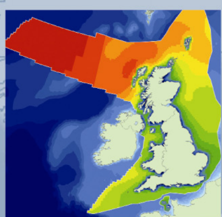
ERM Ltd and
Humber Aggregates Dredging Association (HADA)

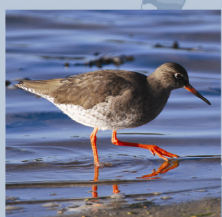
Humber MAREA - Physical Processes Study: Baseline Characterisation

Report R.1820

January 2012

Creating sustainable solutions for the marine environment

ERM Ltd and
Humber Aggregates Dredging Association (HADA)

Humber MAREA - Physical Processes Study: Baseline Characterisation

Date: January 2012

Project Ref: R/3965/01

Report No: R.1820

Version	Details of Change	Authorised By	Date
1	Draft	A J Houghton	15.07.2011
2	Draft Final	A J Houghton	12.08.2011
3	Final	A J Houghton	02.09.2011
4	Final	A J Houghton	26.09.2011
5	Final	A J Houghton	19.01.2012

Document Authorisation		Signature	Date
Project Manager:	A J Houghton		19.01.2012
Quality Manager:	J J Williams		19.01.2012
Project Director:	W S Cooper		19.01.2012

ABP Marine Environmental Research Ltd
Suite B, Waterside House
Town Quay
SOUTHAMPTON
Hampshire
SO14 2AQ

Tel: +44(0)23 8071 1840
Fax: +44(0)23 8071 1841
Web: www.abpmer.co.uk
Email: enquiries@abpmer.co.uk

ABPmer is certified by:

Summary

The Humber MAREA study area forms part of the semi-enclosed Southern North Sea Basin, whose current configuration was formed during the last major glaciation some 18000 years ago. The seabed in the study area is predominantly flat and slopes gently away from the coast to water depths are typically around 30 m at the eastern boundary. However, the seabed is intersected by major bathymetric features, including deeps such as Silver Pit, which reach depths of over 100 m, and both shore-connected and offshore sandbanks. The bedrock in the study area is predominantly Chalk, but there are few areas where this is exposed. The main Quaternary sediment is a glacial till sheet known as the Bolders Bank Formation. Two major estuaries are within the study area. However, neither The Wash nor The Humber contributes significant volumes of riverine sediments (fines) to the adjacent coastlines.

Surficial seabed sediments are predominantly sands and gravels derived either from erosion and reworking of the till sheet or from glacio-fluvial activity. There is a distinct regional sediment distribution, with coarser sediments in the western part of the region and finer, sandy sediments to the east. There are numerous areas of mobile bedforms including sandwaves and sand ribbon patches. There are also areas where gravel waves are present but their orientation opposes the prevailing transport direction and the features are assumed therefore to be relict.

The mean spring tidal range increases in a westerly direction along the North Norfolk coast from 4 m to a maximum of 6 m at Hunstanton and at Skegness. The range decreases slightly in a northerly direction to 5 m at Bridlington. Tidal currents are typically moderate close to the coast and stronger offshore. Approximately rectilinear tidal currents are southerly on the flood and northerly on the ebb. The study area is exposed to waves from the north, east and south with the largest and most frequent waves from the north and north east.

In the nearshore region sediments are transported as bedload in a southerly direction, with a complex pathway across the Humber. A proportions of these are deposited around Donna Nook with the remainder continuing southwards towards The Wash. Further offshore, the net transport direction is northerly. Superimposed upon this regime are complex local transport pathways, particularly around seabed features and between the coast and the nearshore region.

There are three main coastlines within the MAREA study area – Holderness, Lincolnshire and North Norfolk. The Holderness coast is characterised by eroding glacial till cliffs, fronted by a wide, flat shore platform that is also eroding. Cliff recession along this coast is dramatic and has been ongoing for thousands of years at an average rate of around 2 m/year. The only substantial coastal defences are at Hornsea, Withernsea, Mappleton and Easington.

The Holderness coast is the primary source of modern sediment for the Humber region. Sediments eroded from the cliffs and shore platform are transported southwards, mainly as littoral drift to feed the beaches at Spurn Point and north Lincolnshire. Spurn Head is a recurved sand and shingle spit, which has suffered breaching on numerous occasions during the recent past. The peninsula is currently in an unstable state and a further breach is predicted within 5 to 10 years.

The mouth of the Humber and the North Lincolnshire coast are a major sink for sediments derived from the Holderness cliffs. There is a complex pathway across the Humber, which varies between calm conditions and storm events. The Humber itself is a mature sediment sink with little additional sediment

storage capacity. Northcoates to Donna Nook have large inter-tidal areas that merge with the offshore sandflats that form the Humber tidal delta. This stretch of coast is backed by dunes and saltmarshes.

From Mablethorpe to Skegness the beaches are backed almost continuously by hard defences. The coastal frontage suffers severe erosion owing to limited sediment suppy from the north are. Since 1994 there has been an ongoing programme of beach nourishment to maintain an appropriate standard of protection along a 24 km stretch of coast. However, the erosional trend continues, necessitating the continuation of the scheme beyond its original target lifetime.

From Skegness to Gibraltar Point the coastline is characterised by dunes and saltmarsh, fronted by a wide inter-tidal area which is accreting. Some sediment is received from the north but there are also exchanges with the nearshore banks at the mouth of the Wash and a potential supply of sediment from offshore.

The North Norfolk coast is morphologically highly complex. It is characterised by Chalk cliffs at Hunstanton in the west, extensive dunes, saltmarsh and inter-tidal sandflats that are intersected by tidal deltas in the middle section and shingle beaches backed by eroding cliffs to the east. The most prominent features are the recurved barrier islands of Scolt Head and Blakeney Point. These are extending/migrating to the west and are also transgressing landwards through roll back processes. Erosion is experienced along much of the coast but the effects are typically localised due to the extensive inter-tidal expanses that front the beaches and saltmarshes. There are few hard defences.

Sediment transport processes are also complex along this frontage with both easterly and westerly littoral drift. It is thought that transport is typically to the west along the beach face and to the east in the nearshore regions. The main sources of sediment are the cliffs between Weybourne and West Runton and an offshore source from Burnham Flats.

Virtually the entire coastline within the Humber MAREA study area may be considered vulnerable to changes in the hydrodynamic regime as a result of climate change and/or anthropogenic activity although some areas are naturally more sensitive than others.

- In the future, the main threats to the system in response to both natural and anthropogenic influences are:
- A reduction in sediment supply from Holderness, which may occur if the configuration of the coastline changes through variable recession rates.
- A breach at Spurn Head, which may result in the modification or even loss of the feature. This would potentially alter the way sediment is moved across and into the Humber.
- Change in the configuration or nature of offshore sediment features and particularly The Binks, the Humber sandflats and the nearshore banks that shelter the Lincolnshire coastline.
- Climate change effects such as sea level rise creating an increased sediment demand in the Humber, thereby reducing the sediment supply to the Lincolnshire coast and increased storminess (waves and surges).
- Cessation of the Lincshore beach recharge scheme;
- Continued roll back of Scolt Head and Blakeney Point until they merge with the coast, and are lost from the active sedimentary system.

Abbreviations

ABPmer	ABP Marine Environmental Research Ltd
BCD	Below Chart Datum
BGS	British Geological Survey
BP	years Before Present
CD	Chart Datum
CIRIA	Construction Industry Research and Information Association
cSAC	candidate Special Area of Conservation
EA	Environment Agency
ERYC	East Riding of Yorkshire Council
ha	Hectare
HADA	Humber Aggregates Dredging Association
HAT	Highest Astronomical Tide
LAT	Lowest Astronomical Tide
MAREA	Marine Aggregates Regional Environmental Assessment
MHWN	Mean High Water Neaps
MHWS	Mean High Water Springs
MLWN	Mean Low Water Neaps
MLWS	Mean Low Water Springs
ODN	Ordnance Datum Newlyn
pSAC	potential Special Area of Conservation
Ramsar	The Convention on Wetlands (Ramsar, Iran, 1971)
REC	Regional Environmental Characterisation
rRA	recommended Reference Area
rMCZ	recommended Marine Conservation Zone
RSPB	Royal Society for the Protection of Birds
RSLR	Relative Sea Level Rise
SAC	Special Area of Conservation
SBU	Shoreline Behaviour Unit
SMP2	Shoreline Management Plan 2
SNS	Southern North Sea
SNSSTS2	Southern North Sea Sediment Transport Study Phase 2
SPA	Special Protection Area
UKHO	UK Hydrographic Office

Humber MAREA - Physical Processes Study: Baseline Characterisation

Contents

Page

Tables

Images

Figures

1. Introduction

The Humber Aggregates Dredging Association (HADA) has commissioned ERM to carry out a Marine Aggregate Regional Environmental Assessment (MAREA) for the Humber region, which extends from Flamborough Head to Cromer. 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. This will inform both the renewal process for existing licences and applications for dredging in new areas.

There are nine active licences within the Humber area. Dredging is carried out in these by the HADA companies: Tarmac Marine Dredging Ltd, Hanson Marine Aggregates Ltd, CEMEX UK Marine Ltd, Westminster Dredging Ltd and Van Oord Ltd.

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. As part of this study it is necessary to establish an appropriate baseline against which the potential effects of dredging may be assessed and to characterise the environmental receptors to be tested in the assessment. A scoping study was carried out in 2009, which identified the following main physical processes and receptors:

- The hydrodynamic regime;
- The seabed; and
- The coast.

1.1 Report Structure

This report presents the results of a partly desk-based and partly field-based study, which describes the physical and morphological processes which operate across the Humber Region. The remainder of this document is structured as follows:

Section 2: Provides an overview of the geological history, geological processes and the geological features within the study area;

Section 3: Presents the present day bathymetry, seabed sediments and main morphological features;

Section 4: Describes the present day hydrodynamic regime;

Section 5: Summarises regional sediment transport;

Section 6: Provides a detailed characterisation of the coast and coastal processes within the study region;

Section 7: Describes the conservation designations and the other human activities that are carried out in the study area; and

Section 8: Presents the receptors and impact pathways to be tested during the assessment.

