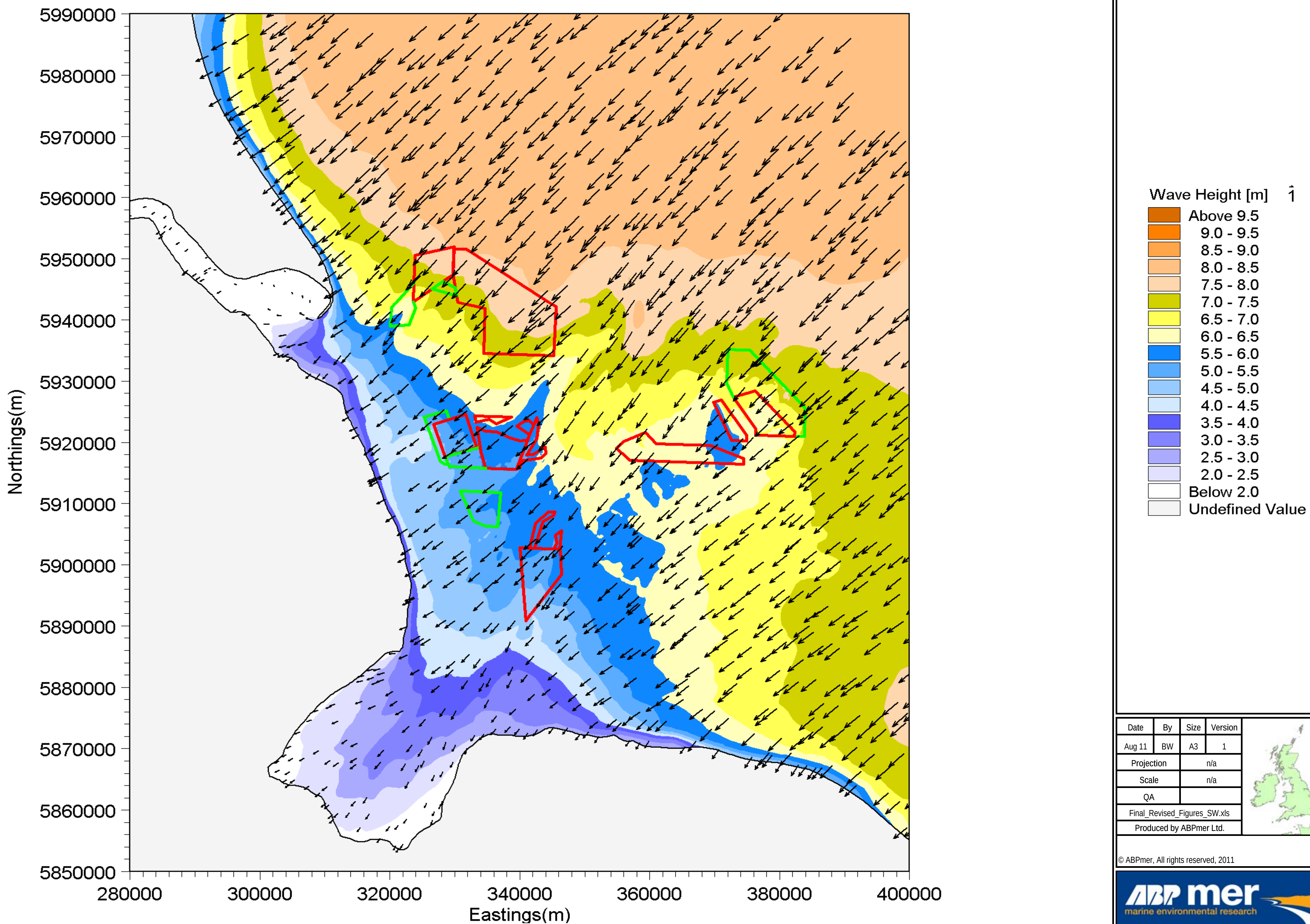
Wave height and direction at MHWS for 1 in 200yr NE wave (pre-dredging)

Figure 7.9



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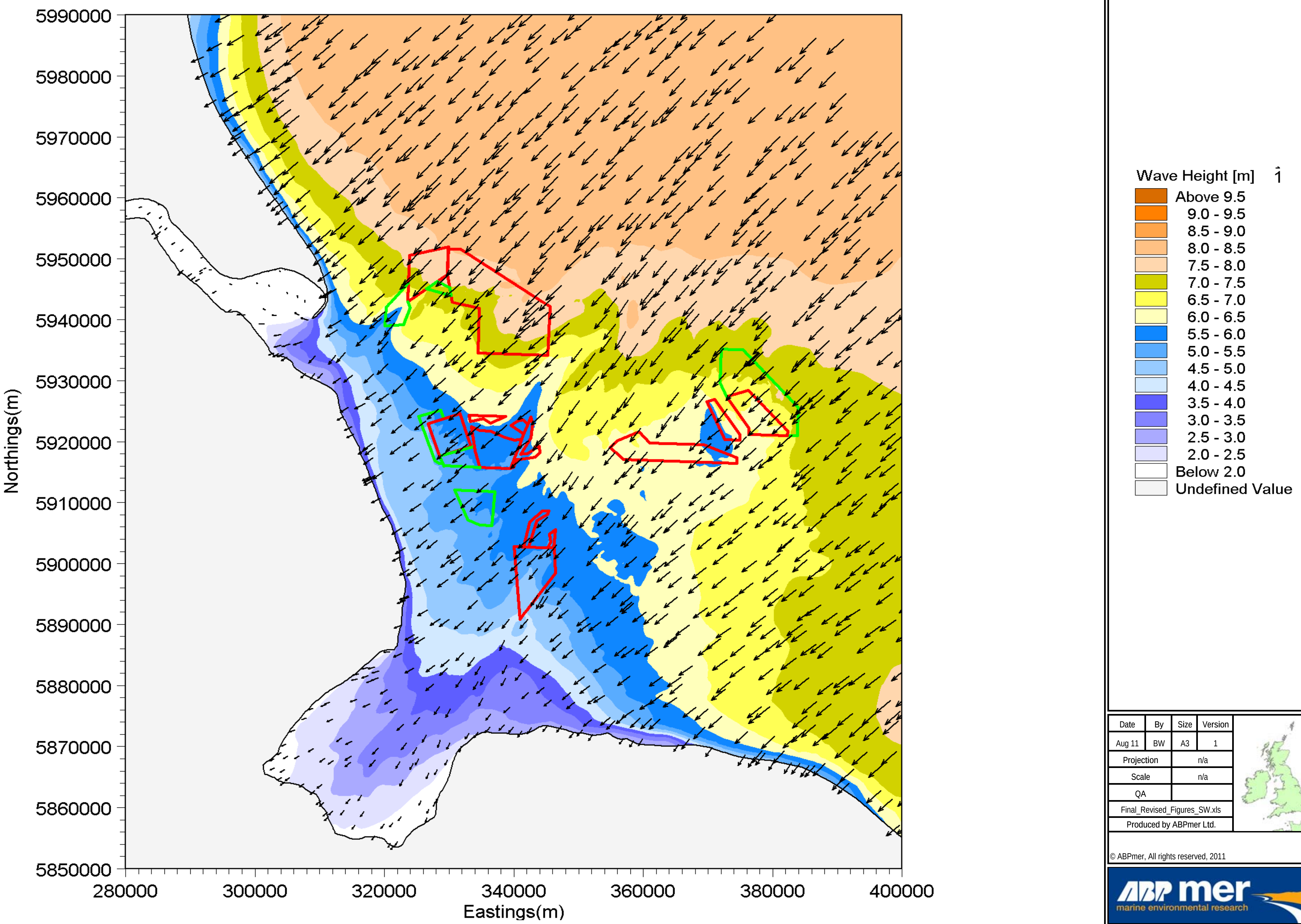
Wave height and direction at MHWS for 1 in 200yr NE wave (present)

Figure 7.10



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Projection		n/a	
Scale		n/a	
QA			

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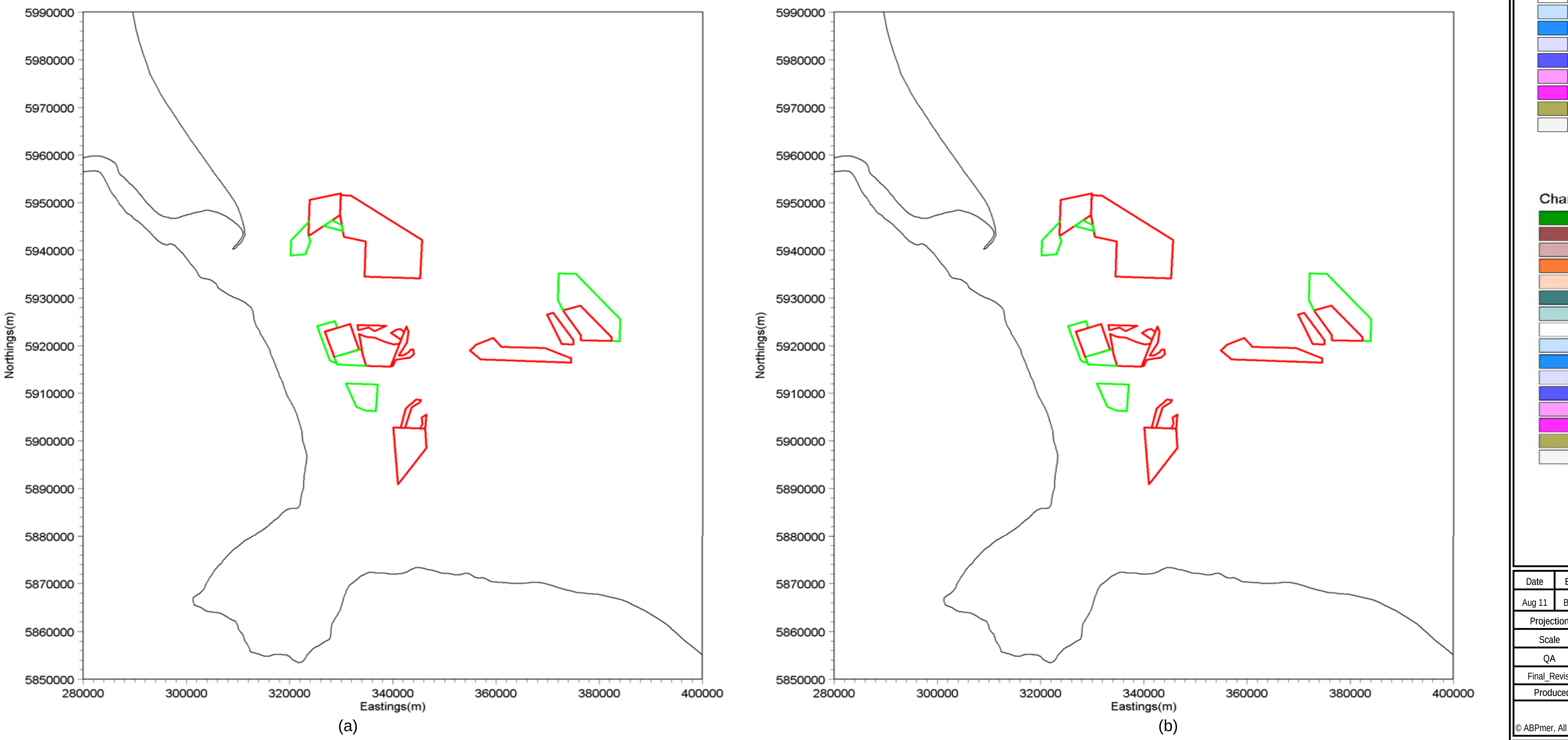
Wave height and direction at MHWS for 1 in 200yr NE wave (future)

Figure 7.11



Change in Wave Height [m]

- Above 0.7
- 0.6 - 0.7
- 0.5 - 0.6
- 0.4 - 0.5
- 0.3 - 0.4
- 0.2 - 0.3
- 0.1 - 0.2
- -0.1 - 0.1
- -0.2 - -0.1
- -0.3 - -0.2
- -0.4 - -0.3
- -0.5 - -0.4
- -0.6 - -0.5
- -0.7 - -0.6
- Below -0.7
- Undefined Value

Change in Wave Height [%]

- Above 25
- 20 - 25
- 15 - 20
- 10 - 15
- 5 - 10
- 3 - 5
- 2 - 3
- -2 - 2
- -3 - -2
- -5 - -3
- -10 - -5
- -15 - -10
- -20 - -15
- -25 - -20
- Below -25
- Undefined Value

Date	By	Size	Version
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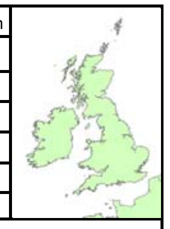

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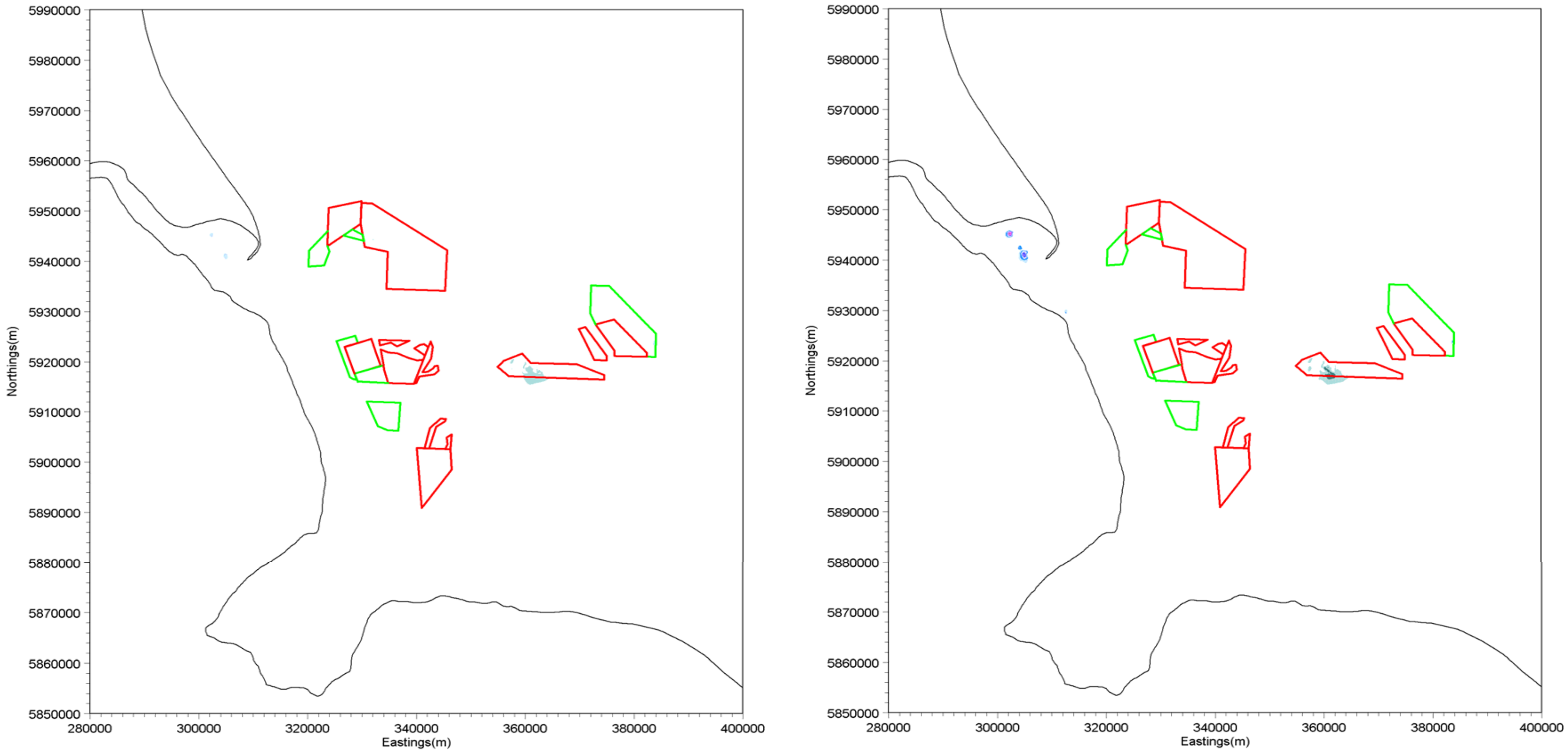
Change in wave height at MHWS for 1 in 200yr NE wave (present minus pre-dredging) (a) absolute values (b) percentages

Figure 7.12



(a) (b)

Change in Wave Height [m]

Above 0.7	
0.6 - 0.7	
0.5 - 0.6	
0.4 - 0.5	
0.3 - 0.4	
0.2 - 0.3	
0.1 - 0.2	
-0.1 - 0.1	
-0.2 - -0.1	
-0.3 - -0.2	
-0.4 - -0.3	
-0.5 - -0.4	
-0.6 - -0.5	
-0.7 - -0.6	
Below -0.7	
Undefined Value	

Change in Wave Height [%]

Above 25	
20 - 25	
15 - 20	
10 - 15	
5 - 10	
3 - 5	
2 - 3	
-2 - 2	
-3 - -2	
-5 - -3	
-10 - -5	
-15 - -10	
-20 - -15	
-25 - -20	
Below -25	
Undefined Value	

Date	By	Size	Version
Aug 11	BW	A3	1
Projection		n/a	
Scale		n/a	
QA			
Final_Revised_Figures_SW.xls			
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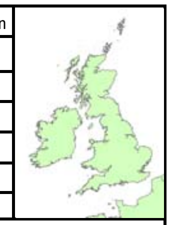

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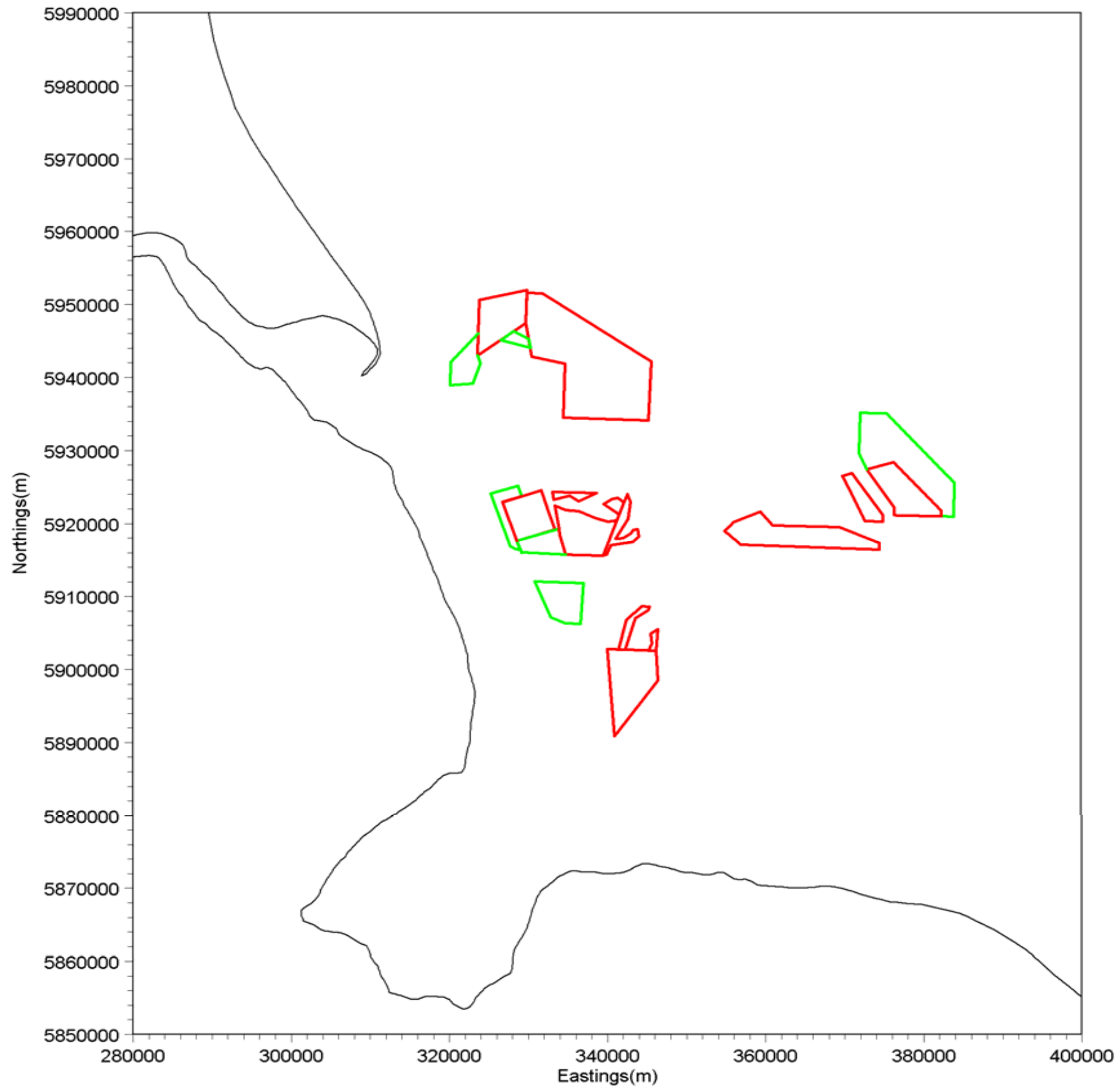
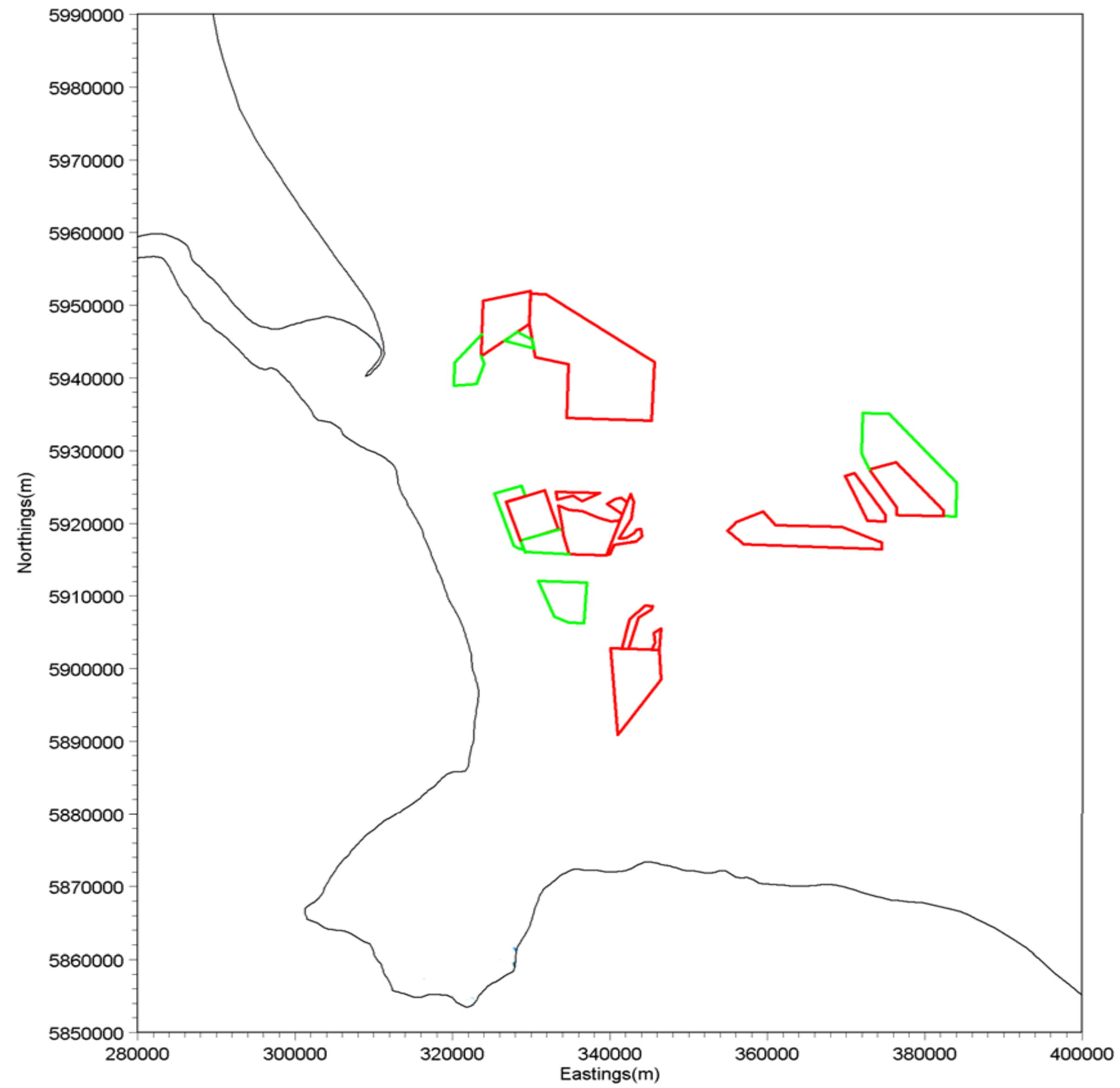
Change in wave height at MLWS for 1 in 200yr NE wave (present minus pre-dredging) (a) absolute values (b) percentages

Figure 7.13



(a)



(b)

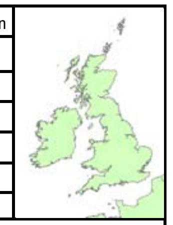
Change in Wave Height [m]

Above 0.7
0.6 - 0.7
0.5 - 0.6
0.4 - 0.5
0.3 - 0.4
0.2 - 0.3
0.1 - 0.2
-0.1 - 0.1
-0.2 - -0.1
-0.3 - -0.2
-0.4 - -0.3
-0.5 - -0.4
-0.6 - -0.5
-0.7 - -0.6
Below -0.7
Undefined Value

Change in Wave Height [%]

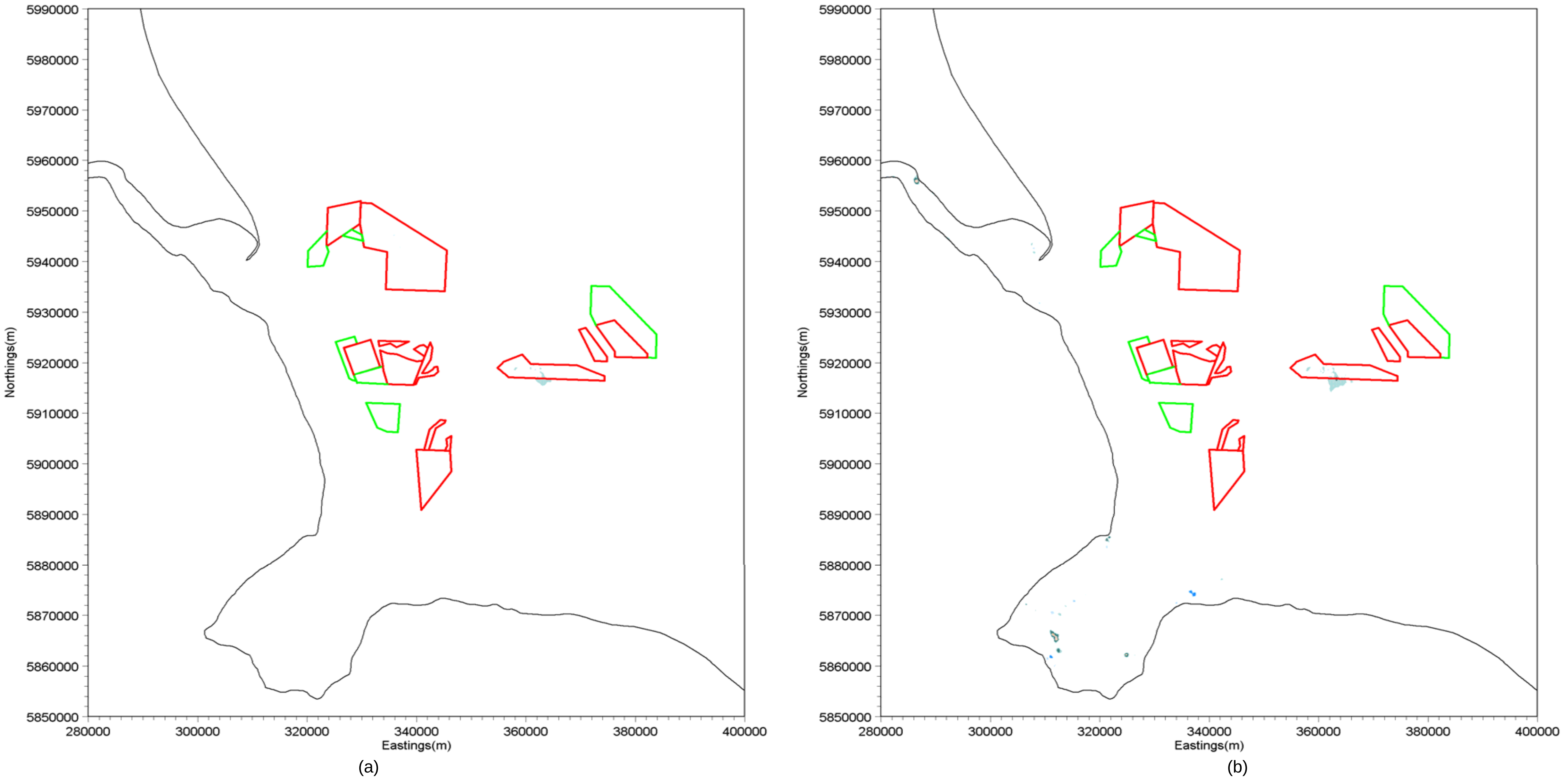
Above 25
20 - 25
15 - 20
10 - 15
5 - 10
3 - 5
2 - 3
-2 - 2
-3 - -2
-5 - -3
-10 - -5
-15 - -10
-20 - -15
-25 - -20
Below -25
Undefined Value

Date	By	Size	Version
Aug 11	BW	A3	1
Projection		n/a	
Scale		n/a	
QA			
Final_Revised_Figures_SW.xls			
Produced by ABPmer Ltd.			

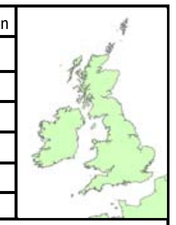


Change in wave height at MHWS for 1 in 200yr SE wave (present minus pre-dredging) (a) absolute values (b) percentages

Figure 7.14



Date	By	Size	Version
Aug 11	BW	A3	1
Projection		n/a	
Scale		n/a	
QA			
Final_Revised_Figures_SW.xls			
Produced by ABPmer Ltd.			



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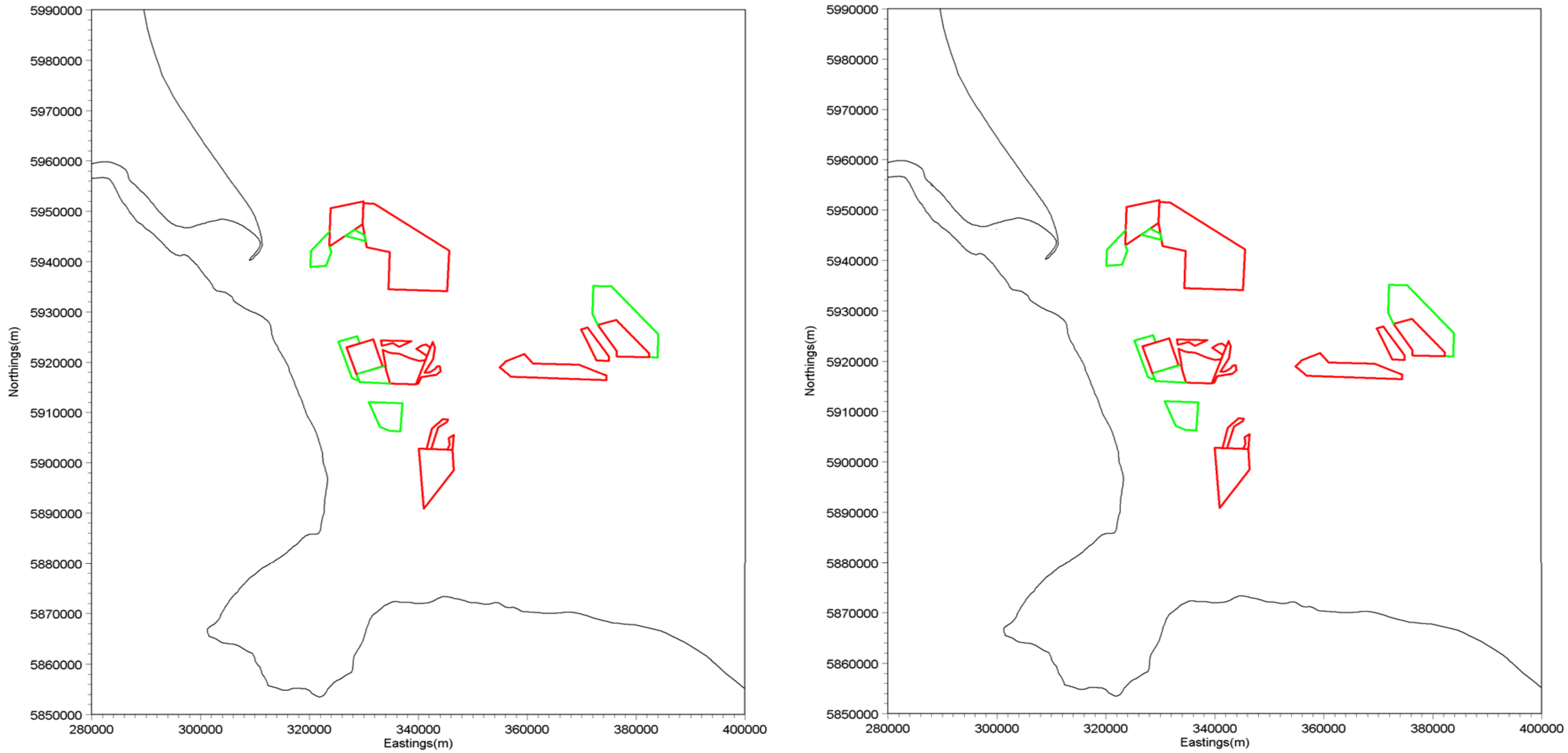
Change in wave height at MLWS for 1 in 200yr SE wave (present minus pre-dredging) (a) absolute values (b) percentages

Figure 7.15



(a) (b)

Change in Wave Height [m]

	Above 0.7
	0.6 - 0.7
	0.5 - 0.6
	0.4 - 0.5
	0.3 - 0.4
	0.2 - 0.3
	0.1 - 0.2
	-0.1 - 0.1
	-0.2 - -0.1
	-0.3 - -0.2
	-0.4 - -0.3
	-0.5 - -0.4
	-0.6 - -0.5
	-0.7 - -0.6
	Below -0.7
	Undefined Value

Change in Wave Height [%]

	Above 25
	20 - 25
	15 - 20
	10 - 15
	5 - 10
	3 - 5
	2 - 3
	-2 - 2
	-3 - -2
	-5 - -3
	-10 - -5
	-15 - -10
	-20 - -15
	-25 - -20
	Below -25
	Undefined Value

Date	By	Size	Version
Aug 11	BW	A3	1
Projection		n/a	
Scale		n/a	
QA			

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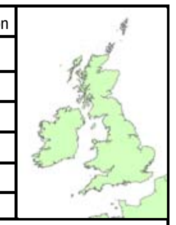

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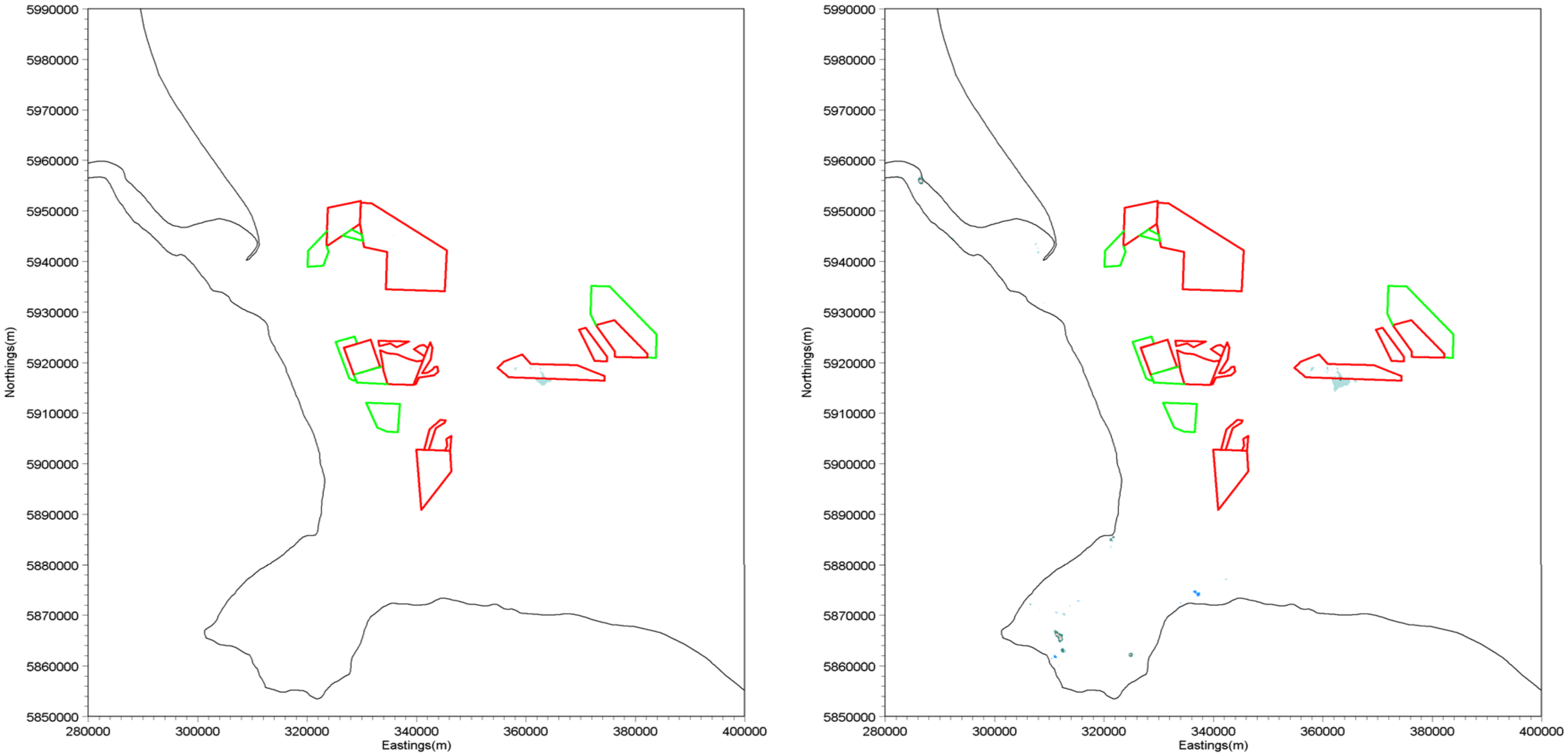
Change in wave height at MHWS for 1 in 200yr N wave (present minus pre-dredging) (a) absolute values (b) percentages

Figure 7.16



(a) (b)

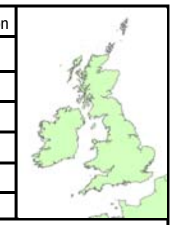
Change in Wave Height [m]

Above	0.7
0.6 -	0.7
0.5 -	0.6
0.4 -	0.5
0.3 -	0.4
0.2 -	0.3
0.1 -	0.2
-0.1 -	0.1
-0.2 -	-0.1
-0.3 -	-0.2
-0.4 -	-0.3
-0.5 -	-0.4
-0.6 -	-0.5
-0.7 -	-0.6
Below	-0.7
Undefined Value	

Change in Wave Height [%]

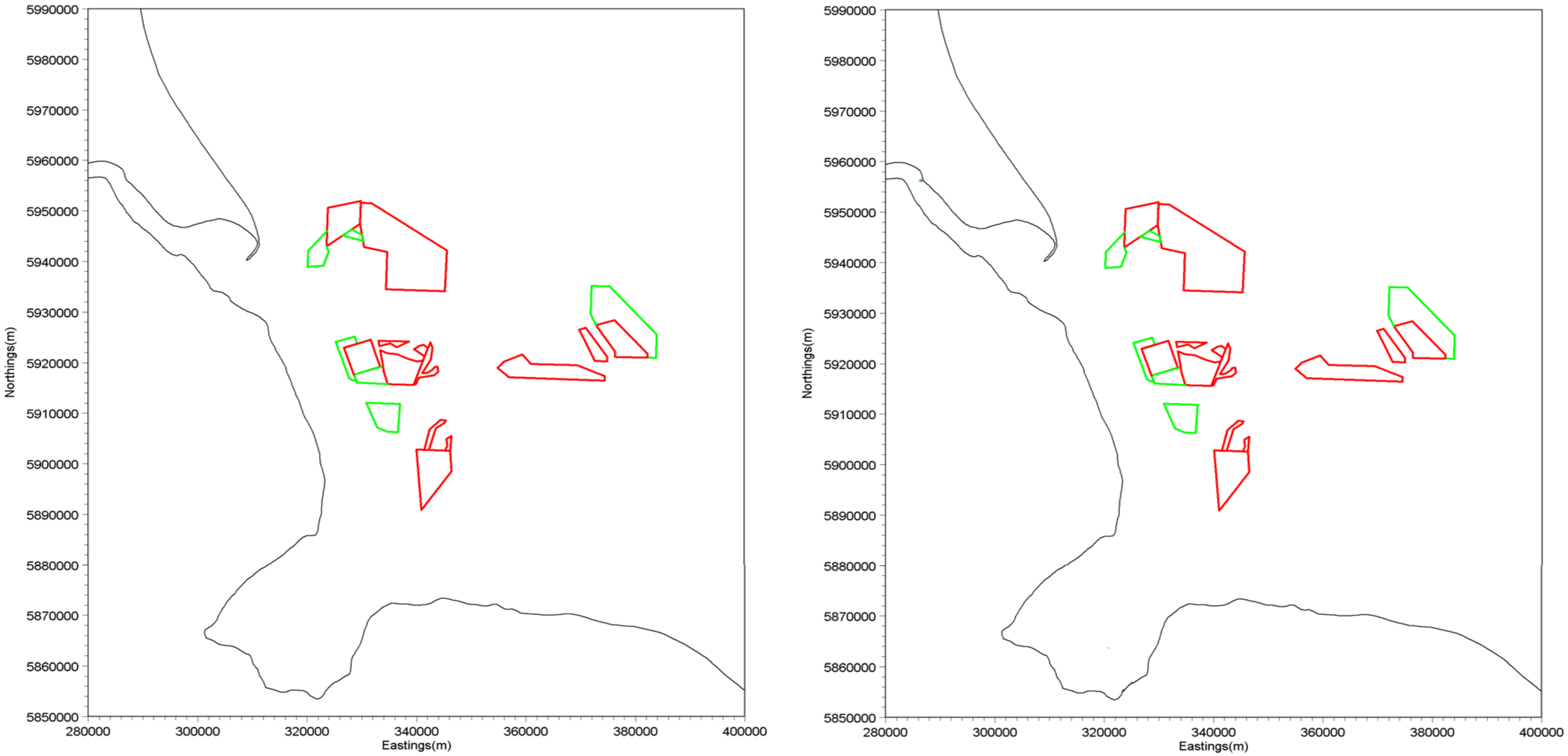
Above	25
20 -	25
15 -	20
10 -	15
5 -	10
3 -	5
2 -	3
-2 -	2
-3 -	-2
-5 -	-3
-10 -	-5
-15 -	-10
-20 -	-15
-25 -	-20
Below	-25
Undefined Value	

Date	By	Size	Version
Aug 11	BW	A3	1
Projection	n/a		
Scale	n/a		
QA			
Final_Revised_Figures_SW.xls			
Produced by ABPmer Ltd.			



Change in wave height at MLWS for 1 in 200yr N wave (present minus pre-dredging) (a) absolute values (b) percentages

Figure 7.17



(a)

(b)

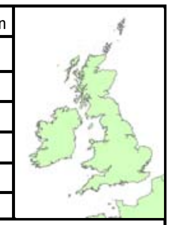
Change in Wave Height [m]

- Above 0.7
- 0.6 - 0.7
- 0.5 - 0.6
- 0.4 - 0.5
- 0.3 - 0.4
- 0.2 - 0.3
- 0.1 - 0.2
- -0.1 - 0.1
- -0.2 - -0.1
- -0.3 - -0.2
- -0.4 - -0.3
- -0.5 - -0.4
- -0.6 - -0.5
- -0.7 - -0.6
- Below -0.7
- Undefined Value

Change in Wave Height [%]

- Above 25
- 20 - 25
- 15 - 20
- 10 - 15
- 5 - 10
- 3 - 5
- 2 - 3
- -2 - 2
- -3 - -2
- -5 - -3
- -10 - -5
- -15 - -10
- -20 - -15
- -25 - -20
- Below -25
- Undefined Value

Date	By	Size	Version
Aug 11	BW	A3	1
Projection	n/a		
Scale	n/a		
QA			
Final_Revised_Figures_SW.xls			
Produced by ABPmer Ltd.			