1.2 The Study Area

The coastline within the Humber MAREA study area extends from Flamborough Head in the North to Cromer in the south and includes the open coastlines of Holderness, Lincolnshire, and North Norfolk (Figure 1.1). The study area boundaries have been selected on the basis that the potential effects of dredging within the Humber Region will be confined within this area and the two extremes also represent important process boundaries in terms of sediment transport.

1.3 Sources of Information

This study draws upon a variety of existing sources of information such as the recently completed Humber Regional Environmental Characterisation (REC) (BGS *et al*, 2011), Flamborough Head to Gibraltar Point and North Norfolk Shoreline Management Plans (2), Coastal Impact Studies for previous aggregate licence applications, physical processes assessments for offshore wind farms, the Southern North Sea Sediment Transport Study (Phase 2) and other sources of published and unpublished information. Notably, the results of a site visit to the coast of the study area and the results of new offshore bathymetric and geophysical surveys are presented.

2. Geological Overview

It is widely accepted that the seafloor of the Southern North Sea basin was formed during the last glaciation that occurred between 30,000 and 18,000 BP (Eisma and Kalf, 1979). The following provides a brief summary of the recent geological history of the study area in order to understand the processes that shaped the existing geomorphology, along with the nature of the seabed sediments. Some of the information and accompanying figures have been provided by Tarmac Marine Dredging Ltd with the remainder extracted predominantly from the Humber REC (BGS, 2011).

2.1 Geological Processes

The geological processes affecting the seabed in the study area span 30,000 years from the last glacial advance during the Late Devensian cold stage and sea level low stand to the early Holocene marine transgression and subsequent shallow marine incursion into the North Sea basin. To illustrate this, four drawings of the key geological events in this time interval are provided (Figures 2.1 – 2.4). The drawings were originally recently presented in a public exhibition in Holderness and do not purport to show precise boundaries but instead demonstrate how glacial and interglacial events have shaped the region.

During the last major ice sheet advance over the British Isles, between 30,000 and 18,000 years before present (BP), an ice lobe extended south over present day north-eastern England and the adjacent North Sea basin as shown in Figure 2.1. At this time, a sheet of glacial till, the Bolders Bank Formation, was deposited under the ice sheet, draped over the Cretaceous Chalk of the Holderness area and infilling channels cut into the Chalk bedrock in the North Sea basin. Immediately beyond the ice sheet margin, glacial meltwater lakes developed and a periglacial tundra environment existed both over the southern British Isles and the exposed floor of the Southern North Sea basin.

Global temperatures began to rise after the last glacial maximum some 15,000 years BP and the ice margin retreated leading to the exposure of the glacial till and the increased discharge of meltwater (Figure 2.2). Sands and gravels were carried with the meltwater over braided river plains. With the melting of the ice sheet over the British Isles (and others globally) sea level rose to flood the North Sea basin so that by about 7,000 years ago the coastline began to resemble its present form as shown in Figure 2.3. The marine transgression not only inundated extensive lowland areas of the continental shelf, but also caused the retreat of the easily eroded landscape of glacial till, left by the ice sheet. Reworking of sands and gravels left by the ice sheet and its meltwater streams occurred at this time in shallow marine and coastal environments, leading to the formation of extensive, thin but coarse-grained seabed sediment veneers over the till surface. By Roman times, sea levels similar to the present day were reached (Figure 2.4), but erosion of the glacial till coastline of Holderness continued as the till cliffs were undercut by the sea at high tide and the shoreface was lowered by scour due to constant wave and tidal action. The loss of land and settlements continued into the mediaeval period and is ongoing today.

2.2 Pre-Quaternary Geology

Within the Humber region, bedrock is only exposed in a small number of isolated locations and, as such, its relevance to the present study is limited. Much of the study area is underlain by Upper Cretaceous, fine grained limestones of the Chalk Group (BGS, 1995). Cretaceous Chalk and underlying marl is exposed on the seabed within the Silver Pit and also within the Chalk cliffs of Hunstanton and Flamborough Head. Elsewhere, older, Jurassic rocks are exposed within the Sole Pit, which is located to the east of the study area.

2.3 Quaternary Geology

Within the study area representatives of both the early Quaternary deltaic sediments and the later glacial and interglacial sediments are present. The former are only exposed along the flanks of the deep channels such as Silver Pit. Of the latter, Middle – Upper Pleistocene deposits are represented in order of decreasing age by the Swarte Bank, Sand Hole, Egmond Ground, Eem, Bolders Bank and Botney Cut Formations.

The Swarte Bank Formation is Anglian in age (approximately 478 ka BP to 423 ka BP). It consists of stiff clayey diamictons (likely glacial tills), glacio-lacustrine clay and shallow marine clay. The Formation infills a fan like array of tunnel valleys such as the Inner Silver Pit that are up to 12 km wide and 450 m deep. These were cut into the bedrock during the first glacial advance into the North Sea basin, most probably by subglacial meltwater (Boulter and Hindmarsh, 1987).

The late Devensian Bolders Bank Formation is the best preserved and the most widespread Quaternary sediments present in the study area. This is present at or near seabed in over 90% of the study area. Indeed this is the sediment from which the Holderness cliffs and underlying shore platform are formed. It was deposited during the last glacial advance in the region between circa 30,000 and 18,000 BP. The till is up to 20 m thick and consists of firm or stiff grey - reddish brown clays with clasts of sandstone, a range of igneous and metamorphic lithologies, chert, limestone, chalk and mudstone, reflecting the diverse rock types and exposures of the ice centres in the uplands of northern England and Scotland (Harrison, 1992).

The Botney Cut Formation (glacial diamictons and water-lain muds) infills channels cut into the Bolders Bank Formation which is up to 80 m deep and 5 km wide. The common orientation of these channels is NNW-SSE and they are in places anastomosing in form. Some channels are completely infilled with Botney Cut Formation sediments whilst others such as Well Hole are only partially filled.

After the maximum extent of the Devensian ice sheet was reached circa 18,000 BP, ice retreat led to the accumulation of localised glacio-fluvial sands and gravels on the newly exposed till surface, remnants of which remain preserved today. Progressive ice sheet decay and rapidly rising sea level as climate ameliorated in the post glacial period caused glacio-fluvial and glacio-marine sedimentation to cease in the North Sea basin. Inter-tidal muds and peats (the Elbow Formation) are locally preserved off Lincolnshire (and further south and east beyond the study area) and record the transition from glacial/periglacial to early interglacial, Holocene, shallow marine environments in the study area. Marine transgression continued until present sea level was attained approximately 6700 years ago. Details of Holocene marine sedimentary features associated with the last transgression in the study area are discussed in Section 3.2 below.

3. Bathymetry and Seabed Sediments

3.1 Bathymetry and Topographic Features

Water depths are quoted in metres below chart datum, (BCD), (lowest astronomical tide)

The Southern North Sea is a semi-enclosed basin forming part of the continental shelf separating the UK from continental Europe. Within the study area the water depths are mainly shallow, commonly less than 30m, increasing eastward from the coast across a gentle gradient to around 30 m between 20 km and 40 km offshore (Figure 3.1). Depths exceed 30 m towards the north and north-east of the study area, offshore from Flamborough Head, and also along a major central depression extending from the Wash out to the Silver Pit. Whilst the seabed is commonly either flat or gently undulating in the study area, superimposed upon this platform are a number of large scale bathymetric features, including pronounced deeps and banks, which are presented in Figure 3.2(a+b) and are described below.

The seabed immediately offshore from the Holderness coastline is a gently sloping shore platform, which extends offshore for several kilometres, with an average gradient of between 1:50 and 1:200. Water depths 10 km offshore commonly reach only 10 m to 15 m. A linear arrangement of high spots, known locally as ‘mud huts’ is found on the shore platform off Easington.

At the mouth of the Humber Estuary (referred here as between Spurn Head on the northern side of the estuary to Northcoates Point on the southern side), the channel reaches a maximum depth of approximately 23 m CD just off Spurn Head where the Bull and Hawke channels join. The depths in this area are noted by the UK Hydrographic Office (UKHO) on their charts as being highly variable. Eastwards from the Humber, the navigational channel curves around the sand and gravel banks of The Binks (situated to the east of Spurn Head and forming its offshore extension), and heads in a north easterly direction.

Offshore from the Humber, the seabed is almost flat, dipping very gradually to the east, in water depths between 12 m and 20 m. Carved into this landscape are a number of ‘deeps’, in particular, New Sand Hole and Silver Pit (Figure 3.2a and b). Both features have been defined as glacial tunnel valleys (unusually large, deep seabed incisions cut by the pressurised sub-glacial flow of glacial melt-water), possibly deepened by tidal scour and/or fluvial erosion during times of lower sea levels (Donovan, 1973). New Sand Hole is approximately 10 km in length, and 1.5 km in width and provides access into the navigational channel of the Humber Estuary, cutting through the highly mobile sandbanks and sub-tidal areas flanking the channel. Maximum depths within New Sand Hole are around 45 m. Silver Pit is situated around 30 km from the Lincolnshire coast and is approximately 55 km in length, and 2 km to 5 km in width. Here depths reach up to 100 m, but are typically less than 60 m. With the exception of New Sand Hole, across which the littoral currents flow, Silver Pit and other deeps such as the Outer Dowsing Chanel, Sole Pit, Cole Pit and Well Hole are generally aligned with the tidal currents and form geomorphological divides, with sediment being transported parallel to them rather than across them (Evans *et al*, 1998). The floors of these deeps typically remain unfilled, indicating a low rate of sediment transport (Balson, 1999). To the east of Silver Pit, and keeping within the study area the seabed remains at a fairly uniform depth of 15 m to 20 m, with only localised variations.