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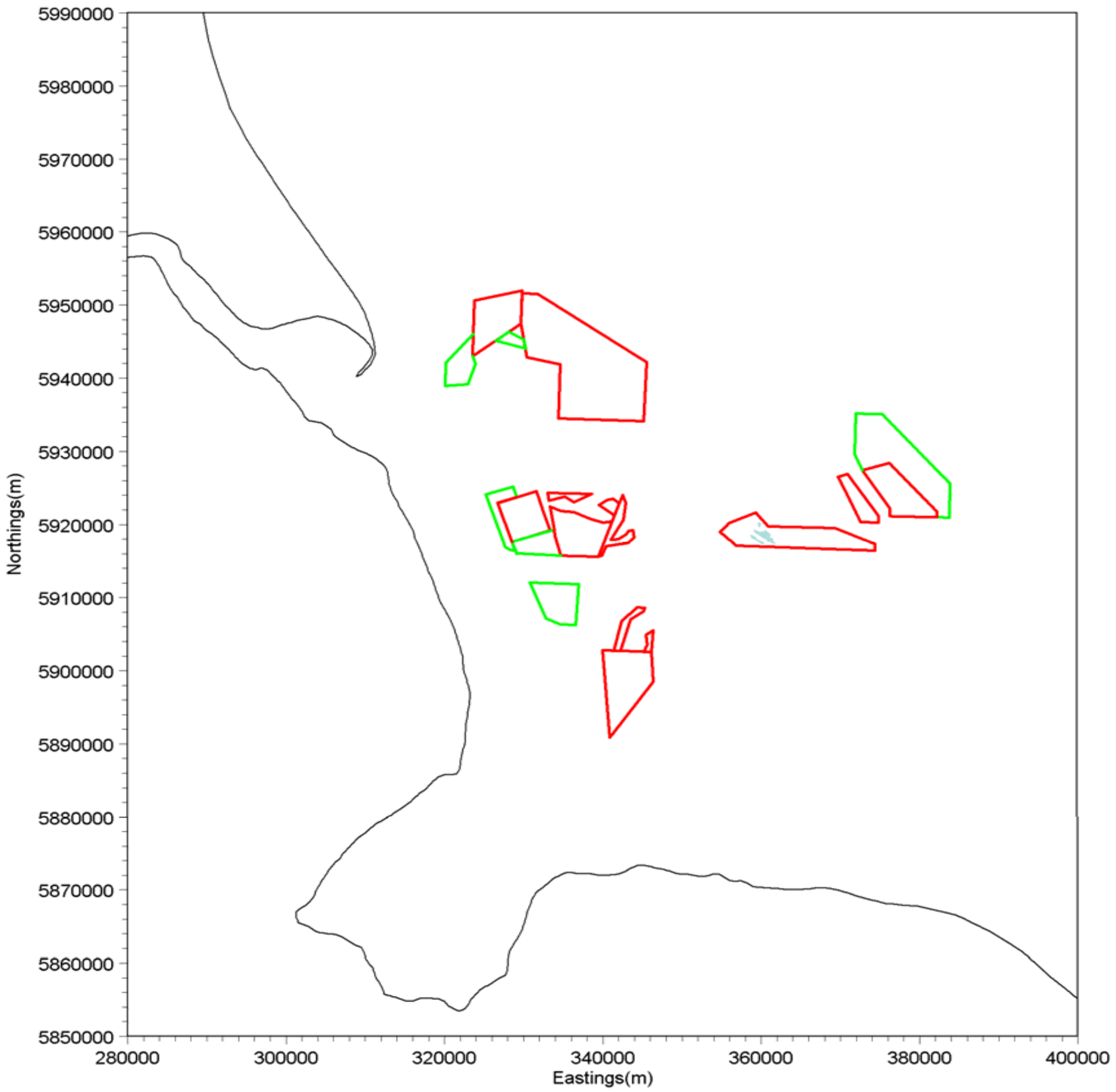
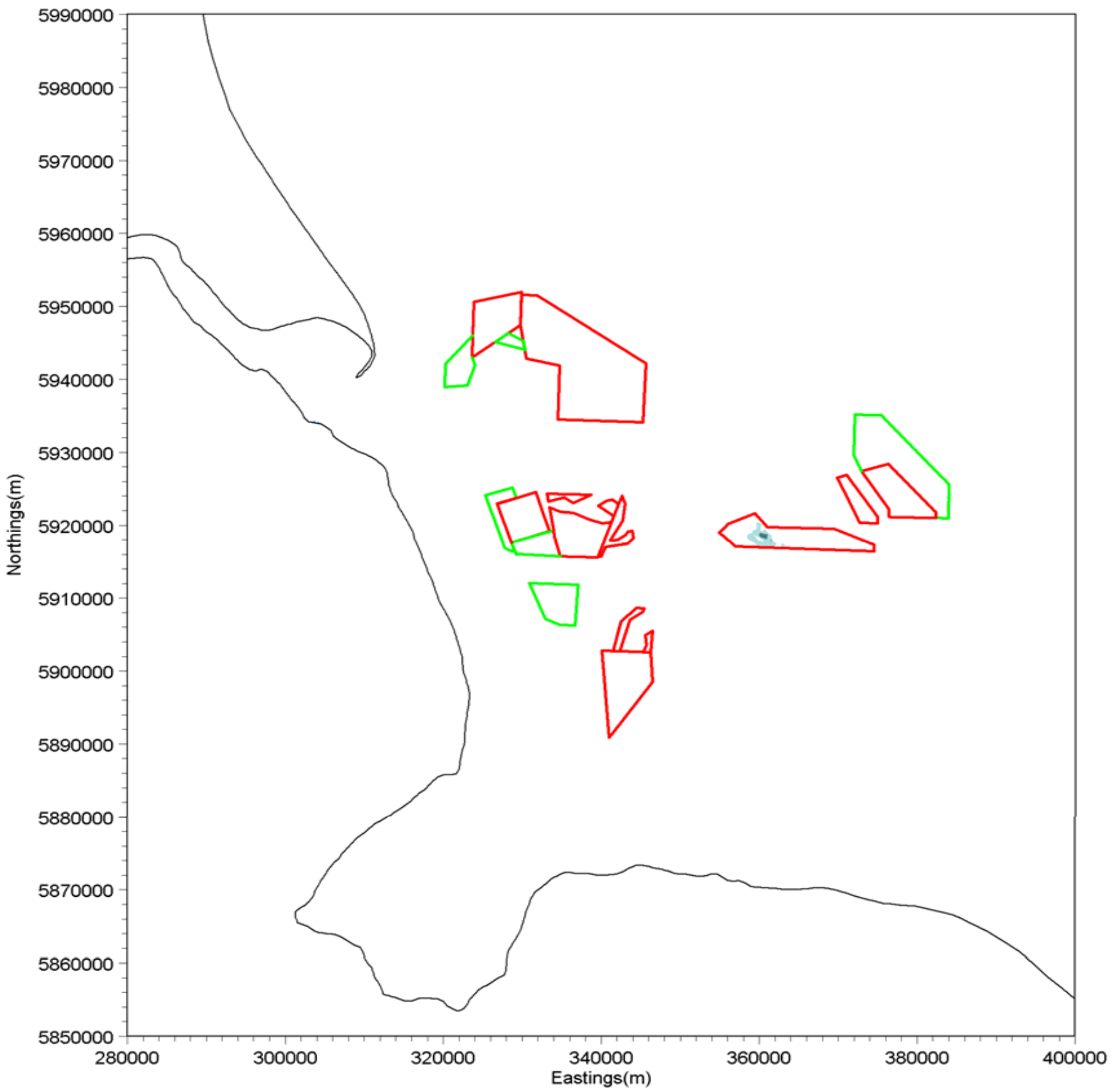
Change in wave height at MHWS for 1 in 200yr E wave (present minus pre-dredging) (a) absolute values (b) percentages

Figure 7.18



(a)



(b)

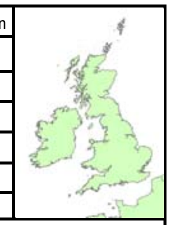
Change in Wave Height [m]

- Above 0.7
- 0.6 - 0.7
- 0.5 - 0.6
- 0.4 - 0.5
- 0.3 - 0.4
- 0.2 - 0.3
- 0.1 - 0.2
- -0.1 - 0.1
- -0.2 - -0.1
- -0.3 - -0.2
- -0.4 - -0.3
- -0.5 - -0.4
- -0.6 - -0.5
- -0.7 - -0.6
- Below -0.7
- Undefined Value

Change in Wave Height [%]

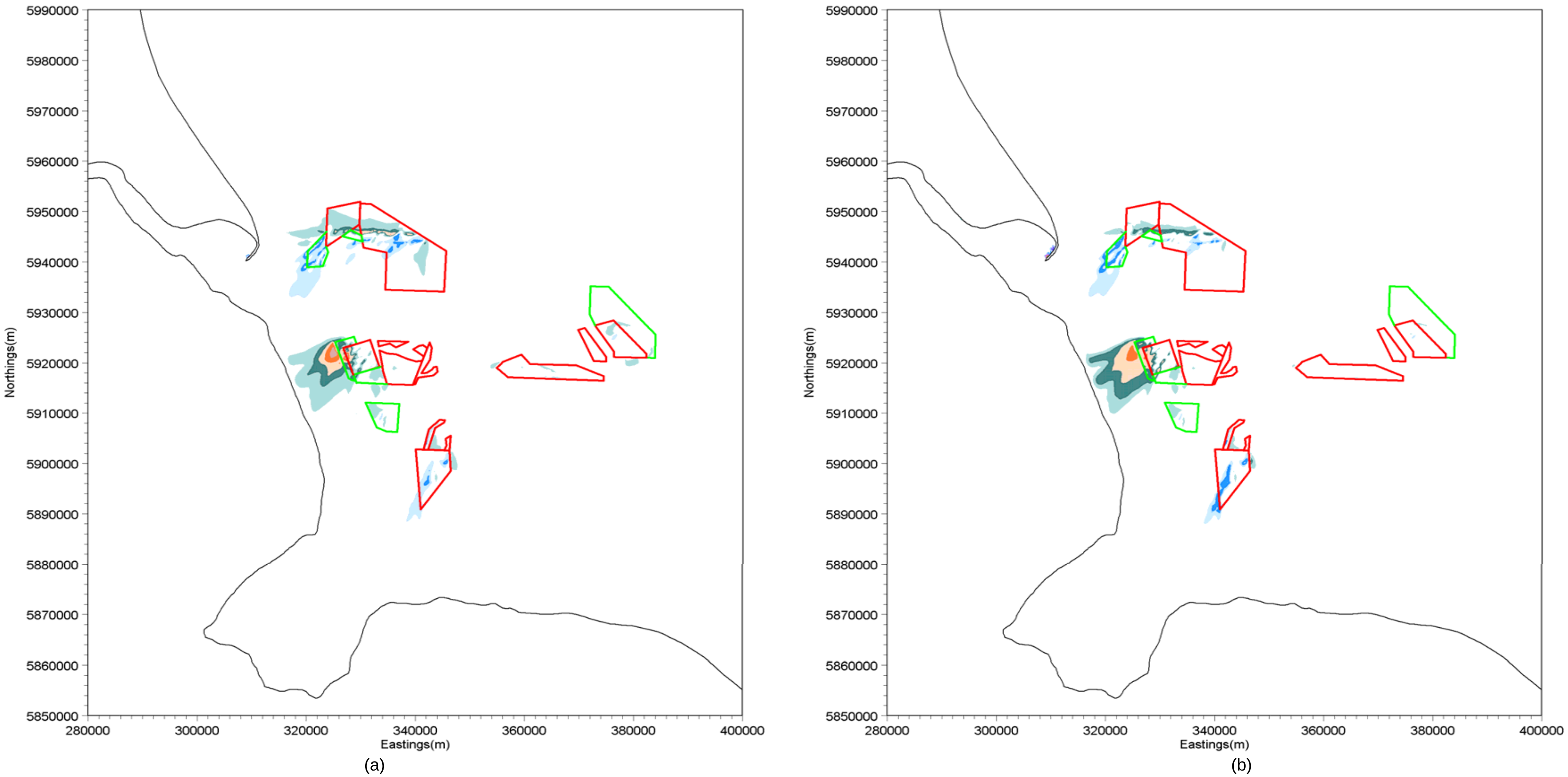
- Above 25
- 20 - 25
- 15 - 20
- 10 - 15
- 5 - 10
- 3 - 5
- 2 - 3
- -2 - 2
- -3 - -2
- -5 - -3
- -10 - -5
- -15 - -10
- -20 - -15
- -25 - -20
- Below -25
- Undefined Value

Date	By	Size	Version
Aug 11	BW	A3	1
Projection	n/a		
Scale	n/a		
QA			
Final_Revised_Figures_SW.xls			
Produced by ABPmer Ltd.			



Change in wave height at MLWS for 1 in 200yr E wave (present minus pre-dredging) (a) absolute values (b) percentages

Figure 7.19



(a) (b)

Change in Wave Height [m]

- Above 0.7
- 0.6 - 0.7
- 0.5 - 0.6
- 0.4 - 0.5
- 0.3 - 0.4
- 0.2 - 0.3
- 0.1 - 0.2
- -0.1 - 0.1
- -0.2 - -0.1
- -0.3 - -0.2
- -0.4 - -0.3
- -0.5 - -0.4
- -0.6 - -0.5
- -0.7 - -0.6
- Below -0.7
- Undefined Value

Change in Wave Height [%]

- Above 25
- 20 - 25
- 15 - 20
- 10 - 15
- 5 - 10
- 3 - 5
- 2 - 3
- -2 - 2
- -3 - -2
- -5 - -3
- -10 - -5
- -15 - -10
- -20 - -15
- -25 - -20
- Below -25
- Undefined Value

Date	By	Size	Version
Aug 11	BW	A3	1
Projection		n/a	
Scale		n/a	
QA			

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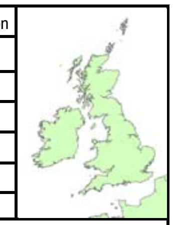
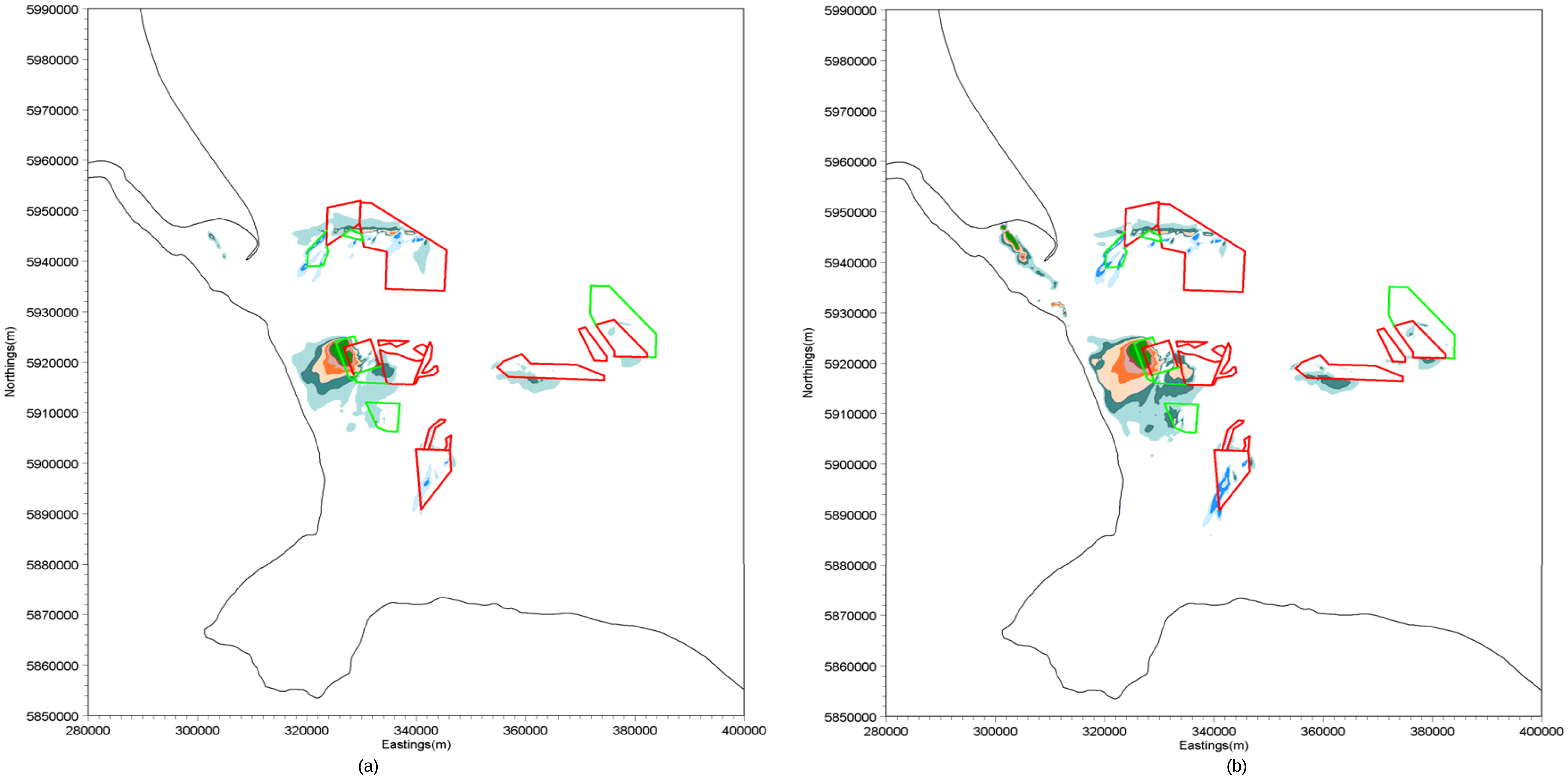
Produced by ABPmer Ltd.



Change in wave height at MHWS for 1 in 200yr NE wave (future minus present)
(a) absolute values (b) percentages

Figure 7.20



Change in Wave Height [m]

Above 0.7	
0.6 - 0.7	
0.5 - 0.6	
0.4 - 0.5	
0.3 - 0.4	
0.2 - 0.3	
0.1 - 0.2	
-0.1 - 0.1	
-0.2 - -0.1	
-0.3 - -0.2	
-0.4 - -0.3	
-0.5 - -0.4	
-0.6 - -0.5	
-0.7 - -0.6	
Below -0.7	
Undefined Value	

Change in Wave Height [%]

Above 25	
20 - 25	
15 - 20	
10 - 15	
5 - 10	
3 - 5	
2 - 3	
-2 - 2	
-3 - -2	
-5 - -3	
-10 - -5	
-15 - -10	
-20 - -15	
-25 - -20	
Below -25	
Undefined Value	

Date	By	Size	Version
Aug 11	BW	A3	1
Projection		n/a	
Scale		n/a	
QA			

Final_Revised_Figures_SW.xls

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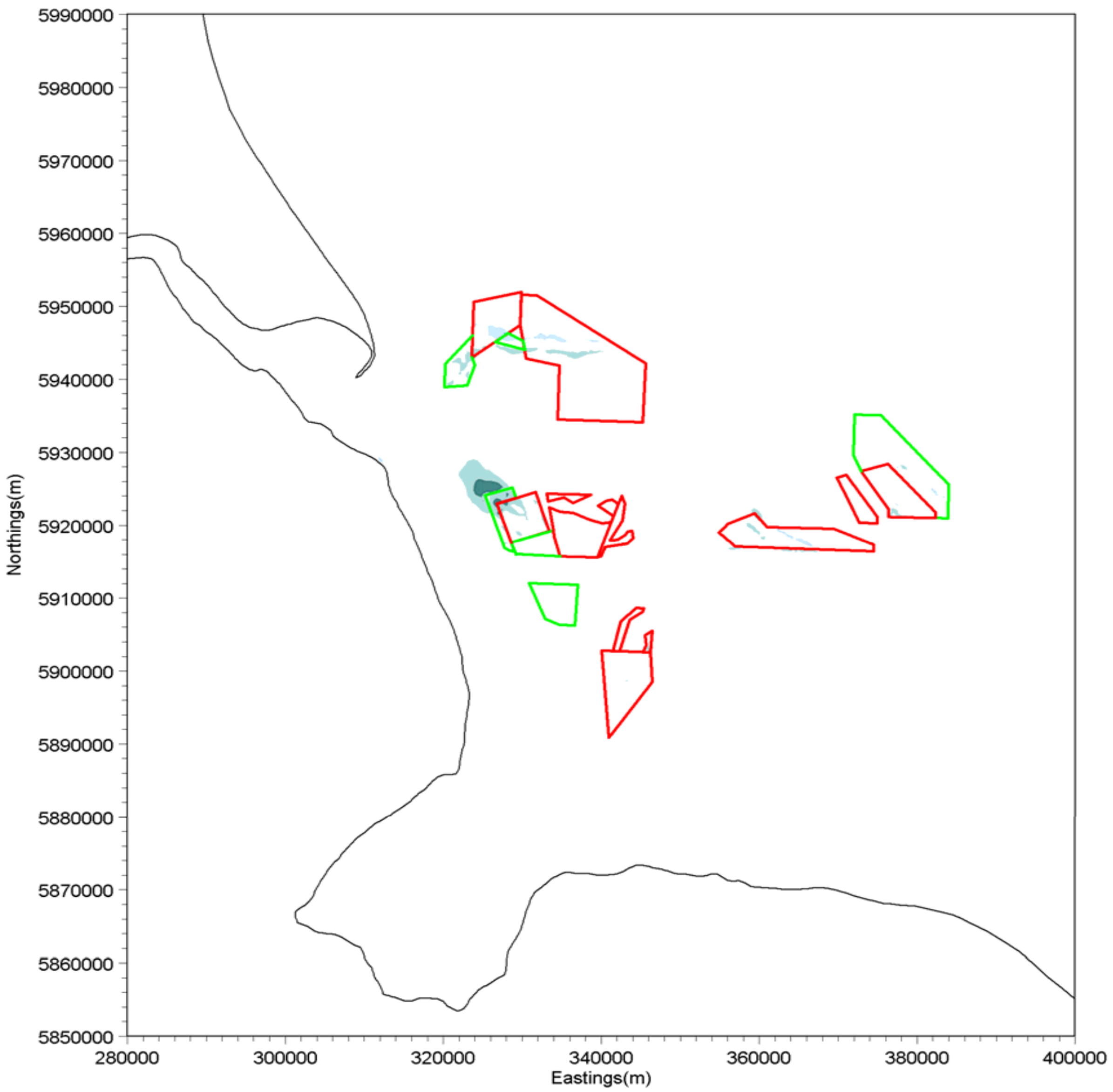
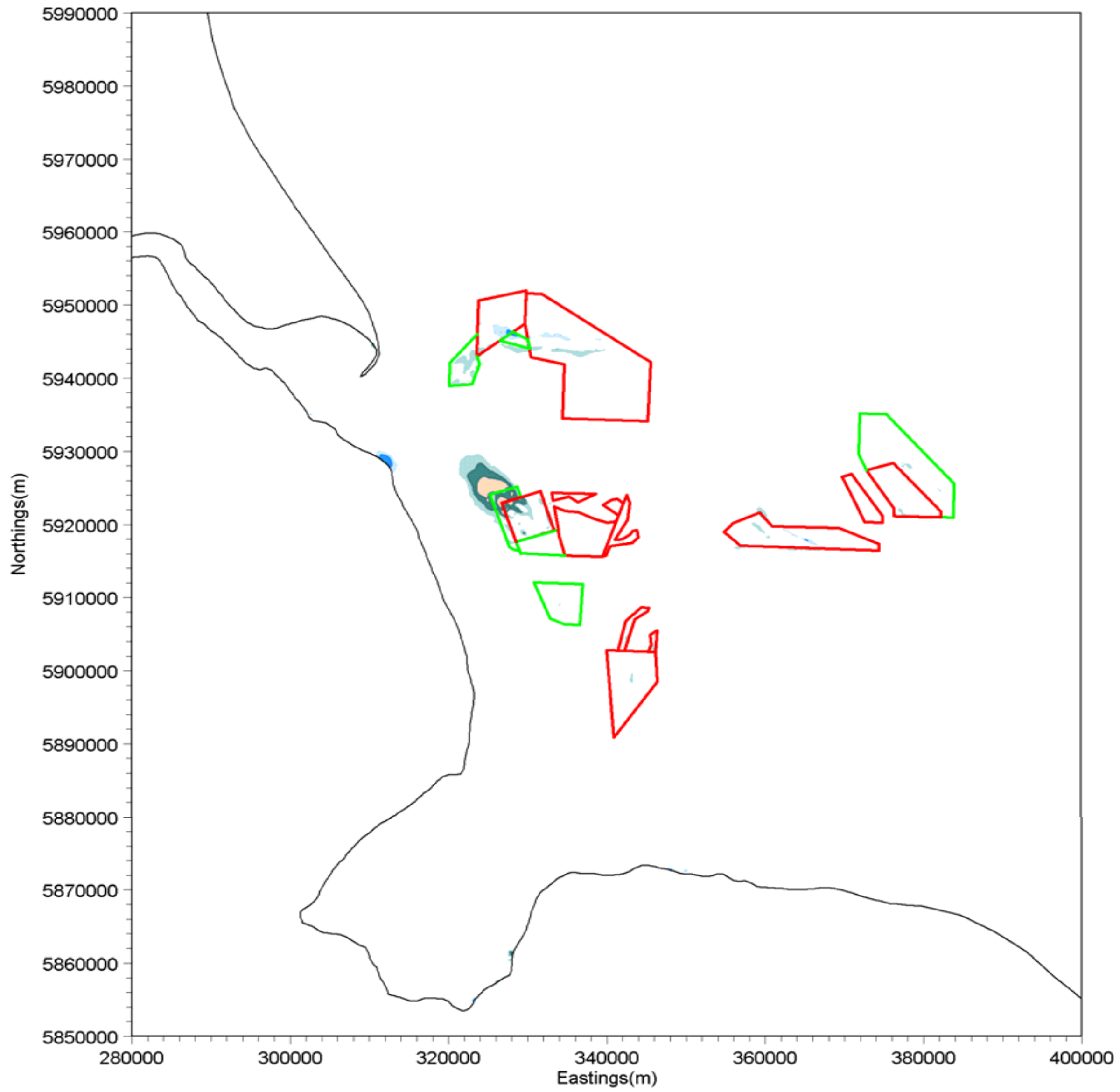
Change in wave height at MLWS for 1 in 200yr NE wave (future minus present)
(a) absolute values (b) percentages

Figure 7.21



(a)



(b)

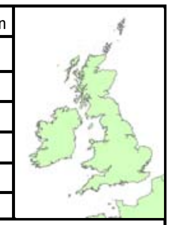
Change in Wave Height [m]

- Above 0.7
- 0.6 - 0.7
- 0.5 - 0.6
- 0.4 - 0.5
- 0.3 - 0.4
- 0.2 - 0.3
- 0.1 - 0.2
- -0.1 - 0.1
- -0.2 - -0.1
- -0.3 - -0.2
- -0.4 - -0.3
- -0.5 - -0.4
- -0.6 - -0.5
- -0.7 - -0.6
- Below -0.7
- Undefined Value

Change in Wave Height [%]

- Above 25
- 20 - 25
- 15 - 20
- 10 - 15
- 5 - 10
- 3 - 5
- 2 - 3
- -2 - 2
- -3 - -2
- -5 - -3
- -10 - -5
- -15 - -10
- -20 - -15
- -25 - -20
- Below -25
- Undefined Value

Date	By	Size	Version
Aug 11	BW	A3	1
Projection		n/a	
Scale		n/a	
QA			
Final_Revised_Figures_SW.xls			
Produced by ABPmer Ltd.			



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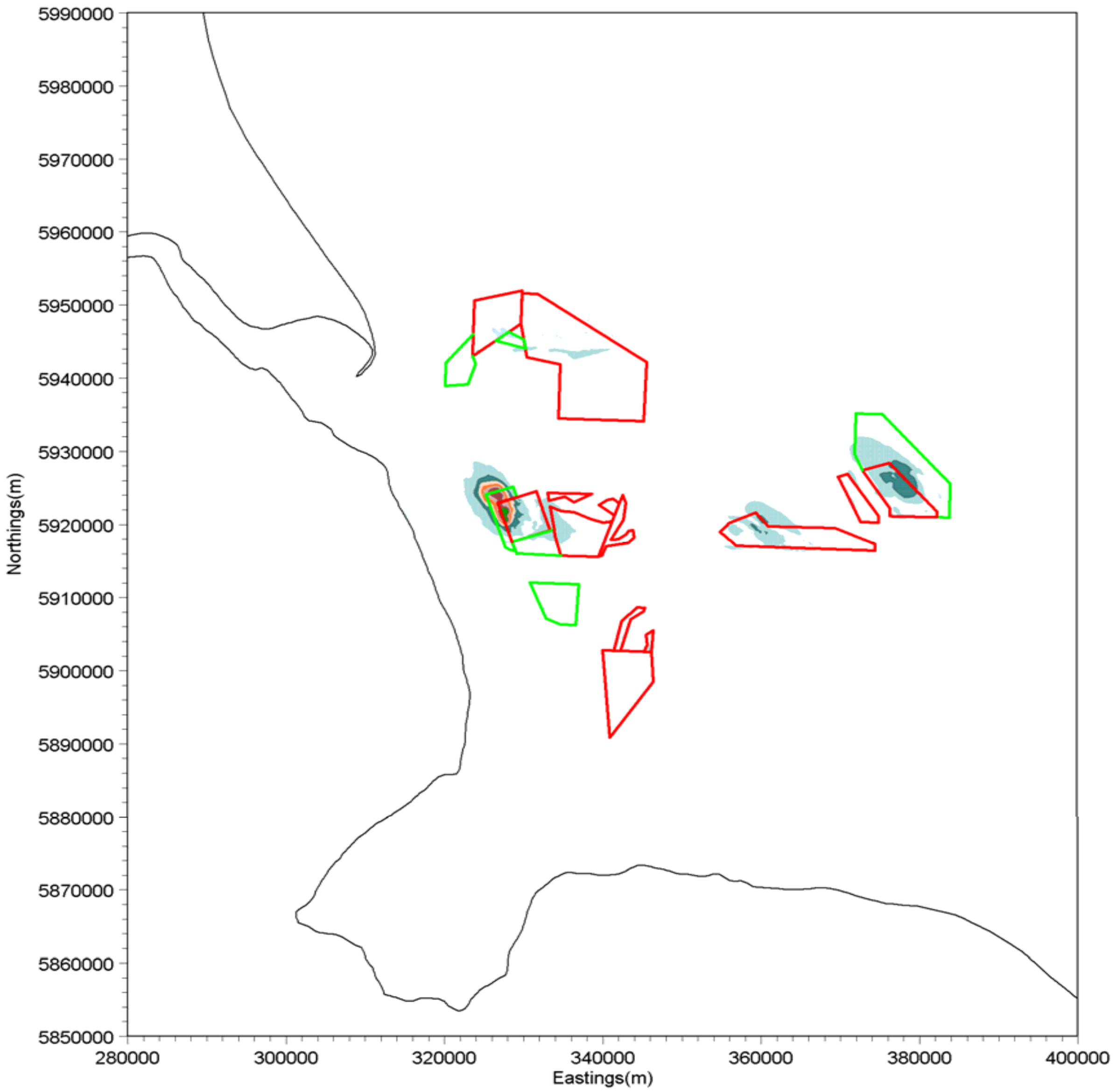
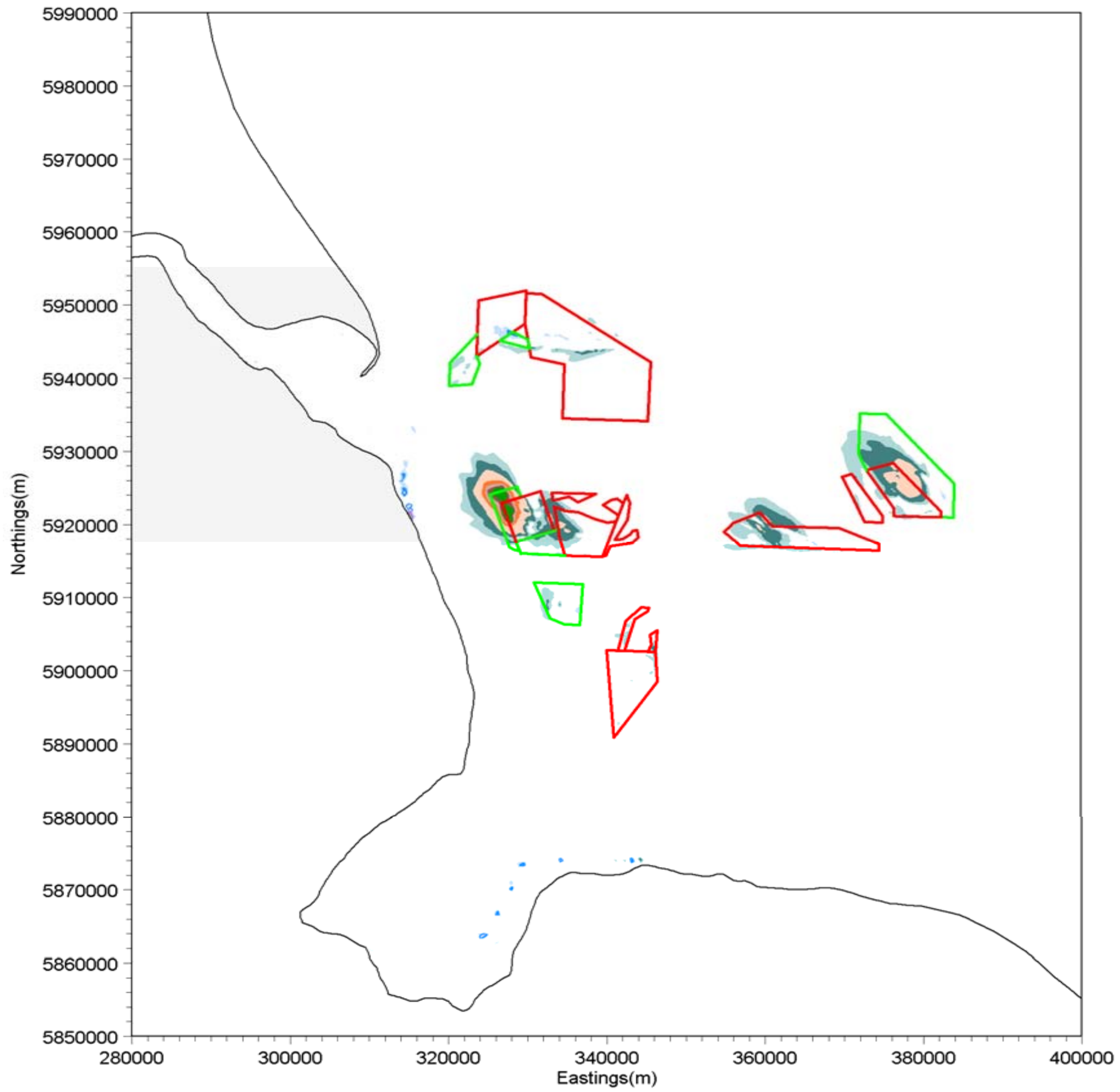
Change in wave height at MHWS for 1 in 200yr SE wave (future minus present)
(a) absolute values (b) percentages

Figure 7.22



(a)



(b)

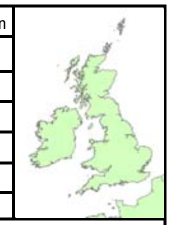
Change in Wave Height [m]

- Above 0.7
- 0.6 - 0.7
- 0.5 - 0.6
- 0.4 - 0.5
- 0.3 - 0.4
- 0.2 - 0.3
- 0.1 - 0.2
- -0.1 - 0.1
- -0.2 - -0.1
- -0.3 - -0.2
- -0.4 - -0.3
- -0.5 - -0.4
- -0.6 - -0.5
- -0.7 - -0.6
- Below -0.7
- Undefined Value

Change in Wave Height [%]

- Above 25
- 20 - 25
- 15 - 20
- 10 - 15
- 5 - 10
- 3 - 5
- 2 - 3
- -2 - 2
- -3 - -2
- -5 - -3
- -10 - -5
- -15 - -10
- -20 - -15
- -25 - -20
- Below -25
- Undefined Value

Date	By	Size	Version
Aug 11	BW	A3	1
Projection		n/a	
Scale		n/a	
QA			
Final_Revised_Figures_SW.xls			
Produced by ABPmer Ltd.			



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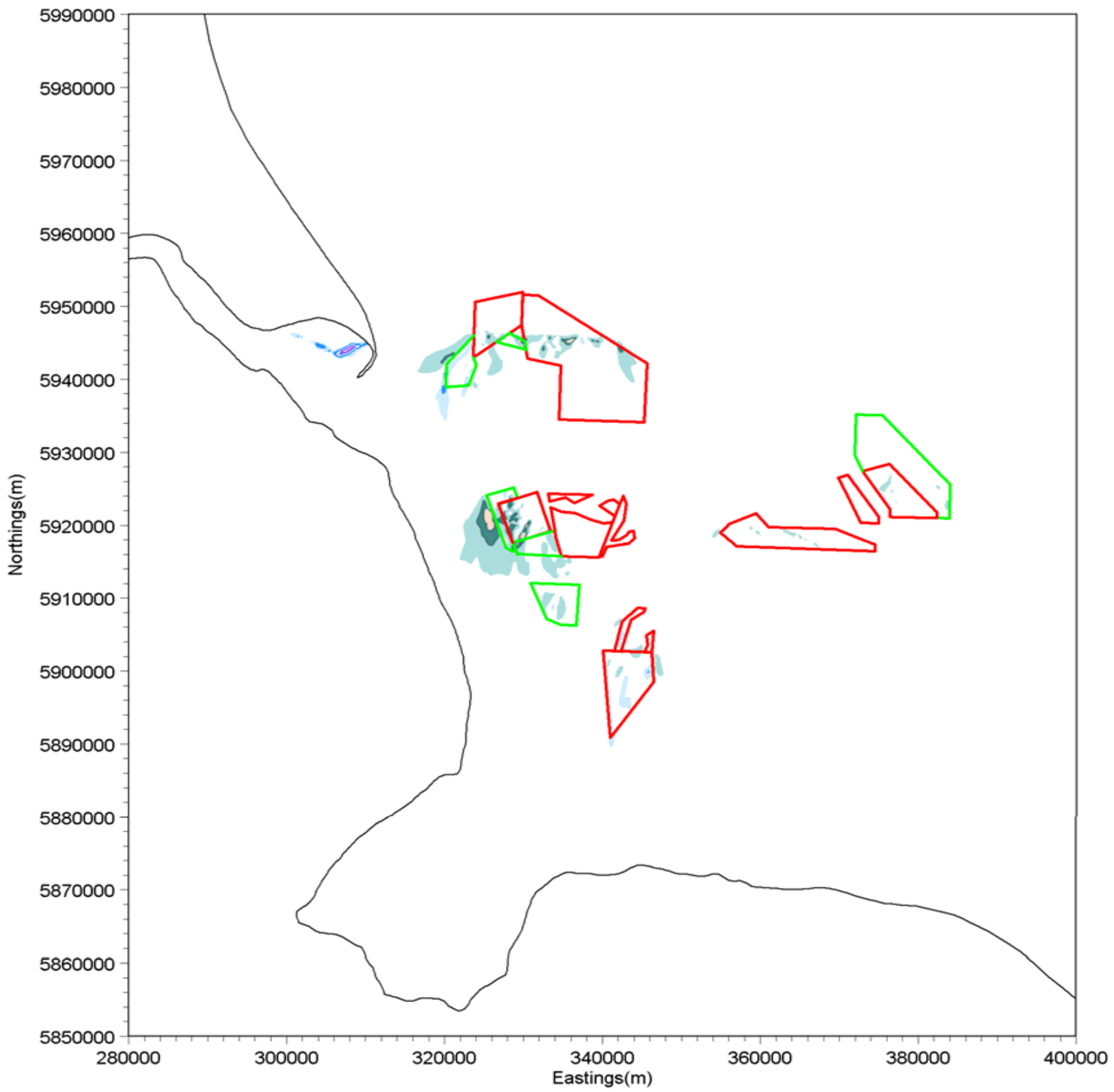
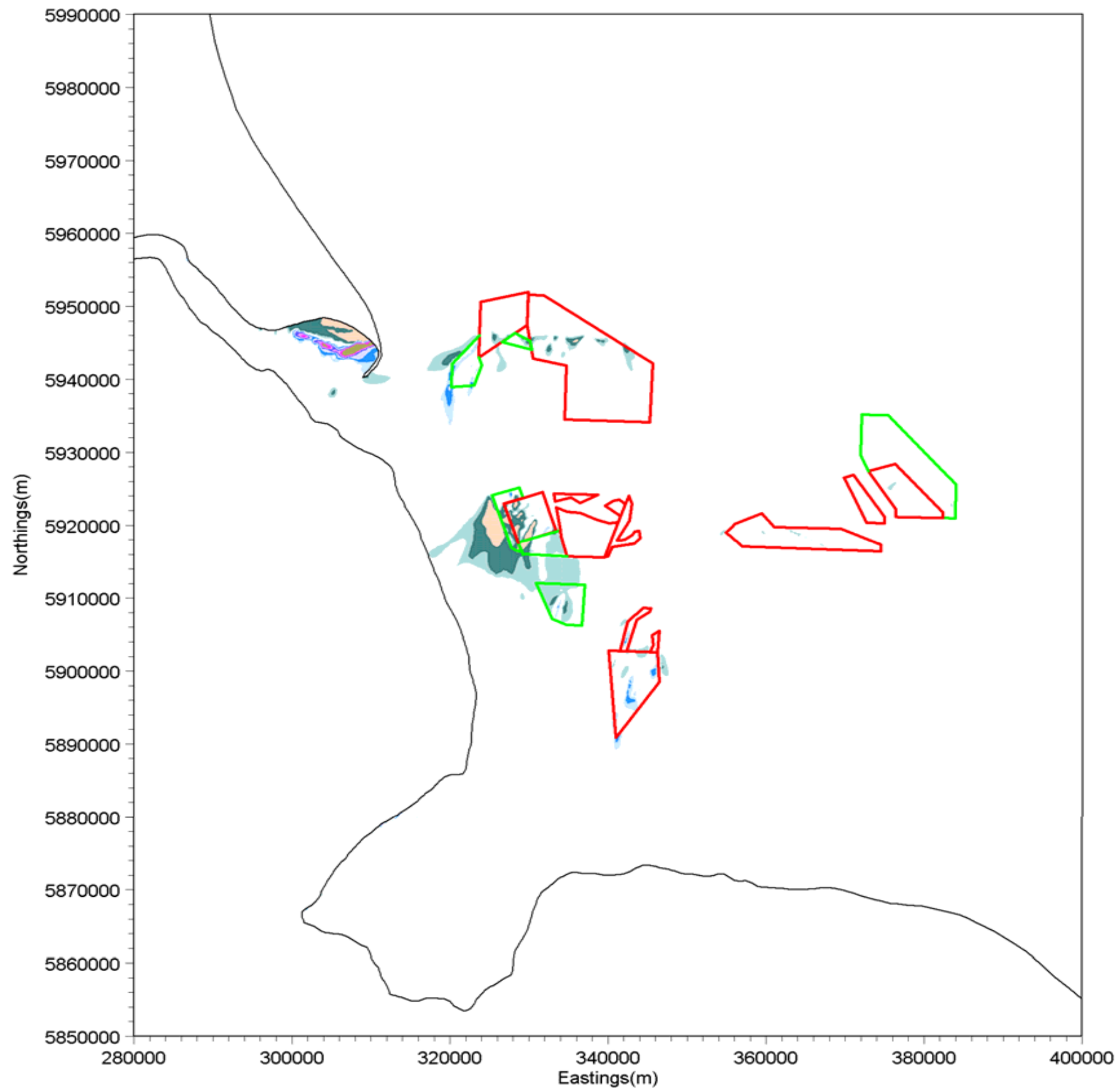
Change in wave height at MLWS for 1 in 200yr SE wave (future minus present)
(a) absolute values (b) percentages

Figure 7.23



(a)



(b)

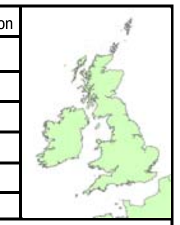
Change in Wave Height [m]

- Above 0.7
- 0.6 - 0.7
- 0.5 - 0.6
- 0.4 - 0.5
- 0.3 - 0.4
- 0.2 - 0.3
- 0.1 - 0.2
- -0.1 - 0.1
- -0.2 - -0.1
- -0.3 - -0.2
- -0.4 - -0.3
- -0.5 - -0.4
- -0.6 - -0.5
- -0.7 - -0.6
- Below -0.7
- Undefined Value

Change in Wave Height [%]

- Above 25
- 20 - 25
- 15 - 20
- 10 - 15
- 5 - 10
- 3 - 5
- 2 - 3
- -2 - 2
- -3 - -2
- -5 - -3
- -10 - -5
- -15 - -10
- -20 - -15
- -25 - -20
- Below -25
- Undefined Value

Date	By	Size	Version
Aug 11	BW	A3	1
Projection		n/a	
Scale		n/a	
QA			
Final_Revised_Figures_SW.xls			
Produced by ABPmer Ltd.			



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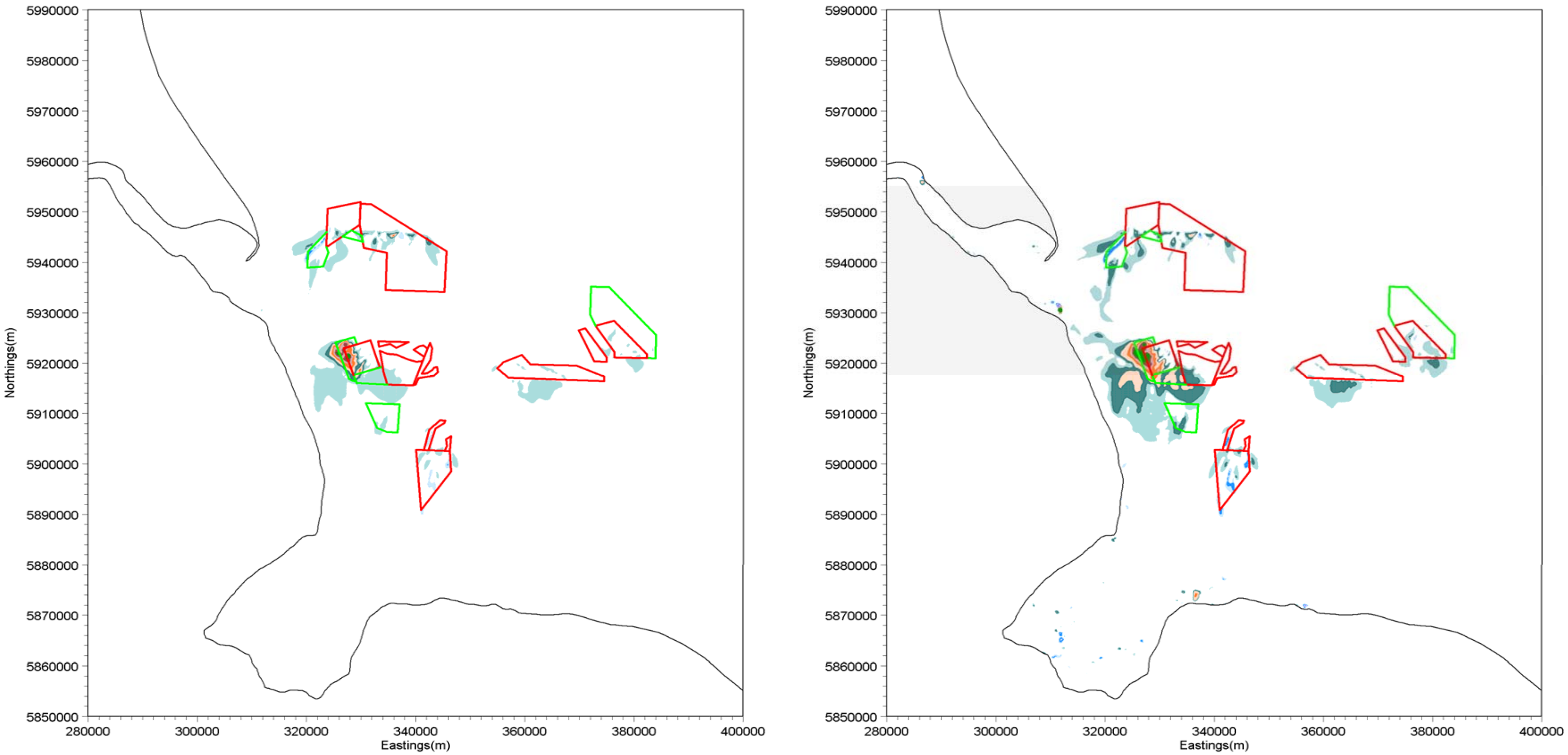
Change in wave height at MHWS for 1 in 200yr N wave (future minus present) (a) absolute values (b) percentages

Figure 7.24



(a) (b)

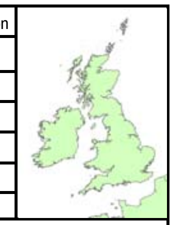
Change in Wave Height [m]

Above 0.7	
0.6 - 0.7	
0.5 - 0.6	
0.4 - 0.5	
0.3 - 0.4	
0.2 - 0.3	
0.1 - 0.2	
-0.1 - 0.1	
-0.2 - -0.1	
-0.3 - -0.2	
-0.4 - -0.3	
-0.5 - -0.4	
-0.6 - -0.5	
-0.7 - -0.6	
Below -0.7	
Undefined Value	

Change in Wave Height [%]

Above 25	
20 - 25	
15 - 20	
10 - 15	
5 - 10	
3 - 5	
2 - 3	
-2 - 2	
-3 - -2	
-5 - -3	
-10 - -5	
-15 - -10	
-20 - -15	
-25 - -20	
Below -25	
Undefined Value	

Date	By	Size	Version
Aug 11	BW	A3	1
Projection		n/a	
Scale		n/a	
QA			
Final_Revised_Figures_SW.xls			
Produced by ABPmer Ltd.			