Along the Lincolnshire coastline, south of the mouth of the Humber Estuary, the seabed slopes gently from the coast through the existing sand flats, banks and other features situated nearshore between Donna Nook and Skegness. The shoreface is steeper offshore from the eroding sections of this coast between Mablethorpe and Skegness than from the accreting sections at Donna Nook and Gibraltar Point. The base of the shoreface is in only about 6 m of water offshore from the flatter sections and in about 8m offshore from the steeper sections. The inclination of the shoreface off the Lincolnshire coast is shallower than to the north with the 10 m isobath generally 2 km to 4 km offshore compared to an average distance of 1 km to 2 km offshore from Holderness (BGS, 1998). Inshore of the 15 m isobath, there are several isolated sandbanks. These are more steep sided than the offshore banks and do not have the asymmetry that is indicative of net movement. There are also a number of shore attached features along the Lincolnshire coast, including Haile Sands, which is an area of fine sands that merges with the inter-tidal area at Donna Nook and the Mablethorpe and Skegness Middle Banks further to the south. In the nearshore zone there are also areas of ‘rough ground’, which form shoaling areas over which waves break. These irregular shaped features are typically relict accumulations of sand and gravel, left behind by the retreating ice during the last period of glaciation. As a result of the shallow water depths over these features, and tidal current flow over their crests, these features are known locally as Overfalls; which include the Saltfleet, Theddlethorpe, Protector and Inner Dowsing Overfalls. These features have an influence on the local patterns of tidal flow, wave action and resulting sediment transport (MES, 2003) and may also be important when considering the effects of dredging on coastal wave action.

The entrance to The Wash is morphologically complex and comprises a series of drying banks: Sunk Sand, Middle and Gore. These flank the main channel, the Lynn Deeps, lying in depths of 20 m to 30 m and continuing to Silver Pit over 50 km to the north. The deepest part of this channel, The Well, is almost 50 m deep. On the western side of The Wash a further channel – Boston Deep - lies adjacent to the wide inter-tidal flats to the south of Gibraltar Point. The Boston Deep is narrow relative to Lynn Deeps, is separated from the main channel by Long Sand and its depth does not exceed 15 m.

The complex form of the coast between Weybourne and Hunstanton in north Norfolk, with creeks, spits and other accretionary features, is mirrored in the complexity of the nearshore zone. Burnham Flats are connected to the North Norfolk shore between Hunstanton and Wells-next -the-Sea. These are shallow, planar sand sheets locally covered in sandwaves and mega-ripples and the 5 m isobath is typically over 10 km off the coast. The exception to this is an east-west trending depression that is more than 20 m deep, situated offshore between Blakeney Overfalls and Blakeney Point. This forms a westward arm of the generally deeper seabed east of Burnham Flats.

To the east of Weybourne the erosive nature of the coast has created a shoreface with a base of about 10 m locataed only 700 m of the shore. This widens to around 2 km at Cromer, where an extensive platform of chalk is exposed at the seabed. Offshore is a broad, planar surface, which slopes gently to the north east. The 15 m isobath parallels the coast between 2 km and 4 km offshore. The only notable bathymetric feature in this area is Sheringham Shoal, an isolated sandbank 10 km long, 1 km wide and over 10 m high. Seaward of Sheringham Shoal, depths commonly vary only slightly around the 20 m isobath until they shallow to less than 10 m at the Outer Dowsing Shoal, a 20 km long sandbank over 50 km off north Norfolk and at the margin of the study area (Figure 3.2).

Other sandbank complexes dominate the bathymetry offshore from the Lincolnshire and north Norfolk coastline and complete this outline bathymetric characterisation. The main examples are Inner Dowsing, Docking Shoal and the Race Bank/Dudgeon Shoal (Figure 3.2a+b). Inner Dowsing is a south-north trending linear bank located on flat seabed immediately east of a spur of the deeper Wash Channel. The bank is 13 km long with an undulating crest 5 m to 10 m above the general level of the seabed. Crestline water depths are commonly less than 5 m and the bank's northern tip merges with a series of shoals immediately inshore (Inner Dowsing Overfalls), which lie in less than 8 m of water.

Docking Shoal forms the seaward extension of Burnham Flats but is only marginally deeper, lying in 5 m to 8 m depth at its tapering northern tip 28 km off the Norfolk coast. Water depths on the bank crests are commonly less than 5 m and the banks are approximately 10 m high and over 1 km wide. Race Bank, Dudgeon Shoal and Triton Knoll are a series of sinuous banks that are formed of gravelly sand, overlying Bolders Bank tills, with fine to medium sand at the crest. They are some 15 km to 20km long, 1.5 km to 3 km wide and around 10 m high. The banks are asymmetric in form and would appear to migrate in a south westerly direction. Race Bank in particular is covered in SE-NW trending sandwaves. Further offshore the Outer Dowsing Shoal and Cromer Knoll lie 10 km to the north east of Triton Knoll. The banks exist as a single morphological feature that is 50 km long, 5 m high and orientated NNW-SSE They are strongly asymmetric with their steepest flanks facing south west.

3.1.1 Mobile Bedforms

Within the study area are a number of sand wave and ribbon fields (Figure 3.3). Sand wave fields are tidally transverse ridges of sand with wave-lengths of circa 30 m to 1 km and heights of around 3 m to 18 m. These fields occur where sand is abundant and where current velocities are between approximately 0.55 m/s and 0.9 m/s. These fields may be symmetrical or asymmetrical depending on the direction of the net-tidal sand transport (ABPmer, 2009). Sand ribbon fields are low relief, elongate sand strips which may be up to 15 km long, 200 m wide and 1 m high. Ribbon fields are indicative of sediment starved environments with strong tidal flows (Kenyon, 1970). There are two large sand ribbon fields within the study area (Figure 3.3).

3.2 Distribution of Holocene Surficial Sediments

Within the study boundary, Holocene sediments generally form a veneer over Pleistocene formations. The majority of seabed sediments are derived from the re-working of Quaternary deposits during the last marine transgression and these typically comprise sands and gravels. The distribution of surficial seabed sediments has been mapped for the REC study (BGS, 2011) using the standard Folk classification (Figure 3.4). This mapping is broadly similar to the BGS maps produced during the 1980s and 1990s but the grain-size boundaries were modified to produce an improved map that more clearly reflects the relationship between sediment type and seabed features. Whilst forming a useful reference for this investigation, it is important to note that the REC does not provide complete coverage of the MAREA study area and its data has been supplemented with information produced previously by BGS.

Figure 3.4 shows a regional distribution of sand dominated Holocene sediments at the eastern margin of the study area. This contrasts with the western part of the region, which is characterised by gravelly sand, gravel and muddy sandy gravel. Away from large bedforms the Holocene sediment cover is commonly less than 1 m thick. The region between Silver Pit and Sole Pit represents a transition from gravelly seabed sediment to mainly slightly gravelly sand, albeit with a large tongue of sandy gravel extending from the south. There are large areas of sandwaves in this area.

4. Hydrodynamics

4.1 Water Elevations

4.1.1 Tidal Range

A tidal amphidrome centred off the west coast of Denmark governs the tidal phase conditions in the Southern North Sea, with the tidal wave rotating anticlockwise, flooding south-east and ebbing north-west twice a day (a semi-diurnal tide). The mean spring tidal range along the Holderness coast is around 5.5 m, increasing into the Humber.

South of the Humber, the mean spring tidal range further increases along the Lincolnshire coast to 6.0 m at Skegness (Table 4.1), before reaching an approximate mean spring tidal range maximum of 6.5 m at Hunstanton (the Norfolk coast entrance to the Wash). The tidal range then decreases in an easterly direction along the Norfolk coast to 4.4 m at Cromer, the limit of the study area. A summary of tidal range variation across the study area from the Marine Renewables Atlas (ABPmer *et al,* 2008) can be seen in Figure 4.1 and Table 4.1.

Table 4.1 Summary tidal data for Humber MAREA study area

Station	Levels (m ODN)					CD to ODN correction
	MHWS	MHWN	MSL	MLWN	MLWS	
Cromer	2.4	1.3	0.05	-0.6	-2	-2.8
Blakeney Bar	4.9	3.7	no value	no value	no value	-0.8
Wells Bar	5.2	4.0	no value	no value	no value	-0.7
Hunstanton	3.6	1.8	0.05	-1.2	-2.8	-3.7
Skegness	3.1	1.5	0.2	-1.2	-2.8	-3.7
Grimsby	3.2	1.8	0.2	-1.3	-2.8	-3.9
Bull Sand Fort	3	1.6	0.1	-1.2	-2.8	-3.9
Spurn Head	3	1.6	0.1	-1.2	-2.7	-3.9
Bridlington	2.7	1.3	0.2	-1.0	-2.25	-3.3

4.1.2 Storm Surges

Water levels within the study area are the summation of a predictable “astronomical” tidal level, and an episodic “residual” (surge) component. Surges are formed by rapid changes in atmospheric pressure, with low atmospheric pressure raising the water surface (positive surge) and high atmospheric pressure depressing the water surface (negative surge). The surge component is generally much smaller in the summer than the winter, when deep atmospheric depressions and strong winds can have a significant effect on tidal levels and propagation at high tide. In addition to flooding effects, positive surges can also have a significant impact on sediment transport in the nearshore zone (HR Wallingford *et al*., 2002).

Storm surges within the study area are usually generated by pressure gradients travelling from the deep Atlantic waters onto the shallow continental shelf and by strong winds to the north of Scotland causing an increase in tidal levels (Pugh, 1987). As the resultant water movements propagate into the North Sea, they are affected by the earth’s rotation and by the rapidly decreasing depth (The average depth of the North Sea is in the region of 40 m). This effect is accentuated as the surge moves southwards down the east coast of Britain. These disturbances are commonly known as external surges, as the forcing mechanisms are generated outside the North Sea. Internal surges may also occur although they are much less frequent than external events (Pratt, 1995). As the name suggests, internal surges are generated within the North Sea basin. These events usually occur in response to north or north westerly winds produced by low pressure over the continent and areas of high pressure to the west of Ireland (Pratt, 1995). Although internal events occur less often than external ones, they generally produce more severe surges. Numerical modelling of storm surge events (Flather & Davies, 1978) with a 50 year return period, indicated surge heights between 2.0 m and 2.5 m along the Holderness, Lincolnshire and North Norfolk coastlines.