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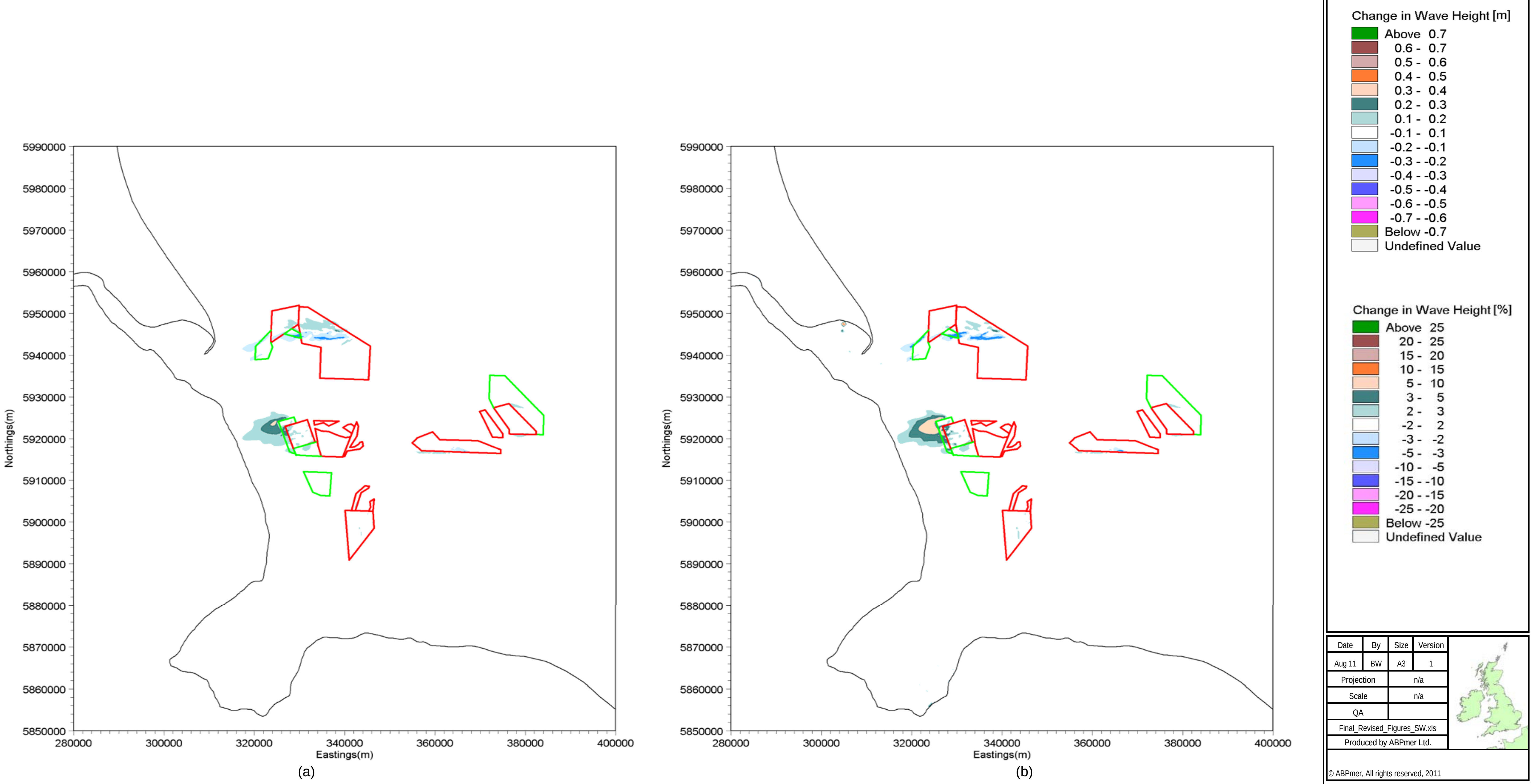
Change in wave height at MLWS for 1 in 200yr N wave (future minus present)
(a) absolute values (b) percentages

Figure 7.25



Date	By	Size	Version
Aug 11	BW	A3	1
Projection		n/a	
Scale		n/a	
QA			

Final_Revised_Figures_SW.xls

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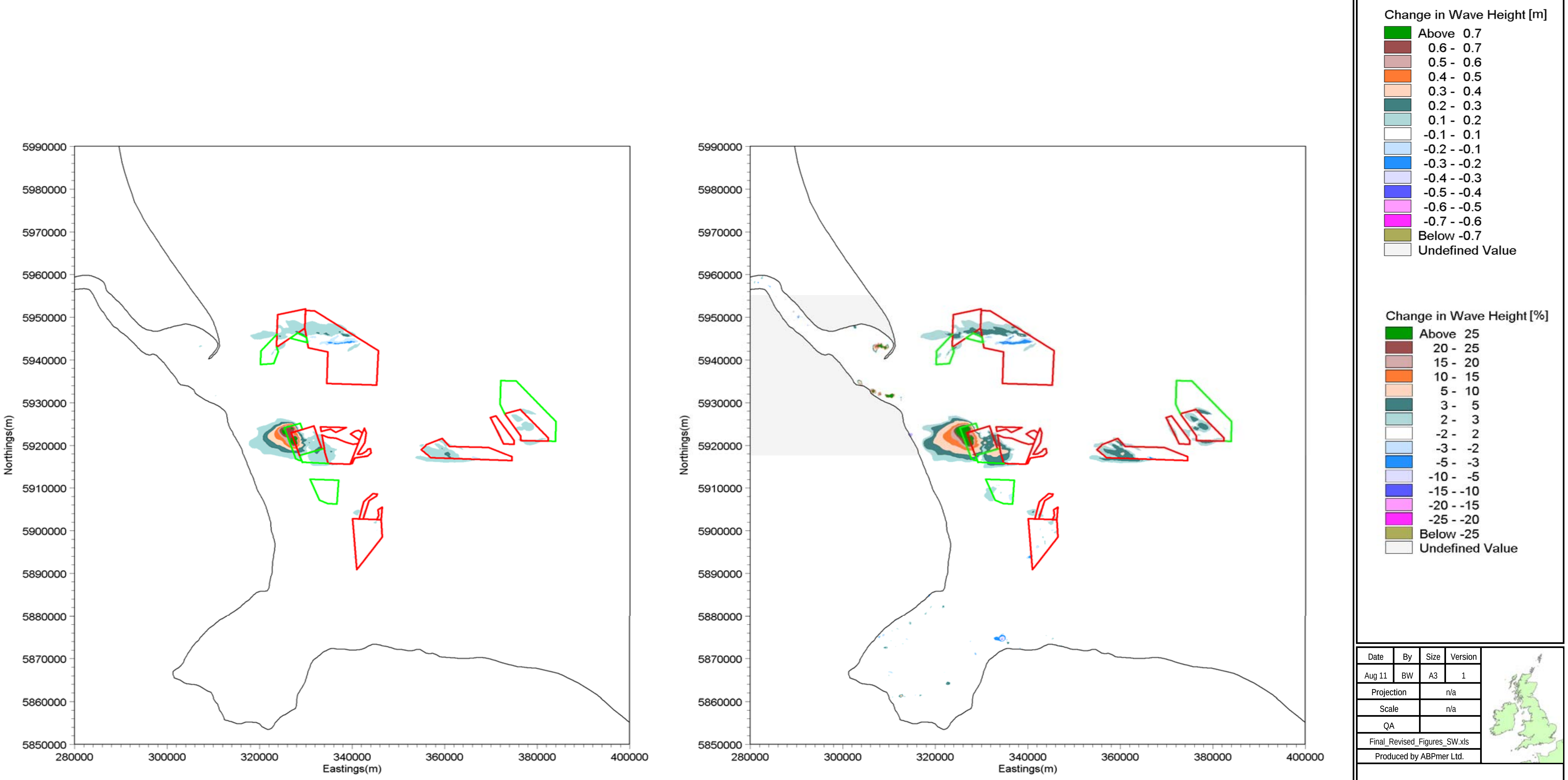
Change in wave height at MHWS for 1 in 200yr E wave (future minus present) (a) absolute values (b) percentages

Figure 7.26



Date	By	Size	Version
Aug 11	BW	A3	1
Projection		n/a	
Scale		n/a	
QA			
Final_Revised_Figures_SW.xls			
Produced by ABPmer Ltd.			

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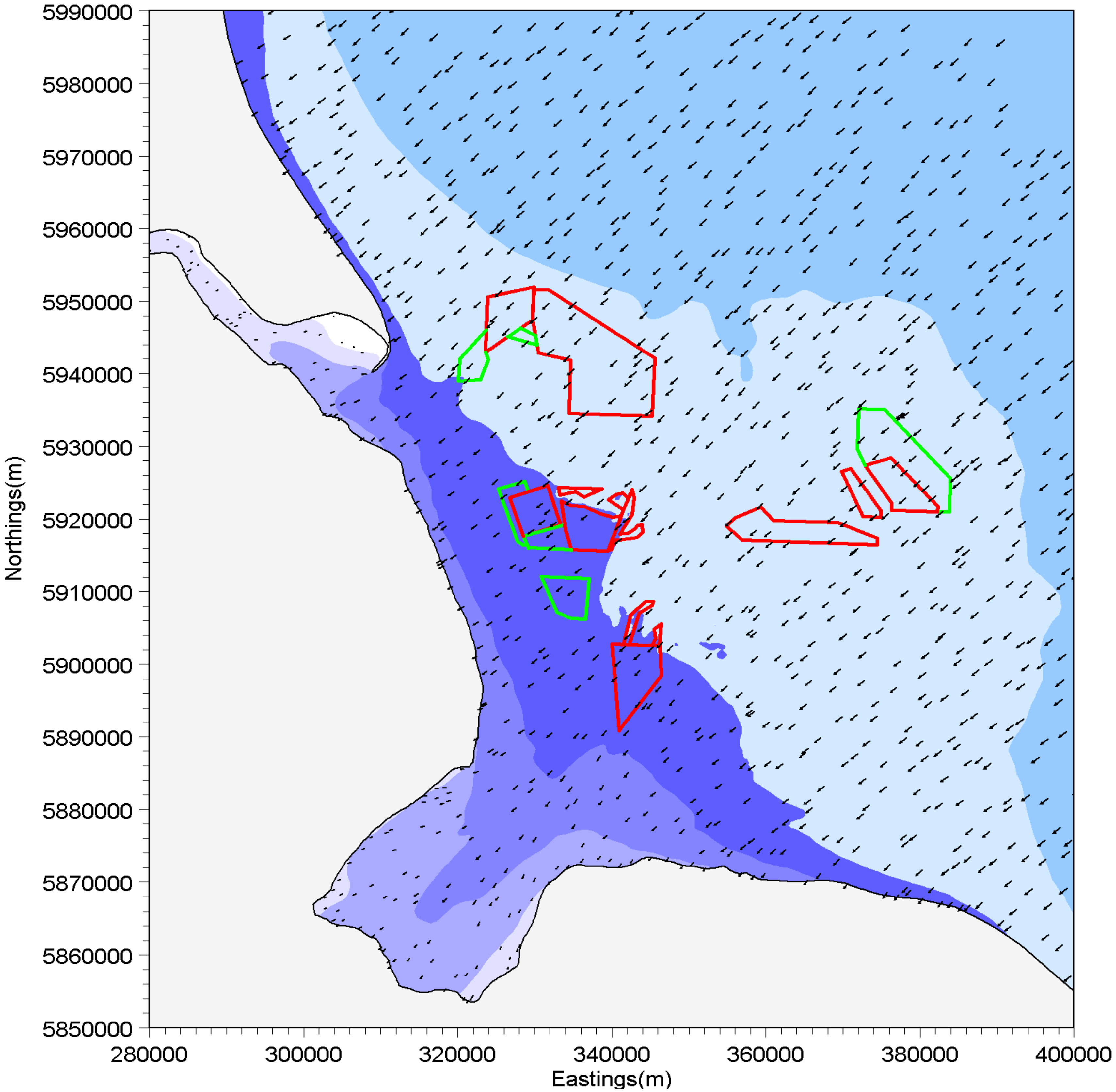
Change in wave height at MLWS for 1 in 200yr E wave (future minus present) (a) absolute values (b) percentages

Figure 7.27



Date	By	Size	Version
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Projection		n/a	
Scale		n/a	
QA			
Final 10in1 figs.xls			
Produced by ABPmer Ltd.			

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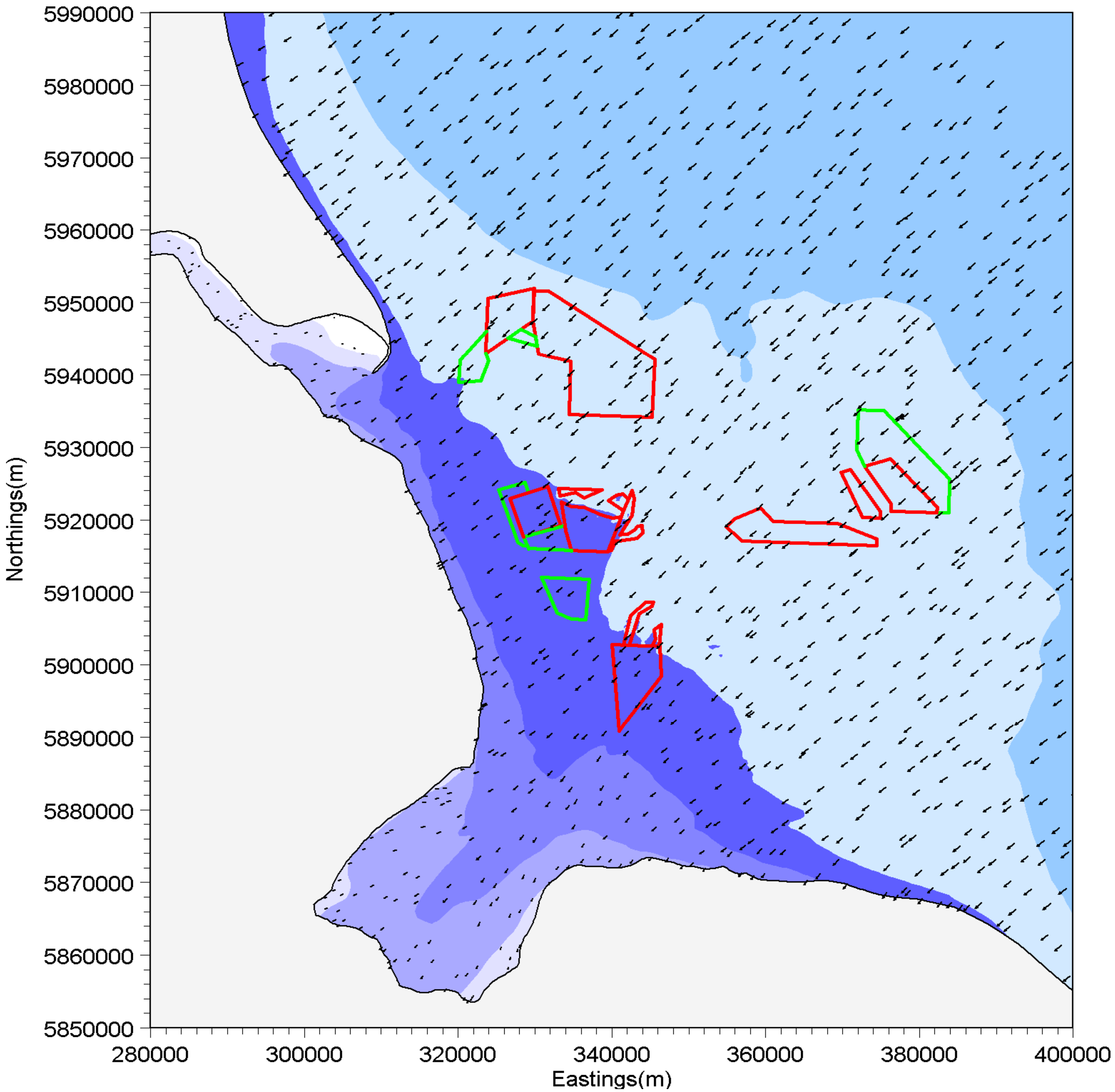
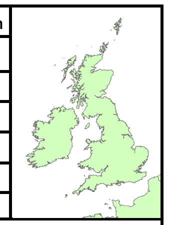
Wave height and direction at MHWS for 10 in 1yr NE wave (pre-dredging)

Figure 7.28



Date	By	Size	Version
Aug 11	BW	A3	1
Projection	n/a		
Scale	n/a		
QA			
Final 10in1 figs.xls			
Produced by ABPmer Ltd.			



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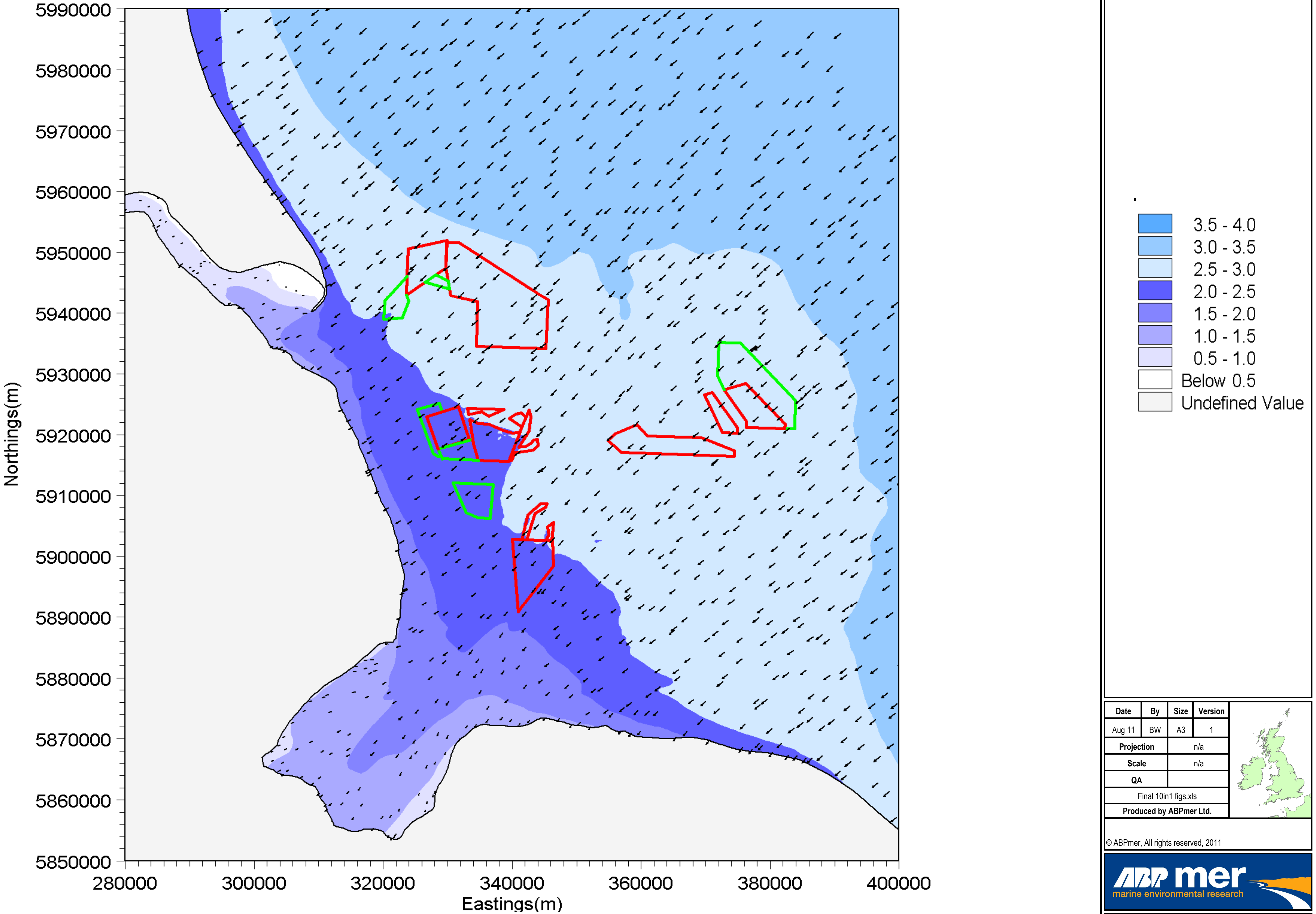
Wave height and direction at MHWS for 10 in 1yr NE wave (present)

Figure 7.29



Date	By	Size	Version
Aug 11	BW	A3	1
Projection		n/a	
Scale		n/a	
QA			
Final 10in1 figs.xls			
Produced by ABPmer Ltd.			

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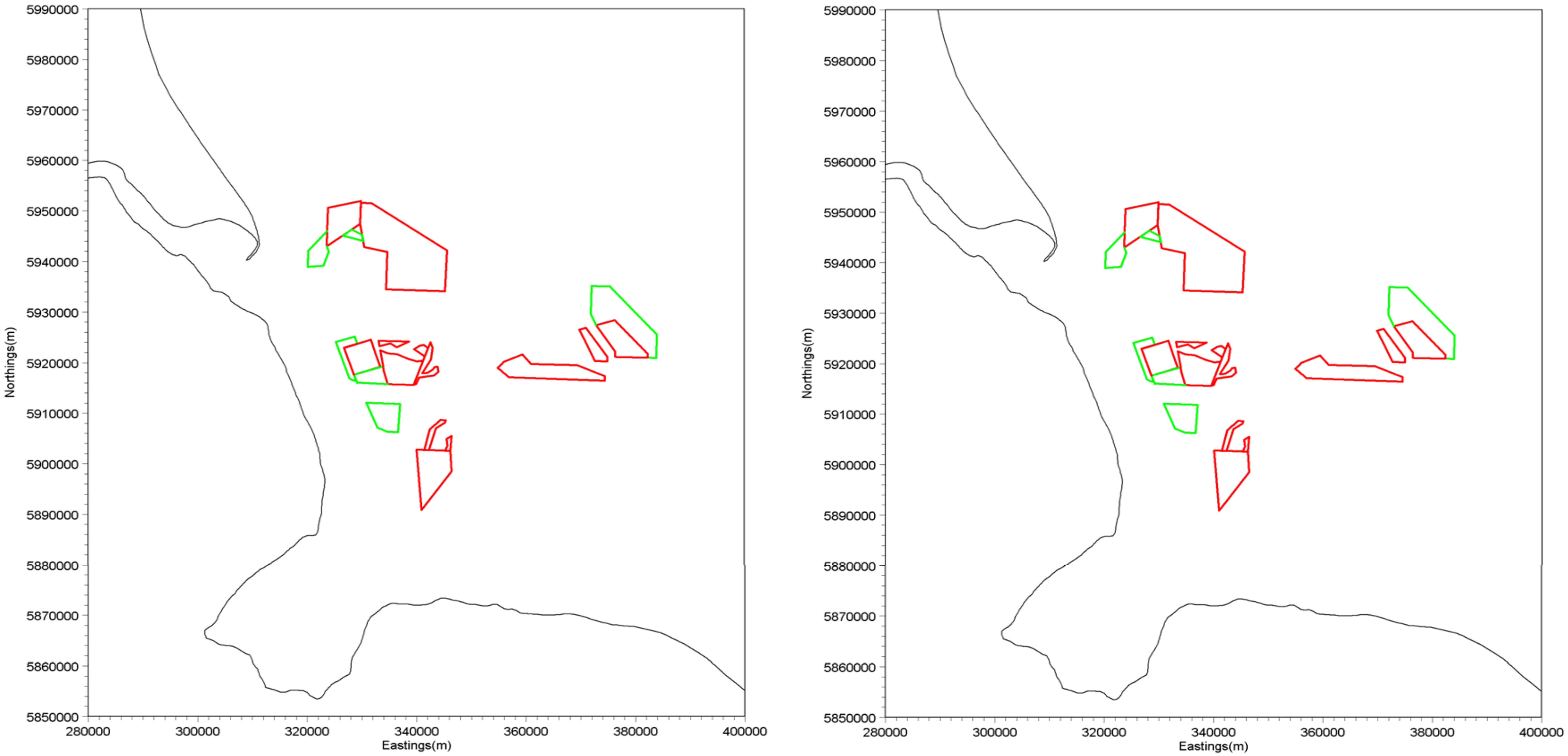
Wave height and direction at MHWS for 10 in 1yr NE wave (future)

Figure 7.30



(a)

(b)

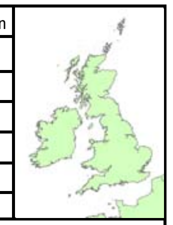
Change in Wave Height [m]

- Above 0.7
- 0.6 - 0.7
- 0.5 - 0.6
- 0.4 - 0.5
- 0.3 - 0.4
- 0.2 - 0.3
- 0.1 - 0.2
- -0.1 - 0.1
- -0.2 - -0.1
- -0.3 - -0.2
- -0.4 - -0.3
- -0.5 - -0.4
- -0.6 - -0.5
- -0.7 - -0.6
- Below -0.7
- Undefined Value

Change in Wave Height [%]

- Above 25
- 20 - 25
- 15 - 20
- 10 - 15
- 5 - 10
- 3 - 5
- 2 - 3
- -2 - 2
- -3 - -2
- -5 - -3
- -10 - -5
- -15 - -10
- -20 - -15
- -25 - -20
- Below -25
- Undefined Value

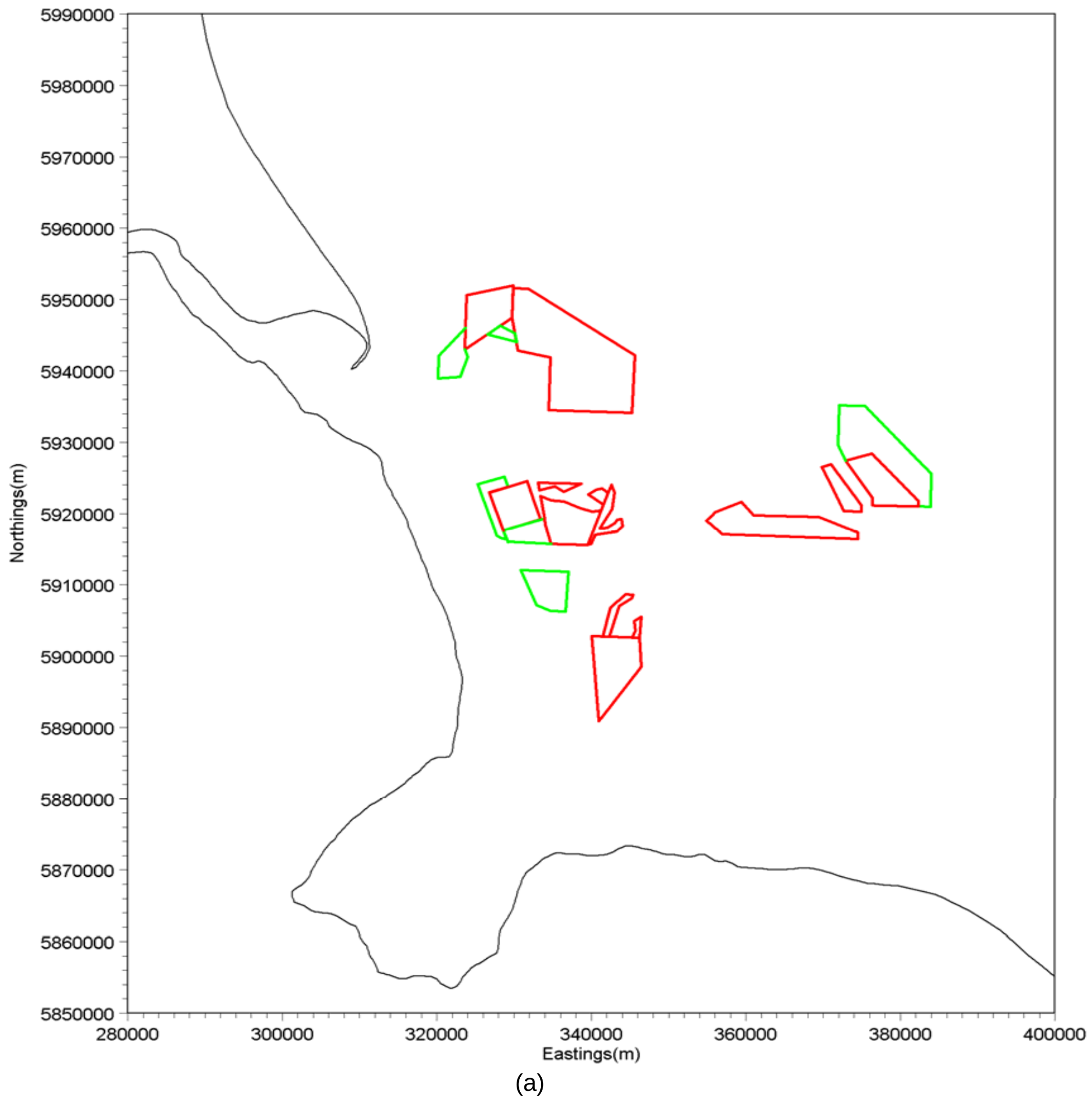
Date	By	Size	Version
Aug 11	BW	A3	1
Projection		n/a	
Scale		n/a	
QA			
Final_Revised_Figures_SW.xls			
Produced by ABPmer Ltd.			



ABP mer marine environmental research

Change in wave height at MHWS for 10 in 1yr NE wave (present minus pre-dredging) (a) absolute values (b) percentages

Figure 7.31



Change in Wave Height [m]

- Above 0.7
- 0.6 - 0.7
- 0.5 - 0.6
- 0.4 - 0.5
- 0.3 - 0.4
- 0.2 - 0.3
- 0.1 - 0.2
- -0.1 - 0.1
- -0.2 - -0.1
- -0.3 - -0.2
- -0.4 - -0.3
- -0.5 - -0.4
- -0.6 - -0.5
- -0.7 - -0.6
- Below -0.7
- Undefined Value

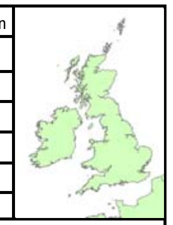
Change in Wave Height [%]

- Above 25
- 20 - 25
- 15 - 20
- 10 - 15
- 5 - 10
- 3 - 5
- 2 - 3
- -2 - 2
- -3 - -2
- -5 - -3
- -10 - -5
- -15 - -10
- -20 - -15
- -25 - -20
- Below -25
- Undefined Value

Date	By	Size	Version
Aug 11	BW	A3	1
Projection		n/a	
Scale		n/a	
QA			

Final_Revised_Figures_SW.xls

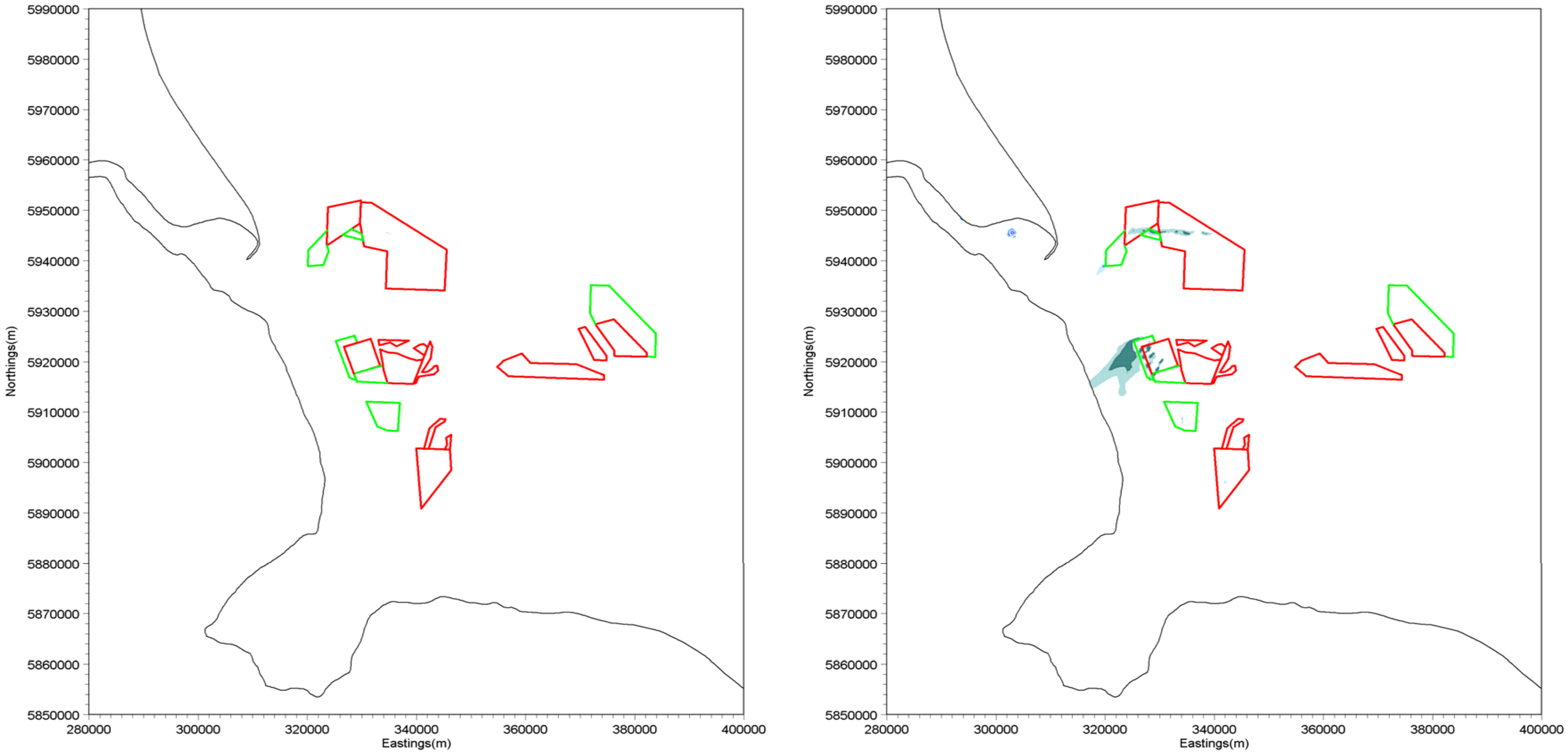
Produced by ABPmer Ltd.



ABP mer marine environmental research

Change in wave height at MLWS for 10 in 1yr NE wave (present minus pre-dredging) (a) absolute values (b) percentages

Figure 7.32



(a) (b)

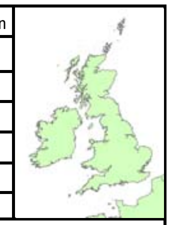
Change in Wave Height [m]

Above	0.7
0.6 -	0.7
0.5 -	0.6
0.4 -	0.5
0.3 -	0.4
0.2 -	0.3
0.1 -	0.2
-0.1 -	0.1
-0.2 -	-0.1
-0.3 -	-0.2
-0.4 -	-0.3
-0.5 -	-0.4
-0.6 -	-0.5
-0.7 -	-0.6
Below	-0.7
Undefined Value	

Change in Wave Height [%]

Above	25
20 -	25
15 -	20
10 -	15
5 -	10
3 -	5
2 -	3
-2 -	2
-3 -	-2
-5 -	-3
-10 -	-5
-15 -	-10
-20 -	-15
-25 -	-20
Below	-25
Undefined Value	

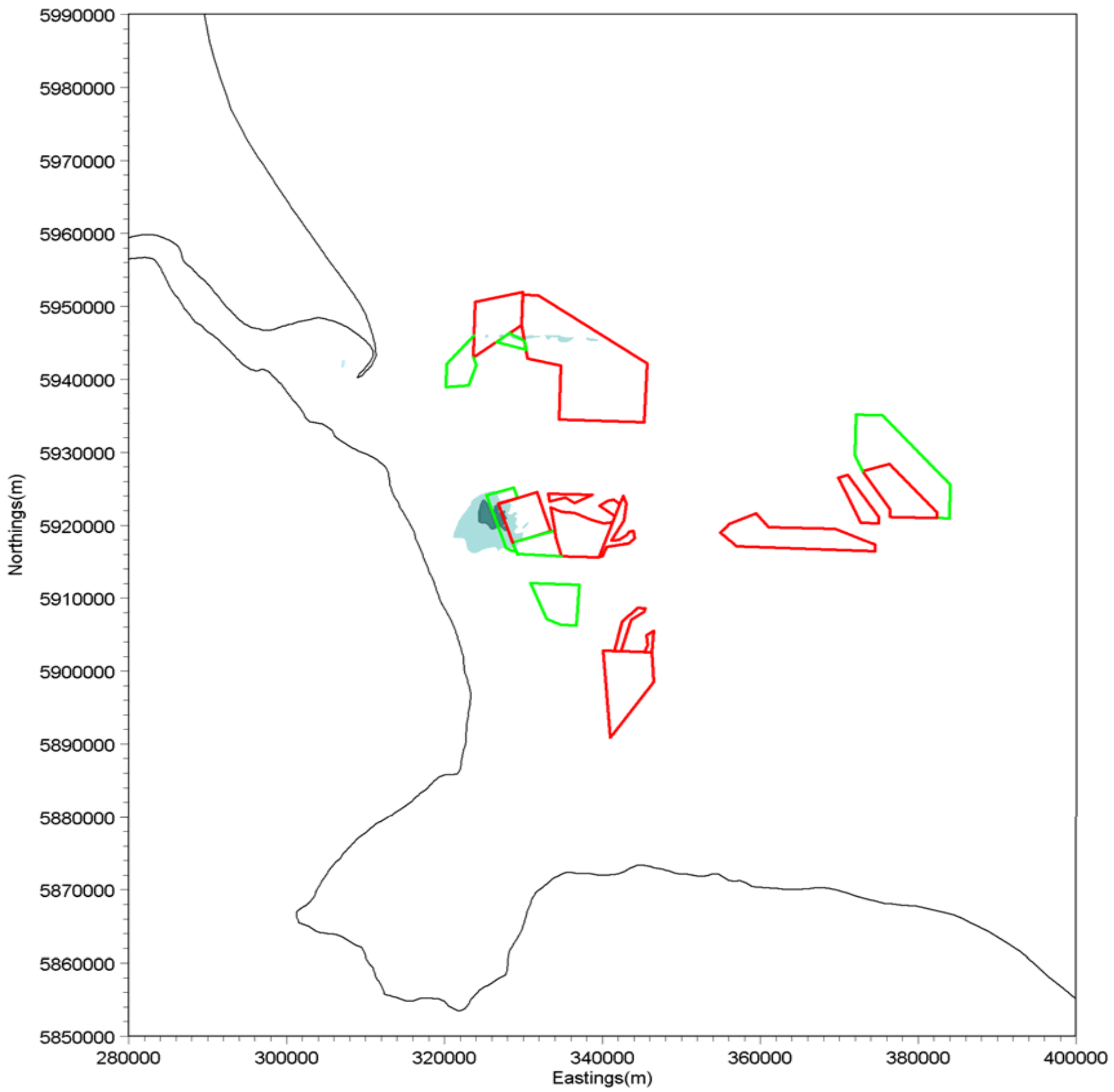
Date	By	Size	Version
Aug 11	BW	A3	1
Projection	n/a		
Scale	n/a		
QA			
Final_Revised_Figures_SW.xls			
Produced by ABPmer Ltd.			



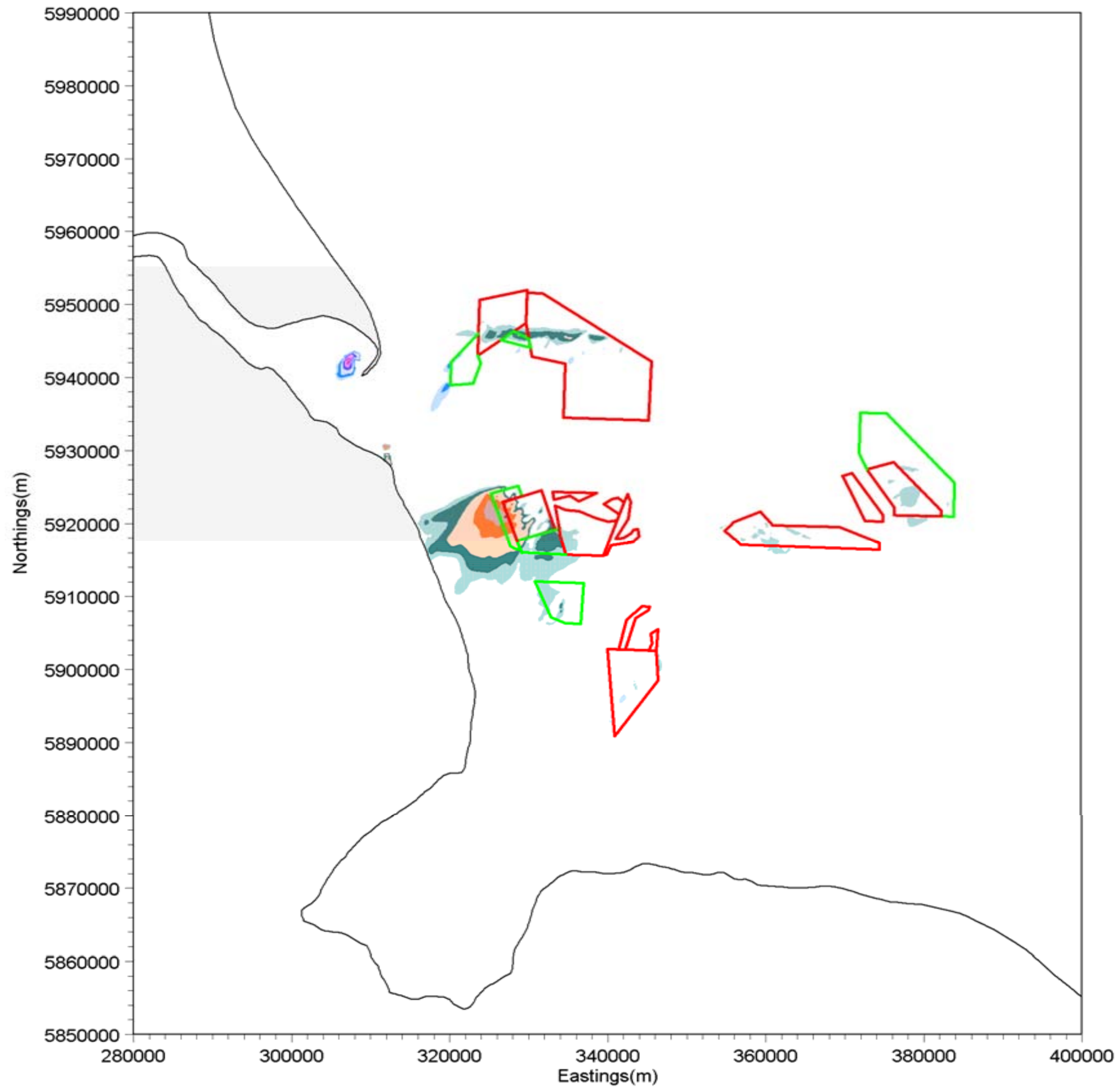
ABP mer marine environmental research

Change in wave height at MHWS for 10 in 1yr NE wave (future minus present)
(a) absolute values (b) percentages

Figure 7.33



(a)



(b)

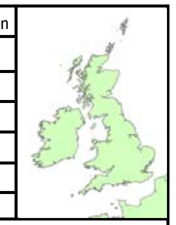
Change in Wave Height [m]

- Above 0.7
- 0.6 - 0.7
- 0.5 - 0.6
- 0.4 - 0.5
- 0.3 - 0.4
- 0.2 - 0.3
- 0.1 - 0.2
- -0.1 - 0.1
- -0.2 - -0.1
- -0.3 - -0.2
- -0.4 - -0.3
- -0.5 - -0.4
- -0.6 - -0.5
- -0.7 - -0.6
- Below -0.7
- Undefined Value

Change in Wave Height [%]

- Above 25
- 20 - 25
- 15 - 20
- 10 - 15
- 5 - 10
- 3 - 5
- 2 - 3
- -2 - 2
- -3 - -2
- -5 - -3
- -10 - -5
- -15 - -10
- -20 - -15
- -25 - -20
- Below -25
- Undefined Value

Date	By	Size	Version
Aug 11	BW	A3	1
Projection		n/a	
Scale		n/a	
QA			
Final_Revised_Figures_SW.xls			
Produced by ABPmer Ltd.			



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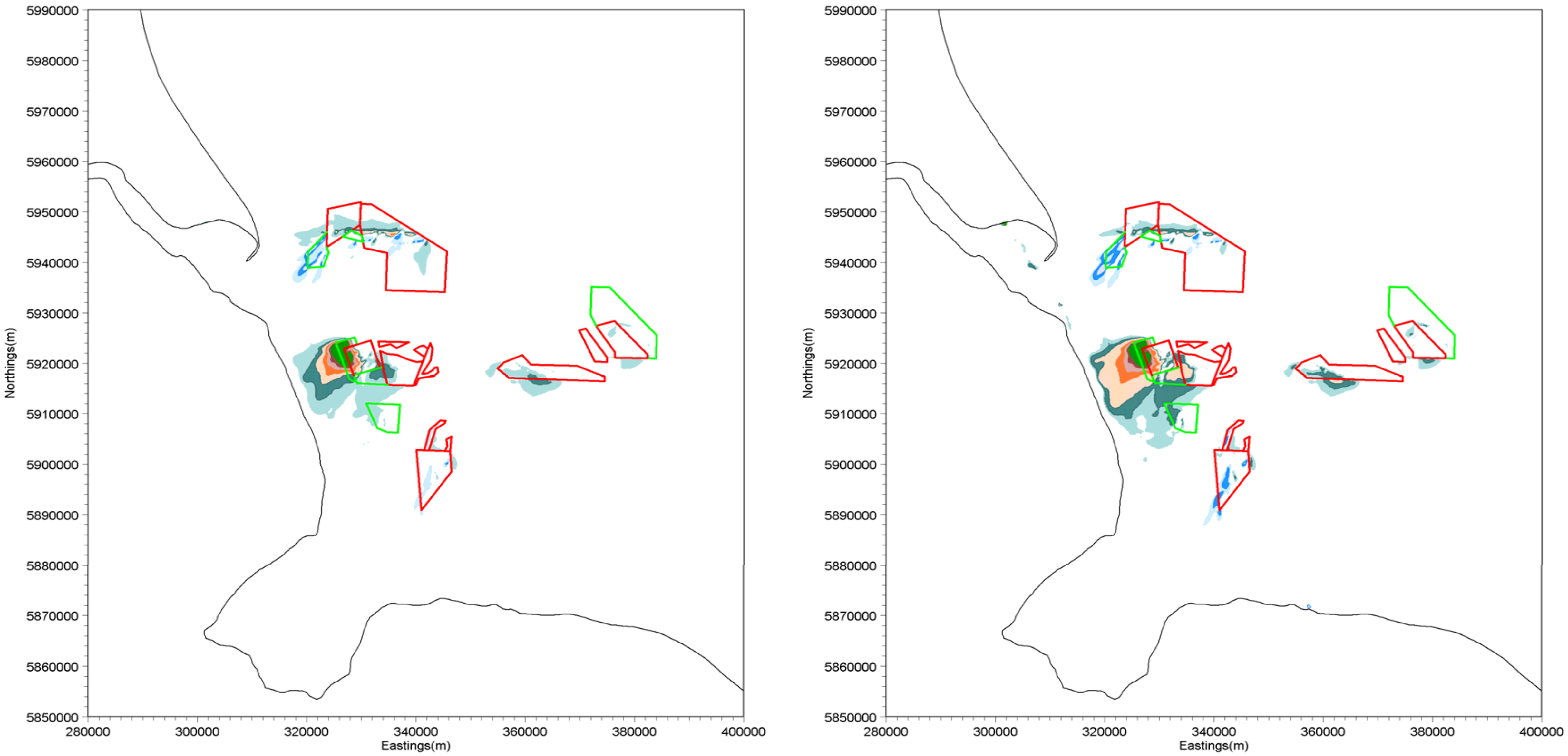
Change in wave height at MLWS for 10 in 1yr NE wave (future minus present)
(a) absolute values (b) percentages

Figure 7.34



(a) (b)

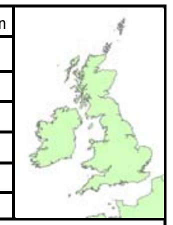
Change in Wave Height [m]

Above	0.7
0.6 -	0.7
0.5 -	0.6
0.4 -	0.5
0.3 -	0.4
0.2 -	0.3
0.1 -	0.2
-0.1 -	0.1
-0.2 -	-0.1
-0.3 -	-0.2
-0.4 -	-0.3
-0.5 -	-0.4
-0.6 -	-0.5
-0.7 -	-0.6
Below	-0.7
Undefined Value	

Change in Wave Height [%]

Above	25
20 -	25
15 -	20
10 -	15
5 -	10
3 -	5
2 -	3
-2 -	2
-3 -	-2
-5 -	-3
-10 -	-5
-15 -	-10
-20 -	-15
-25 -	-20
Below	-25
Undefined Value	

Date	By	Size	Version
Aug 11	BW	A3	1
Projection		n/a	
Scale		n/a	
QA			
Final_Climate_Waves.xls			
Produced by ABPmer Ltd.			



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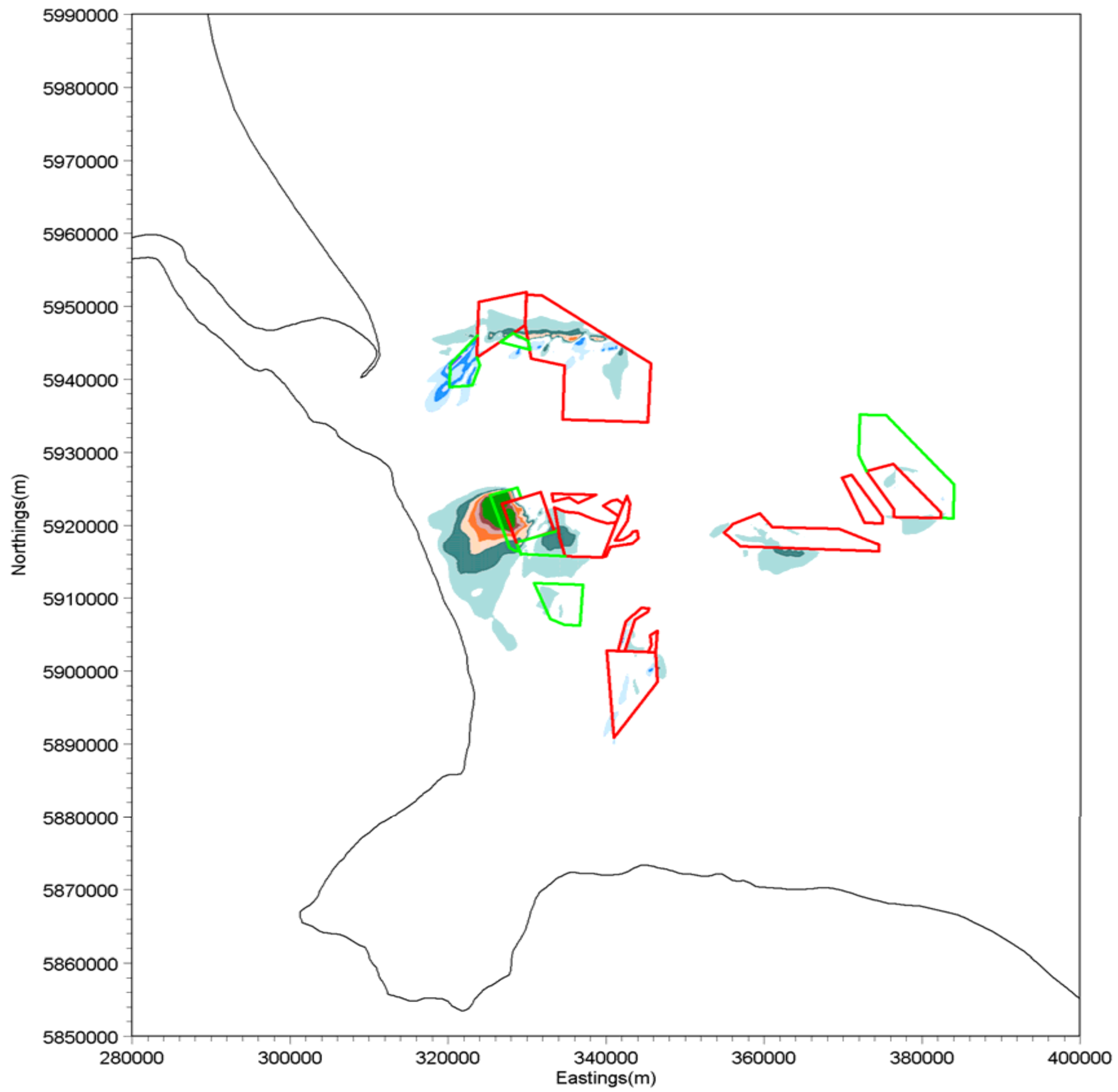
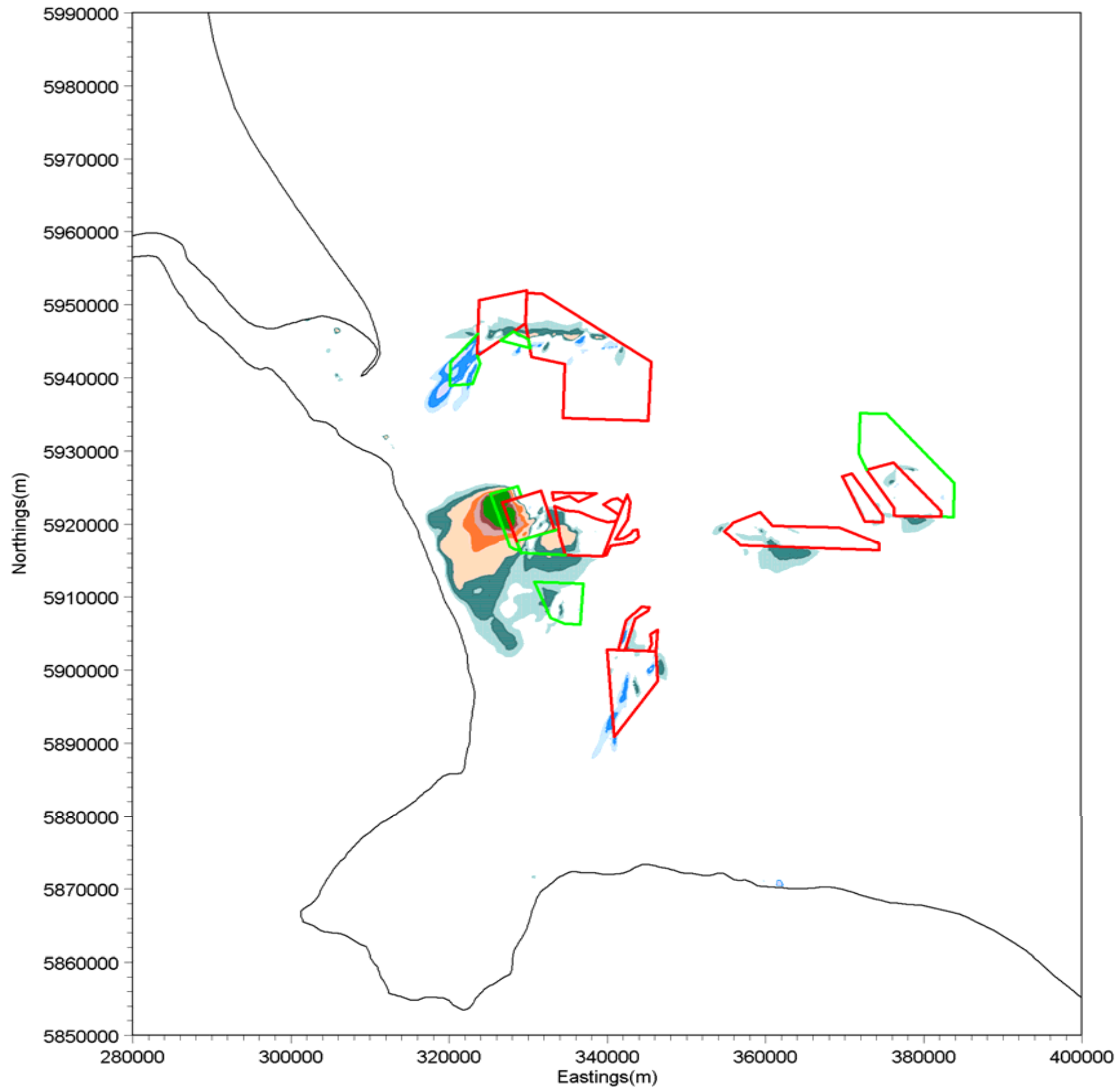
Change in wave height at MLWS for 1 in 200yr NE wave (+5%)
(future minus present)
(a) absolute values (b) percentages

Figure 7.35



(a)



(b)

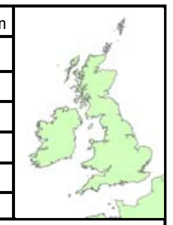
Change in Wave Height [m]

Above	0.7
0.6 -	0.7
0.5 -	0.6
0.4 -	0.5
0.3 -	0.4
0.2 -	0.3
0.1 -	0.2
-0.1 -	0.1
-0.2 -	-0.1
-0.3 -	-0.2
-0.4 -	-0.3
-0.5 -	-0.4
-0.6 -	-0.5
-0.7 -	-0.6
Below	-0.7
Undefined Value	

Change in Wave Height [%]

Above	25
20 -	25
15 -	20
10 -	15
5 -	10
3 -	5
2 -	3
-2 -	2
-3 -	-2
-5 -	-3
-10 -	-5
-15 -	-10
-20 -	-15
-25 -	-20
Below	-25
Undefined Value	

Date	By	Size	Version
Aug 11	BW	A3	1
Projection		n/a	
Scale		n/a	
QA			
Final_Climate_Waves.xls			
Produced by ABPmer Ltd.			



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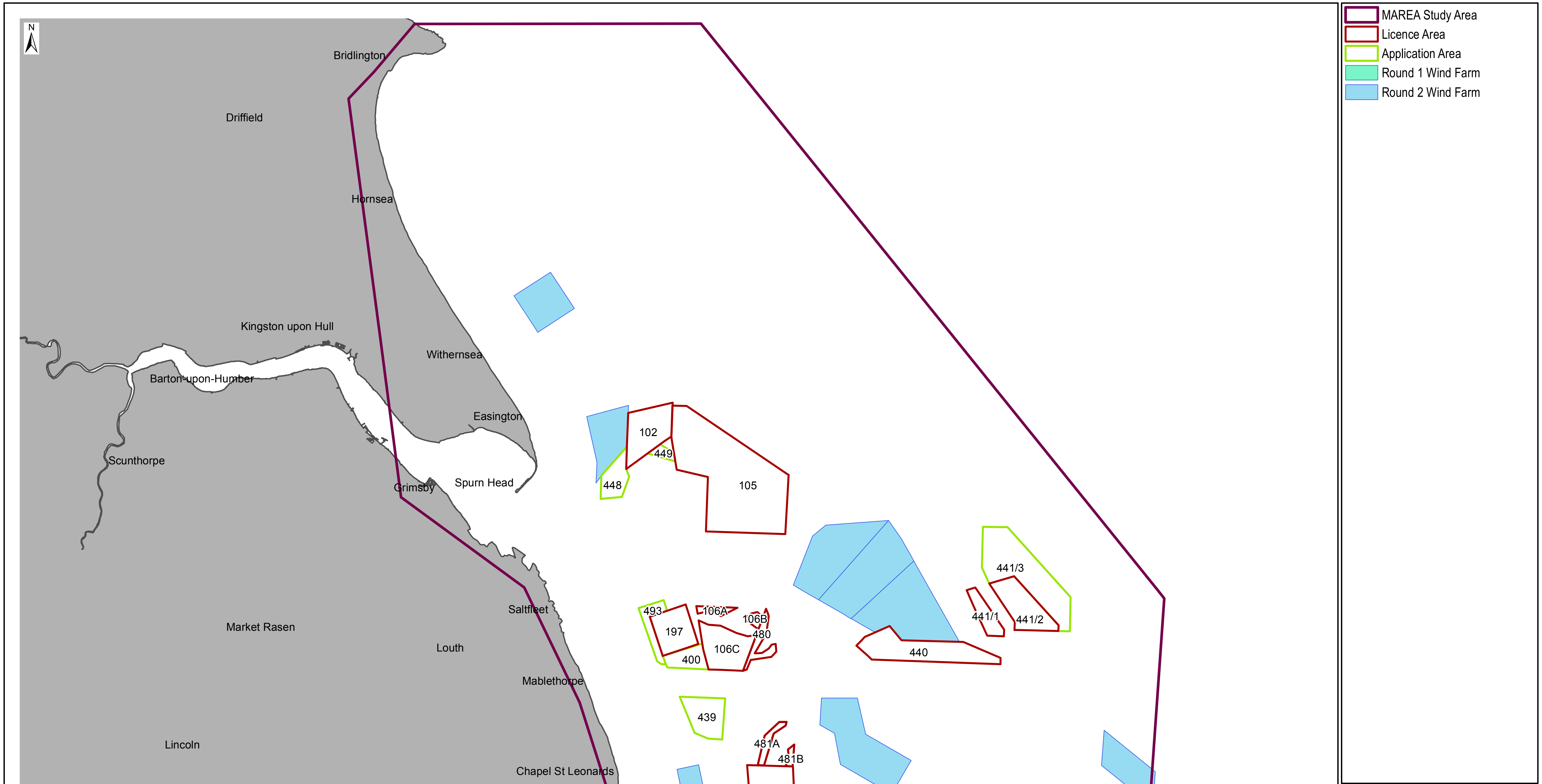
Change in wave Height at MLWS for 1 in 200yr NE wave (+10%)
(future minus present)
(a) absolute values (b) percentages

Figure 7.36



Date	By	Size	Version
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Scale		1:532,689	
QA		FMM	
3965 - fig7.37_OWF_Aggregates.mxd			
Produced by ABPmer Ltd			

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Offshore Windfarms and Marine Aggregates

Figure 7.37

Date	By	Size	Version
Aug 11	NJG	A3	2
Projection		WGS84 UTM31	
Scale		1:540,000	
QA		MCE	

3965 - fig_7.38_SedTransPaths.mxd

Produced by ABPmer Ltd

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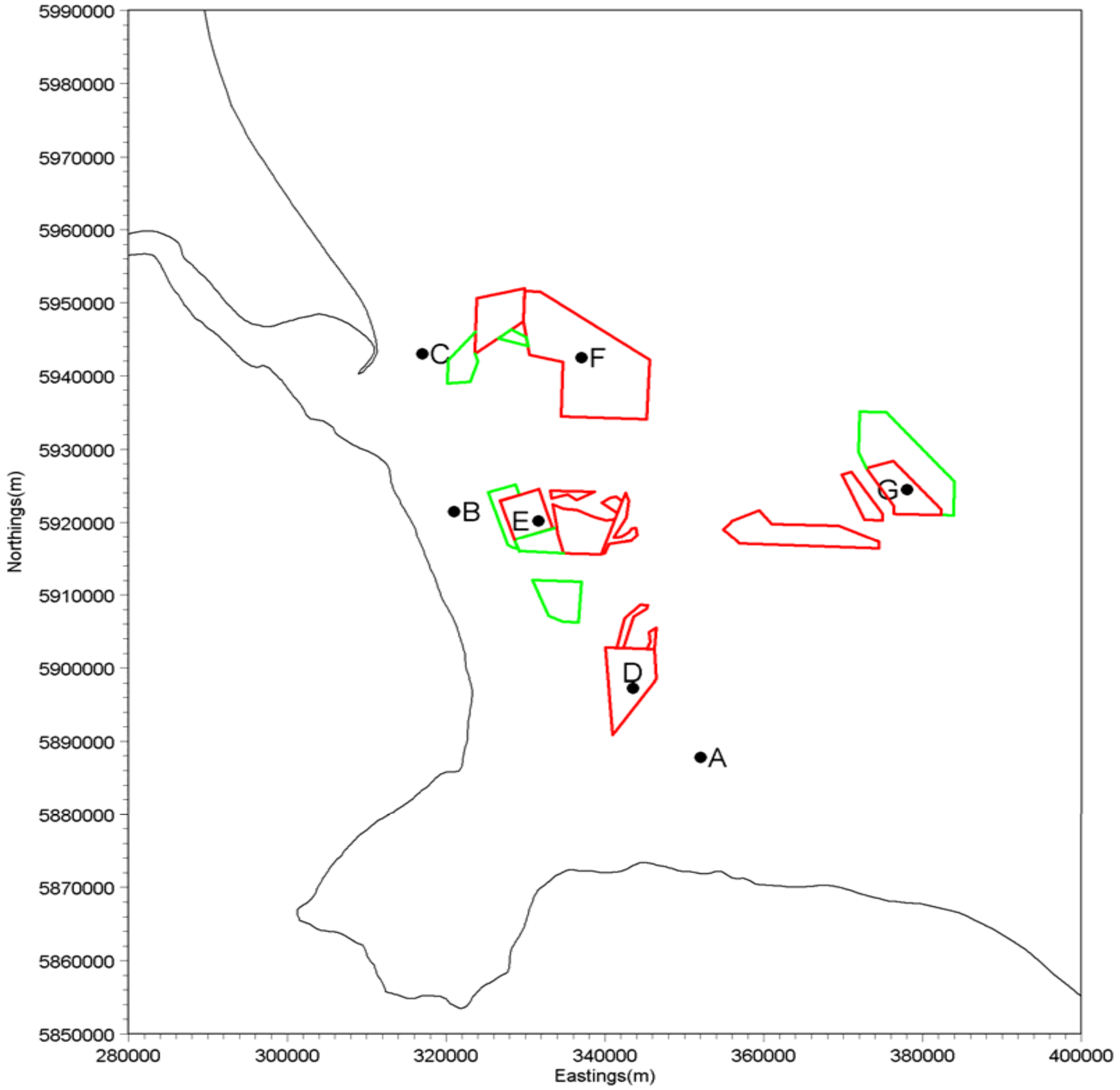
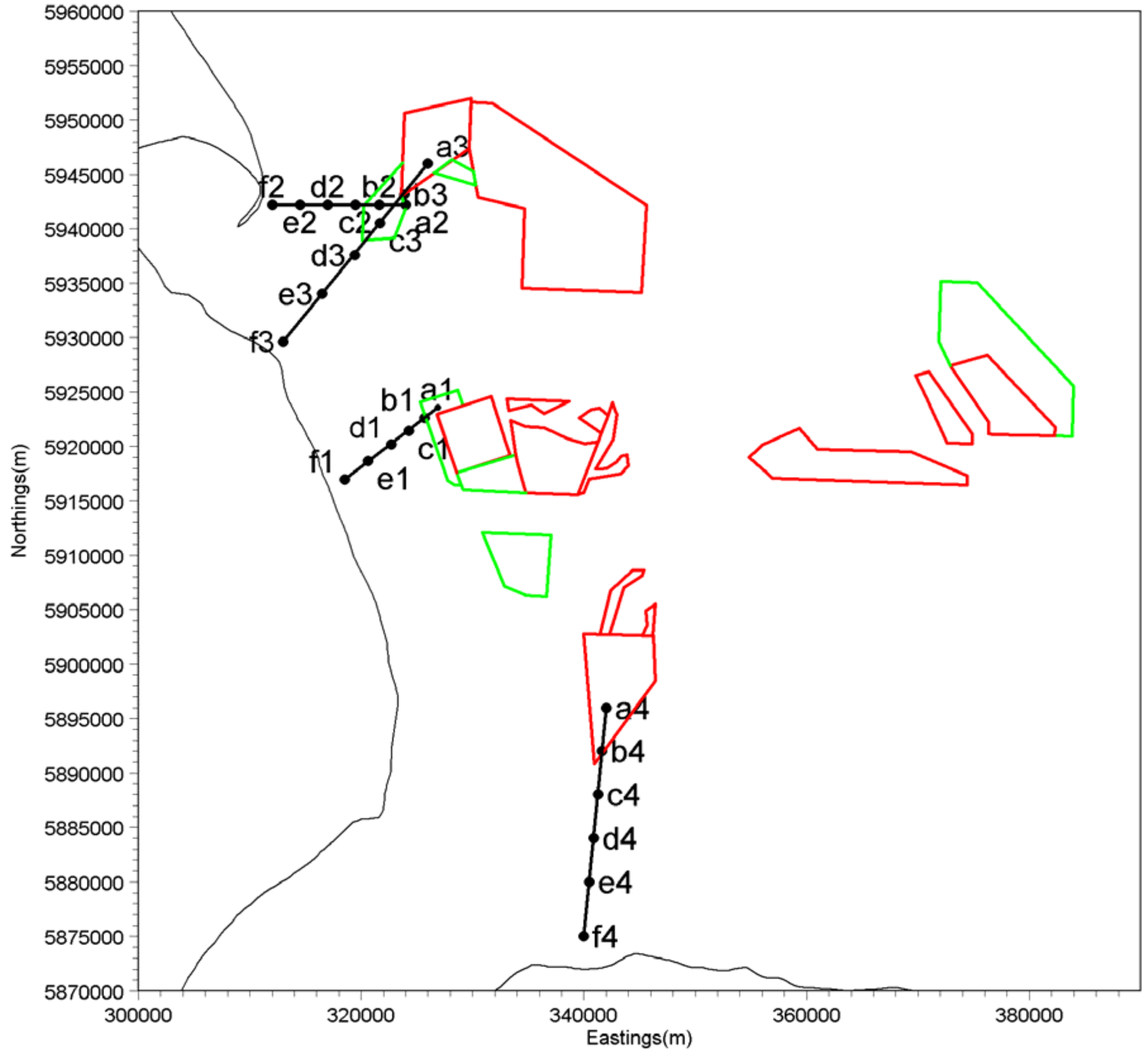
Bedload Sediment Transport Pathways

Figure 7.38



(a)



(b)

Date	By	Size	Version
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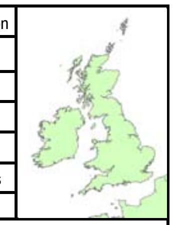
Scale		n/a	
QA			
Final_Revised_Figures37_SW.xls			
Produced by ABPmer Ltd.			



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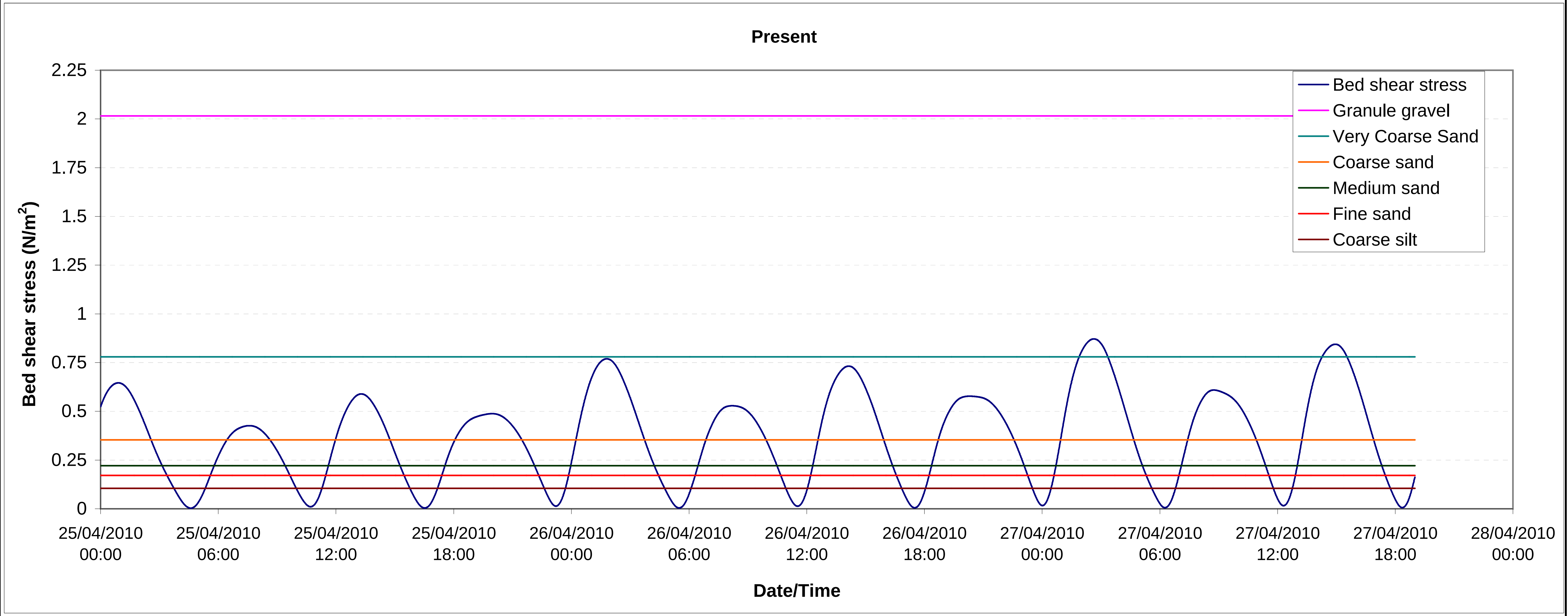
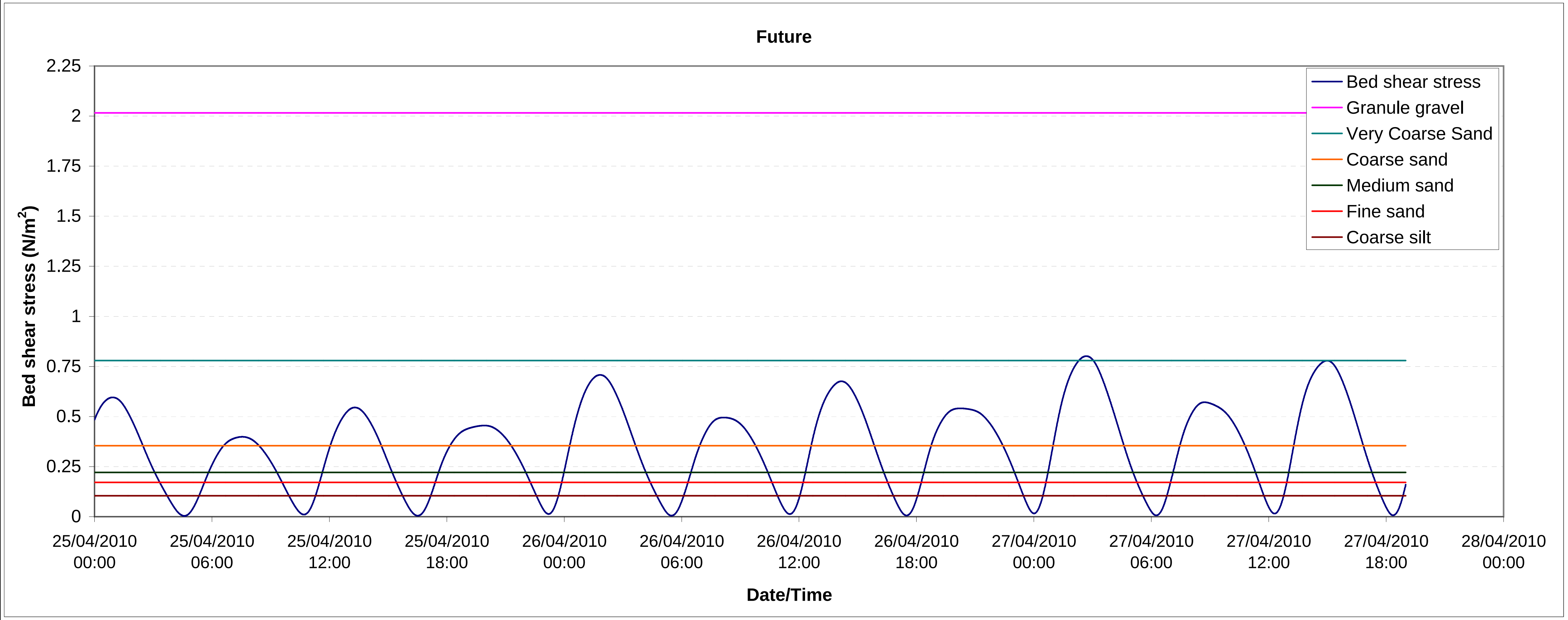
Location of analysis points
a)Currents b)Waves

Figure 7.39

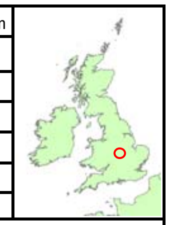




Date	By	Size	Version
Aug 11		A3	
Projection		n/a	
Scale		n/a	
QA			

Sediment Transport Figures.xls

Produced by ABPmer Ltd.



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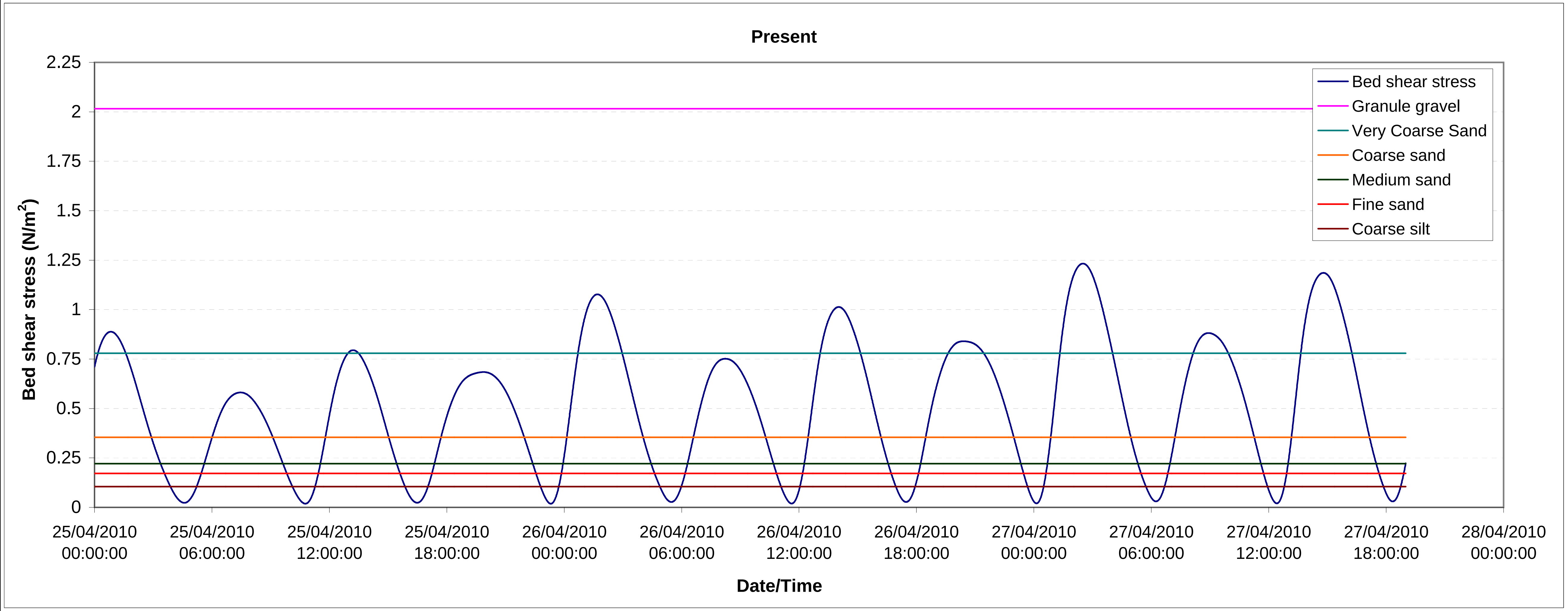
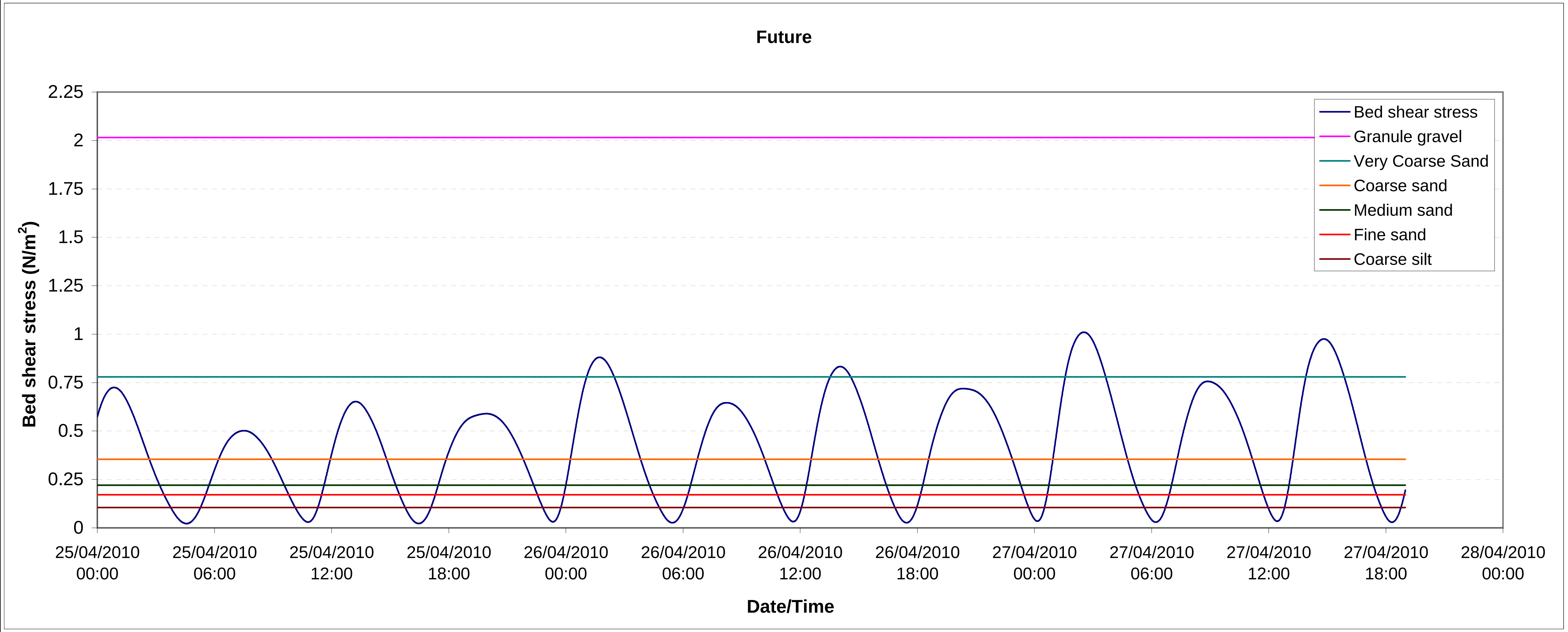
Spring tidal current bed shear stress variability
Point B (Present and Future)

Figure 7.40





Date	By	Size	Version
Aug 11	AJH	A3	1
Projection		n/a	
Scale		n/a	
QA			
Sediment Transport Figures.xls			
Produced by ABPmer Ltd.			

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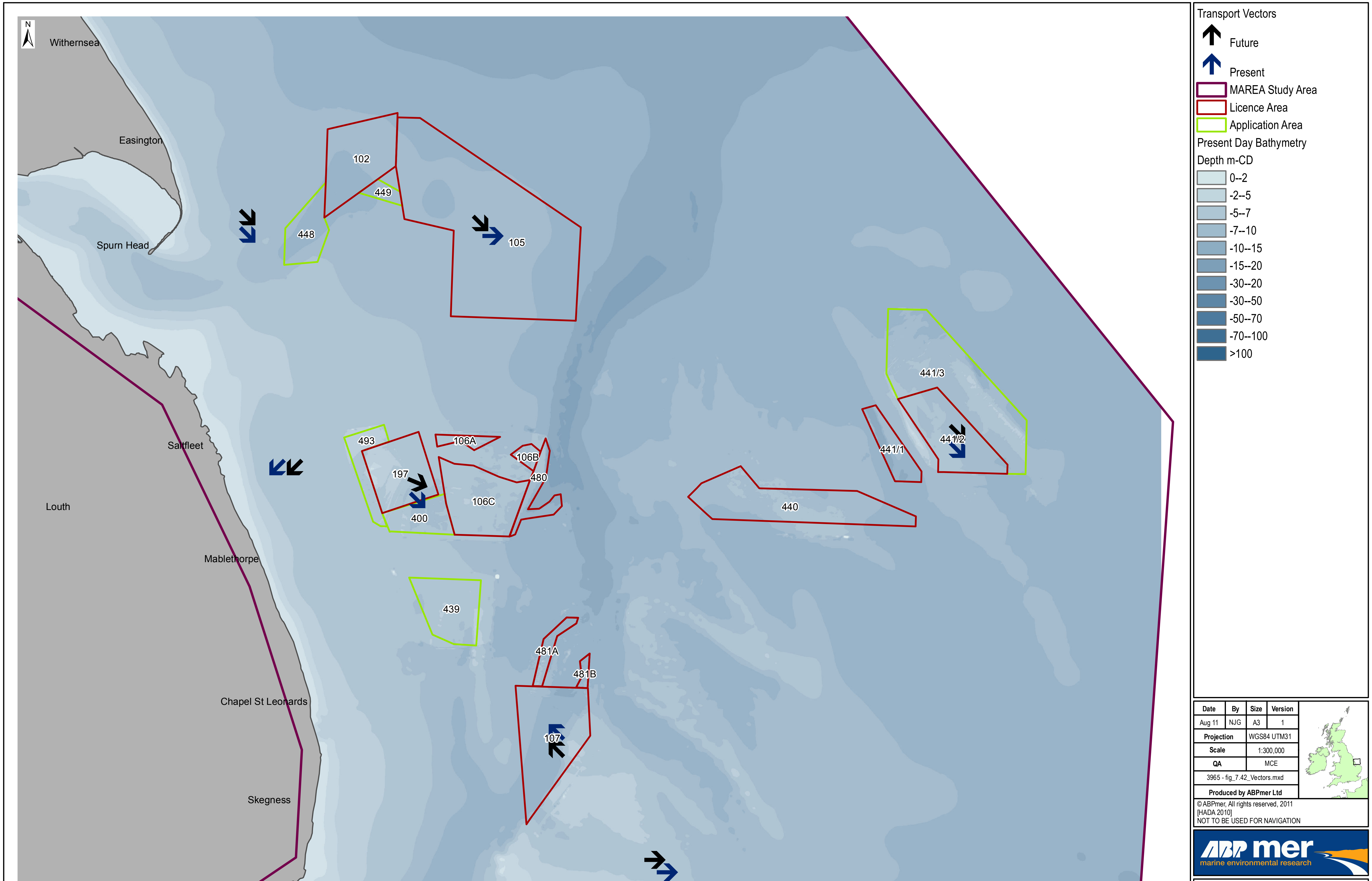
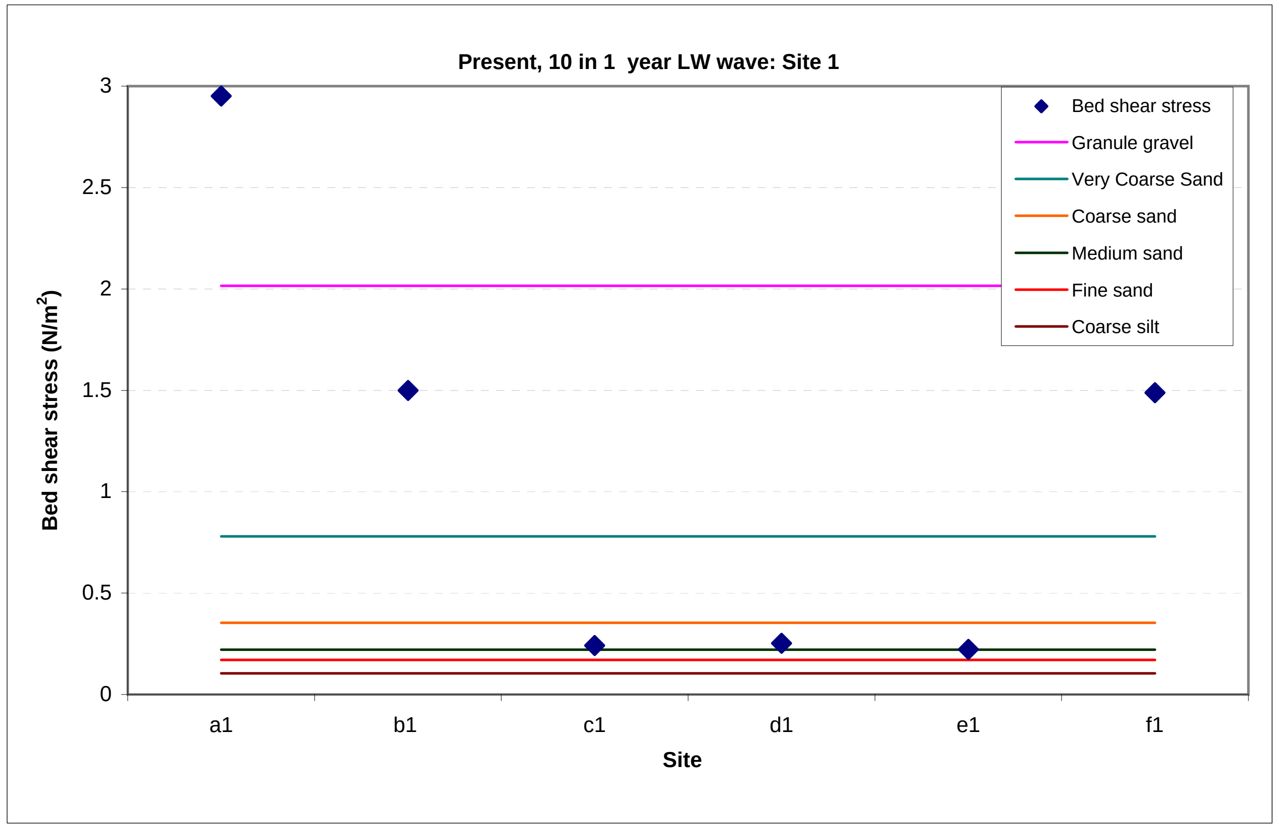
Spring tidal current bed shear stress variability
Point E (Present and Future)