The most intense surge in recent history took place between 31st January and 2nd February 1953. During this event, elevated water levels up to 3 m above the astronomical tidal level were recorded and were attributable to an externally generated surge event propagating through the North Sea and becoming enhanced by an internally-generated surge caused by high wind speeds.

Modelling as part of the UK Climate Impacts Programme (UKCIP) projections (Lowe *et al*, 2009) attempted to project possible future changes to storm surges resulting from climate change. This indicated that predicted changes to the magnitude of storm surges as a result of climate change along this part of the coast are largely insignificant and indistinguishable from background variability.

4.2 Tidal Currents

Tidal currents across the study area generally follow the orientation of the coastline and flow in a southerly direction during the flood tide and in a northerly direction during the ebb tide. Asymmetry between the peak flood and ebb tidal currents results in a net (residual) current vector. These residual tidal currents have different influences depending on the distance from the shore:

- Inshore tidal residuals do not contribute significantly to the movement of sediment as the transport is dominated by wave action;
- Further offshore these residuals control the sediment dynamics and in particular the changes affecting the offshore sand banks; and
- The amplitude of tidal currents is usually greatest at or near the sea surface, decreasing with increasing water depth due to friction with the seafloor. The shallow nature of the Southern North Sea, at depths typically < 30 m, implies that frictional effects probably extend through the whole water column (ABP R&C, 1996).

The Marine Renewable Atlas provides an overview of peak current flows within the study area for both a mean spring and neap tide respectively (Figures 4.2 and 4.3). Additionally, tidal flow vectors extracted from TotalTide are presented in Figures 4.4 and 4.5. Data from the Admiralty Tidal Stream Atlases provides an understanding of the temporal and spatial variability of surface tidal currents over one tidal cycle across the study area:

- Holderness Coast - falling ebb tides induce north westerly currents up to 0.3 m/s, and advancing flood tides set up south easterly currents of up to 0.5 m/s. Offshore currents are much stronger, with peak flows on a spring tide recorded at a point offshore of Easington reaching a little over 1.3 m/s;
- Humber Estuary - on spring tides, over 160 Mm^3 of water passes in through the mouth of the estuary, with a maximum flood tide discharge being over 0.1 Mm^3/s. However, not all of this water volume will progress into the estuary, with the water moving a short distance inland before returning on the ebb tide (ABPmer, 2010). As a consequence, current velocities can be extremely high, with peak flows on a spring tide reaching 2.2 m/s;
- Lincolnshire Coast - tidal currents along the coast are moderate, with peak flows on a spring tide exceeding 1.0 m/s.
- North Norfolk Coast – tidal currents along the coast are relatively. Peak flood flows on a spring tide rarely exceed 0.6 m/s to the west of Scolt Head. Further to the east, peak spring current speeds exceed 1.0 m/s on the flood tide.

4.3 Sea Level Rise

The sea level rise allowances for the study area extracted from guidelines provided by Department for Environment, Food and Rural Affairs (Defra, 2006) are shown in Table 4.2.

Table 4.2 Regional net sea level rise allowances and indicative sensitivity ranges to climate change

Administrative or Devolved Region	Assumed Vertical Land Movement (mm/yr)	Net Sea Level Rise (mm/yr)				Previous Allowance
		1990-2025	2025-2055	2055-2085	2085-2115	
East of England, East Midlands, London, SE England (South of Flamborough Head)	-0.8	4.0	8.5	12.0	15.0	6 mm/yr* constant
Extreme Wave Height	-	+5%		+10%	+10%	-
Offshore Wind Speed		+5%		+10%	+10%	

* Updated figures now reflect an exponential curve, and replace the previous straight-line graph representations.

(Source: Defra, 2006)

In addition to the guidance supplied by Defra, more recent UKCIP projections (UKCP09) can be extracted at various positions along the study area coastline as either relative values (including the movement of the coastline) or absolute values (excluding the movement of the coastline). The UKCP09 projections for a high carbon emissions scenario and the 95 percentile of the results, which present a worst case scenario, are the most comparable to the Defra allowances (Table 4.3). However, it should be noted that the UKCP09 projections are greater than the Defra allowances until 2070, as the UKCP09 projections become more linear over time.

Table 4.3 Relative sea-level rise for east of England using a baseline elevation in 2010

Parameter	Source	2010	2020	2030	2040	2050	2060	2110
Relative Sea Level Rise (mm)	Defra (2006)	0	40	102.5	187.5	272.5	375	1050
	UKCP09 (2009)*	0	66	137	213	295	382	NA

* UKCP09 values refer to the 95 percentile extracted from Skegness (Location 19418).

For the east of England, the Defra (2006) allowances indicate that the sea level could potentially rise by a little more than 1.0m over the next 100 years (Table 4.2). It should be noted that these are the current government recommended guidelines with respect to sea level rise and flood and coastal defence management.

4.4 Wave Climate

The wave regime frequently plays an important role in the erosion, transport and deposition of sediments and must be considered within any coastal environment. Due to the extent of the study area, the wave regime has been subdivided into: offshore waves; and nearshore waves.

4.4.1 Offshore Waves

Offshore wave data is taken from the Dowsing Wavenet Buoy situated at a depth of approximately 22 m CD, and covers the 2 year period between October 2008 and October

2010. The data identifies that the primary direction for waves is from the north-northwest, whilst the largest waves are from the north-northeasterly sector. Further wave characteristics for the offshore study area are defined below:

- The primary direction for waves from the north-northwest (between 330° and 360°N) and account for more than 22% of all records;
- The largest wave heights (5.00 m to 5.25 m) occur from the north-northeasterly sector (between 000° and 060°N) with a frequency of occurrence of less than 0.01%;
- The most frequent wave period is in the range 5 s to 6 s, accounting for approximately 19% of all records; and
- The most common wave height is in the range 0.75 m to 1.00 m, accounting for just over 19% of all records.

4.4.2 Nearshore Waves

The characterisation of nearshore wave data is taken from a Nortek AWAC Buoy situated in an area which is fairly shallow at 11 m CD and approximately 10.5 km off the Holderness coast (Easington), between March 2004 and November 2004. The short-term data identifies that both the largest and most frequent waves arrive from the north-northeasterly sector (ABPmer, 2005). Further wave characteristics for the nearshore study area are defined below:

- The primary direction for waves are events from north-northeast (between 000° and 030°N) over 42% of all records;
- The largest wave heights (class 3.75 m to 4.00 m) occur from the north-northeasterly sector (between 000° and 030°N) with a frequency of occurrence of 0.04%;
- The most frequent wave period is in the range 5 s to 6 s, accounting for more than 20% of all records; and
- The most common wave height is in the range 0.25 m to 0.5 m, accounting for over 25% of all records.

4.4.3 Summary

In deep offshore water the wind dominates the character of the waves. However, as waves travel into shallower water interaction with the seabed causes shoaling, refraction, and eventually breaking. These processes act to realign the wave crests with the bed contours. These processes generate complex patterns of wave-induced currents, to the north and south of the Humber, as well as across the entrance which can influence the transport of sediments. These currents can act independently or in conjunction with the tidal and wind induced currents (ABPmer, 2008). The Marine Renewable Atlas (ABPmer *et al.*, 2008) illustrates the spatial distribution of modelled annual mean significant wave height across the study area (Figure 4.6 where waves are largest offshore and generally decrease in a landwards direction.

5. Regional Sediment Transport

Sediment transport in the Southern North Sea has been the subject of numerous studies. The present study will draw upon the work of Kenyon and Cooper (2005) and the Southern North Sea Sediment Transport Study Phase 2 (HR Wallingford *et al*, 2002). A detailed discussion of sediment transport is included in the coastal characterisation (Section 6) and a regional overview of the bedload transport pathways is provided below.

Bedload transport within the Humber region is dominated by tidal currents. Away from the coast near surface tidal currents exceed 0.75 m/s and are frequently in excess of 1.7 m/s in the western part of the study area. A combined map of bedload sediment transport pathways from Kenyon and Cooper and SNSSTS2 is presented in Figure 5.1.

Sediments eroded from the Holderness cliffs are transported in a southerly direction by both wave induced littoral drift and offshore tidal currents, some accumulating at Spurn Head and the Binks and some passing the mouth of the Humber to be deposited at Donna Nook or southwards towards The Wash. The majority of the eroded volume (~60%) is composed of silts and clays, which are transported in suspension, whilst the coarser material is transported as bedload. Based on the analysis of bedform asymmetry as an indicator of net transport direction, offshore transport to the west of Silver Pit is typically southerly. Further offshore there is evidence of a net northerly transport pathway through the Race Bank/North Ridge/Dudgeon Shoal area.

The transport pathways shown in Figures 5.1 provide a simplified overview of the broad-scale sediment movements through the study area. Superimposed upon this are numerous smaller scale pathways and circulatory systems, particularly where the bathymetry is complex such as near the mouth of the Humber or the Wash and around sandbank features. It is worth noting that over much of the study area, and in particular where there are accumulations of gravel, the seabed sediments are largely immobile during all but the most extreme wave and surge conditions.

6. Coastal Characterisation

6.1 Objectives

The aim of the coastal characterisation is to develop an understanding of the interactions between various coastal system elements that control coastal evolution. This understanding will inform the MAREA of which areas could be sensitive to changes in the hydrodynamic and sedimentary regime as a result of aggregate dredging.

One of the main outputs from the assessment is a Coastal Characterisation Map, which is available as GIS layer. The coastal characterisation forms part of the wider MAREA GIS and provides a description of the coastline within the study area in terms of the foreshore sediment type and backshore morphology. The information will be used during the assessment phase to determine whether modification to the waves, tidal flows or sediment transport pathways result in changes along the coast, and in particular the identification of areas that have been identified as sensitive.

6.2 Sources of Information

The study draws upon existing sources of information such as the Flamborough Head to Gibraltar Point and North Norfolk Shoreline Management Plans (2), Coastal Impact Studies for previous aggregate licence applications, physical processes assessments for offshore wind farms and other sources of published and unpublished information. The characterisation describes those aspects of the coastline that are considered when assessing the potential effects of aggregate dredging (CIRIA, 1998) including:

- Coastal morphology i.e. beach and backshore type;
- Historic evolution and present behaviour;
- Hydrodynamic and sedimentary processes including near-shore sediment transport;
- Coastal defence and management; and
- Future response to climate change.