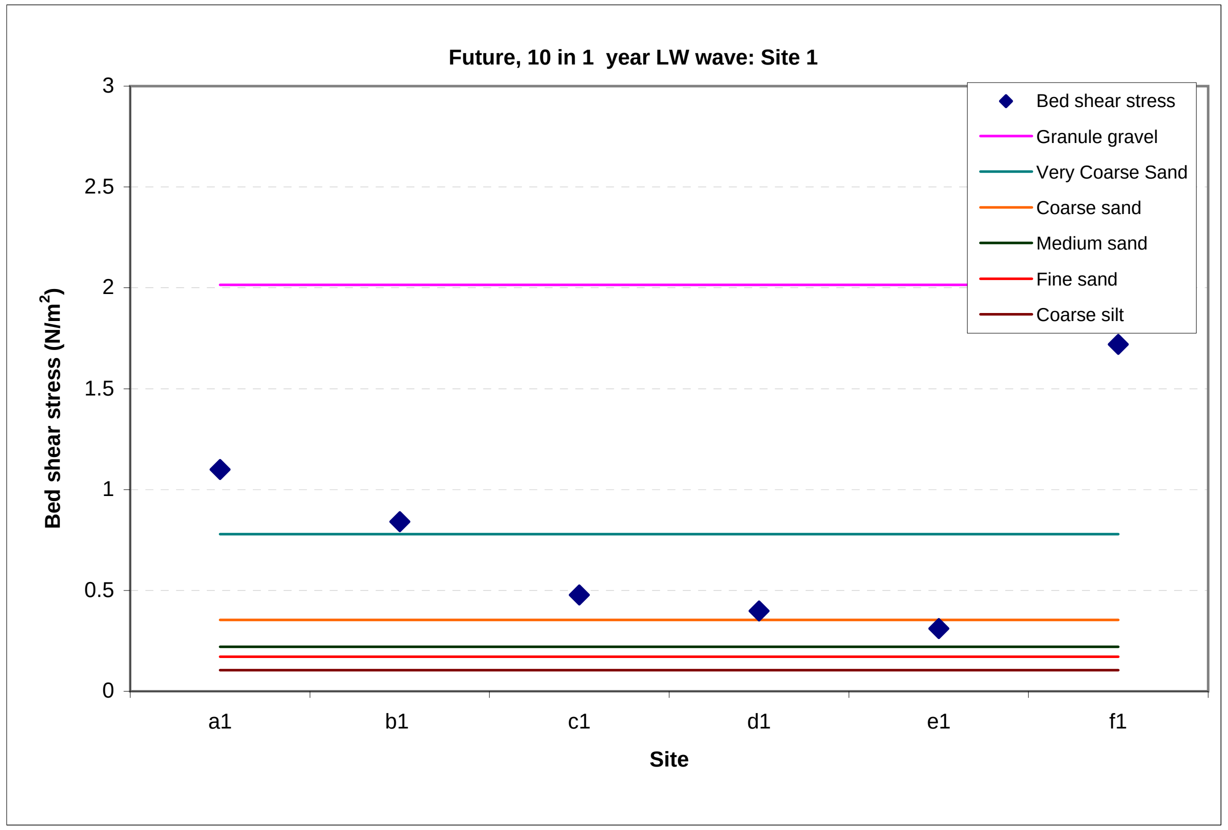
Figure 7.41

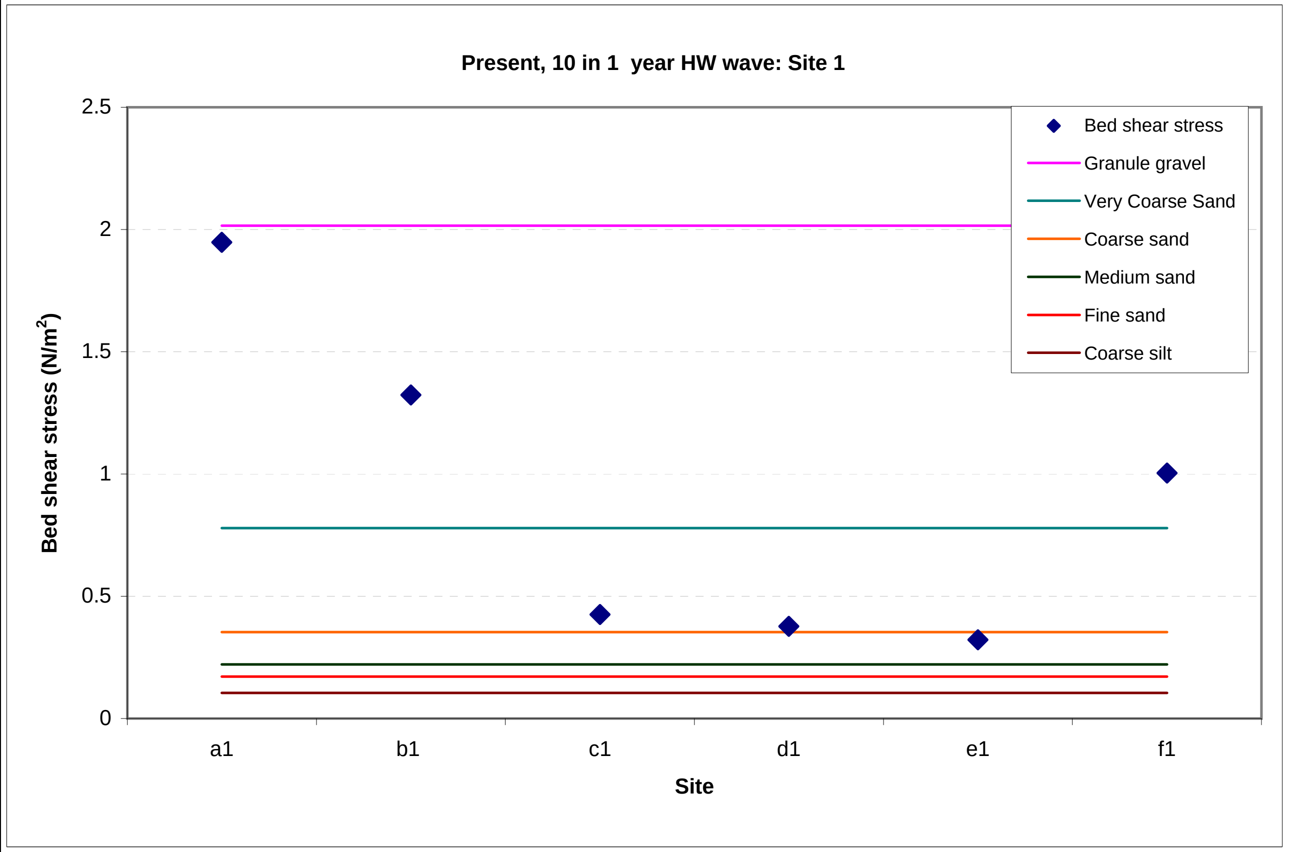


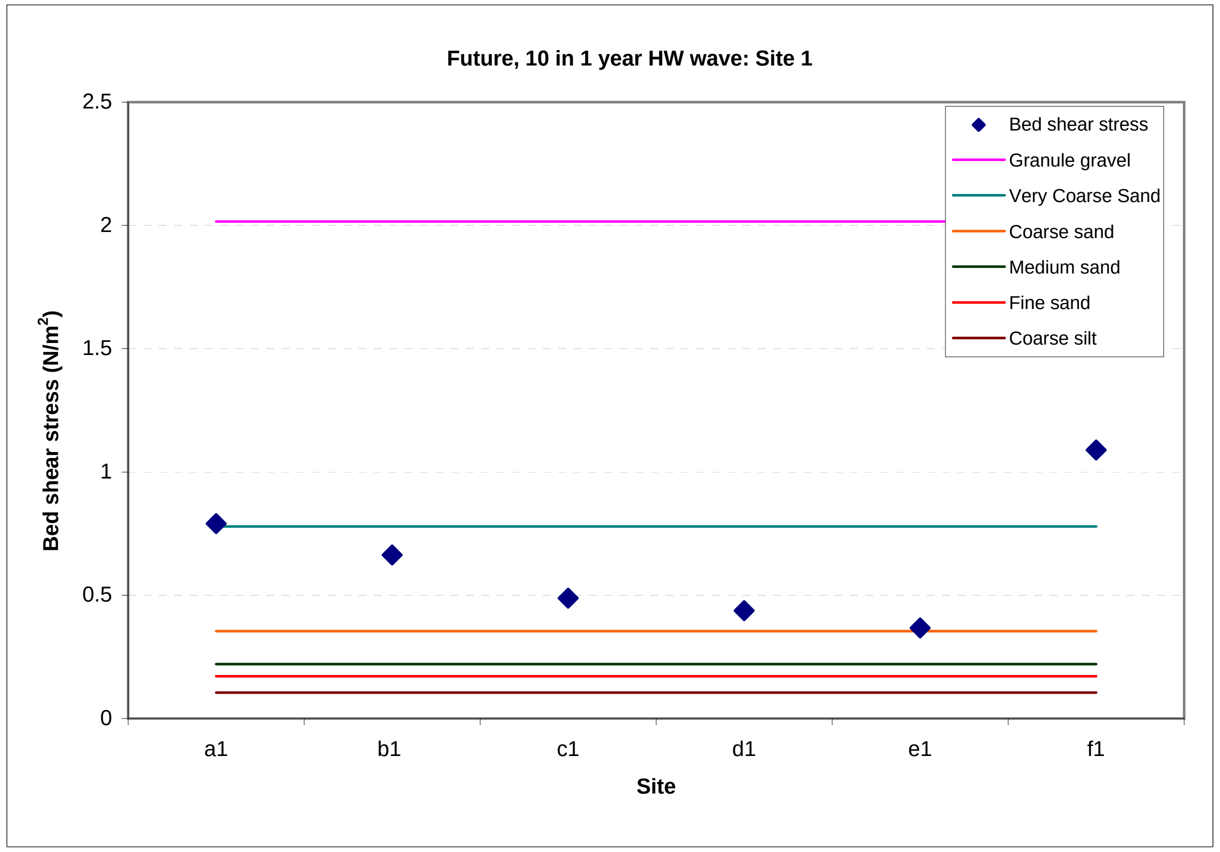
Progressive Vector Analysis

Figure 7.42









Date	By	Size	Version
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Scale	n/a		
QA			
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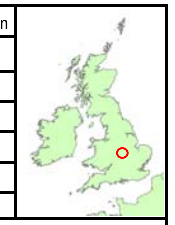
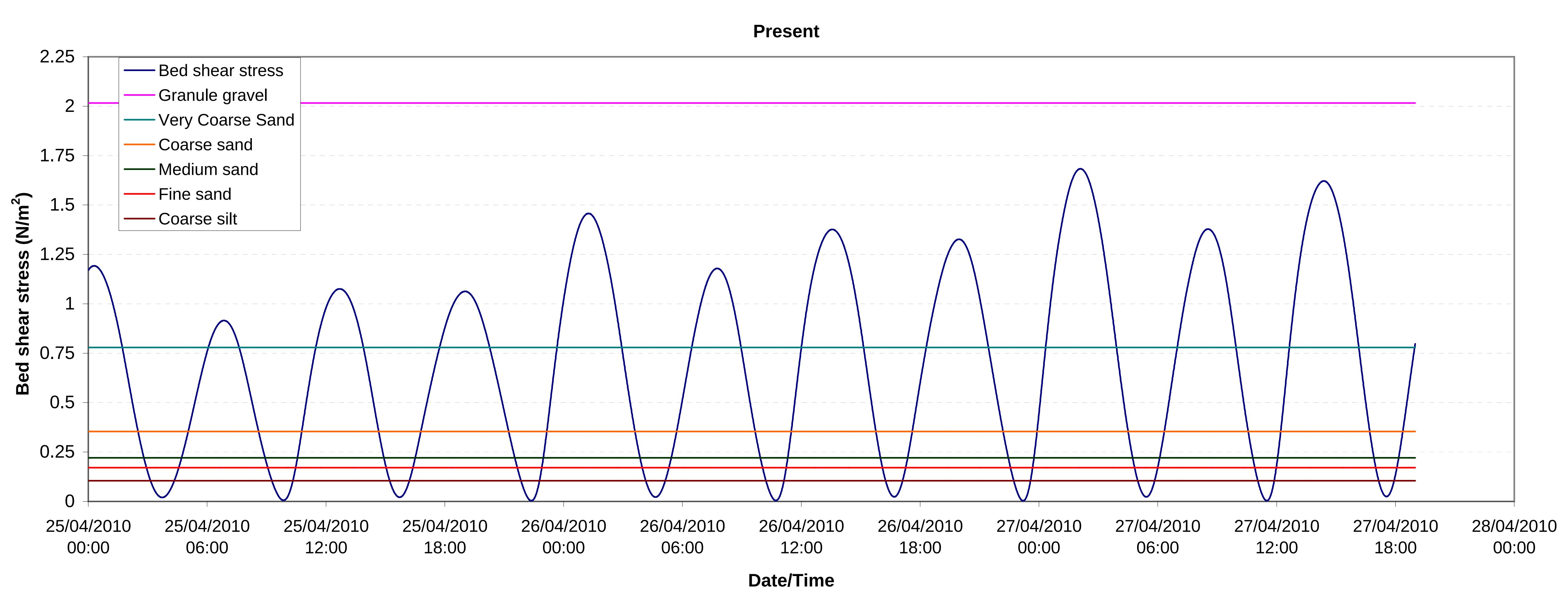
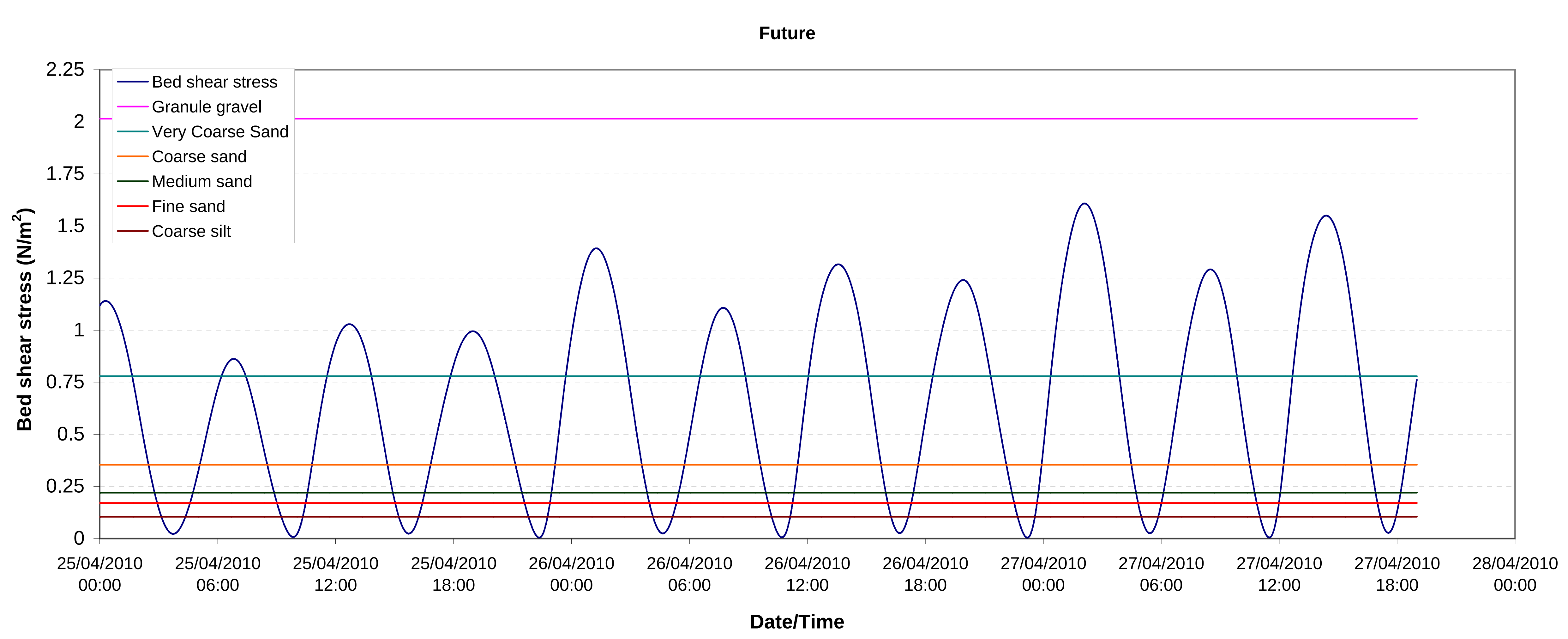
Produced by ABPmer Ltd.			



Wave induced bed shear stress - Zone 1 (Present and Future)

Figure 7.43





Date	By	Size	Version
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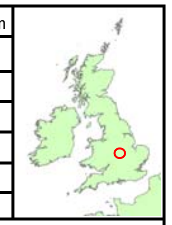
Projection		n/a	
Scale		n/a	
QA			
Sediment Transport Figures.xls			
Produced by ABPmer Ltd.			



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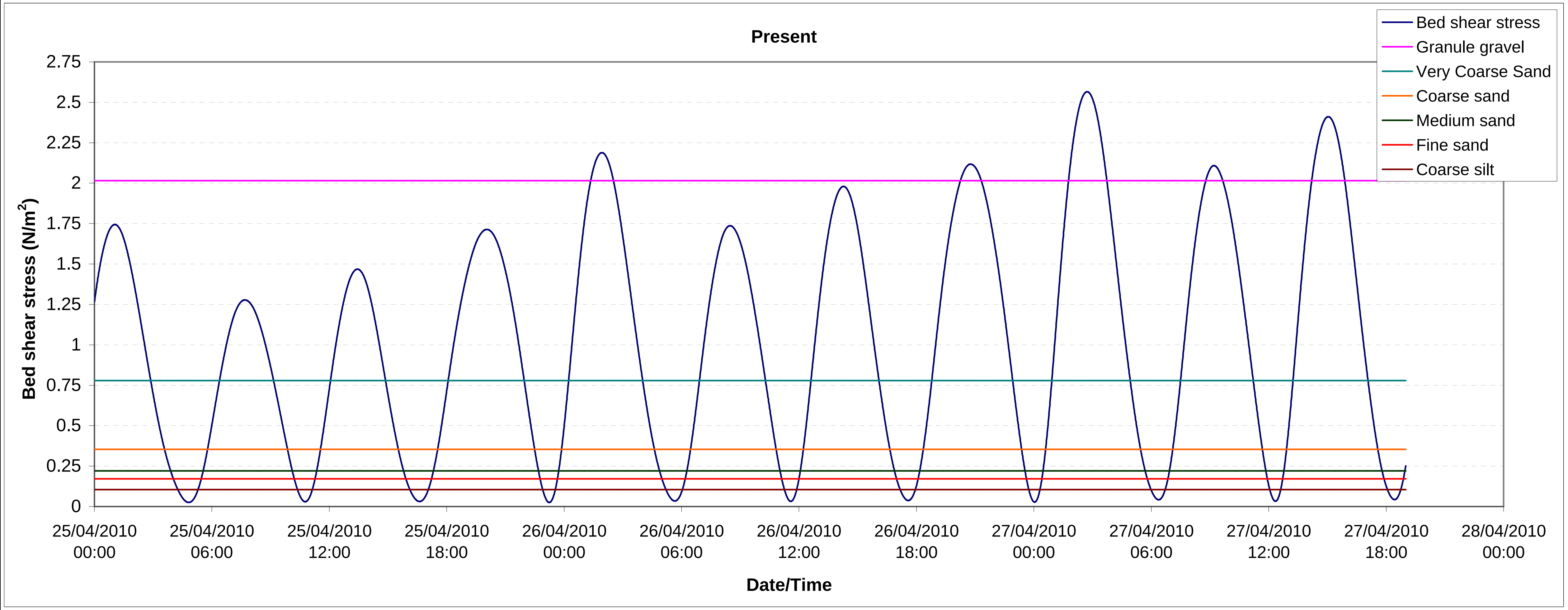
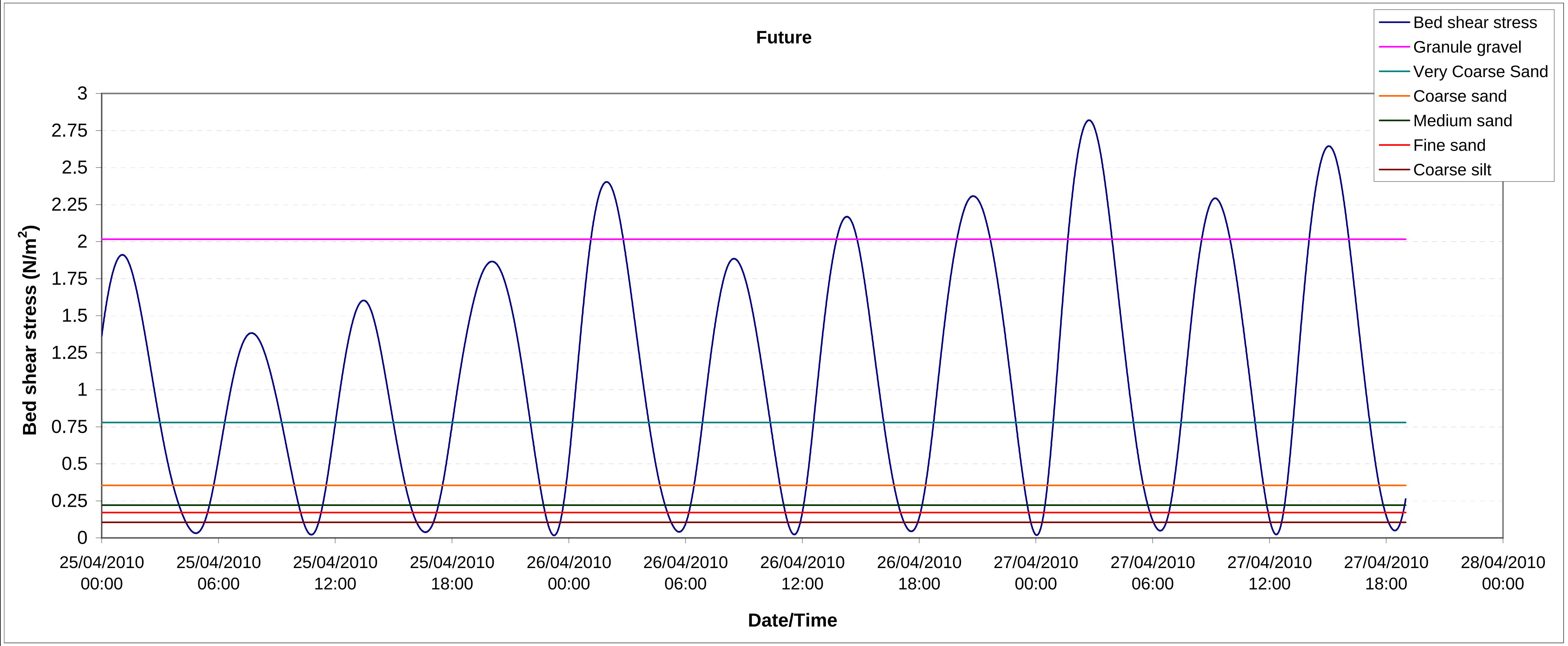
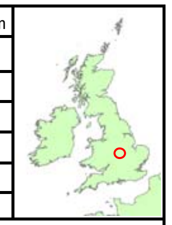
Spring tidal current bed shear stress variability Point C (Present and Future)

Figure 7.44





Date	By	Size	Version
Aug 11	AJH	A3	1
Projection	n/a		
Scale	n/a		
QA			
Sediment Transport Figures.xls			
Produced by ABPmer Ltd.			



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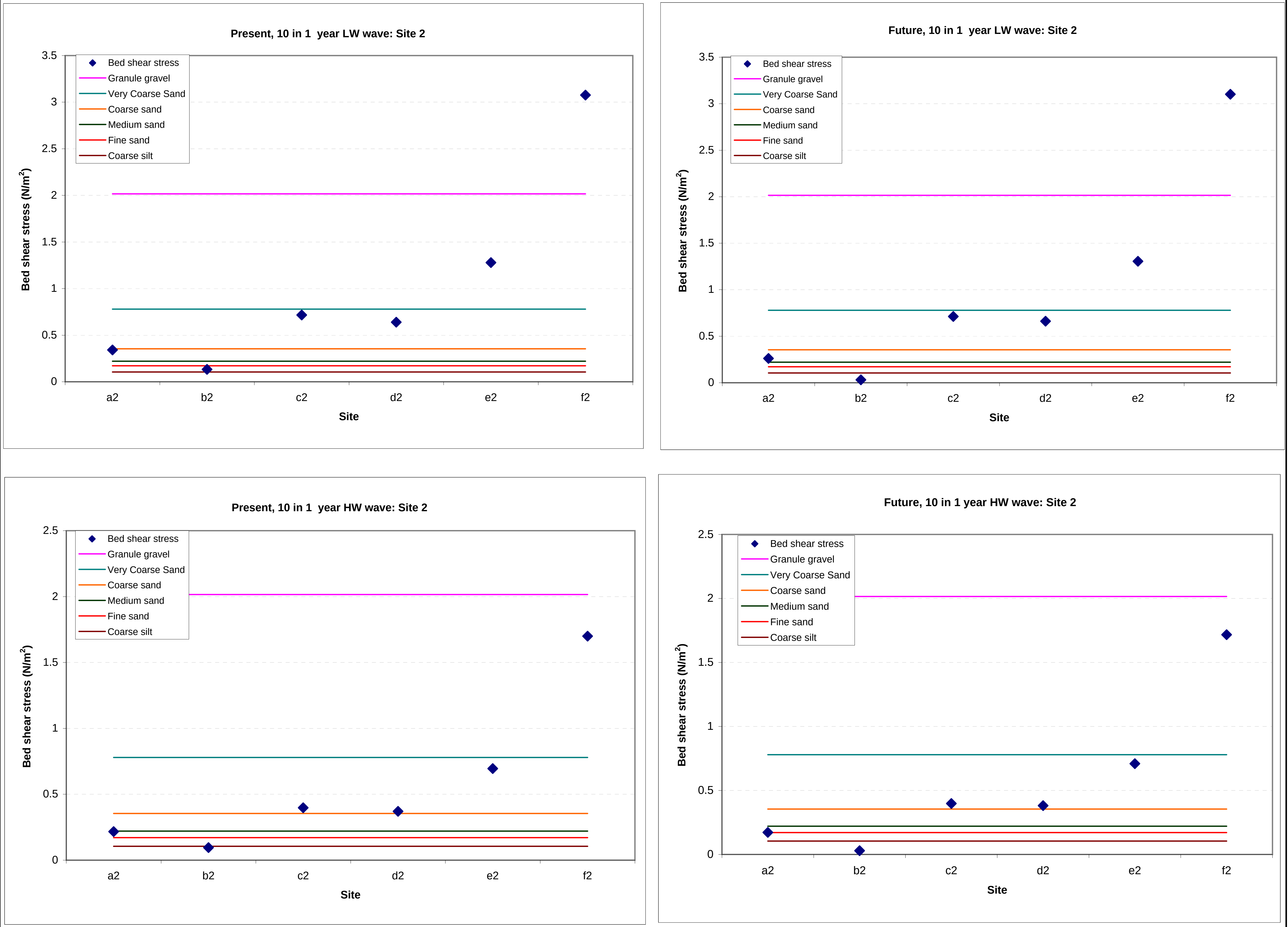
Spring tidal current bed shear stress variability
Point F (Present and Future)

Figure 7.45



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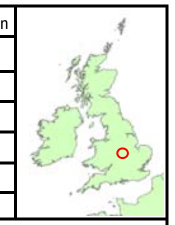

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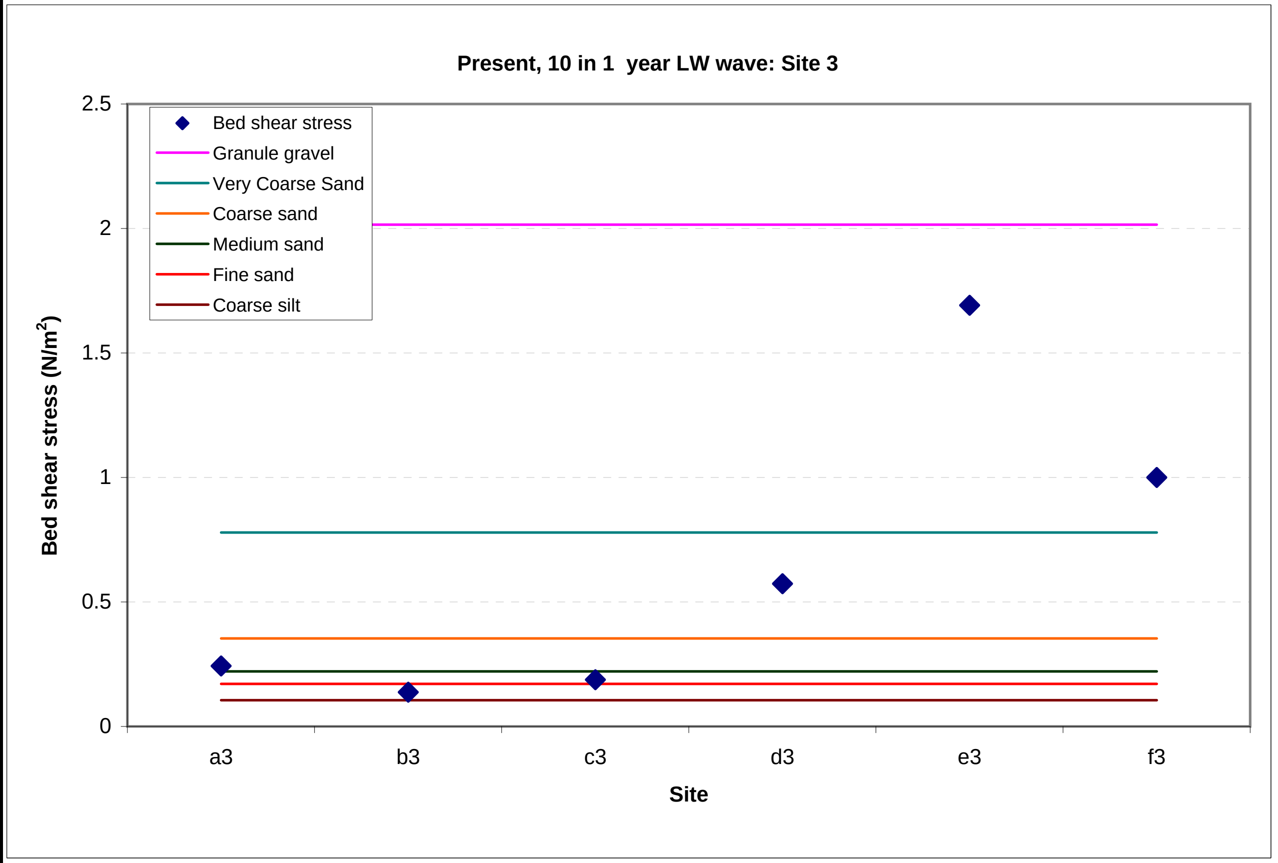
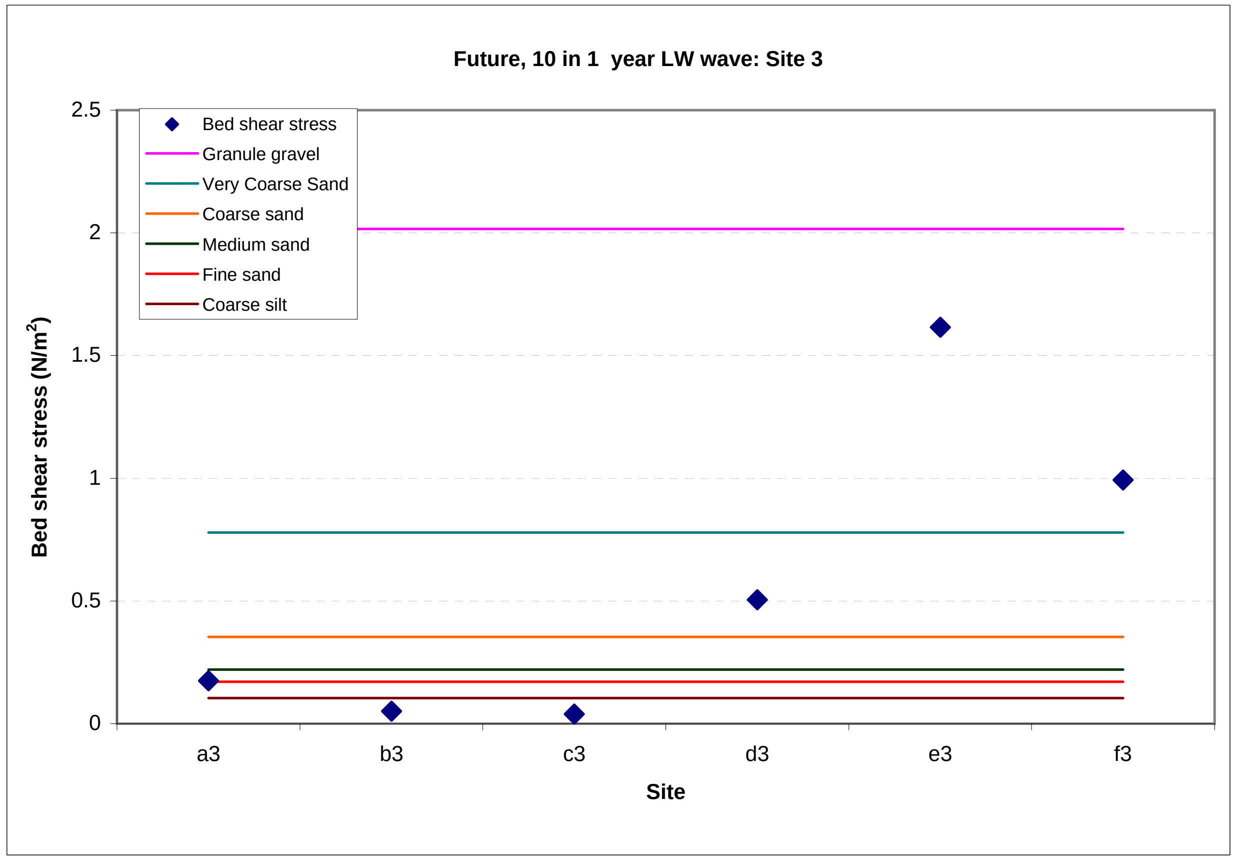
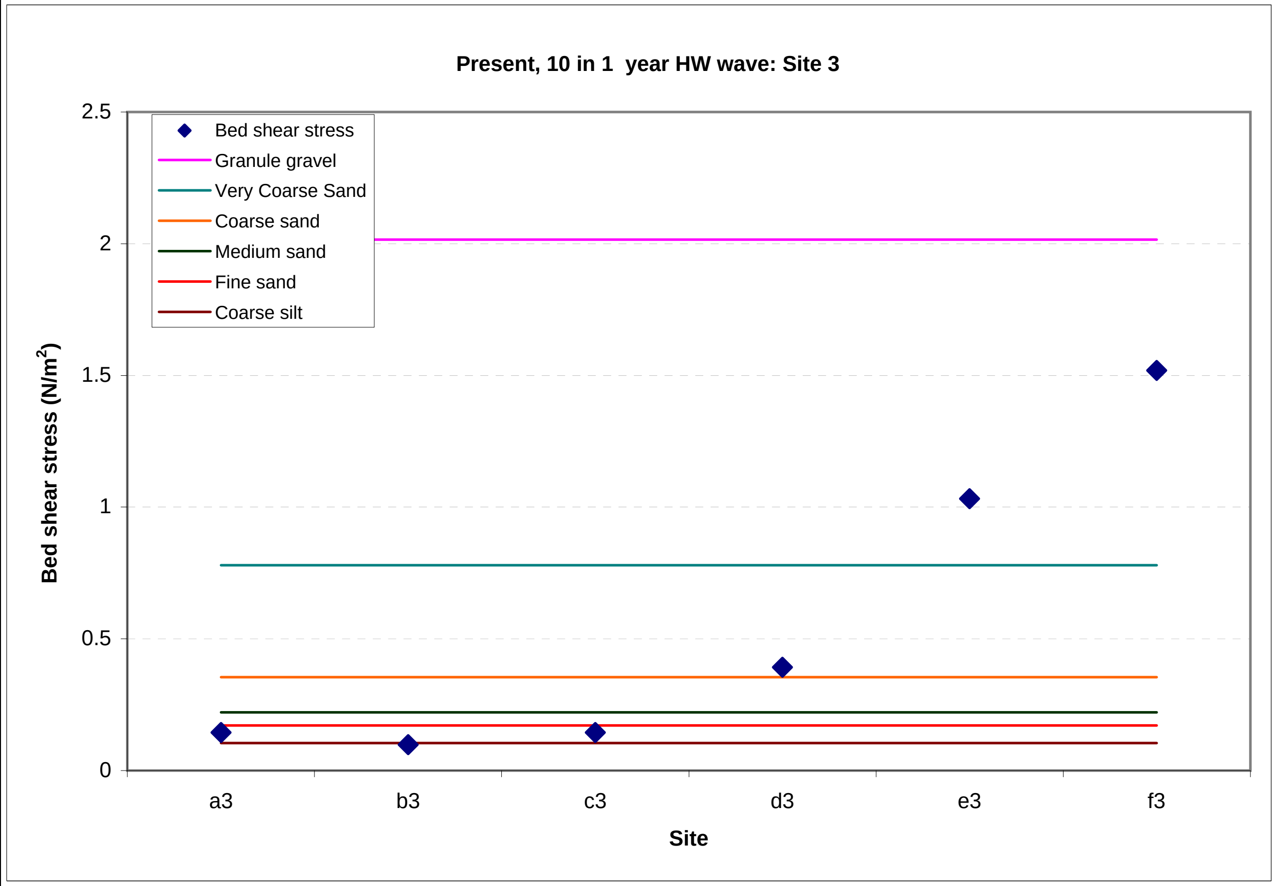
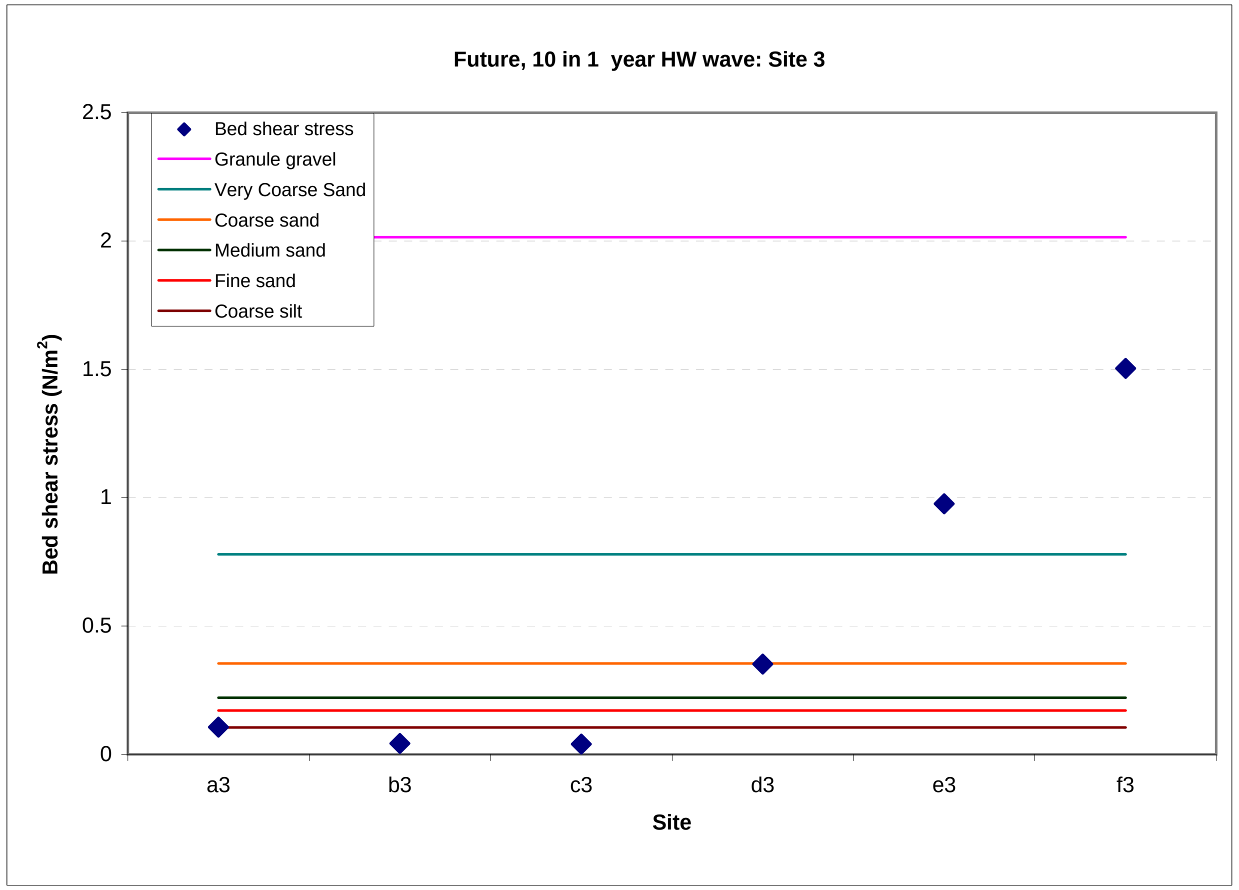
Wave induced bed shear stress - Zone 2 (Present and Future)

Figure 7.46









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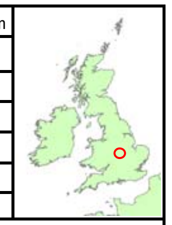

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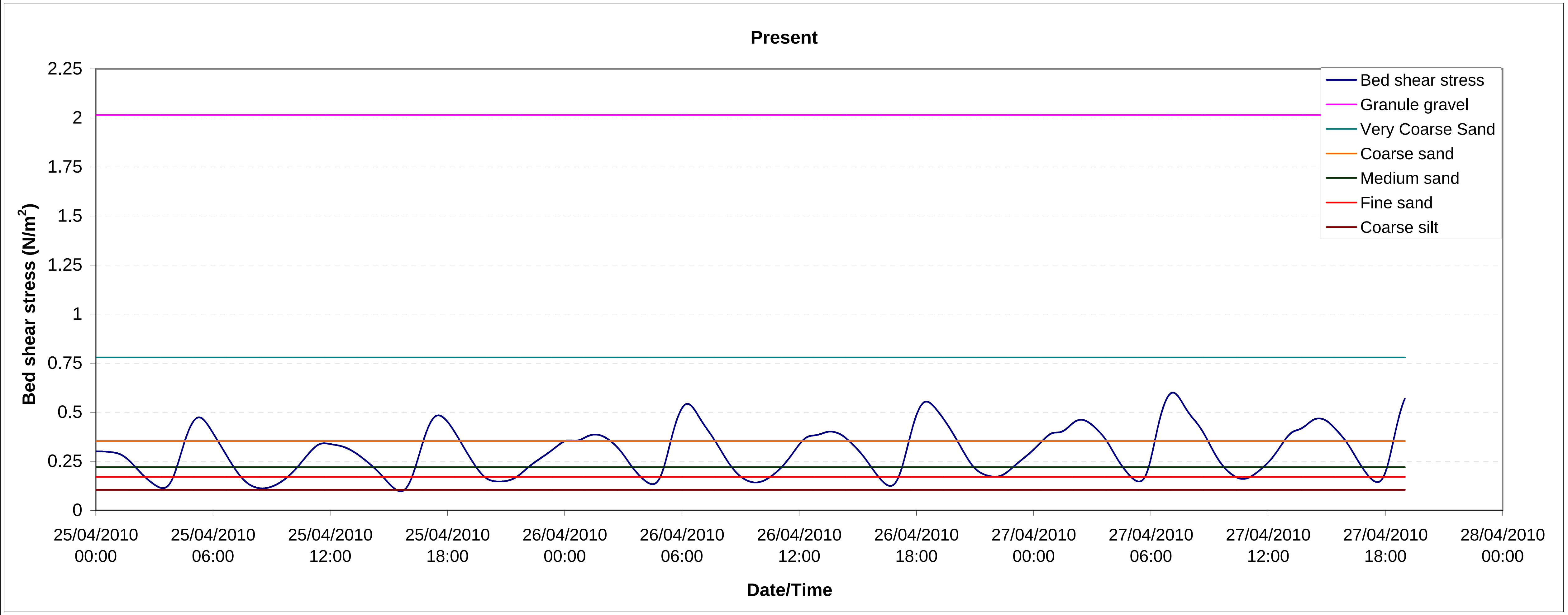
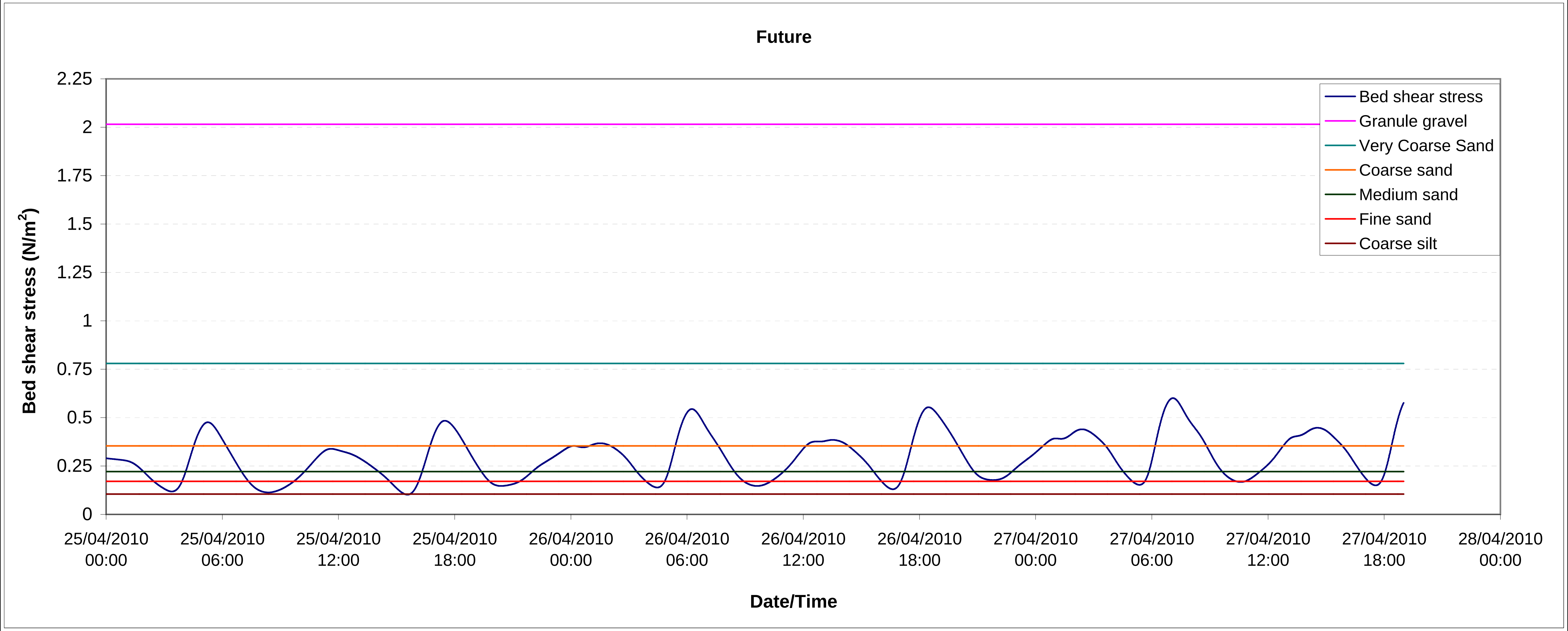
Wave induced bed shear stress - Zone 3 (Present and Future)

Figure 7.47





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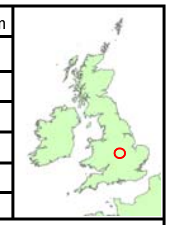

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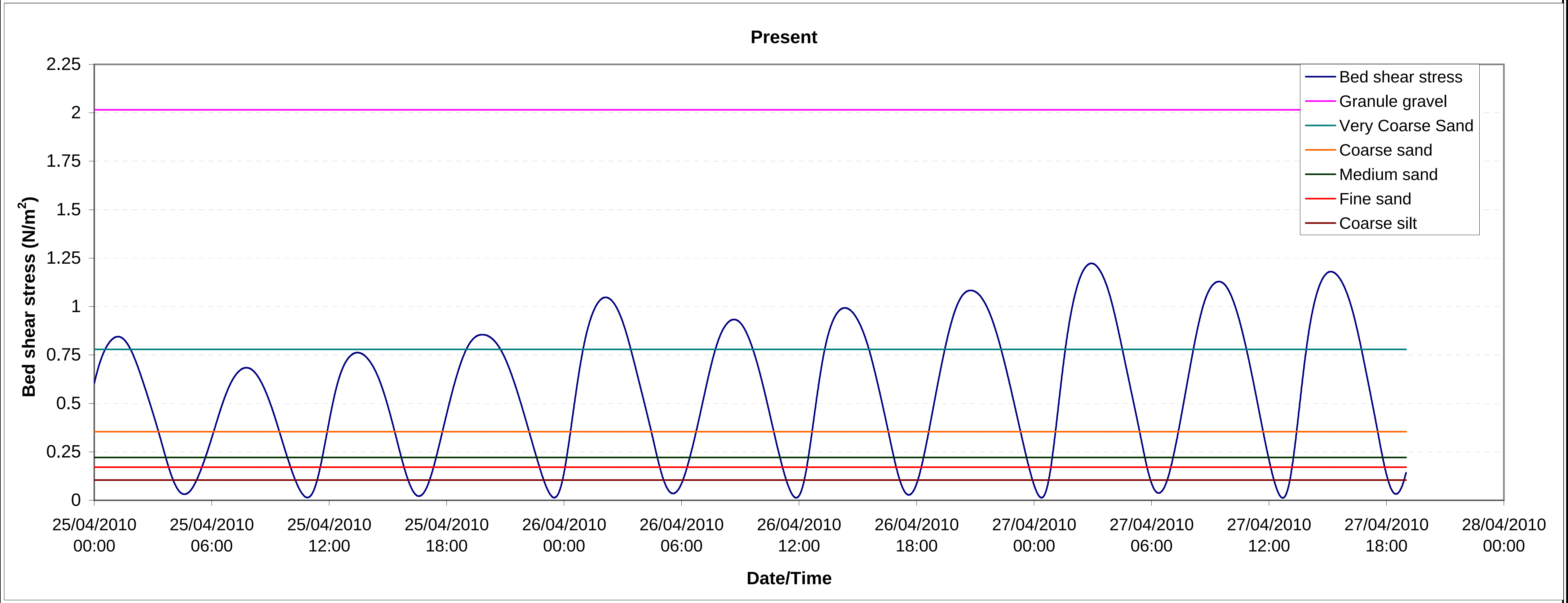
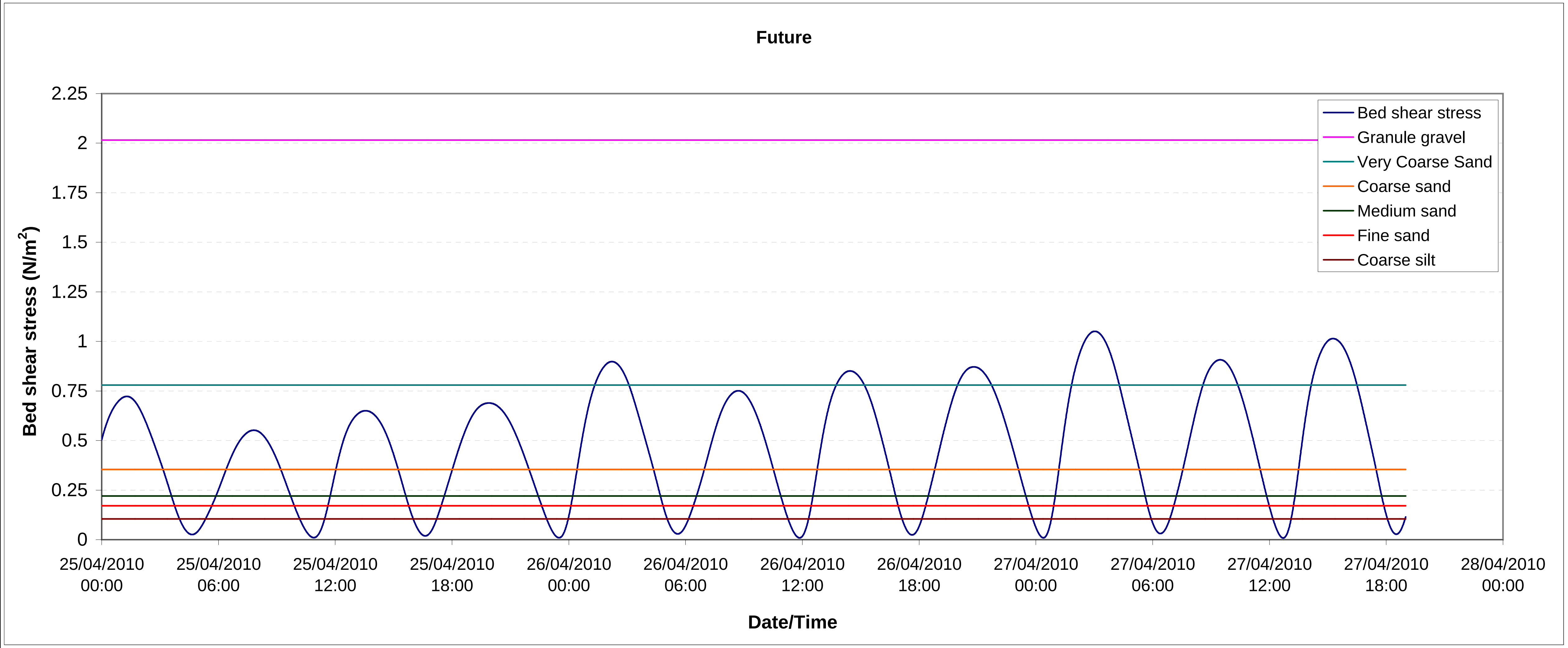
Spring tidal current bed shear stress variability
Point A (Present and Future)

Figure 7.48





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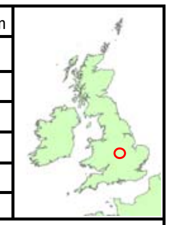

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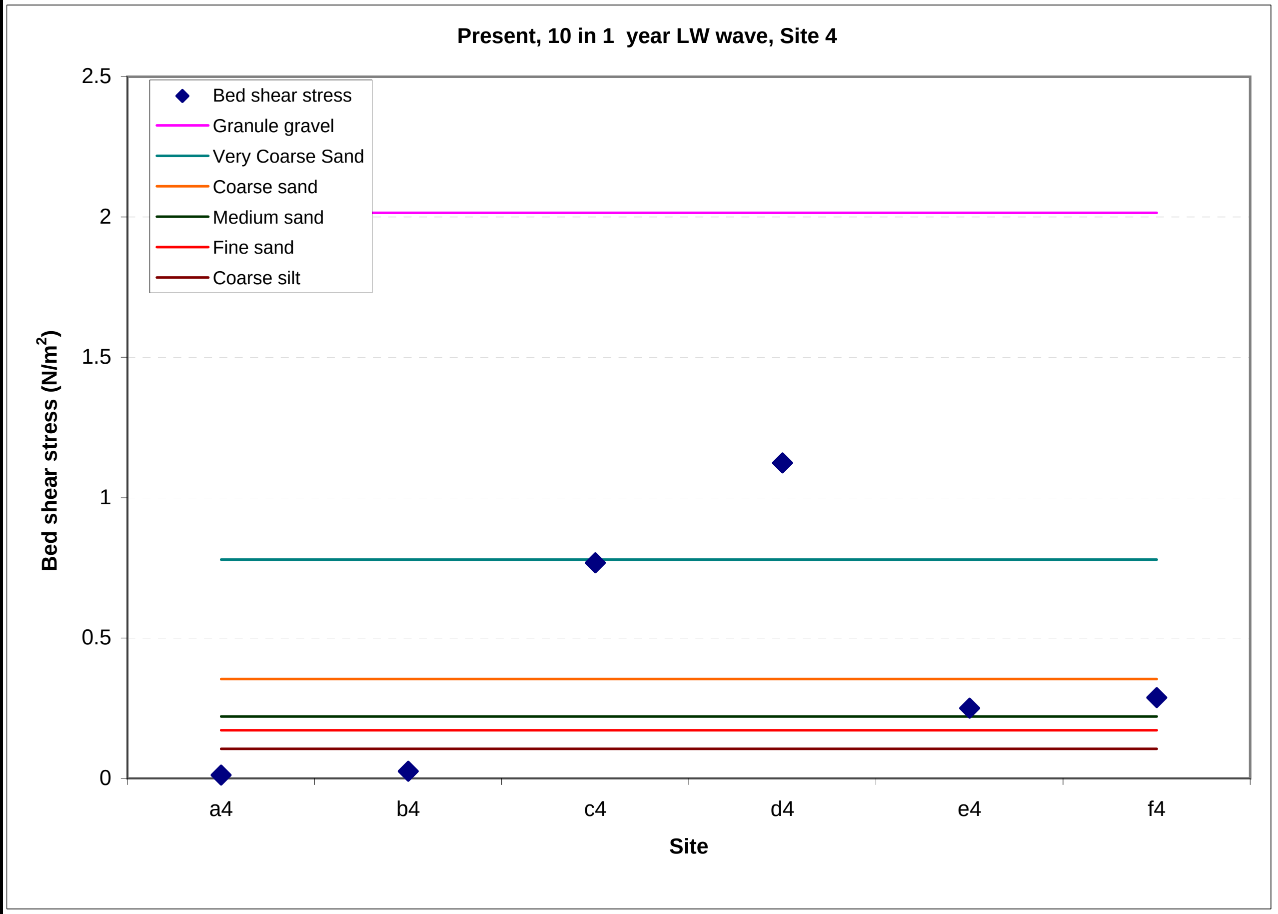
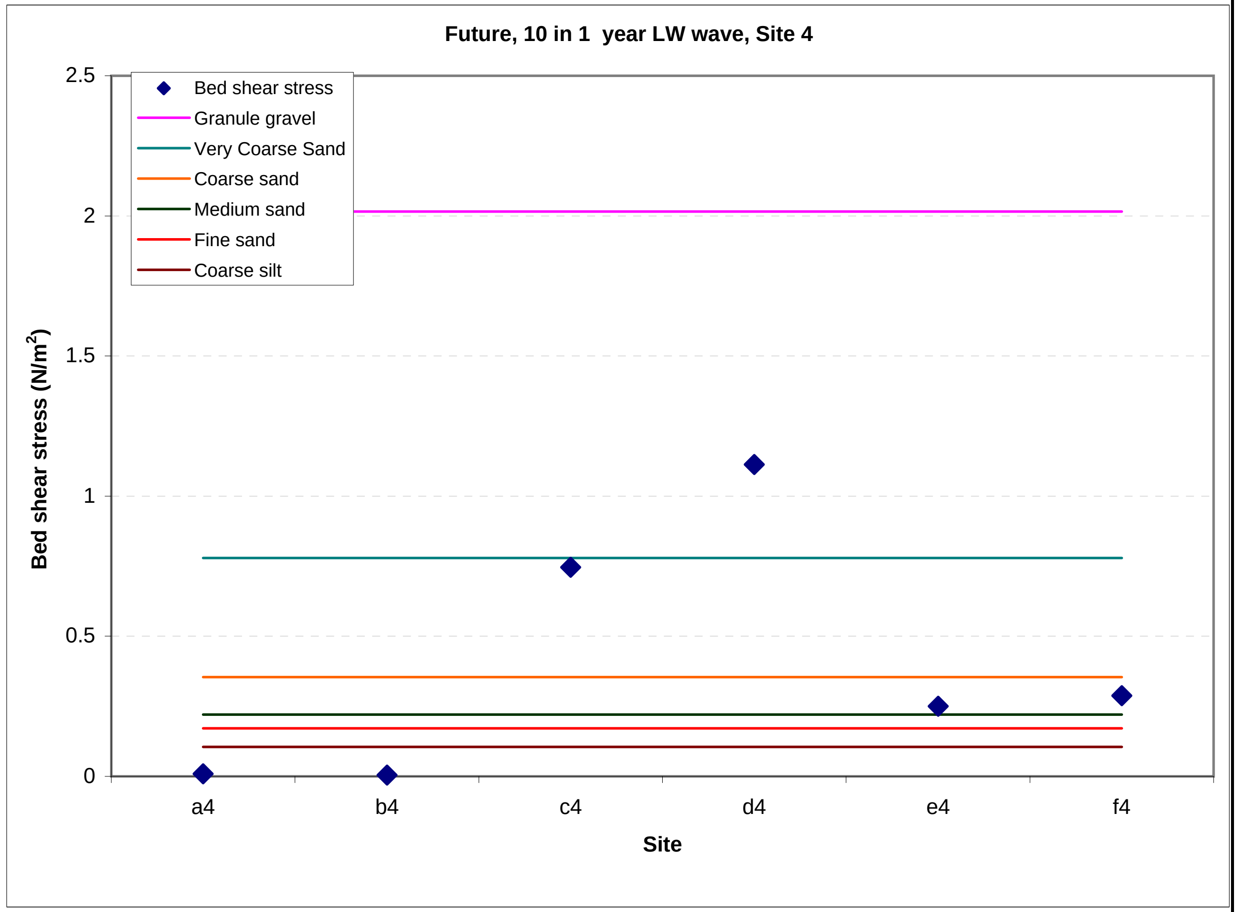
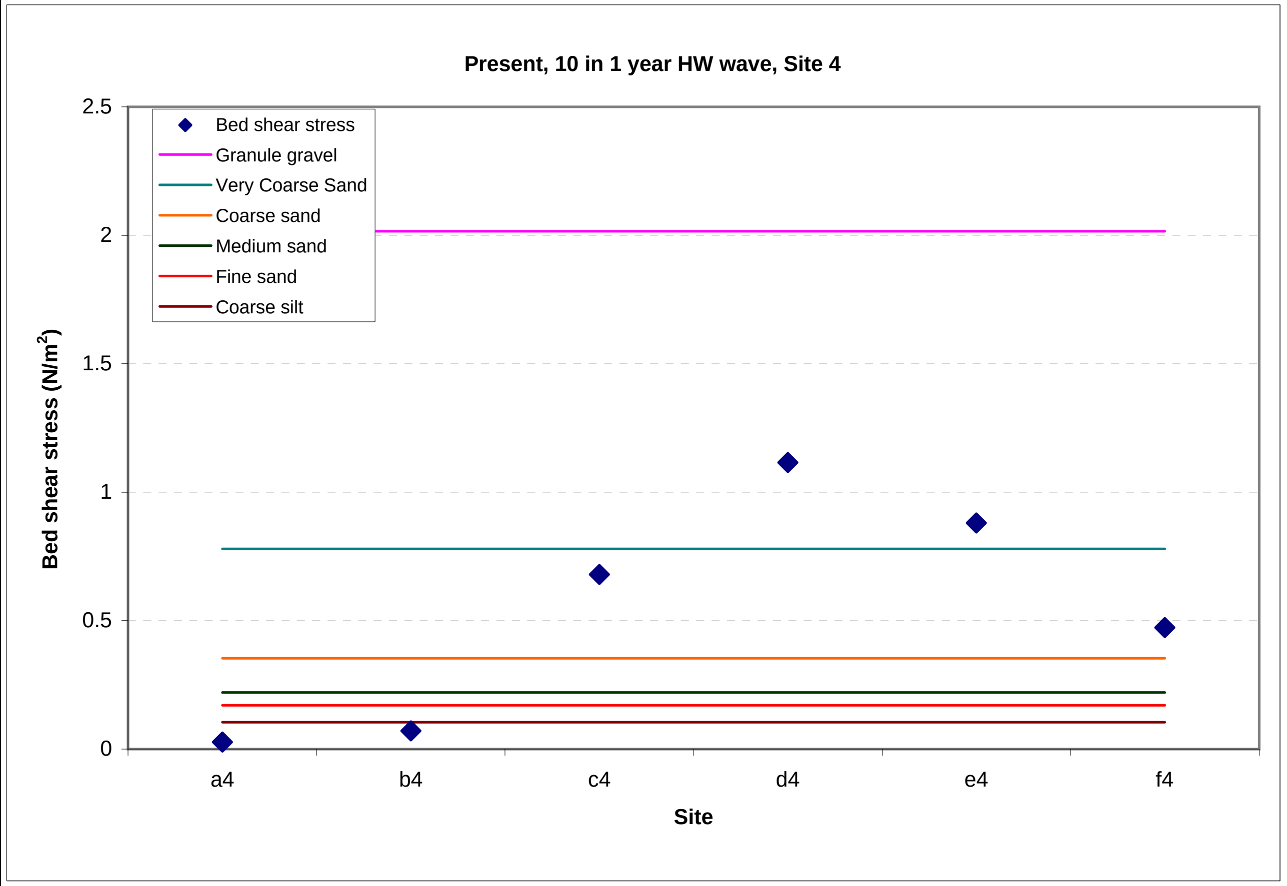
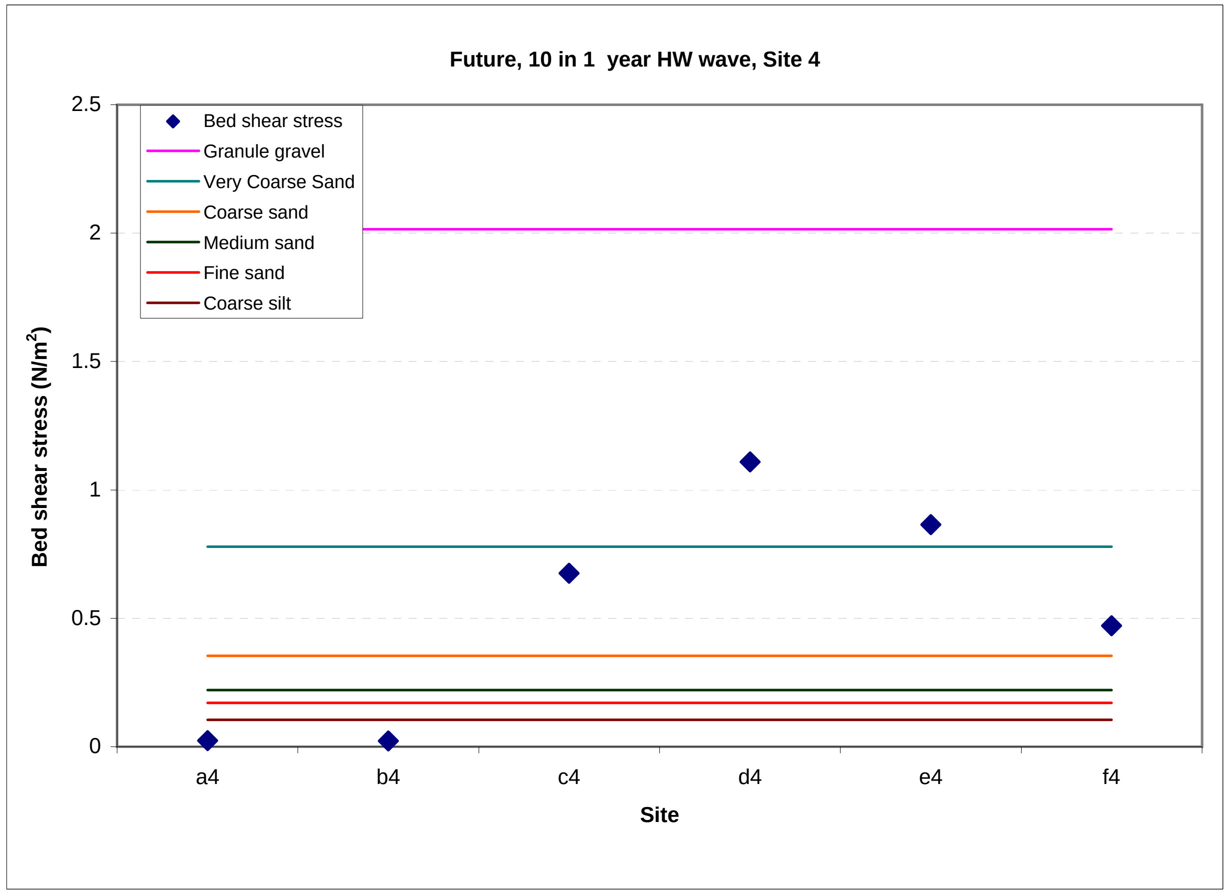
Spring tidal current bed shear stress variability Point D (Present and Future)

Figure 7.49









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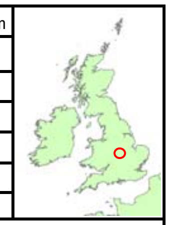

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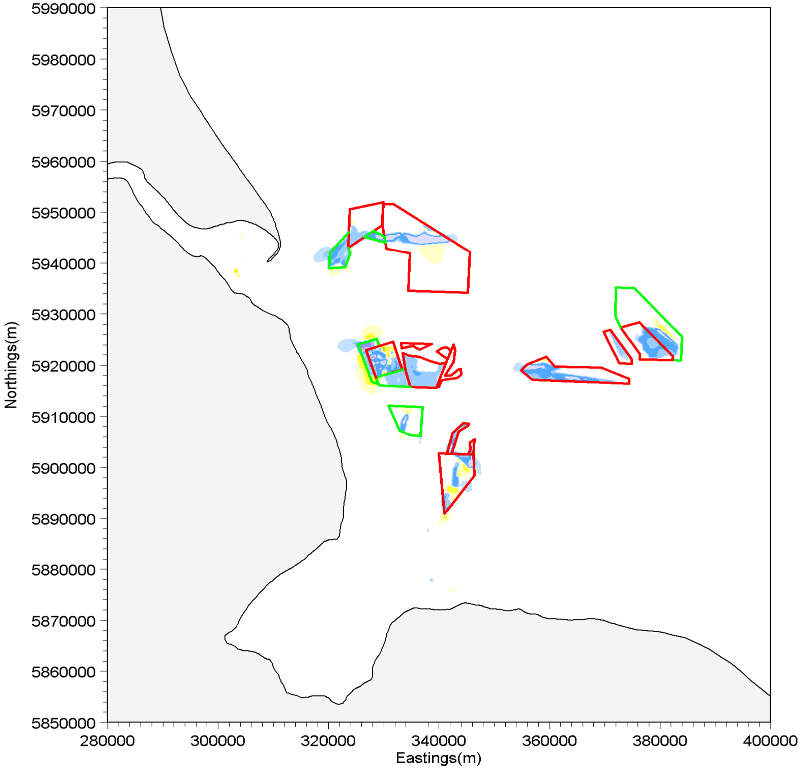
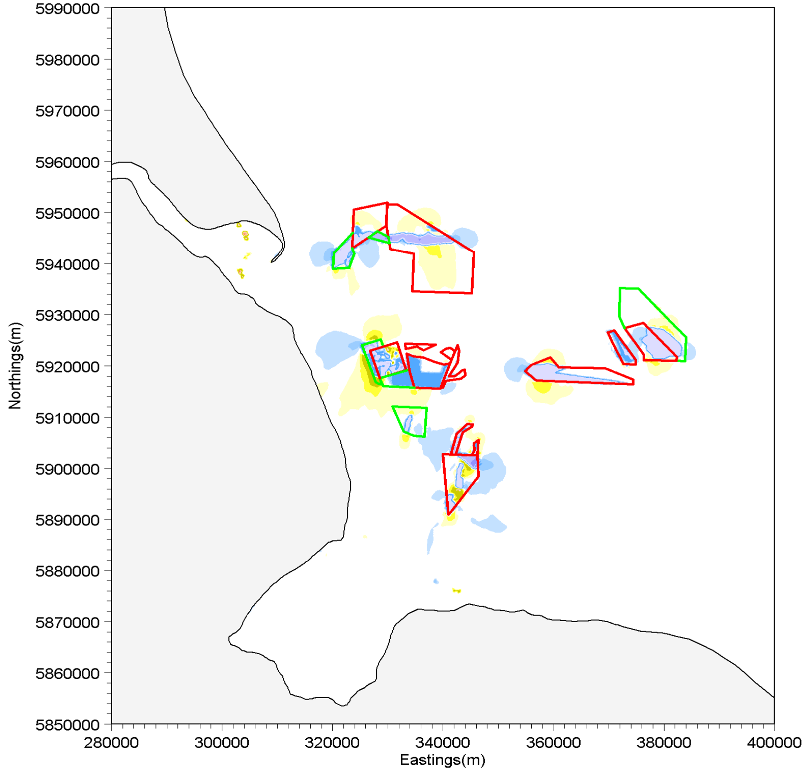
Wave induced bed shear stress - Zone 4 (Present and Future)

Figure 7.50



a: Absolute Change (N/m2)



b:% Change

Change in Bed Shear Stress

- Above 2.5
- 2.0 - 2.5
- 1.5 - 2.0
- 1.0 - 1.5
- 0.5 - 1.0
- 0.2 - 0.5
- 0.1 - 0.2
- -0.1 - 0.1
- -0.2 - -0.1
- -0.5 - -0.2
- -1.0 - -0.5
- -1.5 - -1.0
- -2.0 - -1.5
- -2.5 - -2.0
- Below -2.5
- Undefined Value

Change in Bed Shear Stress [%]

- Above 40
- 30 - 40
- 20 - 30
- 10 - 20
- 5 - 10
- 2 - 5
- -2 - 2
- -5 - -2
- -10 - -5
- -20 - -10
- -40 - -20
- -50 - -40
- -60 - -50
- Below -60
- Undefined Value

Date	By	Size	Version
Mar 12	BW	A4	1
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QA		AJH	
Figure 7.X to 7.Y.xls			
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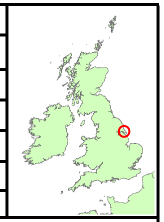

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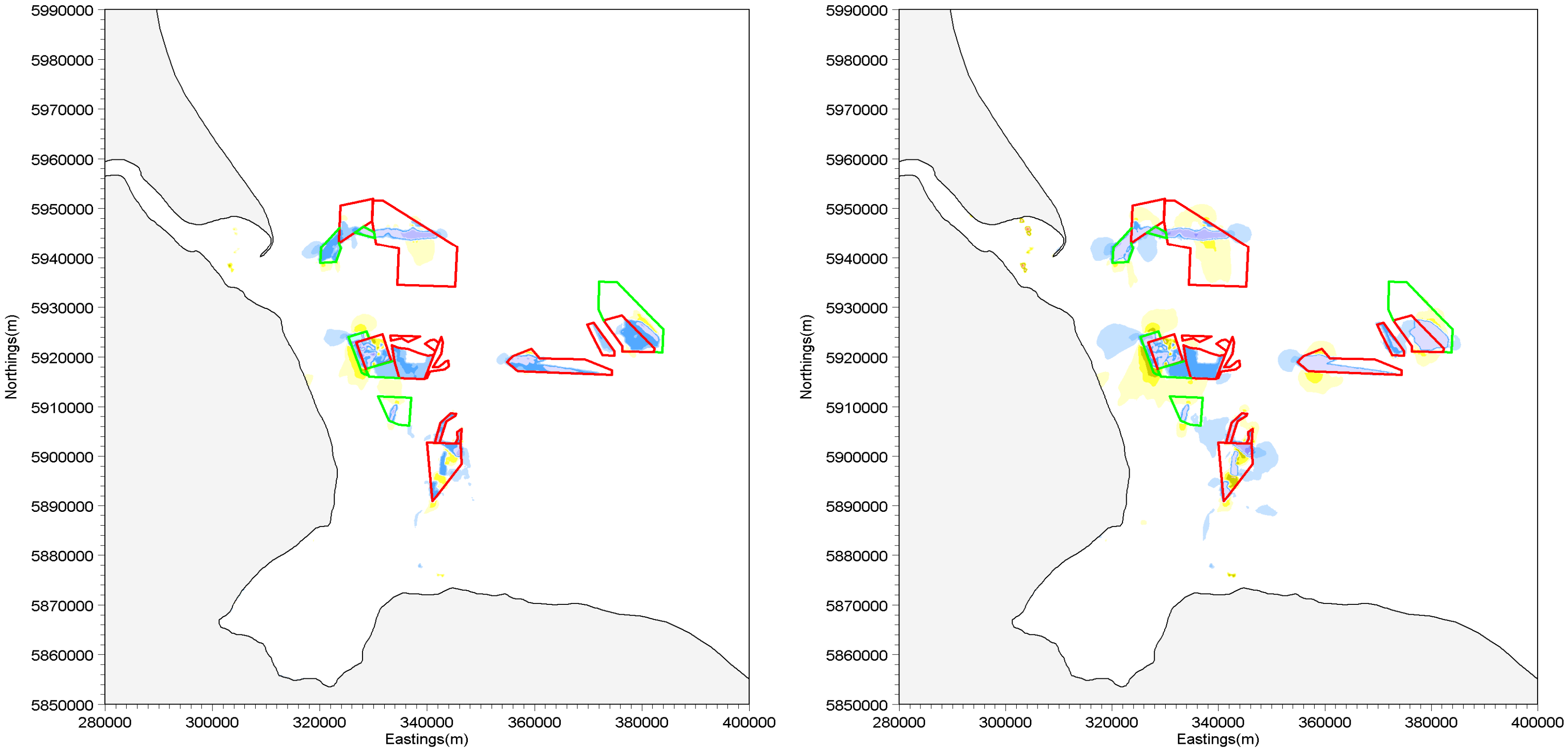
Changes to Combined Bed Shear Stress - Medium Sand

Figure 7.51



a: Absolute Change (N/m2)

b:% Change

Change in Bed Shear Stress

- Above 2.5
- 2.0 - 2.5
- 1.5 - 2.0
- 1.0 - 1.5
- 0.5 - 1.0
- 0.2 - 0.5
- 0.1 - 0.2
- -0.1 - 0.1
- -0.2 - -0.1
- -0.5 - -0.2
- -1.0 - -0.5
- -1.5 - -1.0
- -2.0 - -1.5
- -2.5 - -2.0
- Below -2.5
- Undefined Value

Change in Bed Shear Stress [%]

- Above 40
- 30 - 40
- 20 - 30
- 10 - 20
- 5 - 10
- 2 - 5
- -2 - 2
- -5 - -2
- -10 - -5
- -20 - -10
- -40 - -20
- -50 - -40
- -60 - -50
- Below -60
- Undefined Value

Date	By	Size	Version
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QA		AJH	
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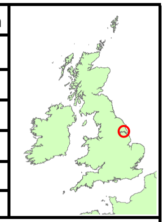
Produced by ABPmer Ltd.			



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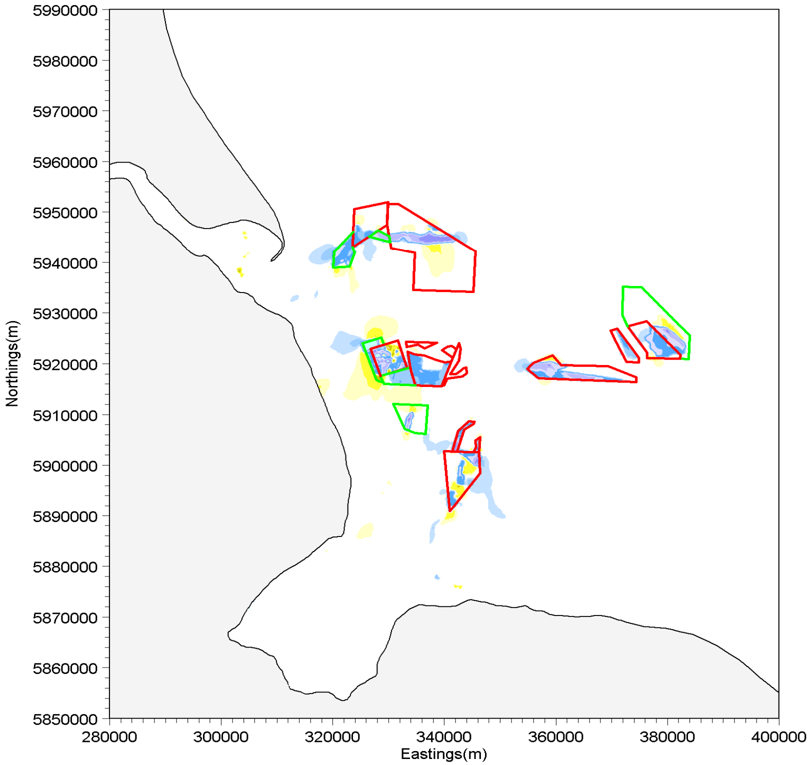
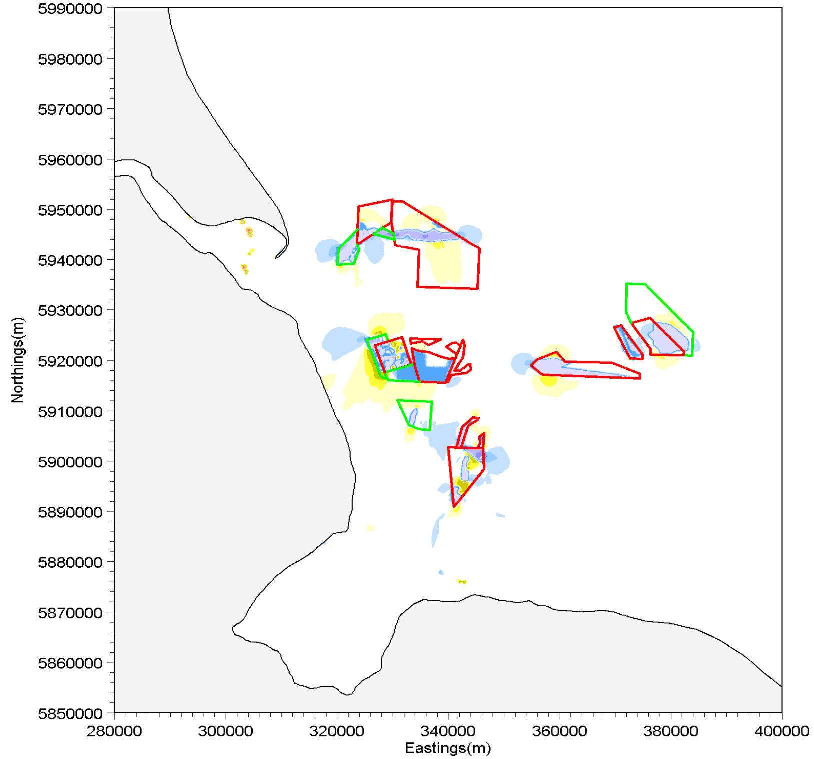
Changes to Combined Bed Shear Stress - Coarse Sand

Figure 7.52



a: Absolute Change (N/m2)



b:% Change

Change in Bed Shear Stress

- Above 2.5
- 2.0 - 2.5
- 1.5 - 2.0
- 1.0 - 1.5
- 0.5 - 1.0
- 0.2 - 0.5
- 0.1 - 0.2
- -0.1 - 0.1
- -0.2 - -0.1
- -0.5 - -0.2
- -1.0 - -0.5
- -1.5 - -1.0
- -2.0 - -1.5
- -2.5 - -2.0
- Below -2.5
- Undefined Value

Change in Bed Shear Stress [%]

- Above 40
- 30 - 40
- 20 - 30
- 10 - 20
- 5 - 10
- 2 - 5
- -2 - 2
- -5 - -2
- -10 - -5
- -20 - -10
- -40 - -20
- -50 - -40
- -60 - -50
- Below -60
- Undefined Value

Date	By	Size	Version
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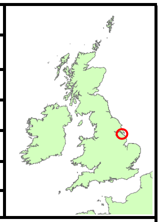

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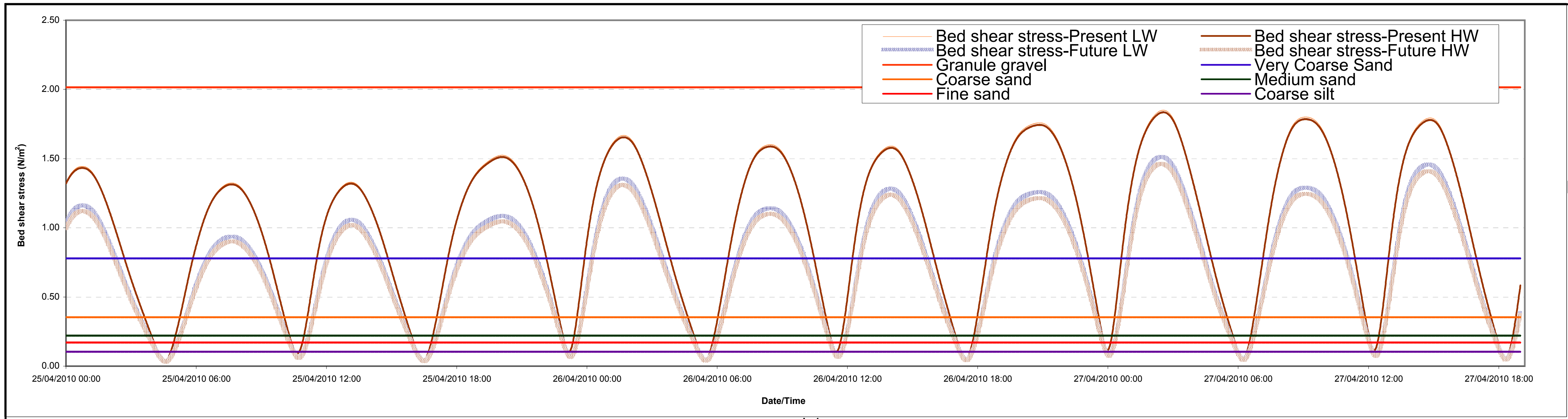
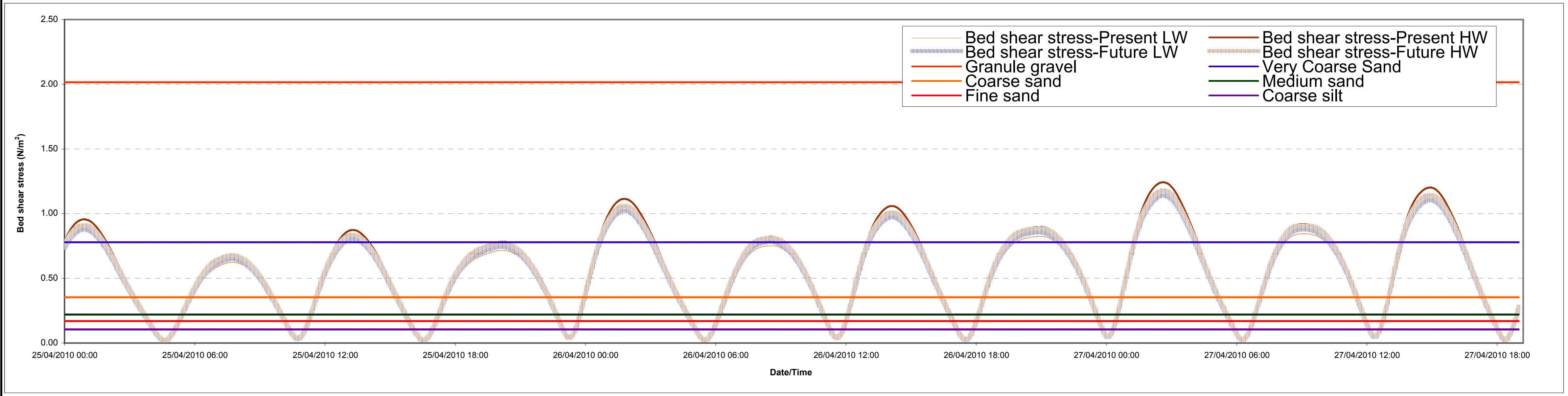
Changes to Combined Bed Shear Stress - Very Coarse Sand

Figure 7.53



b1

b1



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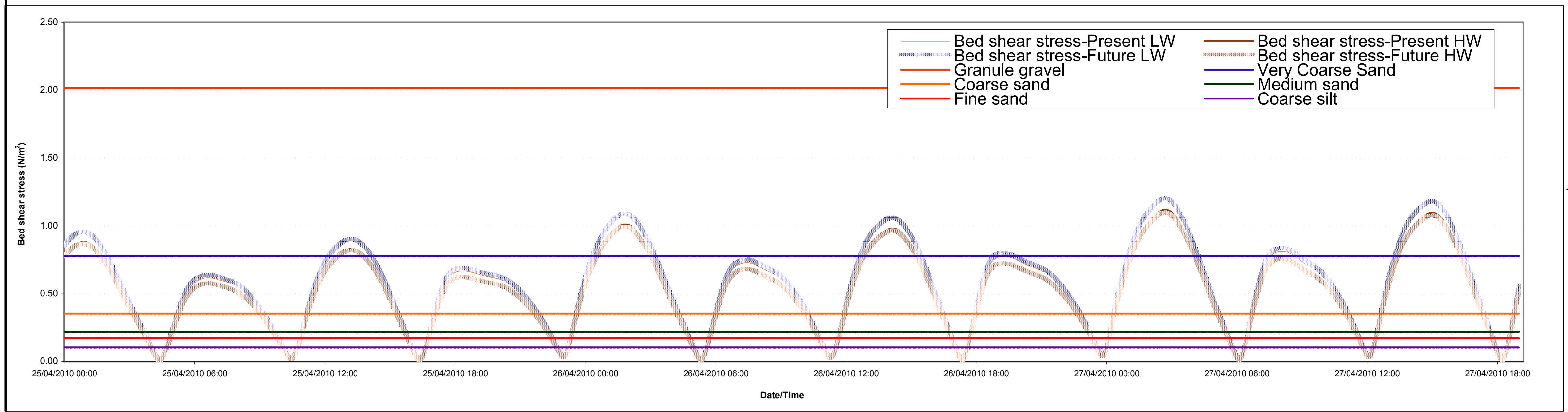

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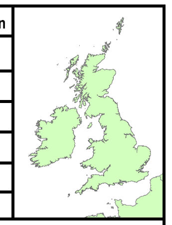

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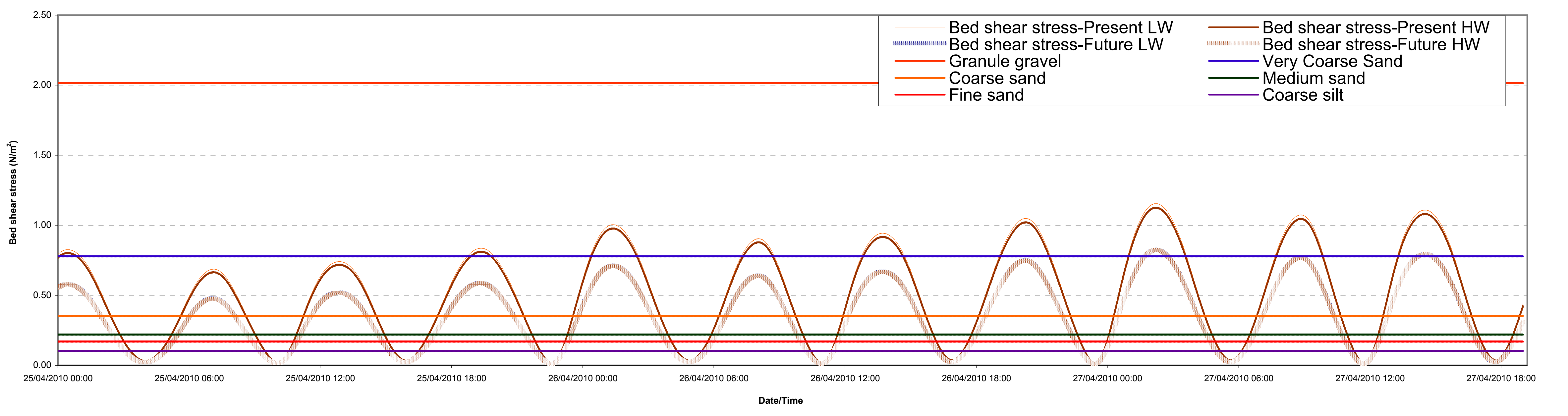
Combined Sediment Mobility (Waves and Currents) Zone 1

Figure 7.54



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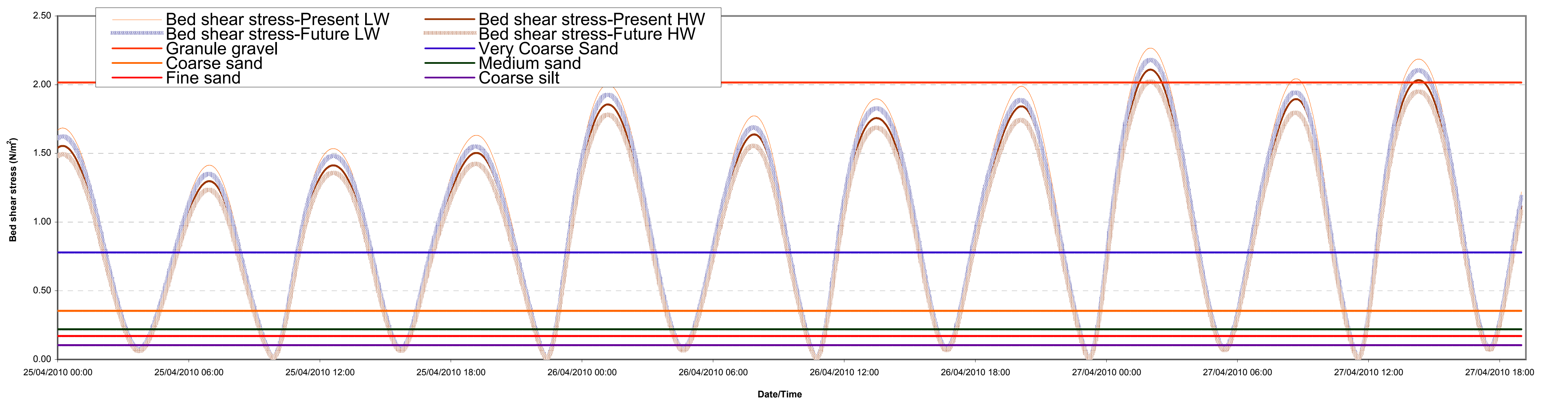

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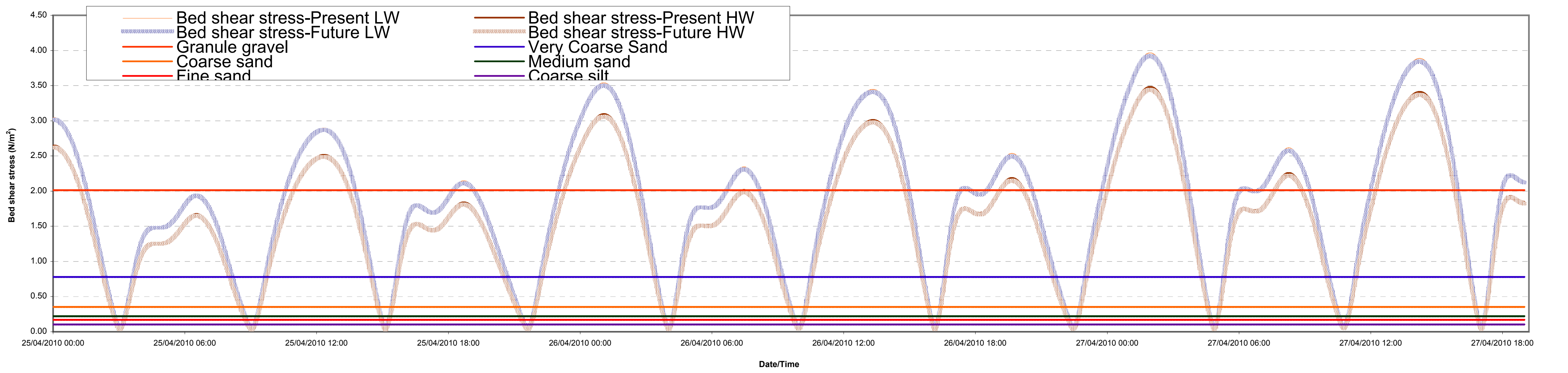

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Scale	n/a		
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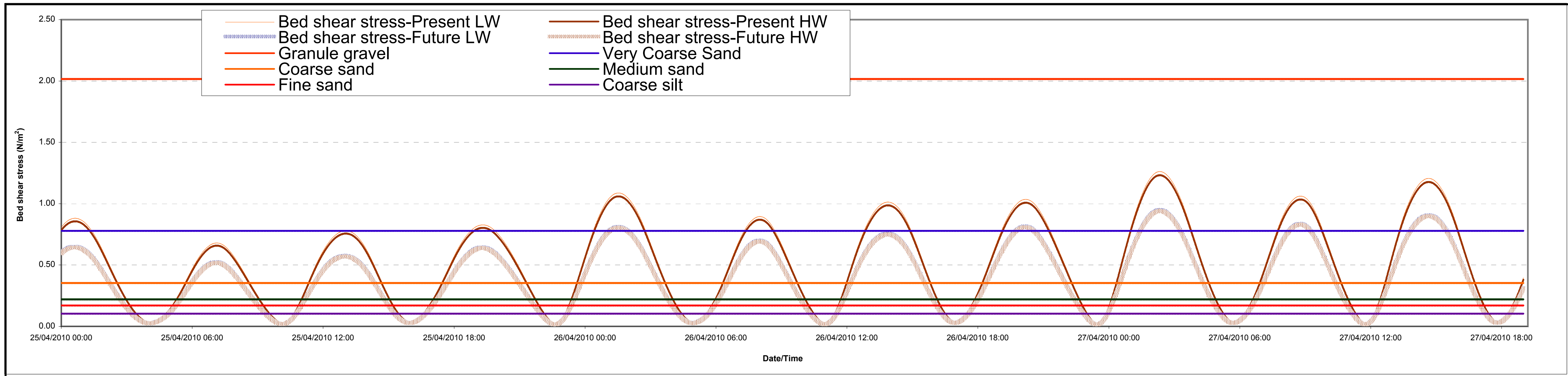
Combined Sediment Mobility (Waves and Currents) Zone 2

Figure 7.55



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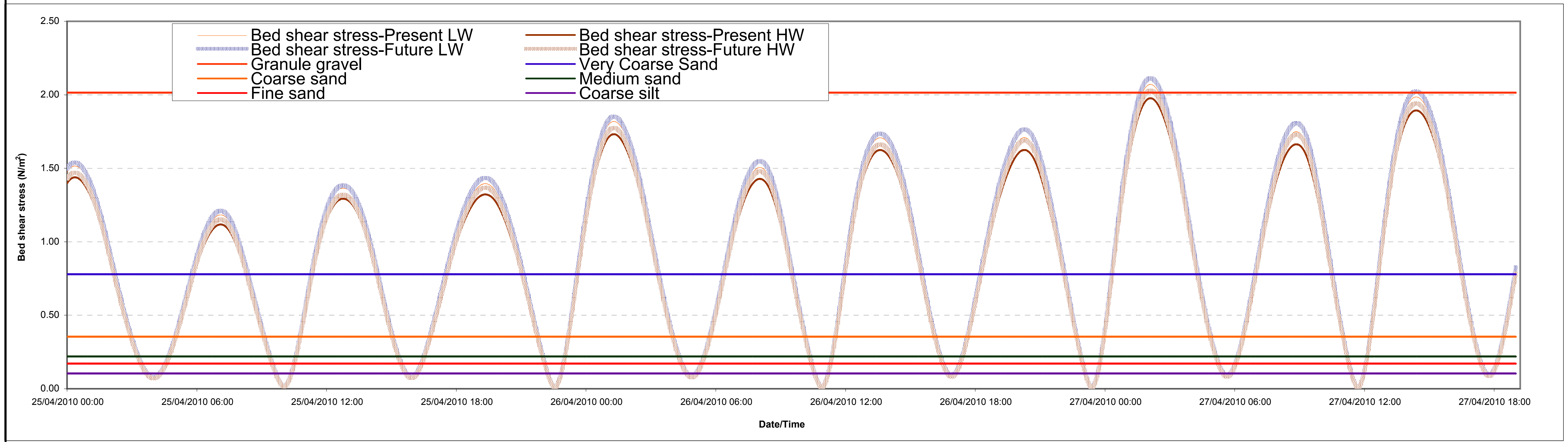

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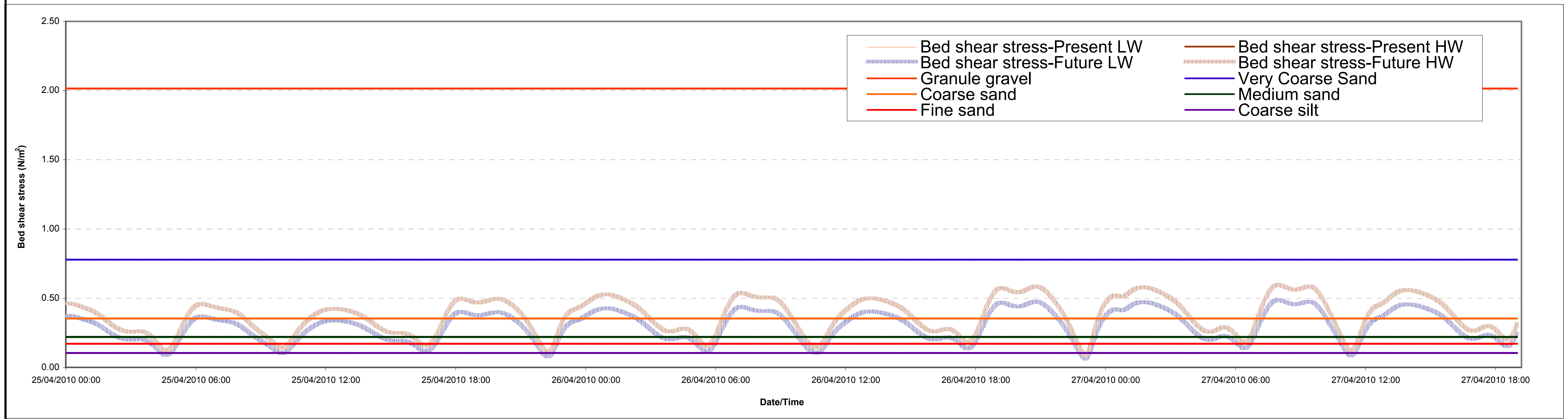

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Figures 7_51 to 7_53.xls			
Produced by ABPmer Ltd.			