To facilitate this assessment a site visit was made of the entire study coastline during October 2010. This involved a visual inspection of the beaches, backshore and coastal defences and the creation of a catalogue of over 300 photographs which have been used to inform the coastal characterisation.

In order to develop a sufficient understanding of the extent of coastline that may be affected by aggregate dredging, it is essential to identify the linkages between coastal and offshore environments. Therefore, one of the key aims of this study is to describe the nearshore sediment regime in terms of sources, pathways and sinks and to identify any interactions between coastal and offshore transport and shallow geological environments.

Additionally, one of the standard assessment criteria in a Coastal Impact Assessment is whether there is a risk of beach drawdown if sediment transported offshore during winter storms becomes trapped in the dredged depressions. In the past, a generic landward limit has been placed upon the minimum water depth where dredging can take place. This limit was typically greater than 15 m water depth or 5 km from the coast. This study provides an opportunity to derive a more realistic and site-specific estimate of the beach toe or closure depth i.e. the limit of seasonal cross-shore sediment movement. This involved a visual assessment of numerous beach and nearshore, bathymetric profiles to identify the *beach toe* (commonly taken to be the first break in beach slope, below low water), supported by empirical calculations of beach closure depth (the offshore limit of seasonal profile variability) where necessary. These profiles have been provided by the Environment Agency (EA) and East Riding of Yorkshire Council (ERYC). Note that the beach profiles are plotted relative to Ordnance Datum Newlyn (ODN). The remainder of depths are relative to Chart Datum. The conversion factors for the study area are shown in Table 4.1

In order to put the coastal characterisation into context with the aggregate licence areas it is necessary to understand the nature of the seabed between the coast and the offshore. Whilst it is not within the scope of the present study to carry out bespoke, regional scale bathymetric surveys, a series of nine multibeam bathymetric, side scan sonar and geophysical profiles have been collected by HADA, which extend from chosen locations along the coast out to the various licence areas as shown in Figure 6.1. This data set has been interpreted and used to link the beach and nearshore bathymetric profiles to the offshore areas. Seabed and shallow geological cross sections have been plotted in order to place the beach closure depth into context with the seabed in the dredging areas. In addition the cross-sections permit an assessment of whether the aggregate deposits are in any way linked to the coastal sediments.

6.3 Subdivision of Coastal Units

For the purpose of this assessment the coastline has been sub-divided into discrete (but linked) units. For consistency with other studies, the Shoreline Behavioural Units (SBU) as presented in the Shoreline Management Plans (2) have been adopted and these are outlined below:

- SBU 1: Flamborough Head to Bridlington;
- SBU 2: Holderness Coast (Bridlington to Easington);
- SBU 3: Spurn Head;
- SBU 4: Outer Humber;
- SBU 5: Lincolnshire (Donna Nook to Gibraltar Point); and
- SBU 6: North Norfolk (Hunstanton to Cromer).

The following sections of the report provide a summary description of these behaviour units including structure, system controls and inter-linkages, at a range of temporal and spatial scales.

6.4 Shoreline Behaviour Unit 1 - Flamborough Head to Bridlington

Image 1. Shoreline Behaviour Unit 1: Flamborough Head to Bridlington

This unit comprises a 10 km stretch of coast at the northern end of the study frontage. Given the distance between this unit and the nearest aggregate licence, and the direction of the prevailing hydrodynamic conditions, it is unlikely that this unit will be affected by aggregate dredging. Consequently this SBU is not included in the Coastal Characterisation Map but a brief overview of the frontage is included as the links between it and the adjacent coastal section are considered important.

Flamborough Head is characterised by high chalk cliffs, fronted by a rocky shore platform, which extends up to 1 km offshore in places. For the most part the cliffs are stable and recession rates are typically less than 0.5 m/year. The coastline faces south east and the prevailing wind and waves are from the northeast but the headland provides a sheltering effect such that sediment transport is generally from south to north.

Smithic Sands, a headland associated banner bank is located to the south of Flamborough Head. There is thought to be an exchange of sediment between this feature and the coast, and *vice versa (*HR Wallingford *et al,* 2002*)* although recent bathymetric monitoring shows a wide channel between the upper beach and the sand bank (ERYC, pers com). In addition to acting as a sink for small volumes of sediment eroded from the Flamborough cliffs, and storm driven sediment transport from Filey Bay to the North, Smithic Sands is also a source of sediment to the Holderness Coast.

To the south of Sewerby, the chalk cliffs give way to softer glacial till, fronted by a wide, sandy beach. The town and harbour of Bridlington are protected by seawalls and groynes. The beaches in the area are supplied with sediment that moves onshore from Smithic Bank and by the net northerly drift from the northern part of the Holderness frontage. This sediment supply is periodically supplemented by sediments transported southwards around Flamborough Head during storm events. Cliff recession rates along this frontage remain low and beach monitoring shows that the Bridlington beaches are generally stable, apart from localised lowering adjacent to the harbour piers.

6.5 Shoreline Behaviour Unit 2 – Holderness

Image 2. Shoreline Behaviour Unit 2: Holderness

The Holderness cliffs extend for around 57 km from Bridlington in the north to Kilnsea which lies at the neck of Spurn Head. The cliff line faces north east and has a gently curving planform between Flamborough Head and Spurn. The frontage is characterised by eroding cliffs formed from glacial tills, which vary in height between 0 m and 40 m. The cliffs are fronted by a broad, gently sloping shore platform that extends several kilometres offshore. The nearshore and inter-tidal region is covered by a veneer of highly mobile sand and gravel that forms the beach (Scott Wilson, 2009). The prevailing wind and wave direction is from the northeast.

6.5.1 Sub Unit 1 - Bridlington to Barmston

To the south of Bridlington the cliffs rise to a height of around 9 m (ODN) within a short distance from the town. At Auburn Sands, (Figure 6.2) there is clear evidence of ongoing cliff erosion including recent slumping. Analysis of annual erosion rates by East Riding of Yorkshire Council (ERYC) between 1951 and 2007 indicates that the cliff line has receded by up to 100 m at an average rate of 1.8 m/year (EYRC, 2008). Comparison of beach profiles from 2003 and 2010 shows that the base of the cliff has retreated by 7 m and that there is a slight lowering (~0.5m) of the upper foreshore, which is commensurate with the landward recession of the profile. At the toe of the cliffs there are areas of exposed till, whilst the beach itself is strewn with building rubble and the remains of World War 2 (WW2) defences. Just to the north of Auburn Farm the beach is intersected by a small stream, Auburn Beck.

The cliff height decreases to the south of Fraisthorpe before rising to a height of around 13 m to the north of Barmston. The hinterland along much of this coast is predominantly flat, comprising mainly agricultural land with a few small settlements. At Barmston the character of the coast changes with a village located approximately 1 km from the coast and a large campsite on the cliff top. The cliffs are fronted by a sandy beach of varying width with cobbles and the remains of WW2 defences, which provide an indication of the rapid recession of the coastline over the past 70 years. There is further, dramatic evidence of rapid cliff recession adjacent to the campsite as part of the cliff top road has been lost to the sea, as has the path along the top of the cliffs. Frequent till exposures are also visible at the foot of the cliffs.

In order to afford some protection from further erosion, rock armour has been placed at the foot of the cliffs in front of the campsite. However, the continued erosion on either side of the defended section has created a small promontory at this location. Monitoring carried out by ERYC indicates that the cliffs have retreated by up to 65 m since 1951 at an average rate of 1.5 m/year. Further analysis of beach profiles also demonstrates both cliff recession and lowering (~1.7m) of the upper foreshore, which is commensurate with the landward recession of the profile. as shown in Figure 6.3. The net littoral drift along this frontage is southerly although the coast is still within the lee of Flamborough Head, which provides shelter from north-easterly waves.

6.5.2 Sub Unit 2 - Barmston to Hornsea

The cliff line continues uninterrupted to the south of Barmston and is characterised by a similar pattern of cliff recession and foreshore lowering. The hinterland is predominantly flat, arable land with occasional cliff top campsites. At Galleon beach (Ulrome), the cliff line is fixed with a high wall constructed from cast concrete units. To the south of the campsite these defences have been undermined and there is evidence of recent cliff falls. The cliffs are fronted by a flat, sandy beach that is strewn with cliff debris and rubble from collapsed cliff top properties. Further to the south, part of the cliff top road at Skipsea has been lost and based on the visual inspection made during the site visit, further cliff collapses are likely.

The higher cliffs at Atwick have retreated by up to 60 m since 1951 at an average rate of up to 1 m/year (ERYC, undated). Comparison of beach profiles from Atwick shows that around 18 m has been lost from the cliffs since 2003. Some beach lowering on the upper part of the profile has occurred during this period, which is commensurate with the landward recession of the profile. Further seawards, beach levels are up to 1 m higher than in 2003 (Figure 6.4). Immediately to the north of Hornsea, the beach becomes wider and is backed by 15 m high cliffs. Beach profile analysis carried out by ERYC indicates that this short stretch of coast is relatively stable and that beach levels are increasing.

6.5.3 Sub Unit 3 - Hornsea

The Hornsea frontage comprises a promenade fronted by a seawall, revetments and a wide, sand and pebble beach with timber groynes. The southern end of the promenade is protected with rock armour.Beach profiles spanning almost 7 years between 2000 and 2010 show that beach levels have dropped by around 1 m in front of the defences but there is little evidence of foreshore steepening (Figure 6.5). Biannual monitoring by ERYC indicates that beach levels are generally stable with some seasonal variability.

6.5.4 Sub Unit 4 - Hornsea to Mappleton

To the south of Hornsea the cliffs and beaches are subject to rapid erosion as sediment supply from the north is restricted by the groynes at Hornsea. Monitoring of annual cliff recession rates indicates that the cliff line has retreated by up to 150 m between 1951 and 2007 at an average rate of around 2.5 m/year - more than twice that of the cliffs to the north of the town (ERYC, undated). The cliffs are fronted by a wide, fine sand beach, but profile analysis shows that beach levels have dropped by up to 3 m since 2000 (Figure 6.6) and the foreshore gradient has decreased, which will expose the cliff toe to increased wave action.