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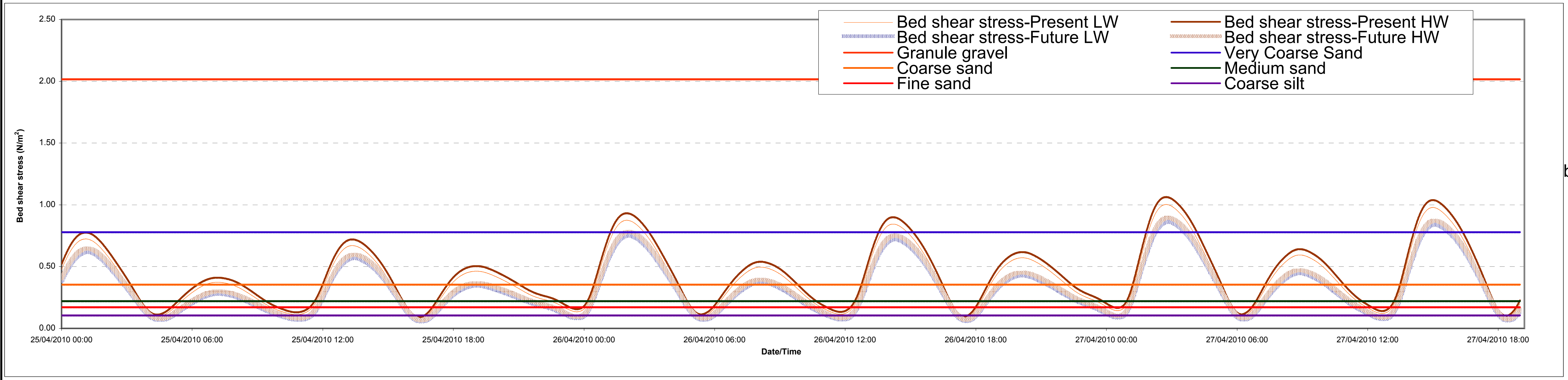
Combined Sediment Mobility (Waves and Currents)
Zone 3

Figure 7.56



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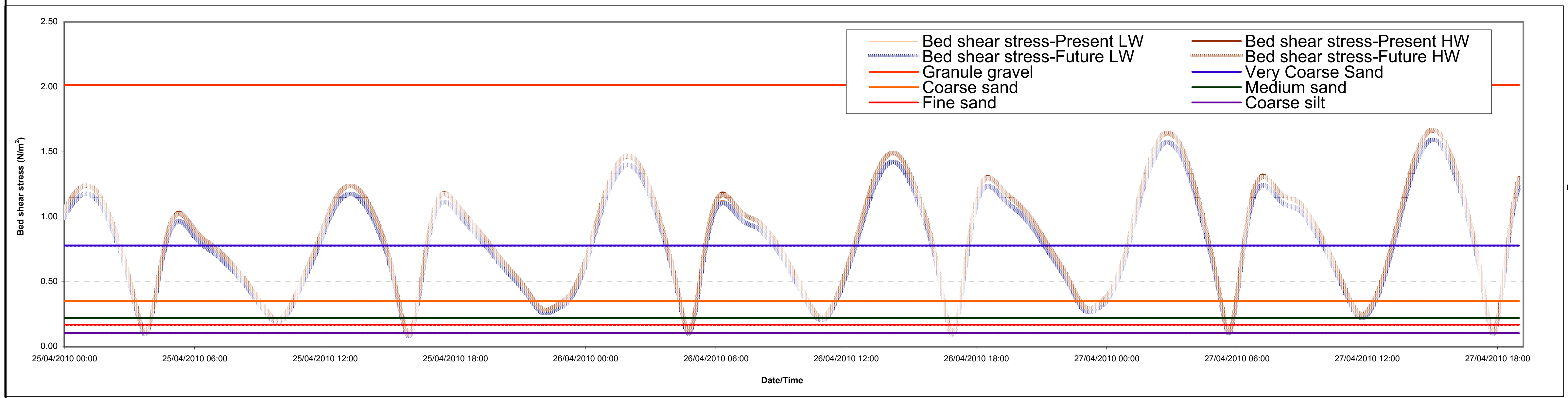

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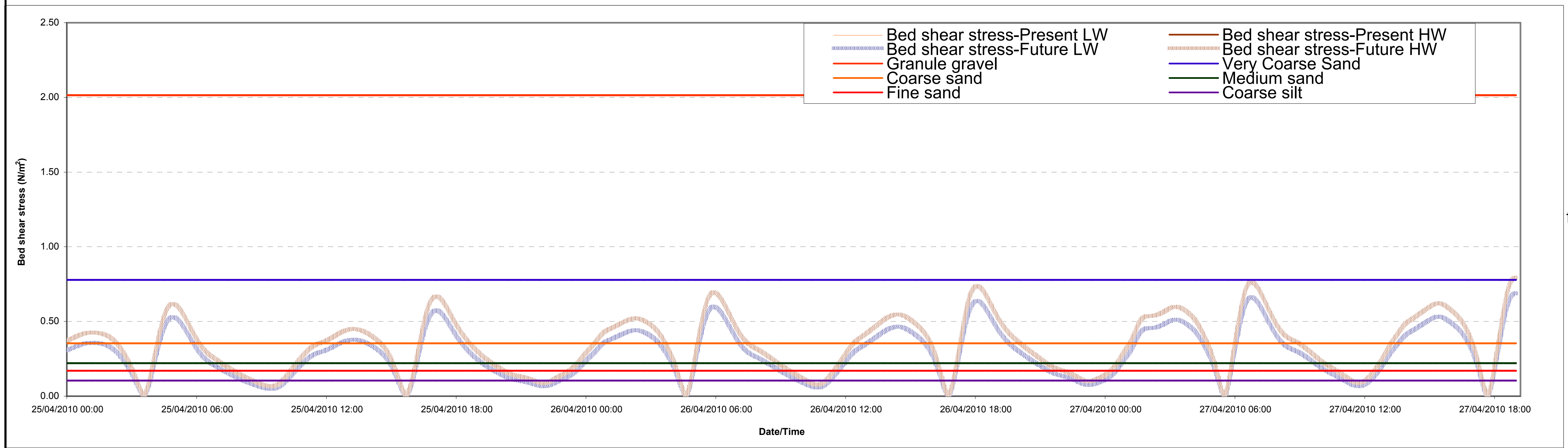

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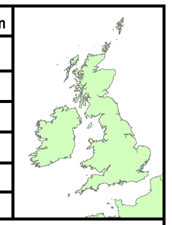

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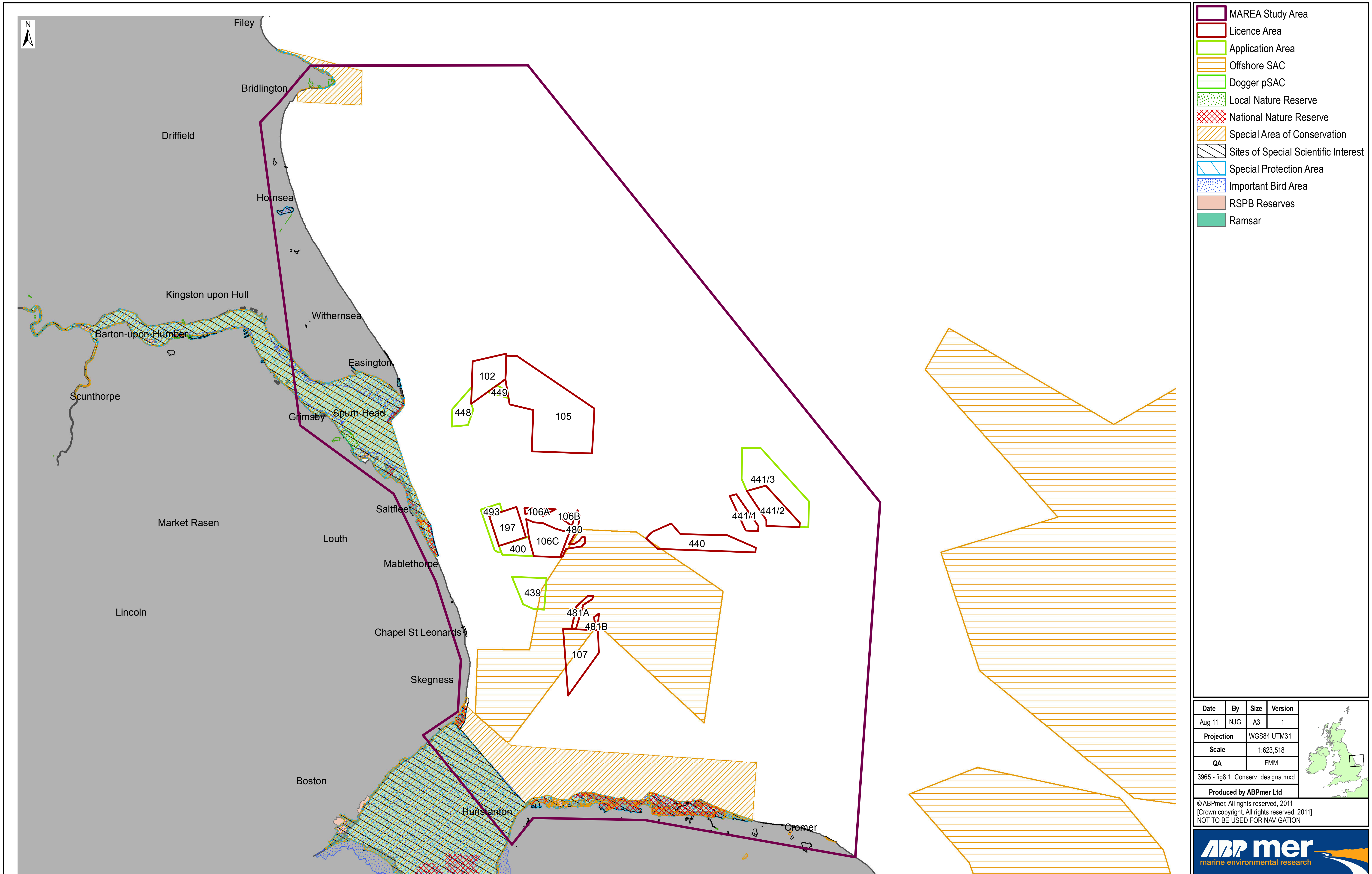
Combined Sediment Mobility (Waves and Currents)
Zone 4

Figure 7.57



Nature Conservation Designations

Figure 8.1

Appendices

Appendix A

Comparison of MIKE SW and SWAN Wave Models

Appendix A. Comparison of MIKE SW and SWAN Wave Models

A1. Physical Phenomena

Physical Phenomena included: MIKE21 SW and SWAN models use unstructured meshes to provide much better representation of complex boundaries of coastline. The following main physical phenomena are included in both models:

No.	Physical Phenomena
1.	Wave growth by action of wind
2.	Non-linear wave-wave interaction
3.	Dissipation due to white-capping
4.	Dissipation due to bottom friction
5.	Depth-induced wave breaking
6.	Refraction and shoaling
7.	Wave current interaction
8.	Diffraction
9.	Reflection
10.	Frequency spreading
11.	Directional spreading

A2. Application of Two Models for Wave Predictions

Moeini & Etemad-Shahidi (2007) examined the accuracy and computation effort of the two models. Their main conclusions are

- SWAN slightly over-estimates Hs and under-estimate Tp; The accuracy of SWAN in the prediction of Hs is more than its accuracy in the prediction Tp.
- MIKE21 SW over-estimates Hs and slightly under-estimates Tp. The accuracy of MIKE21 SW in the prediction of Tp is more than its accuracy in the prediction Hs.
- MIKE21 SW results are slightly more accurate than those of SWAN.
- Computation effort: ratio of CPU time (MIKE21 SW)/(SWAN)=1.12.

A3. Reference

Moeini & Etemad-Shahidi, 2007. Application of two numerical models for wave hindcasting in Lake Erie. Applied Ocean Research, Volume 29, Issue 3, July 2007, Pages 137-145.

Appendix B

Model Calibration and Validation Report

Appendix B. Model Calibration and Validation Report

B1. Introduction

Two modelling software packages, MIKE and Delft3D, are routinely used by ABPmer. Both of them are capable of representing the hydrodynamic and wave processes of interest to present study. The selection of the most suitable tool is determined in part by the environment under investigation. Given the highly dynamic coastline and various geometries of dredging area, MIKE 21 FM (Flexible Mesh) is considered the most suitable model allowing a higher degree of resolution and flexibility than Delft3D, whilst remaining computationally efficient. Therefore, the two-dimensional software package MIKE 21 has been used in this study to determine the extent and magnitude of changes to the flow and waves as a result of aggregate dredging.

The modelling system was developed by the Danish Hydraulic Institute Water & Environment for complex applications within oceanographic, coastal and estuarine environments. It is comprised of various modules enabling the simultaneous modelling of water levels, currents and waves. Two modules of the MIKE 21 FM model have been applied here to resolve the key physical processes. The hydrodynamic module MIKE21 HD simulates the water levels variation and two-dimensional flows in the area of interest. The wave module MIKE 21 SW is a state-of-the-art third generation spectral wind-wave model, which has been applied to simulate the growth, decay and transformation of wind-generated waves and swell.

B2 Model Configuration

B2.1 Mesh Design

The model is bound on its western and southern extents by the Lincolnshire and North Norfolk coasts respectively. The offshore limits are approximately 01°45'E and 54°06'N. Figure B1 shows the detail extents of the model.

Resolution across the model domain is variable. The model has been designed to provide a high resolution in the dredging and nearshore areas. In the offshore area the resolution is around 5,000m while it increases to 200m within the dredging areas. The highest resolution of 200m is sufficient to represent the detailed geometries of dredging area. The model resolution is illustrated in Figure B2.

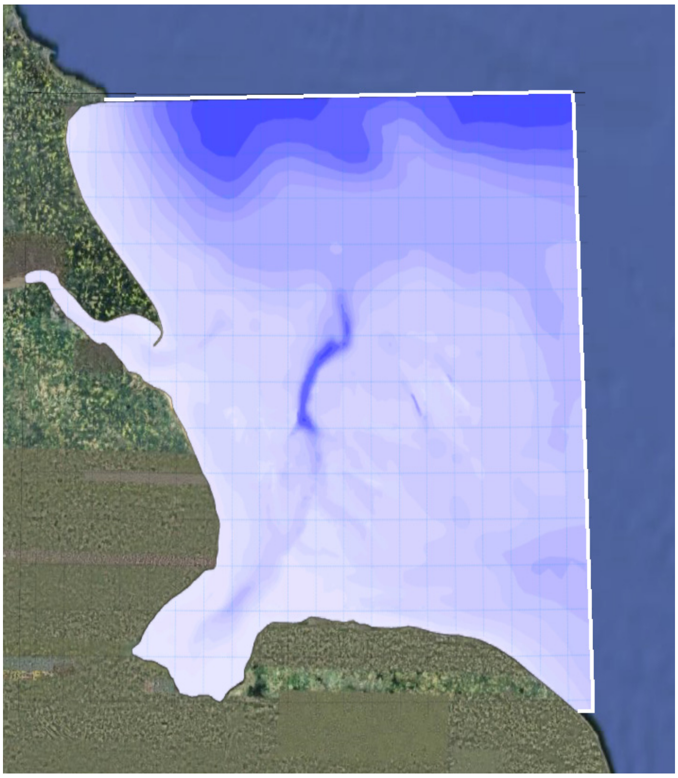


Figure B1. Model Domain

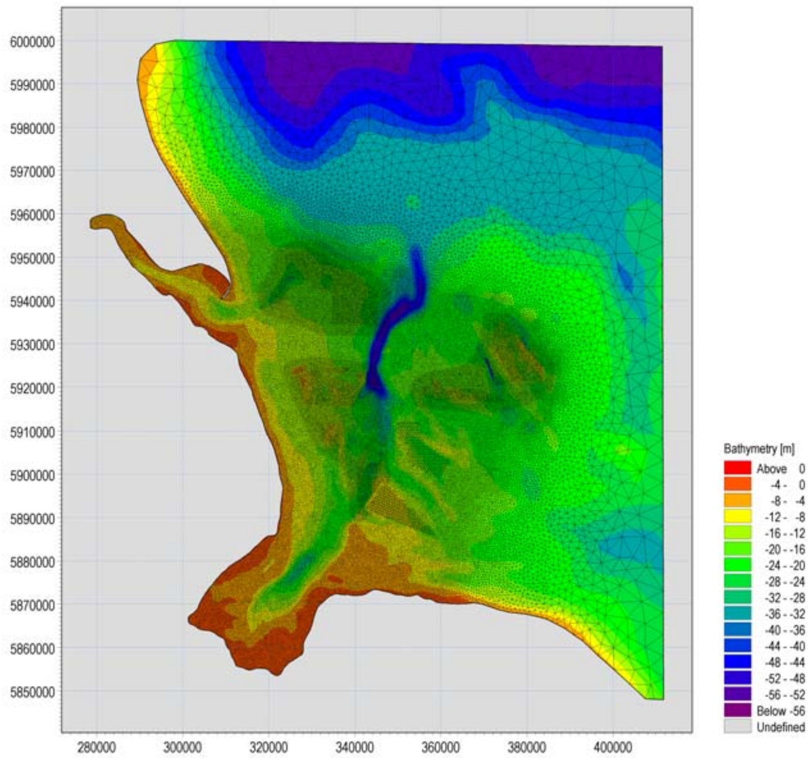


Figure B2. Mesh Resolution

B2.2 Bathymetry

Bathymetry data for the dredging areas were provided by the client. Bathymetry data for the surrounding areas was compiled from Seazone data. The compiled dataset was incorporated into the model domain to a common reference level, Ordnance Datum Newlyn (ODN).

B2.3 Boundary Conditions

For the MIKE21 HD model, the open boundaries apply time-varying water level conditions generated from the spherical grid North Sea model developed previously by ABP Marine Environmental Research Ltd (ABPmer, 2005). To simplify the transfer of boundary conditions, the model has been aligned with the North Sea model grid with a northern boundary defined by latitude 54°06'N and the eastern boundary by longitude 01°45'E.

Offshore boundary wave data from the Met Office was previously acquired by ABPmer for use within previous studies. Data agreements were put in place to allow the re-use of this data within the present study. The offshore wave data was sourced from a location in the domain from the Met Office wave models. The offshore wave height, period and direction were applied along the offshore boundary of the models.

B2.4 Bed Roughness

The Manning number accounts for the effect of bed roughness on the flow field. It is one of main model parameters used to improve the accuracy of calculated flow and model calibration. Its value largely depends on the seabed material and local bed forms. The MIKE 21 User Guide and Reference Manual suggests that values in the range 20-40 m1/3/s are most appropriate. According to its definition in MIKE 21, a small number corresponds to a high bed resistance and vice versa. Without details of seabed information in the whole domain, a wide range of Manning numbers were tested. Finally, a constant Manning number of 37$m^{1/3}$/s for the MIKE 21 HD model has been determined from the model calibration and validation processes.

B2.5 Flooding and Drying

The model uses a standardised approach to the flooding and drying of inter-tidal areas in which a model element is regarded. For the purposes of the numerical scheme, a model element is classed as 'dry', and excluded from the computation, when the water depth in that cell becomes 0.05m or less. As the water level returns the element floods again and is re-included in the computation when the water depth reaches 0.05m.

B2.6 Oceanographic Survey Data

Numerical models typically require significant amounts of data to assist with model calibration and validation. A description of these various datasets is provided in the following sections.

Water level data were available from two tide gauges located at Immingham and Cromer. The tide gauge data were made freely available by the British Oceanographic Data Centre (BODC) as part of the function of the National Tidal and Sea Level Facility, hosted by the Proudman Oceanographic Laboratory and funded by the Environment Agency and the Natural Environment Research Council.

Tidal current data were selected from BODC mooring current meters within in the area. The data records at four sites have been chosen based on their locations, durations and quality, namely b0049843, b0010528, b0015256 and b0008862.

Measured wave data in 2009 from the three WaveNet buoys located at Dowsing, North Well and Blakeney Overfalls were used exclusively for the calibration and validation. These devices make use of modern technology and provide directional wave data. The data from the buoys are subject to rigorous quality checks and is therefore considered to be the best available dataset for model calibration and validation purposes.

The sites of observational data records are shown in Figure B3.

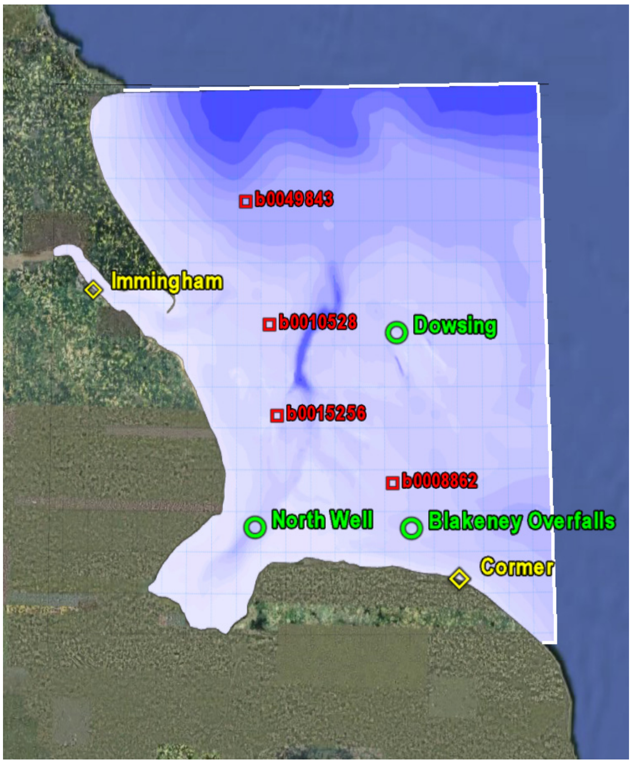


Figure B3. Tidal Gauges, Current Meters and Wave Buoys

B3. Model Calibration and Validation

B3.1 Hydrodynamics

During the model hydrodynamic calibration, the Manning Number was evaluated to improve the agreement between the simulated and observed data. As an extension of the calibration process, the model validation demonstrates the ability of the model to predict field observation for periods separate to the calibration effort. For water levels, the observation data from spring and neap tides in April 2010 were used for calibration purposes and the data in May 2010 were used for model validation. For tidal current calibration and validation, the model has been run for a specific period during which the measurements were carried out.

B3.1.1 Water levels

Model outputs during the calibration periods are presented against measured data in Figures B4 to B7. In general, model outputs at spring and neap tides are in good agreement with the measured data both in terms of phasing and the range of water levels at most sites. To provide a more quantitative assessment of the model performance, a statistical analysis based on comparing observed and modelled high water and low water levels was undertaken. These statistics were calculated over two five day periods, the first period centred on spring tides and the second centred on neaps. The results are presented in Table B1 and Table B2. The results presented are based on the difference between modelled and observed values. Positive values indicate an overestimation of the water level in the model and negative values an underestimate.

The calibration results show that water levels are well predicted by the model for spring tides, with modelled and observed water levels agreeing to within 7.4% for the two sites. However, the results are less favourable for neap tides. The maximum error in High Water levels is found at Cromer where they are under predicted by 0.27m, which represents around -9.8% of a neap tidal range. Low water levels are reproduced to a similar level of accuracy, with levels under predicted by 0.30m (-10.9%).

Phase differences at two tidal gauge sites are within ±23 minutes. The overall consistency in the phase errors suggests that the model is producing the correct processes in the areas of interest.

For the model validation, a series of graphical comparisons of the water level at all sites are demonstrated in Figures B8 to B11. The statistical descriptions of the model performance are also detailed in Table B1 and Table B2. It can be seen that the accuracy achieved during validation is similar to that achieved during the calibration process.

Table B1. Water level statistics for spring tides

Location	Period	High Water Water Level Difference in m (and as % of Range)	Low Water Water Level Difference in m (and as % of Range)	High Water Phasing Difference (Minutes)
Immingham	Calibration	0.05 (0.9%)	-0.35 (-6.2%)	23
	Validation	0.01(0.1%)	-0.30(-5.5%)	16
Cromer	Calibration	-0.19 (-5.0%)	-0.28 (-7.4%)	23
	Validation	-0.22(-5.9%)	-0.25(-6.7%)	15

Table B2. Water level statistics for neap tides

Location	Period	High Water Water Level Difference in m (and as % of Range)	Low Water Water Level Difference in m (and as % of Range)	High Water Phasing Difference (Minutes)
Immingham	Calibration	-0.13 (3.1%)	-0.42 (-10.3%)	4
	Validation	-0.08(-1.9%)	-0.46(-10.1%)	13
Cromer	Calibration	-0.27 (-9.8%)	-0.30 (-10.9%)	-3
	Validation	-0.25(-8.3%)	-0.33(-10.8%)	-2

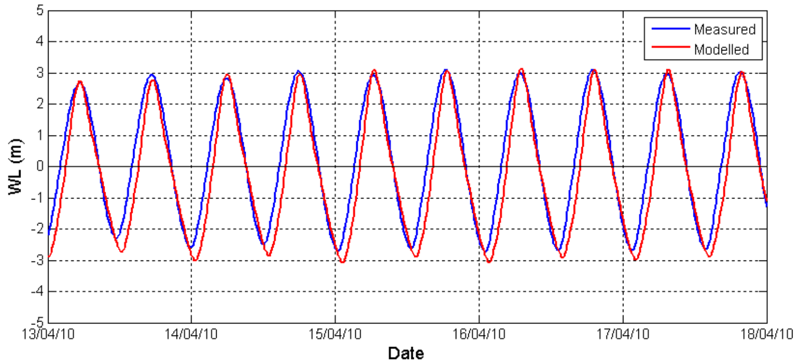


Figure B4. Water Level Calibration at Immingham (Spring Tides)

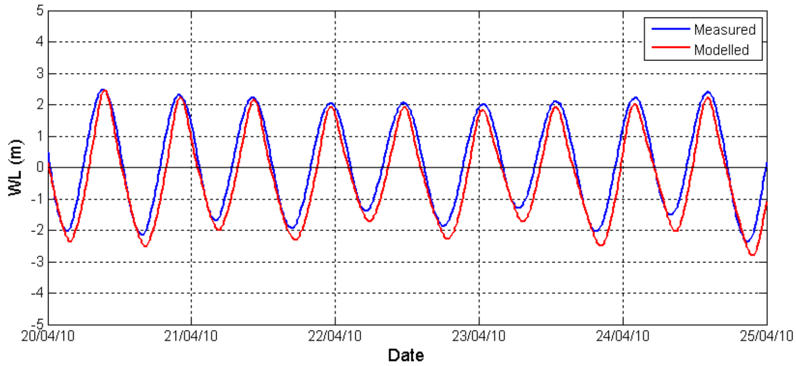


Figure B5. Water Level Calibration at Immingham (Neap Tides)

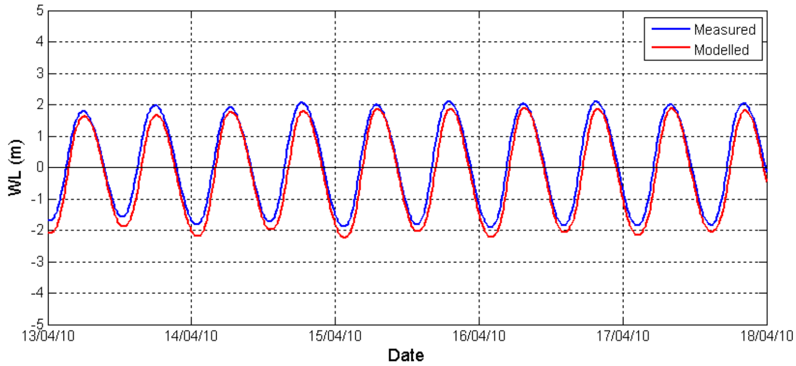


Figure B6. Water Level Calibration at Cromer (Spring Tides)

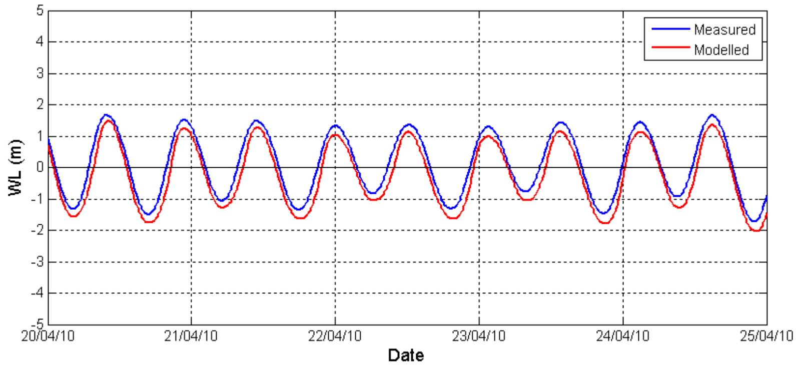


Figure B7. Water Level Calibration at Cromer (Neap Tides)

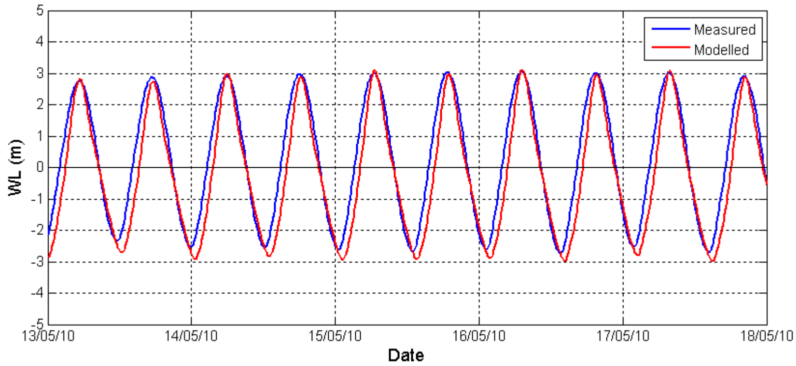


Figure B8. Water Level Validation at Immingham (Spring Tides)

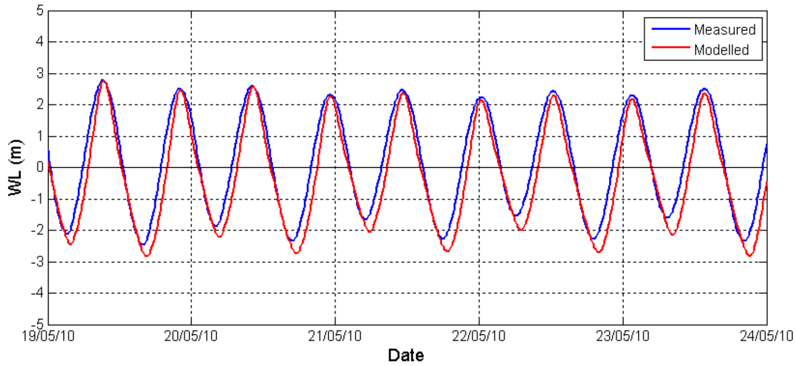


Figure B9. Water Level Validation at Immingham (Neap Tides)

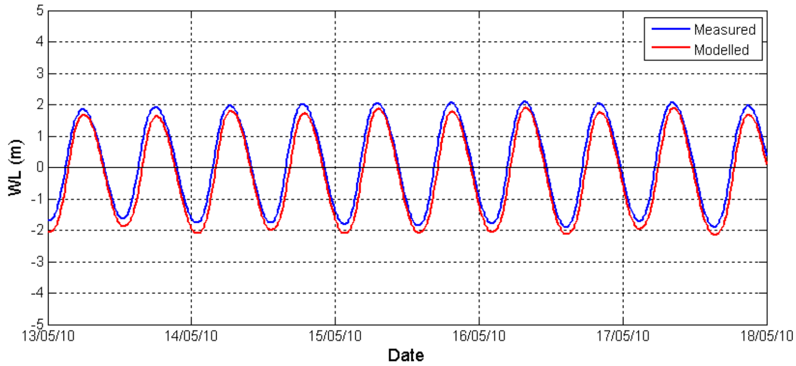


Figure B10. Water Level Validation at Cromer (Spring Tides)

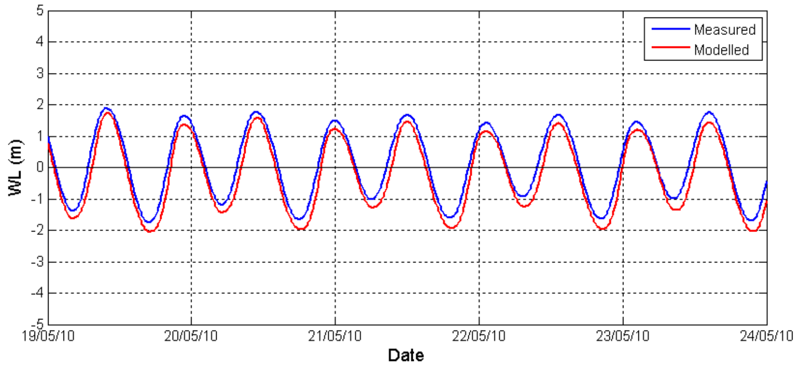


Figure B11. Water Level Validation at Cromer (Neap Tides)

B3.1.2 Currents

The model has also been calibrated and validated against flow velocity data recorded at four sites listed in Section B2.6. To drive the model, the boundaries have been constructed individually for a specific observation period at each site.

Model calibration outputs are presented against measured data in Figures B12 to B19. In general, the calibrated model predictions are found to be in good agreement with the measured data, with the shape and magnitude of the velocity curves well reproduced.

To provide a quantitative assessment of the model performance, a statistical analysis based on comparing observed and modelled peak flood and ebb currents (speed and direction) was undertaken. These statistics were calculated over two five day periods; results are presented in Table B3 and Table B4. The first period is centred on spring tides for calibration and the second is centred on neap tides for validation. The results presented are based on modelled minus observed values. Positive values therefore indicate an overestimation of the current speed in the model and negative values an underestimate. The current calibration focuses on the bed roughness to improve the model prediction.

Spatially constant Manning numbers in a wide range including 30, 32, 35, 37 and 40$m^{1/3}/s$ have been applied in the study. The model results finally led to a value of 37$m^{1/3}/s$, which yielded a good agreement between modelled and measured currents.

The modelled and observed peak current speeds agree to within 0.10m/s, except on the flooding spring tide at Site b0049843. As a percentage of peak flows, the model agrees to within 10% of the observed values for the most tidal states. The duration of flood/ebb is similar between the model predictions and the measurements. Furthermore, the current directions are close to the measured data. Comparison of modelled and observed current directions indicates an agreement to within 15° at the most sites for different tidal states with the exception of spring tide events at b0010528.

Meteorological effects may contribute to the discrepancy between model output and observations. This non-tidal effect is not included in the model. Moreover, the difference may also occur when the depth-averaged velocity from the model is compared with the data observed by one current meter in a fixed depth.

Table B3. Calibration current speed and direction statistics for spring tides

Location		Speed Difference (m/s)		Direction Difference (Deg)	
		Peak Flood	Peak Ebb	Peak Flood	Peak Ebb
1	b0049843	0.12(14.5%)	0.07(7.1%)	4	6
2	b0010528	0.01(0.6%)	0.01(0.7%)	3	27
3	b0015256	-0.07(-6.1%)	-0.10(11.6%)	0	14
4	b0008862	-0.06(-8.1%)	-0.06(-7.8%)	-3	-14

Table B4. Calibration current speed and direction statistics for neap tides

Location		Speed Difference (m/s)		Direction Difference (Deg)	
		Peak Flood	Peak Ebb	Peak Flood	Peak Ebb
1	b0049843	0.10(14.2%)	0.03(3.8%)	1	5
2	b0010528	0.06(5.7%)	0.03(3.2%)	15	9
3	b0015256	0.05(7.6%)	-0.04(-6.3%)	4	-4
4	b0008862	-0.05(-6.2%)	-0.02(-3.2%)	4	-8

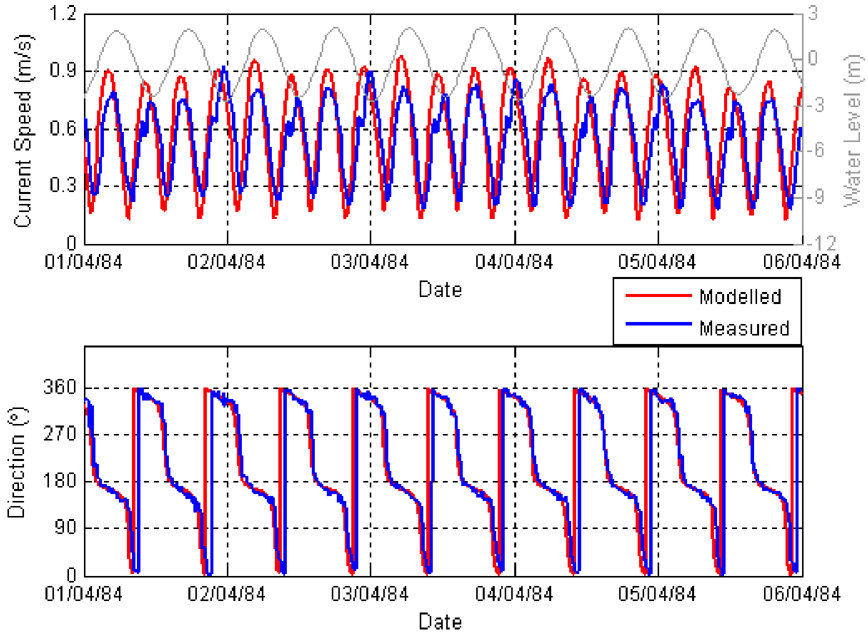


Figure B12. Current Calibration at Site b0049843 (Spring Tides)

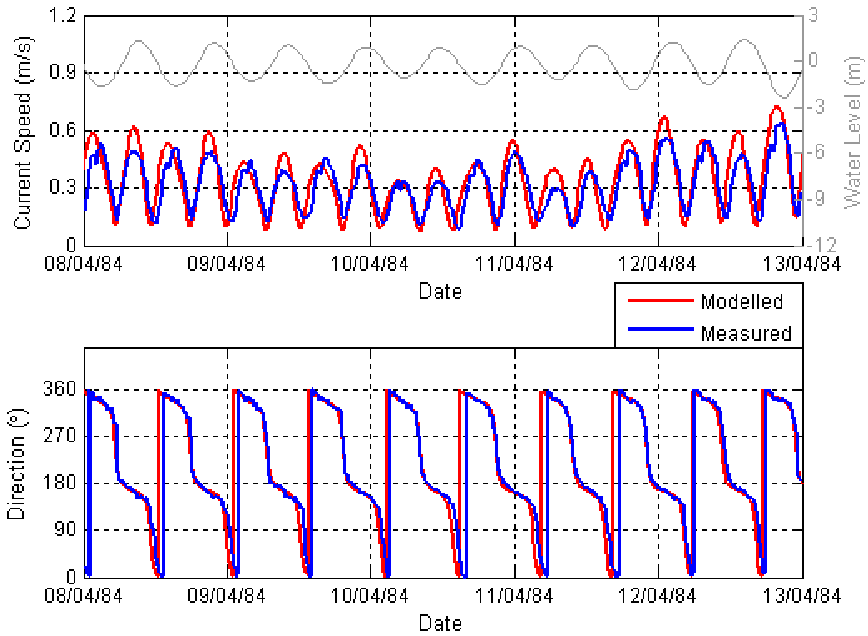


Figure B13. Current Calibration at Site b0049843 (Neap Tides)

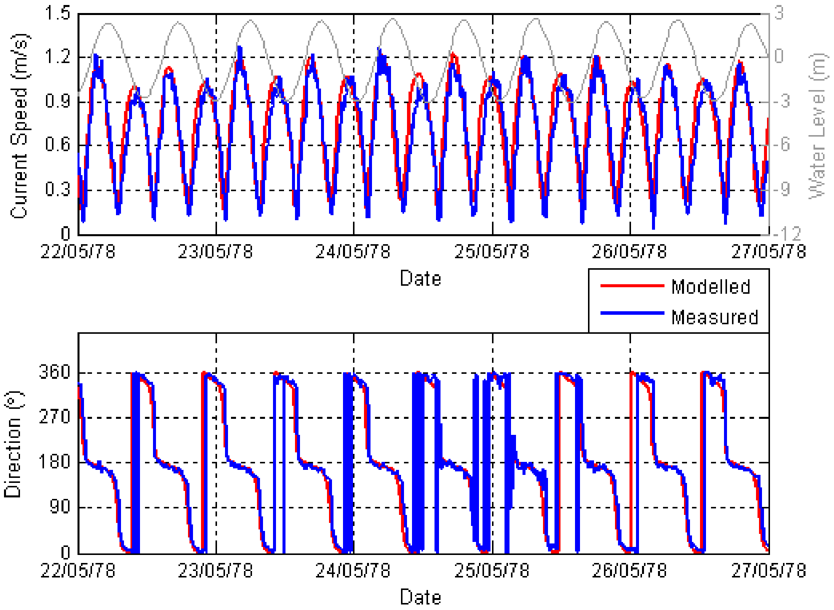


Figure B14. Current Calibration at Site b0010528 (Spring Tides)

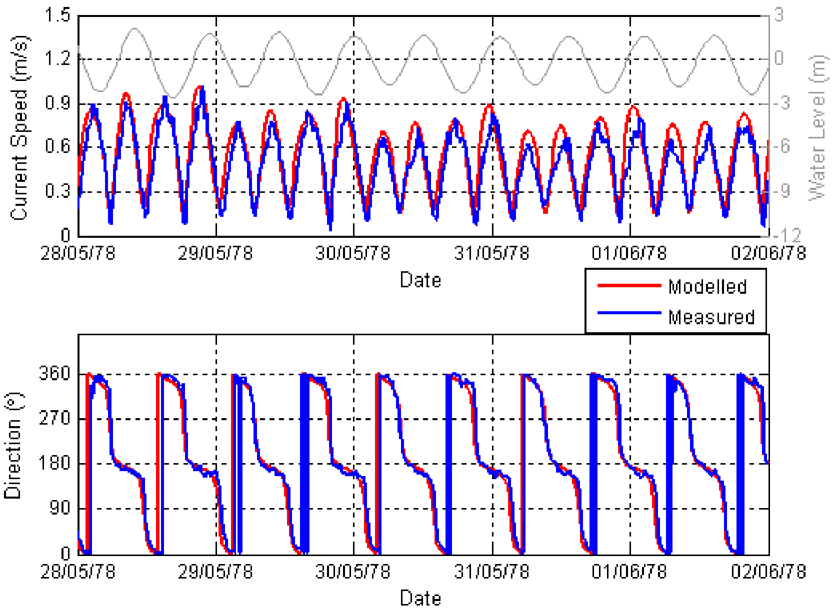


Figure B15 Current Calibration at Site b0010528 (Neap Tides)

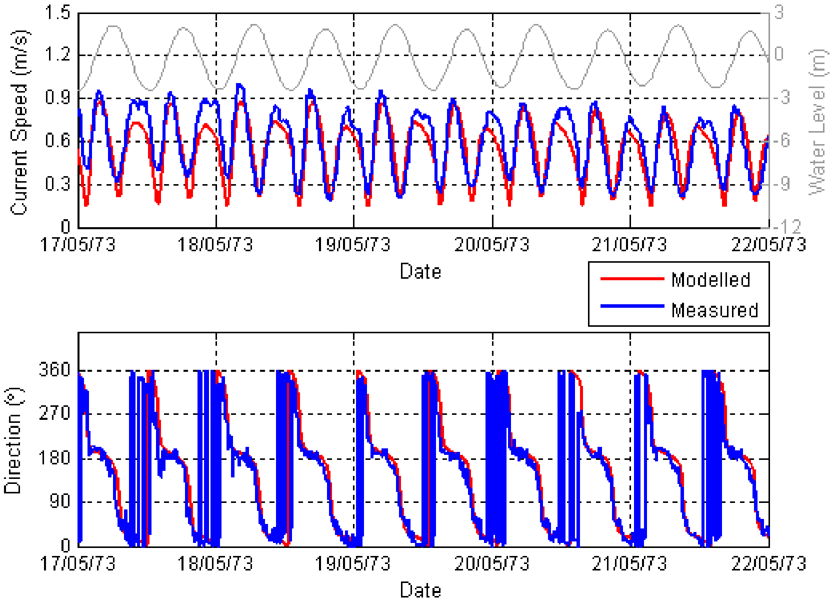


Figure B16. Current Calibration at Site b0015256 (Spring Tides)

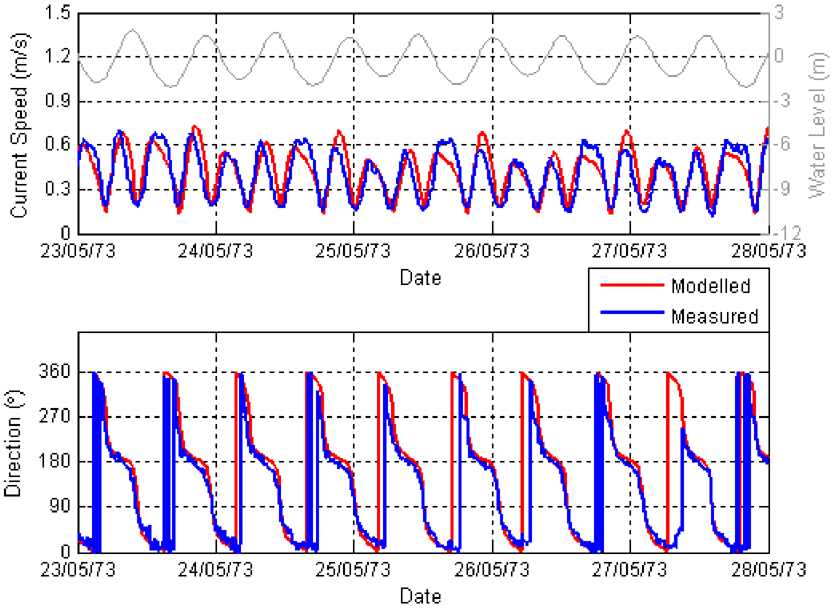


Figure B17. Current Calibration at Site b0015256 (Neap Tides)

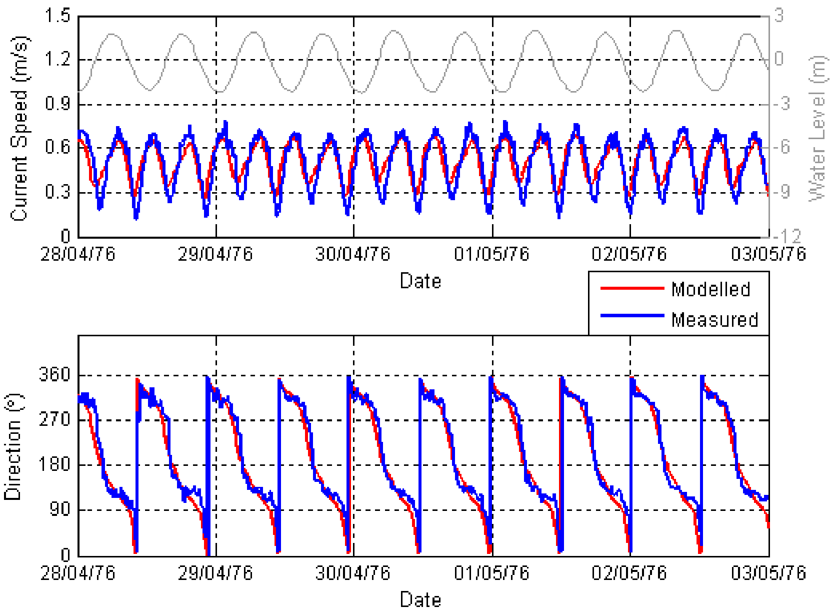


Figure B18. Current Calibration at Site b0008862 (Spring Tides)

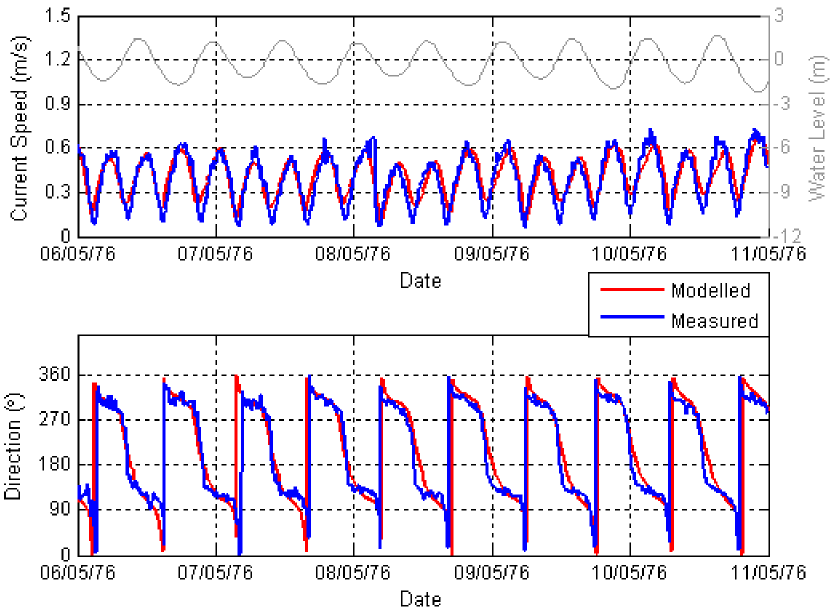


Figure B19 Current Calibration at Site b0008862 (Neap Tides)

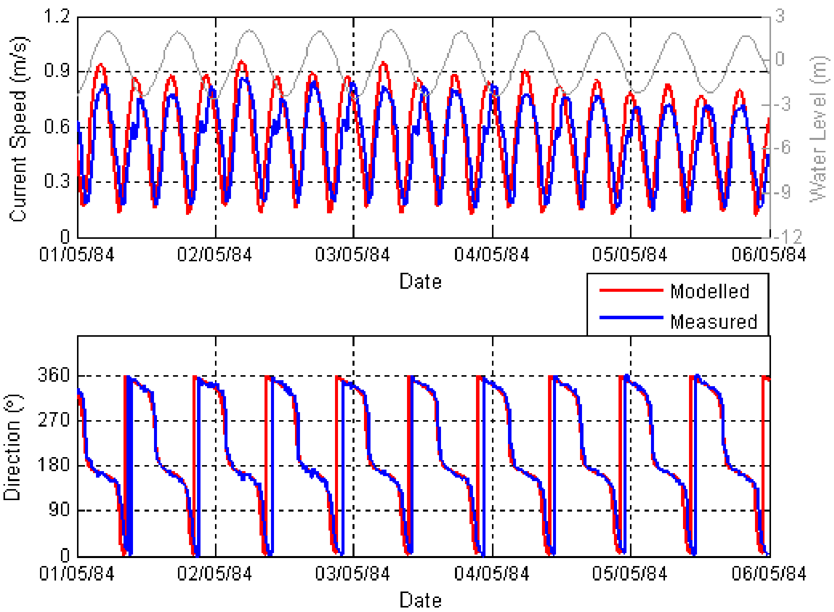
Validated model velocity predictions are plotted against observations in Figures B20 to B27. To further quantify model validation, the statistical analysis results are given in Table B5 and Table B6. It is clear that the accuracy is close to what has been achieved during the calibration process.

Table B5. Validation current speed and direction statistics for spring tides

Location		Speed Difference (m/s)		Direction Difference (Deg)	
		Peak Flood	Peak Ebb	Peak Flood	Peak Ebb
1	b0049843	0.10(11.2%)	0.06 (7.2%)	2	6
2	b0010528	-0.01(-0.8%)	0.03(3.2%)	6	23
3	b0015256	-0.10(-11.0%)	-0.09(-10.1%)	4	-5
4	b0008862	-0.05(-7.0%)	-0.07(-8.7%)	5	-15

Table B6. Validation current speed and direction statistics for neap tides

Location		Speed Difference (m/s)		Direction Difference (Deg)	
		Peak Flood	Peak Ebb	Peak Flood	Peak Ebb
1	b0049843	0.05(8.5%)	0.02(3.2%)	2	1
2	b0010528	0.09(9.9%)	0.03(3.2%)	7	23
3	b0015256	-0.02(-2.4%)	-0.06(-8.3%)	6	-1
4	b0008862	-0.04(-5.4%)	0.01(0.3%)	2	-11



FigureB20. Current Validation at Site b0049843 (Spring Tides)

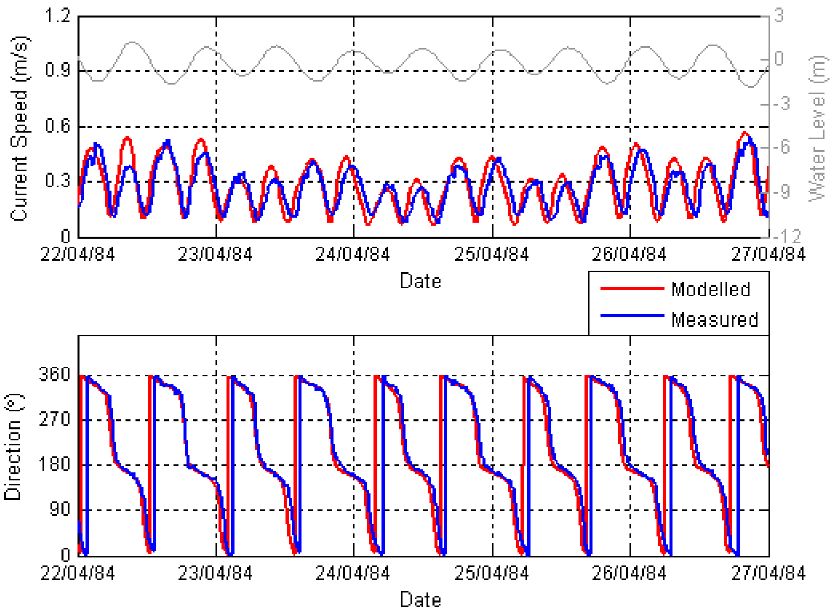


Figure B21. Current Validation at Site b0049843 (Neap Tides)

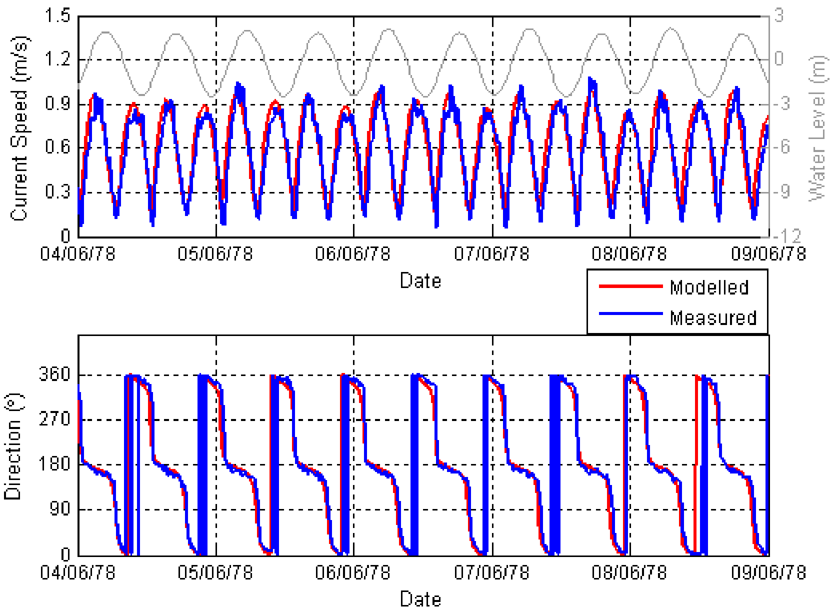


Figure B22. Current Validation at Site b0010528 (Spring Tides)

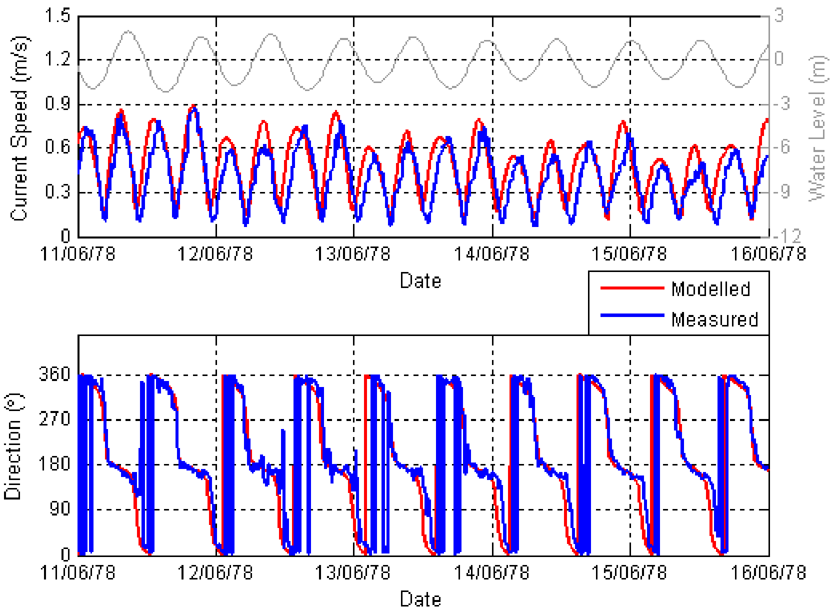


Figure B23. Current Validation at Site b0010528 (Neap Tides)

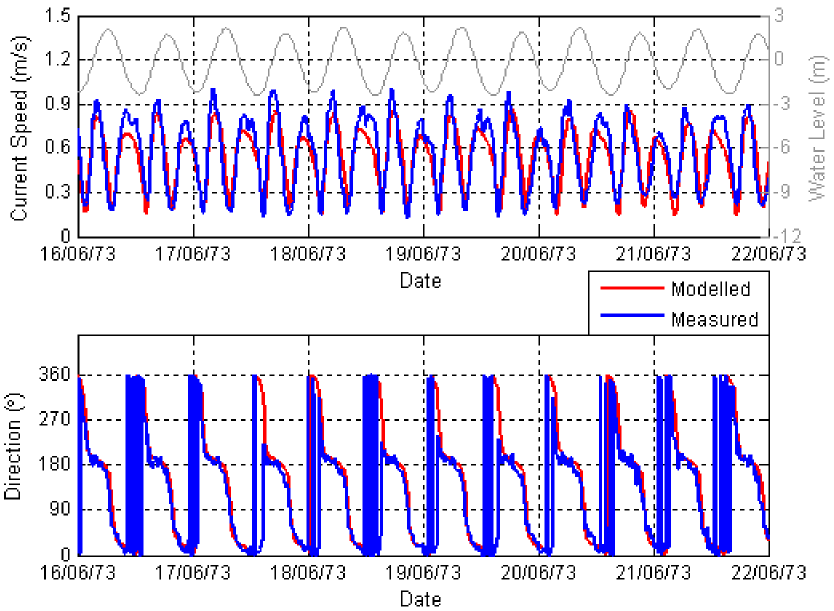


Figure B24. Current Validation at Site b0015256 (Spring Tides)

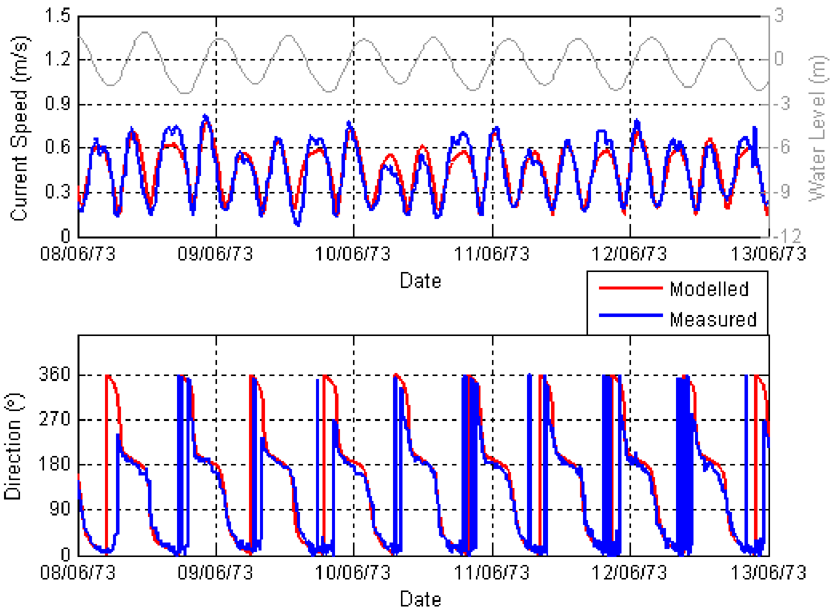


Figure B25. Current Validation at Site b0015256 (Neap Tides)

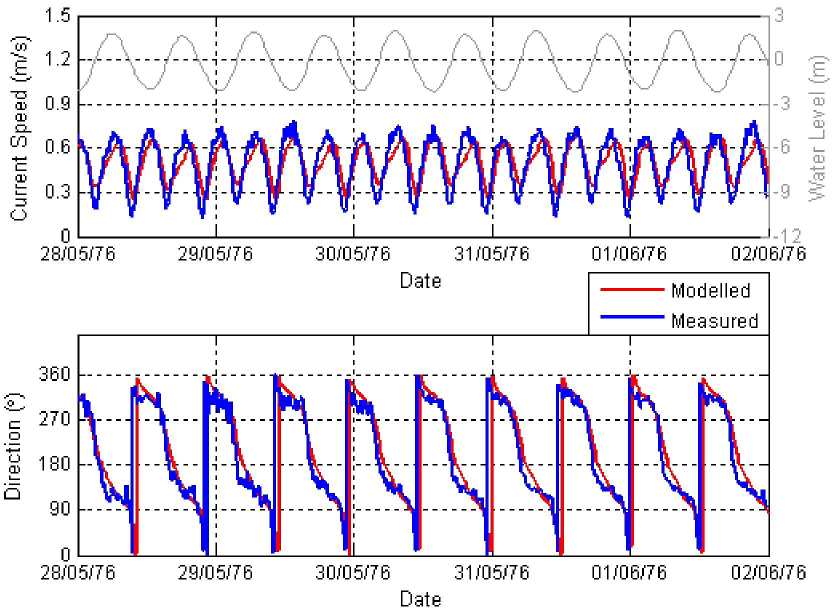


Figure B26. Current Validation at Site b0008862 (Spring Tides)

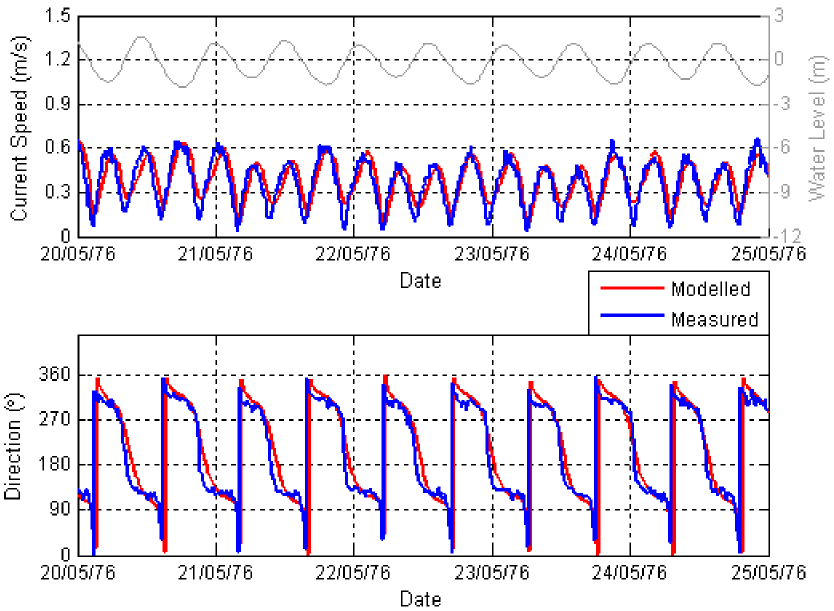


Figure B27. Current Validation at Site b0008862 (Neap Tides)

B4 Waves

The calibration and validation of the MIKE 21 SW model is described in this section. Measured wave data were collected at the three sites, namely Blakeney Overfalls, Dowsing and North Well. Calibration was performed by simulating a period from 1April to 21 May 2009 while validation was performed by comparing the model's performance against the field data from the period 21 May to 15 July 2009.

Calibration of the wave model initially focussed on minimising the difference between predicted wave heights and measured values. There are no established industry standard calibration targets for numerical wave models. However, ABPmer typically aim for wave heights to be predicted within ±10% and wave periods within ±20%.

The level of model calibration achieved has been quantified by analysing time-series data for the key wave parameters. This analysis involved the calculations of the mean absolute error; scatter index (SI) and correlation coefficient (R). The scatter index is the root mean square error normalised with the mean value, calculated using the equation below:

$$SI = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(S_i - O_i)^2}}{\frac{1}{N}\sum_{i=1}^{N}O_i} \times 100$$

in which N is total number of data, O_i is the measured data and S_i is the simulated, or model data.

The high degree of correlation between modelled and measured data confirms that key wave parameters are well reproduced by the model at the three sites, as shown in Figures B28, B29 and B30.

Statistical results from the assessment of model calibration are provided in Table B7 and B8. A lower scatter index and a higher correlation coefficient are indicative of a good level of calibration. Again there are no established guidelines which define appropriate target values for calibration in terms of these parameters. Using these values as an indicator of model calibration, suggested targets for the scatter index would be a value less than 35% and a correlation coefficient higher than 0.65.

In percentage terms the mean errors presented in Tables B7 correspond to between 7.5% and -8.7% of observed values, which is within the suggested calibration target for ±10% of wave height.

For wave period, the mean errors in Table B8 vary from 1.9% to 13.9% of observed values. The largest error lies within the 20% limit. Overall the calibration of wave period is therefore considered to be acceptable.

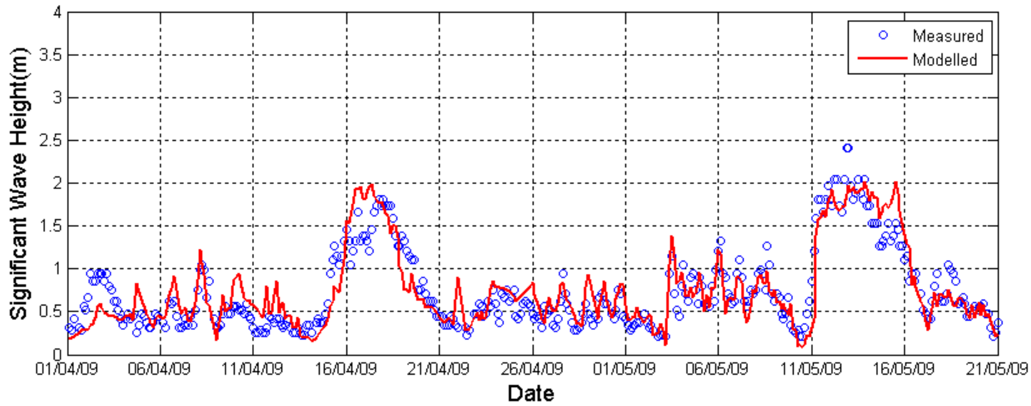
Comparisons of peak wave direction between model results and measurements have also been made in the plots. It can be seen that the model predictions of wave direction are good for the storm events (larger wave height) but become scattered for those under the normal wave conditions.

Table B7. Wave height calibration statistics

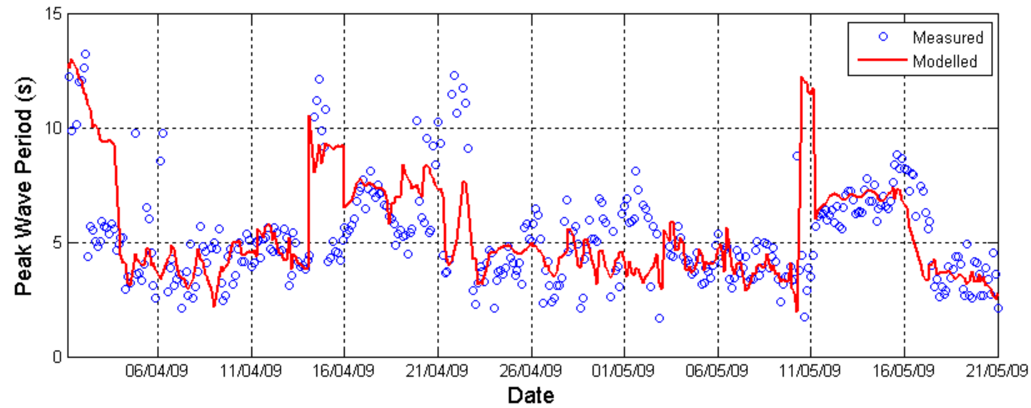
Sites	Model Mean	Obs. Mean	Mean Abs. Err.	Percentage	SI	R
Blakeney Overfalls	0.77	0.75	0.02	2.7%	31	0.99
Dowsing	1.01	0.94	0.07	7.5%	24	0.91
North Well	0.52	0.57	-0.05	-8.7%	40	0.80

Table B8. Wave period calibration statistics

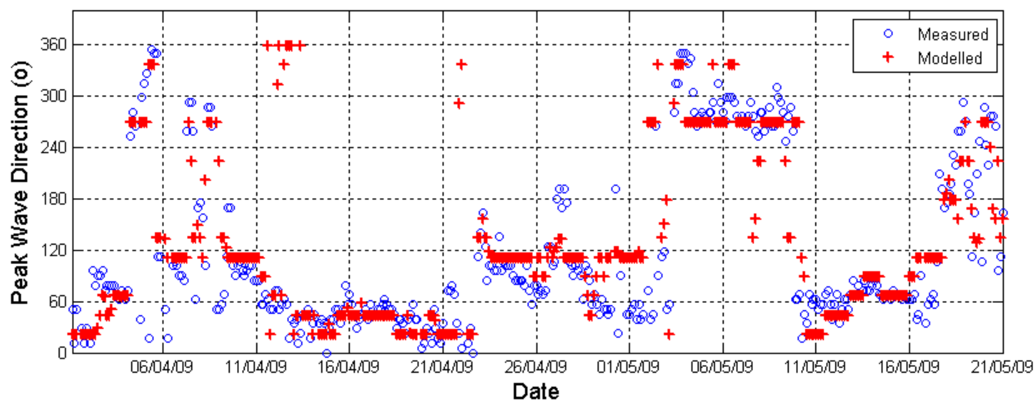
Sites	Model Mean	Obs. Mean	Mean Abs. Err.	Percentage	SI	R
Blakeney Overfalls	5.4	5.3	0.1	1.9%	43	0.48
Dowsing	6.1	5.8	0.3	5.2%	40	0.46
North Well	4.9	4.3	0.6	13.9%	46	0.45



(a) Wave Height

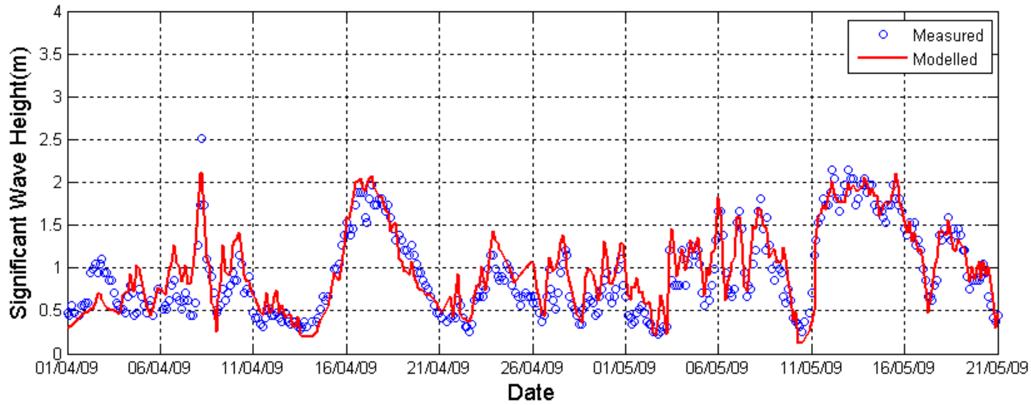


(b) Wave Period

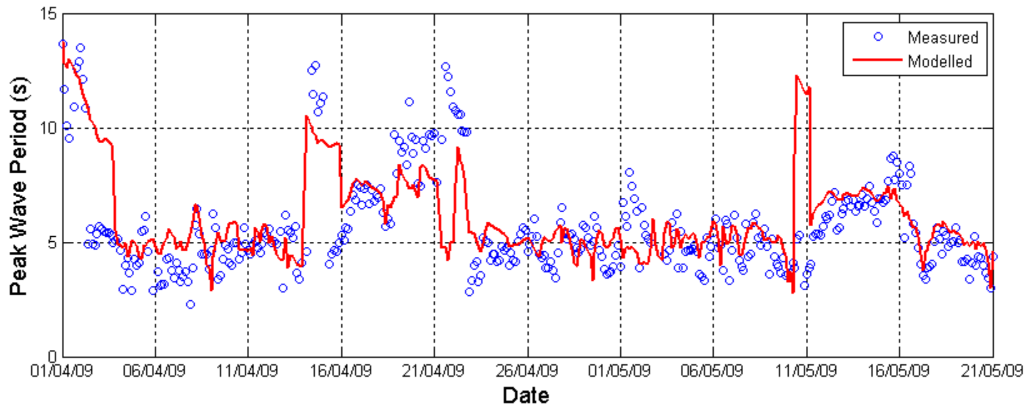


(c) Wave Direction

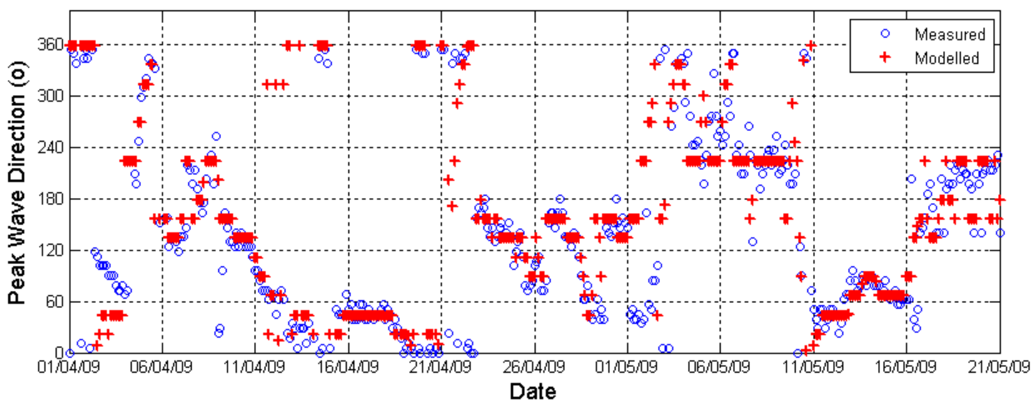
Figure B28. Wave Calibration at Blakeney Overfalls



(a) Wave Height

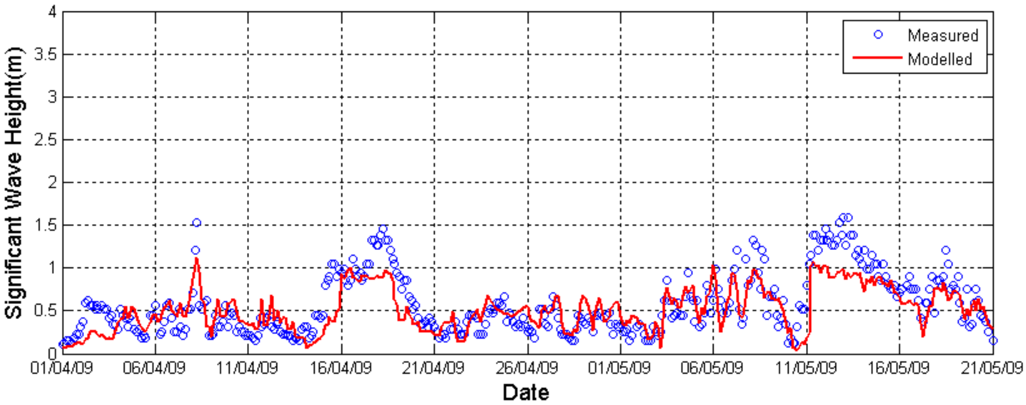


(b) Wave Period

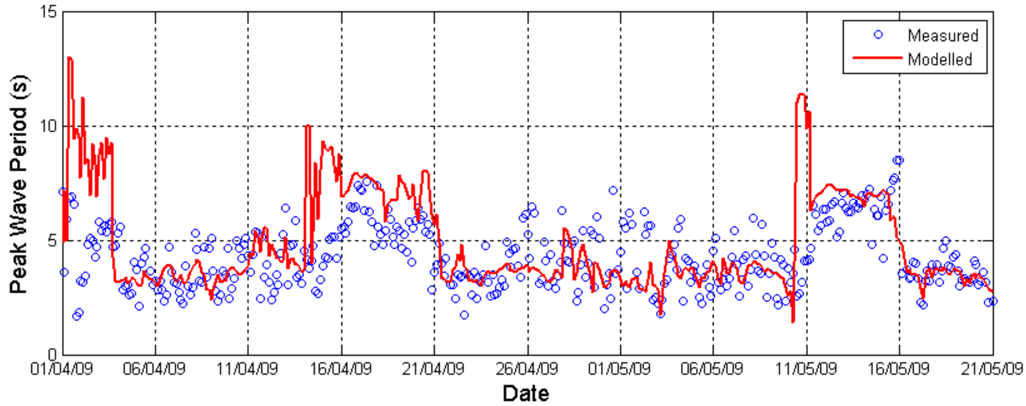


(c) Wave Direction

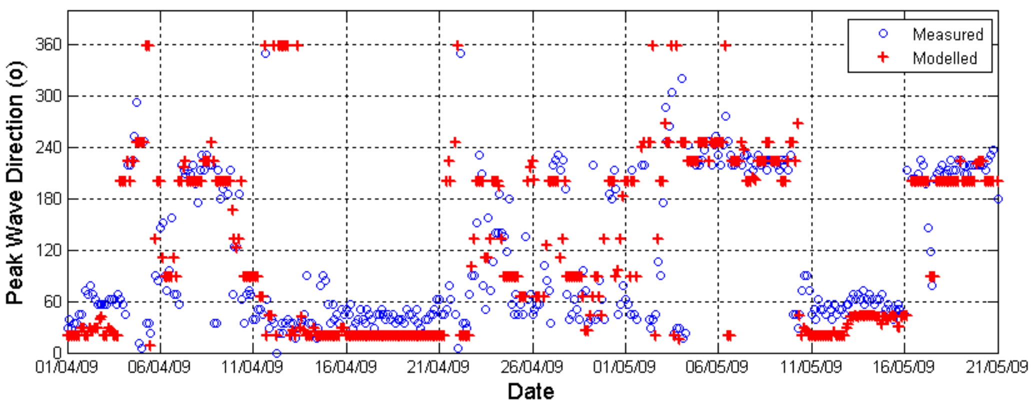
Figure B29. Wave Calibration at Dowsing



(a) Wave Height



(b) Wave Period



(c) Wave Direction

Figure B30. Wave Calibration at North Well

Further assessment of model performance was undertaken for a separate period to validate the model. During the validation stage no further adjustment was made to the model parameters. The comparison of model and measured time-series for the standard wave parameters is presented in Figures B31, B32 and B33 for three sites.

For the validation event the mean errors in wave height are within ±9.3% as shown in Table B9. The proposed calibration targets are therefore achieved at three sites under these conditions.

The mean errors in wave period shown in Table B10 vary from -3.6% to 6.9%. As for wave height, the calibration targets for wave period are also met at three sites.

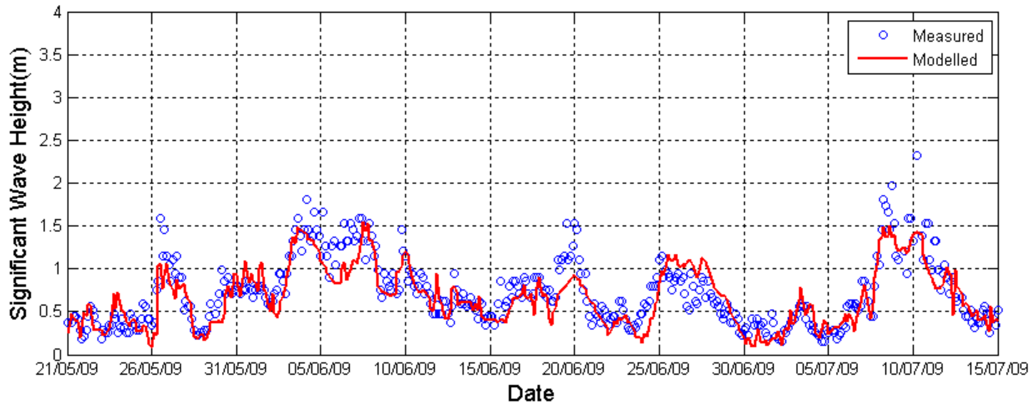
The validation exercise confirms that the calibrated wave model performs well when used to reproduce alternative wave events with a good agreement of the suggested criteria. It is therefore justifiable to accept the overall performance of the wave model based on the results presented.

Table B9. Wave height validation statistics

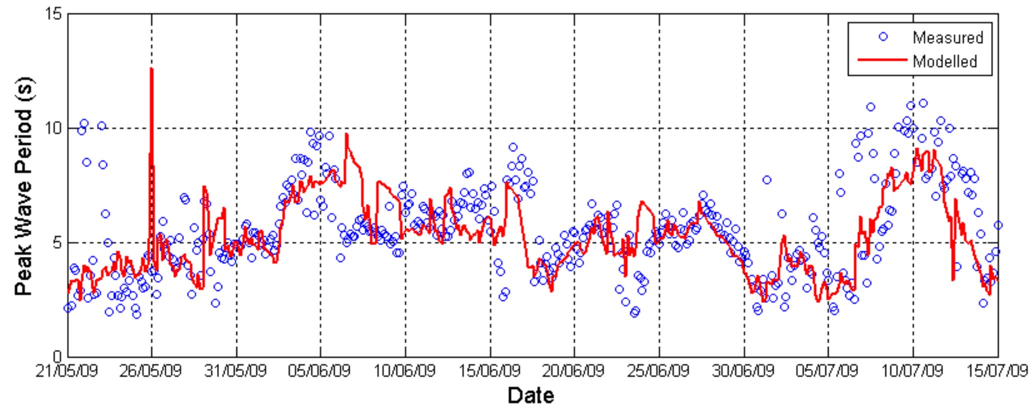
Sites	Model Mean	Obs. Mean	Mean Abs. Err.	Percentage	SI	R
Blakeney Overfalls	0.68	0.73	-0.05	-6.8%	30	0.84
Dowsing	0.85	0.88	-0.03	-3.4%	22	0.93
North Well	0.48	0.53	-0.05	-9.3%	38	0.66

Table B10. Wave period validation statistics

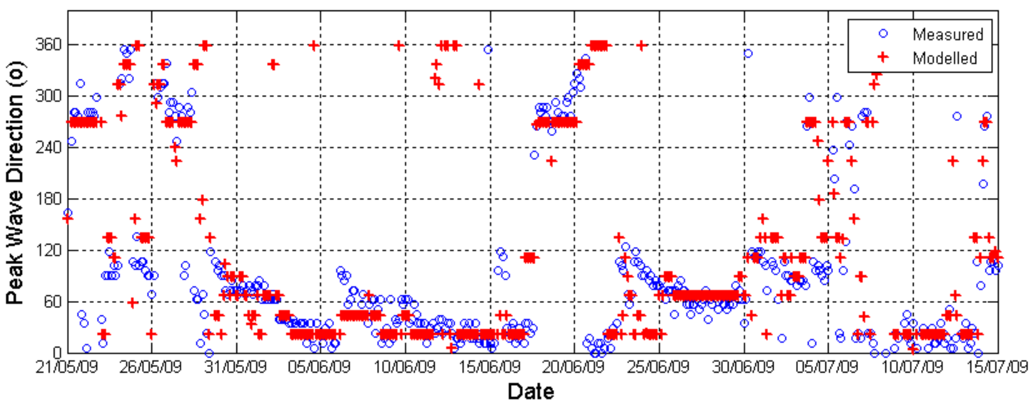
Sites	Model Mean	Obs. Mean	Mean Abs. Err.	Percentage	SI	R
Blakeney Overfalls	5.3	5.5	-0.2	-3.6%	32	0.55
Dowsing	5.6	6.0	-0.4	-6.7%	30	0.55
North Well	4.6	4.3	0.3	6.9%	32	0.54



(a) Wave Height

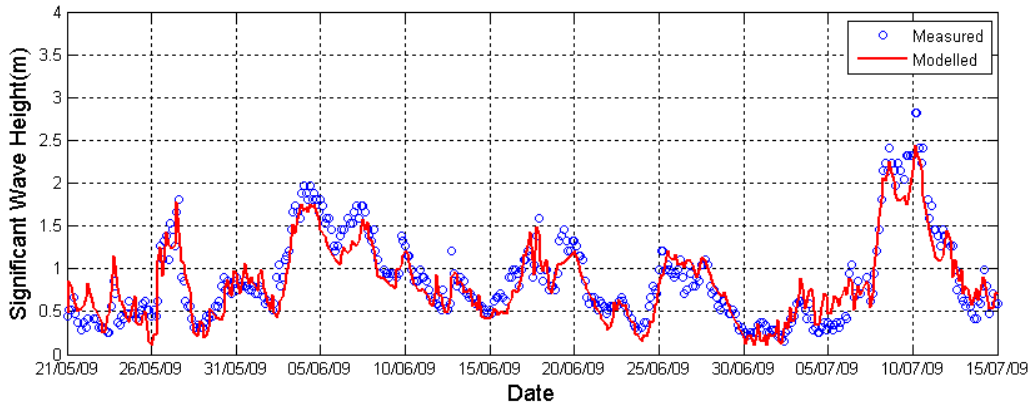


(b) Wave Period

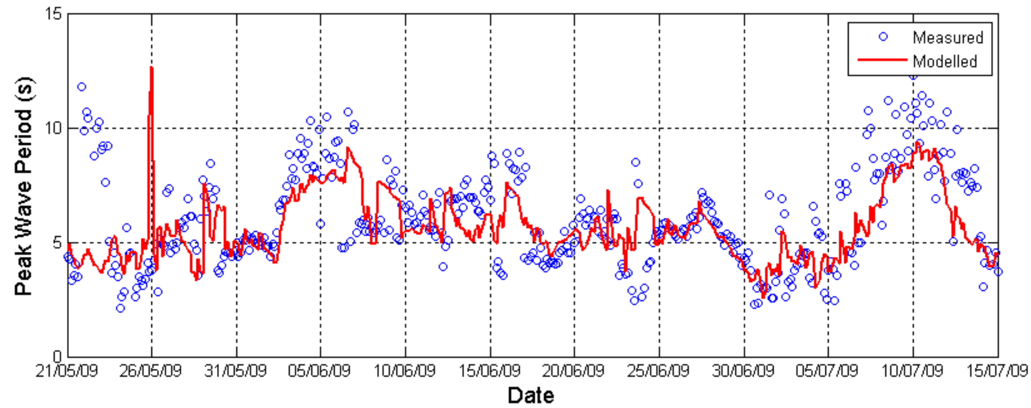


(c) Wave Direction

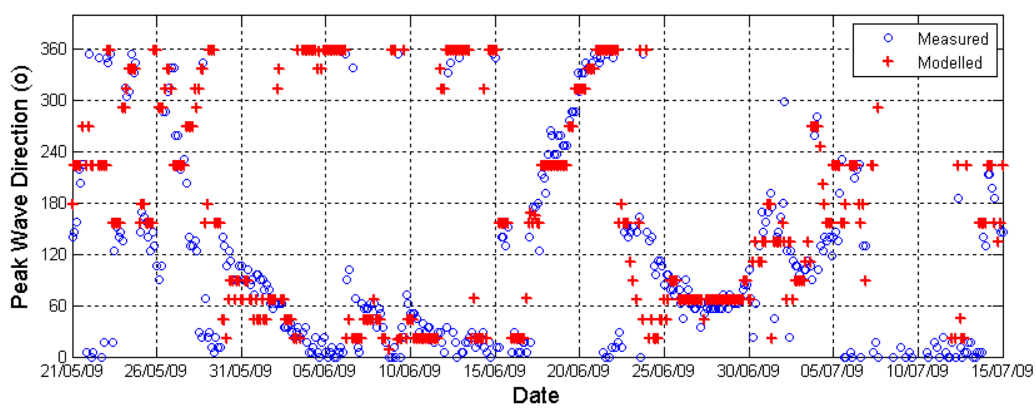
Figure B31. Wave Validation at Blakeney Overfalls



(a) Wave Height

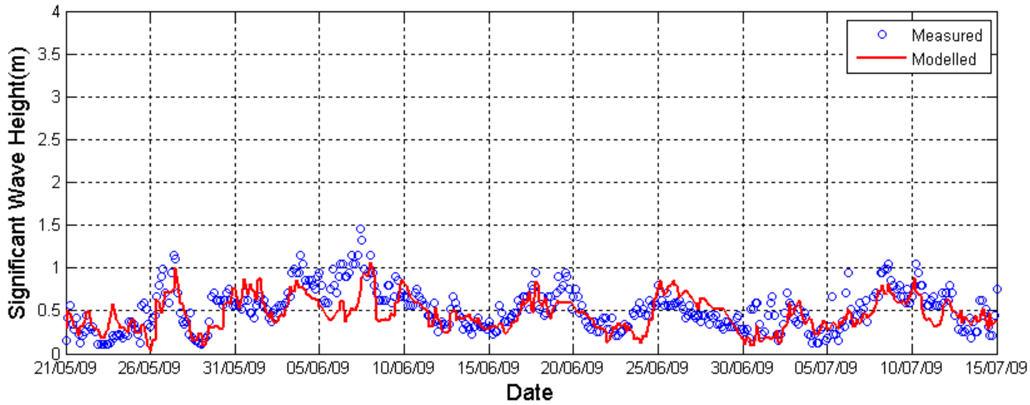


(b) Wave Period

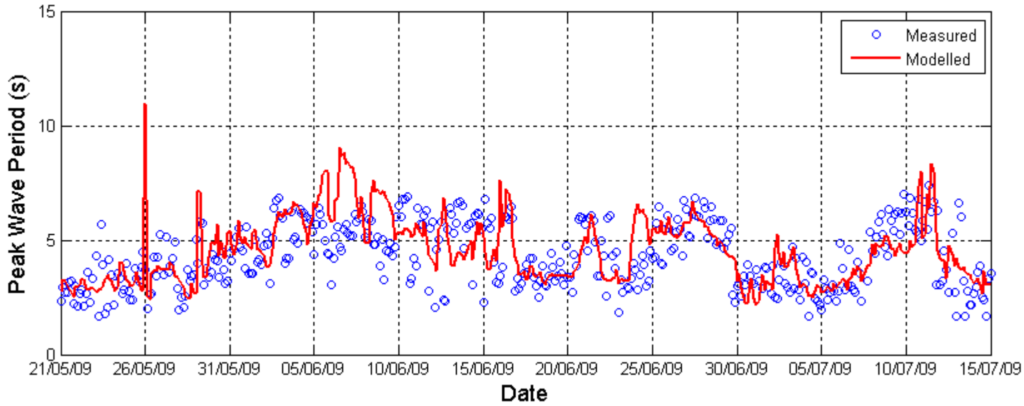


(c) Wave Direction

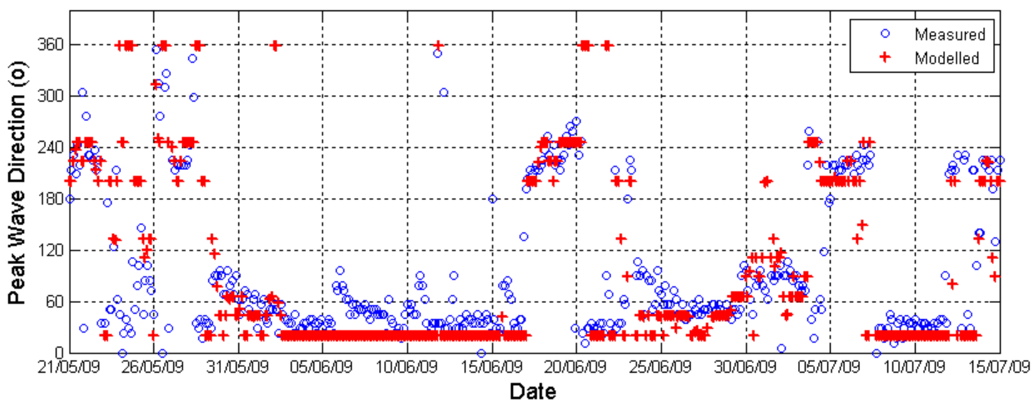
Figure B32. Wave Validation at Dowsing



(a) Wave Height



(b) Wave Period



(c) Wave Direction

Figure B33. Wave Validation at North Well

B4. Reference

ABPmer 2005. Humber Strategy Implementation Study Model Design and Calibration. ABP Marine Environmental Research Ltd, Report No. R.1143.

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