6.5.5 Sub Unit 5 - Mappleton to Withernsea

Mappleton Sands is characterised by 17 m high glacial till cliffs, fronted by a sand and pebble beach. The frontage is protected from wave action by a revetment and rock groynes, which have promoted an increase in beach level along the frontage. To the north of the defences, the cliffs appear relatively stable, both in appearance as observed during the site visit and based on comparison of recent beach profiles. However, erosion post data suggests that the cliff line has retreated by up to 90 m since 1951. This erosion occurred prior to construction of the defences, which indicates that these have since provided effective protection to the cliff toe. On the south side of the defences the toe of the cliffs has receded by around 8 m since 2000 whilst beach levels have dropped by more than 1 m (Figure 6.7). This is consistent with the general pattern of cliff/beach behaviour along the frontage.

To the south of Mappleton, the height of the cliffs and beach width remain fairly constant. The general trend of rapid cliff erosion is also maintained with long-term (60 year) recession rates of 2 m to 3 m in places. At Aldborough the seaward end of the coastal access road has been lost and the cliff inspection carried out during the site visit indicated that further slumps are likely. Comparison of beach profiles from 2003 to 2010 shows that the toe of the cliff has retreated by 22 m and this is accompanied by foreshore lowering of up to 2 m (Figure 6.8).

A similar pattern of cliff erosion is observed at Tunstall where the cliff top Sand Le Mere Campsite will be at risk within the next few years if the current rate of erosion as shown in Figure 6.9 continues. Photographs taken at Tunstall show part of a ridge and runnel formation, with an upper beach of coarse sand and cobbles, and a sandy foreshore, separated by a water filled channel and areas of exposed glacial till. The development of these features, which reflect the shoreline response to extreme wave conditions can result in dramatic variations in foreshore elevation and may lead to accelerated cliff erosion (Pringle, 1985).

6.5.6 Sub Unit 6 - Withernsea

The Withernsea frontage comprises a promenade and seawalls fronted by rock revetments and a sand and pebble beach with groynes. Beach levels at the toe of the seawall have dropped since 2000 (Figure 6.10) , and the rock groynes were constructed to encourage beach build up through the central section of the frontage. At the southern end of the frontage, beach levels have remained fairly stable during the 10 year monitoring period.

6.5.7 Sub Unit 7 - Withernsea to Kilnsea

To the south of Withernsea, the cliff line is re-established and annual monitoring data indicates that the cliffs have retreated by up to 130 m since 1951. Profile analysis shows that the toe of the cliff has retreated landwards by 50 m since 1998 but in spite of this intense erosion and a general lowering of the foreshore, the elevation of the cliff toe has remained fairly constant over time (Figure 6.11).

The Easington frontage is partly protected by a rock revetment particularly opposite the gas terminal. To the south of the defended section, the cliff recession rate is around 1.7 m/year and is accompanied by lowering of the cliff toe as shown in Figure 6.12. The cliffs are fronted by wide, sand and pebble beach but photographs taken during the site visit show that cliff collapses are frequent and cliff top infrastructure continues to be at risk.

To the south of Easington, the cliff line gradually decreases before eventually merging with the dunes and sand/shingle ridge that fronts the Kilnsea Lagoon SSSI. To the rear of the lagoon, a rock gabion embankment protects the low lying agricultural hinterland and isolated residential properties from flooding. Fronting the dunes, at around mid-tide level, the remains of WW2 defences provide some additional protection from wave action to this low lying frontage (Figure 6.13).

6.5.8 Coastal Defences and Management

The East Riding of Yorkshire Council is responsible for coastal defence along the Holderness coast. The nature and extent of coastal defence generally reflects the asset values and the level of risk from coastal erosion and flooding. Excepting the main settlements of Bridlington, Hornsea, Mappleton, Withernsea and Easington, the hinterland within SBU 2 comprises agricultural land with isolated small settlements and numerous cliff top caravan parks. The cliffs provide a degree of natural coastal defence but as described previously these are subject to intense erosion as summarised in Figure 6.14 At many locations cliff top infrastructure such as roads and residential properties has been lost and indeed some 25 villages have been lost from the Holderness coast since Roman times (Figure 6.15).

The coast and flood defence policy as defined in the Shoreline Management Plan provides an indication of where investment will be made into protecting coastal assets over the next 100 years from continued pressure from natural processes and increased climate change. A summary of this policy for each sub unit is presented in Table 6.1.

Table 6.1 Coastal Defence Policy for the Holderness Coast

SBU	Sub Unit	SMP Policy
1	Flamborough Head to Sewerby	No active intervention
2	Bridlington	Hold the line
2	Bridlington to Hornsea	No active intervention
2	Hornsea	Hold the line
2	Hornsea to Mappleton	No active intervention
2	Mappleton	Hold the line
2	Mappleton to Withernsea	No active intervention
2	Withernsea	Hold the line
2	Withernsea to Easington	No active intervention
2	Easington to Kilnsea	Hold the line for currently defended sections, no active intervention elsewhere. Potential for managed realignment at Kilnsea.

At present only 9.2 km of the 56 km Holderness frontage is protected by defences constructed by the East Riding of Yorkshire Council. This is made up of a variety of backstop defences such as seawalls and revetments and beach control structures (rock and timber groynes). Private bodies have also defended a further 2 km of frontage, however these are usually poorly designed structures built on an ad-hoc basis, which can exacerbate erosion rather than prevent it. A summary of the coastal defences is presented in Table 6.2 below.

Table 6.2 Coastal Defences along the Holderness Coast

Location	ERYC Defences	Private Defences	Defence Type
Bridlington	3.6 km		Masonry and concrete walls with groynes
Barmston Caravan Park		0.1 km	Rock and concrete armour
Barmston Drain		0.2 km	Rock and concrete armour
Ulrome North Defences		0.3 km	Concrete seawalls
Ulrome South Defences		0.1 km	Concrete seawalls
Hornsea	1.9 km		Concrete seawall, groynes, and rock armour
Mappleton	0.5 km		Rock revetment and rock groynes
Tunstall North Defences		0.2 km	Rock and concrete armour
Tunstall South Defences		0.1 km	Rock revetment
Withernsea	2.3 km		Concrete seawalls, timber groynes and rock armour
Easington	1.0 km		Rock revetment

6.5.9 Sediment Transport

As described previously, sediments are mobilised and distributed through the Humber MAREA study area in response to interactions between the morphology and the main physical process drivers, wind, waves, tidal currents and river flows. In order to understand how changes to these hydrodynamic forcing mechanisms attributable to aggregate dredging might affect the coast, it is necessary to consider not only how sediment moves near to the shore but also the linkages between coastal and offshore environments. A good way to demonstrate these links is to consider the sources, pathways and sinks for sediment moving through and along the Holderness coast.

Sediment sources

As described in Section 6.4 Smithic Bank, located offshore from Flamborough Head plays an important role in the Holderness sediment transport regime. Sand circulates around the bank in a clockwise direction as a result of residual tidal circulation and it is believed that the feature provides a link between the Holderness coast and Filey Bay (HR Wallingford *et al*, 2002).

The Holderness coast is the main source of sediment within this behaviour unit. It is estimated by Balson *et al* (1998) that the volume of sediment eroded is between 3 Mm^3/year and 4 Mm^3/year. However, it is suggested by Wingfield and Evans (1998) that almost half of this is derived from erosion of the nearshore seabed with a further 23% supplied by cliff erosion and the remainder from the wave induced erosion of the shore platform. Under extreme wave conditions, Smithic Bank also supplies sediment to the Holderness coast.

The majority of sediment eroded from Holderness is fine silt and clay. This is transported offshore and along shore in suspension. The proportion of different size fractions is dependent on the nature of the till being eroded and only coarse-grained sediments derived from the till will remain on the beach, forming a local sediment source.

Pathways

To the north of Bridlington it is generally accepted that net littoral drift is to the north. Transport is tidally driven and the drift rate is relatively low at around 0.05 Mm^3/year. There is a potential pathway between the coast at Sewerby and Smithic Bank, which is driven by tidal circulation in the lee of Flamborough Head. South of Bridlington, the net drift is southerly. Between Barmston and Hornsea the drift rate is around 0.15 Mm^3 (HR Wallingford *et al,* 2002).

South of Hornsea, the longshore drift rate increases to between 0.2 Mm^3 and 0.3 Mm^3 per year. This is due to a reduction in the sheltering effect of Flamborough Head and an increase in sediment availability from rapid cliff erosion on the downdrift side of the Hornsea defences. On this section of the frontage, sediment transport is predominantly wave driven with a significant additional contribution from the frequent tidal surges that propagate through the Southern North Sea (HR Wallingford *et al*, 2002). Modelling carried out for the Southern North Sea Sediment Transport Study (Phase 2) indicates that drift rates are highest along the broad shore platform, within 2 km of the coast. Between Easington and Kilnsea, the drift rate decreases to around 0.15 Mm^3/year. It is believed that sand is transported offshore from this location (Scott Wilson, 2009).

The fine grained silts and clays eroded from the Holderness cliffs are transported in suspension. It is estimated that over 2 Mm^3/year of sediment is removed from the coast in suspension, forming a wide plume that extends several kilometres from the coastline. The fine sediments are transported southwards to be either deposited on the mudflats of the outer Humber Estuary, transported alongshore towards The Wash or offshore towards the German Bight.

The main bedload transport pathway is southwards towards Spurn Point, the Binks and the Humber estuary. This pathway extends for several kilometres offshore. Analysis of bedform asymmetry, offshore, shows both northerly and southerly transport pathways. Although bedforms are sparse, there is some evidence to support the theory behind a convergence zone around 25 km due east of Hornsea.

Sinks

Smithic Bank is the northern-most, active sediment sink in the study area, receiving sandy sediments eroded from the cliffs to the north of Bridlington. Of the 3 Mm^3 of sediment eroded from the Holderness coast each year, around 0.1 Mm^3 is deposited on Spurn Head at the southern end of the frontage. The remainder is exported away from Holderness to sinks in the adjacent behaviour units, which will be described in the next section.

6.5.10 Beach Toe and Offshore Linkages

As described previously the aim here is to identify possible impact pathways between the coast and the aggregate licence areas. This is achieved by determining the offshore limit of seasonal sediment movement from the beach, characterising the seabed and associated sedimentary features between this limit and the dredging areas and putting these into context with the hydrodynamic drivers presented in Section 4 and the sediment transport pathways described in Section 6.5.9 above.

Beach Toe

The beach profiles obtained from East Riding of Yorkshire Council do not extend far enough offshore to identify the beach toe as their primary function was to monitor cliff recession. It has therefore been necessary to calculate the beach closure depth using Hallermeier's 1981 expression for closure depth as follows:

Equation 1. $$h_c = 2.28H_e - 68.5(H_e^2/gT_e^2)$$

Where

h_c = Closure depth (m);
H_e = Nearshore wave height that is exceeded for only 12 hours per year (m);
T_e = Nearshore wave period that is exceeded for only 12 hours per year (s); and
G = Acceleration due to gravity (9.81m/s^2)

Offshore from the Holderness coast, the relevant nearshore wave height and wave period are 2.25 m and 5 s respectively and based on equation 1 above, the closure depth = 3.73m. This is an absolute water depth based on the waves rather than being relative to a position on the profile. Based on the available evidence it is concluded that the beach closure depth along the

Holderness coast located within 500 m of the coast. This represents the limit of seasonal beach sediment movement and is important in the context of aggregate dredging as sediment may be drawn down to this depth during winter storms and then returned to the beach by summer swell.

Offshore linkages

The Holderness coast has retreated several kilometres since the end of the last glaciation and has continued to retreat since sea level reached its present level but there is no evidence for the former coastline or the cliff line in the nearshore or offshore zone. Examination of profile 1 suggests that coastal erosion over the past few thousand years has removed not only the land, cliffs and beaches but also the lower part of the shoreface to a depth of around 10 m below chart datum. The nearshore slope immediately seaward of the beach is likely to be eroding to this level due to shallow water wave action as the coastline continues to retreat. This natural process is accelerated by the highly erodible glacial till, consisting of sand and gravel in a matrix of firm to stiff clay.

Profile 1 Holderness coast north-east to 15 km offshore (Figure 6.16)

The 15 km length of this southwest to northeast trending profile is intended to cover the coastal retreat path of the Holderness glacial till cliff line over the past 10,000 years or so. The near shore zone slopes gently from the beach to 10 m water depth at 1 km along the profile, a gradient of 1 in 100. From this point to the end of the profile at 15 km offshore, the seabed is commonly smooth and almost flat, dipping at an overall gradient of less than 1 in 900. Glacial till underlies the entire profile with veneers of sand and gravel spread widely over the seabed. Isolated bedforms with east-southeast to west-northwest or northwest to southeast trending crests overlie the smooth till surface.

Profile 2 Withernsea east-southeast to dredging Area 102 (Figure 6.17)

Apart from the nearshore slope, which dips from the beach to 10 m water depth over 1.5 km, this profile is notably flat along its length, declining from 10 m to just 19 m CD over a distance of 24 km, at a gradient of approximately 1 in 2500. Such flat surfaces on the sheet of glacial till arose from planation during marine transgression after the last glaciation. Only thin gravelly veneers and isolated sand waves occur on the till along the profile and these locally thicken slightly in Area 102, which at just over 20 km offshore is the closest aggregate dredging area to the Holderness coast. However, the deposits in area 102 are isolated from the distant inshore slope and beach sediments, being separated by an extensive submerged plain of glacial till locally covered with immobile coarse-grained veneers. Such coarse grained sediments lying on a flat till surface are stable and are likely to be inherited from the early stages of marine transgression in the post glacial period (Harrison 1992).

Profile 3 Withernsea south-east to New Sand Hole and Area 448 (Figure 6.18)

This profile demonstrates the isolation of New Sand Hole from the coast and the contrast apparent in the almost flat seabed gradient inshore of the feature. Within New Sand Hole a 1 in 35 slope descends from 10 m to 15 m to over 40 m water depth at the base of the feature, which is eroded into glacial till. Cross bedded coarse-grained sediments up to 6 m thick prograde from the flanks and partly infill the bottom of New Sand Hole and these are isolated from the inshore deposits and coastline by extensive areas of glacial till at the seabed.

Summary

From the description of these 3 profiles, and the estimate of beach closure depth presented above, it is clear that there is no direct impact pathway between the dredging areas and the Holderness coast. However, the southerly sediment transport pathway described in section 6.5.9 lies inshore from the dredging areas. As modification of the hydrodynamic regime has the potential to affect sediment transport in this area it will be necessary to determine the extent of changes to tidal currents and waves.

6.5.11 Future Coastal Evolution

Here, future coastal evolution is considered over the next 100 years. Although the licence period for marine aggregate extraction is typically only 15 years, the dredged depressions are considered to be permanent (given the relict nature of the aggregate deposits and their immobility) and hence it is necessary to consider natural variability over short- to medium-timescales. Given the composition of the Holderness cliffs and the extent of the till outcrop inland, it is expected that erosion will continue into the future and the rate of erosion will depend upon variations in hydrodynamic forcing. The main mechanism for change along this coast is relative sea level rise (RSLR). One of the direct effects of RSLR is the delivery of increased wave energy at the shore, thereby increasing the potential for foreshore lowering and the rate of cliff recession. Whilst this would undoubtedly exacerbate the existing problems of land and asset loss along this coast, additional sediment would be released into the system, either feeding beaches elsewhere or being deposited offshore.

Assuming that the hard defences, as described in Section 6.5.8 above, continue to be maintained, these areas will be prevented from retreating at the same rate as the undefended section. Over very long timescales, embayments will form on either side of these ‘hard points’, most notably between Hornsea and Mappleton and Withernsea and Easington. This would affect wave refraction and change the magnitude and direction of wave energy reaching the toe of the cliffs. In addition the embayments may act as sediment traps and effectively reduce the longshore transport rate. As the beaches within the system are dependent upon sediment supply from the north, any change in longshore transport rate is likely to increase beach erosion and cliff retreat as well as reducing the sediment supply that is exported from the system to the south.

Within the defended sections themselves, there is likely to be continued beach and shore platform lowering as the coast is unable to retreat naturally. Ultimately this may compromise the integrity of the backshore defences, necessitating remedial works. Elsewhere, at Easington for example buried cables and pipelines that cross the inter-tidal may become exposed.

6.6 Shoreline Behaviour Unit 3 – Spurn

Image 3. Shoreline Behaviour Unit 3: Spurn

6.6.1 Coastline Description

The Spurn peninsula is a 5.5 km sand and gravel spit that extends from Kilnsea at the southern end of the Holderness cliffs out into the Humber Estuary, where its length is constrained by the deep channel and fast tidal flows at the mouth of the Humber. Spurn is a dynamic barrier, with morphological changes driven primarily by wave action. The barrier is exposed to waves from all sectors and sediment is moved along the barrier from north to south. The barrier is underlain by glacial till whose surface dips in a southerly direction from around -1 m ODN in the north to -20 m ODN in the south. This forms part of the nearshore platform, which is dominated by exposed till and gravels to the east (Balson and Philpott, 2004) and by a thin veneer of mobile sediments with associated bedforms to the southwest and southeast, which extends seawards towards New Sand Hole. On the western side of Spurn, the barrier abuts estuarine mudflats, which are exposed at low water.

At its northern end, the barrier consists of a thin sand and gravel ridge with vegetated dunes, fronted by a mixed sand and gravel beach. The rounded, southern end of the barrier, which is recurved, is partly covered in densely vegetated, supratidal dunes up to 15 m high. Spurn is a nature reserve and also hosts the Vessel Traffic Services control centre for the various Humber Ports. On the seaward side of the barrier there are timber groynes, which were constructed during the 19th Century. These are not maintained and are no longer functional. There is a substantial volume of sand and gravel forming the beach face at the southern end of Spurn, extending offshore towards The Binks - a series of sand and gravel banks and mounds, partially drying at low tide. These shoals dissipate a proportion of the incoming wave energy and provide shelter to the barrier (ABPmer, 2008).

Spurn is believed to have been breached repeatedly both historically and in the recent past, leading to episodic growth and realignment in response to the retreat of the Holderness Coast, its primary source of sediment. It is also subject to frequent overwashing events and the road is constructed of movable sections to accommodate the dynamic nature of the landform. Various theories have been put forward for the patterns of breaching and restoration but this process is probably driven primarily by large storm events, rather than being cyclic. ABPmer (2008) suggests that gravel extraction during the 18th and 19th centuries contributed to subsequent breaches.

Since the beginning of the 19th Century the long-term retreat rate of Spurn has been around 0.5 m/year. Maintenance of the timber groynes ceased in 1961, and led to their subsequent failure. Other structures including the old sea wall also failed in 2003 and this has led to an increased rate of change (ABPmer, 2008). Monitoring carried out by ERYC indicates that the barrier is migrating westwards, with around 2 m to 4 m erosion on the seaward side each year, but no identifiable sand accumulation on the estuary side. Analysis of beach profiles collected in 2010 shows how the beach has rolled back since the failure of the sea wall in 2003, accompanied by quite substantial foreshore lowering (Figure 6.19). Conversely the beach profile seaward of Spurn Head shows an accumulation of sediment both since 1997 and between 2009 and 2010 (Figure 6.20). An example profile (Figure 6.21) from the Humber side of Spurn is also included for comparison. Recent narrowing of the beach and dune ridge has led to frequent overwashing during storm events and the barrier is now considered to be in a relatively unstable condition.

6.6.2 Coastal Defence and Management

Spurn Peninsula is owned and managed by the Yorkshire Wildlife Trust. The total defence length is given as just over 1 km (ERYC, undated) but the majority of the defences are not maintained by the council and are derelict. The current management policy for Spurn is periodic managed realignment with the intention to intervene as required to maintain access to the facilities at Spurn Point and to maintain the integrity of the barrier until it becomes unstable.

6.6.3 Sediment Transport

Sediment sources

The primary source of sediment to the Spurn Peninsula is the sands and gravels eroded from the Holderness coastline and the lower shore platform. An estimated 0.125 Mm^3 is supplied to Spurn (Valentin, 1954) from both longshore drift and from offshore via a temporary sediment store in the Binks. This is approximately 3% of the total sediment eroded from Holderness each year, with the remainder being transported across the Humber to the south or offshore both as bedload and in suspension.

Transport pathways

Sediments are transported along the barrier towards its distal end. Modelling undertaken by ICES (1992) highlighted an increase in longshore transport rate to the south of Kilnsea. As the orientation of the barrier changes, the longshore wave energy decreases, reducing the transport rate and allowing increased deposition of coarser grained sediment towards the head to the north. However the majority of the sediment load and particularly the finer sand fractions are believed to be carried round the tip by waves and tidal currents (ABPmer, 2008) and onto the inter-tidal flats to the west, where some may contribute to aeolian dune formation.

Sinks

Spurn Peninsula is undoubtedly a sink for coarse sediments eroded from the Holderness cliffs as is The Binks and the sandbanks within the Humber Estuary.

6.6.4 Beach Toe and Offshore Linkages

Beach Toe

The beach profiles obtained from ERYC only include the cliffs and the beach to the low water mark. It is therefore not possible to identify the beach toe and thus Equation 1 (Section 6.5.10) has been used to calculate the closure depth instead. Using an inshore wave height of 2.6 m and an equivalent period of 5.3 s, the beach closure depth is 4.5 m. Hence offshore from Spurn the limit of seasonal cross shore profile variability is within 200 m of the shore.

Offshore linkages

Profile 4 Spurn Head east to New Sand Hole and Area 448 (Figure 6.22)

The seabed from Spurn Head initially dips by 6 m to 200 m offshore but thereafter gradients are gentler until New Sand Hole is reached 10 km offshore. The increase of water depth of 6 m to 12 m over 10 km represents a gradient of only 1 in 1600 over the gravelly veneers and glacial till forming the seabed offshore from Spurn. The geometry of New Sand Hole is very similar to that in profile 3, descending from 12 m water depth at the lip of the feature to over 40 m at the base. New Sand Hole is around 1.5 km wide at the lip with infilling gravelly sands typically 5 m thick. Given the nature and thickness of these sediments and their clear separation from the coast, it is not considered that New Sand Hole is a sink for sediments eroded from Spurn or from Holderness.

Summary

Based on the estimation of beach closure depth, and the description of the offshore seabed, there is evidence that Area 448 and the Spurn Peninsula are not linked by seabed sediment movements. New Sand Hole is located within the Licence Area and the scale of this natural feature eclipses that of any dredged depressions. As there is a potential impact pathway (particularly for waves from the north east) between the dredging areas and The Binks, it will be necessary to quantify any changes to the nearshore wave climate and tidal flows. Changes to sediment transport across this feature or to sediment storage may affect the eventual sediment supply to the Lincolnshire coast and Spurn Head.

6.6.5 Future Coastal Evolution

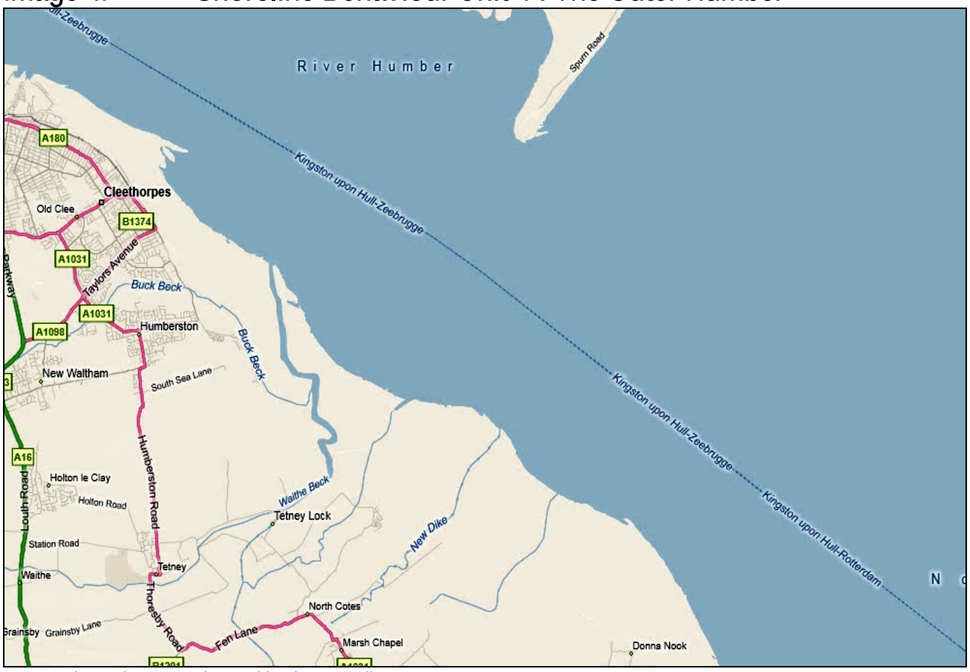
As described in the SMP2 for Flamborough Head to Gibraltar Point the future behaviour of Spurn will be governed by:

- Sediment supply from the Holderness coastline;
- Wave energy inputs at the shoreline and tidal currents at the mouth of the Humber; and
- The extent and location of breaches in the peninsula.

During the next 100 years relative sea level rise is expected to accelerate the morphodynamic processes and trends that have operated on the barrier in the past. Spurn is likely to suffer continued erosion from the seaward beach face and could migrate westwards through roll over. Being constrained by the deep water channel at the mouth of the Humber the barrier is unlikely to move further to the south. It is believed that coastal defences constructed during the 19th century prevented the barrier from rolling back naturally, thereby limiting the transfer of sediment onto the western shore. This lack of deposition, combined with erosion from the seaward side, has led to considerable narrowing of the barrier in places making it vulnerable to increased overwashing and eventual breaching. East Riding of Yorkshire Council estimate that a breach could occur within 5 to 10 years (Scott Wilson, 2009). The ultimate survival of the barrier following such an event is dependent upon the time taken and availability of sediments to repair the breach. Loss of Spurn Point could result in major changes to the configuration of the Humber and potentially the future supply of sediments to the Lincolnshire coast.

6.7 Shoreline Behaviour Unit 4 - The Outer Humber

Image 4. Shoreline Behaviour Unit 4 : The Outer Humber



The Outer Humber is characteristic of a classic macro-tidal system with both tidal ramparts to the south and a flood tide delta. The size and configuration of the delta is governed by the strong tidal currents within the Humber and the nearshore sediment transport pathways. There is no evidence of an ebb delta but this is common in a macro-tidal estuary as sediments are dispersed seawards by the strong ebb currents rather than accumulating at the mouth (Scott Wilson, 2009).

The Outer Humber Estuary comprises the following system components as described in the SMP 2 (Scott Wilson, 2009).

- The estuary bed and outer banks. The seaward extent of the estuary lies between The Binks in the north and Haile Sands in the south. These features have been described previously in Section 3.3.2. To the east of The Binks and Haile Sands lies New Sand Hole (Section 3.3.1).
- Spurn Bight is an area of inter-tidal sand and mud flat which has accumulated in the lee of Spurn Point. This is backed by a narrow strip of saltmarsh.
- The Sunk and Hawk channels run along the southern edge of Spurn Bight. This is the main navigation channel into the Humber and the depths are maintained through dredging when required. The Sunk Channel frequently undergoes dramatic morphological changes including rapid erosion or sedimentation and channel migration.
- A sub-tidal sand and gravel shoal (Middle Shoal) lies to the south of the Sunk Channel. This feature along with Burcom and Clee Sands comprises the flood tide delta.

The inshore boundary of SBU 3 is between Sunk Island and Immingham. However, the boundary of the Humber MAREA is at Cleethorpes and therefore detailed descriptions of the shoreline between Immingham and Cleethorpes are not included.

6.7.1 Sub Unit 1 Cleethorpes to Donna Nook

The coastline within SBU 3 is generally stable and is characterised by wide inter-tidal zone that ranges in width from 1 km at Grimsby to 3 km at Donna Nook.

The Cleethorpes frontage is backed by a promenade and seawall, which protects the town. The foreshore comprises a wide, fine sand beach on glacial till. The alignment of the beach highlights the influence of tidal flows within the Humber Estuary in that a series of channels, banks and ridges run parallel to the shoreline and the migration/evolution of these features results in extensive, short-term profile variability. Overall, however, the beach is considered to be stable by the EA (2008).

To the east of Cleethorpes, the hinterland changes from urban to open, agricultural lowland, which extends some 10 km inland. The wide sandy beach is backed by an accreting saltmarsh and a sand ridge that exceeds the HAT level (EA, 2008). The nearshore bank and channel system described previously also exists along this frontage and profile analysis carried out by the EA, (2008) indicates that the larger banks are continually accreting. Seawards of the banks, the profile is flat and low water is around 1200 m from the shoreline (Figure 6.23). At the eastern end of this frontage, the beach is backed by dunes. The sand ridges at the seaward limit of the beach have widened landwards over time and the channel that existed behind it has gradually been filled, resulting in a higher, flatter profile,

The orientation of the coast changes at Northcoates Point as the shoreline curves to face due east. In the vicinity of Donna Nook, there is considerable marsh coverage with intersecting creeks and channels (Figure 6.24). The lower part of the fine sand beach shows a continuation of the dynamic bank and channel system observed further to the west.

6.7.2 Coastal Defences and Management

North East Lincolnshire Council and the EA share responsibility for the defences along the part of the frontage that is within the MAREA study area. The coastal defence policy for this behaviour unit is 'Hold the Line'. The primary 'hard' defences are: 1) the groynes and concrete seawalls along the Cleethorpes frontage; 2) the concrete revetment and groynes at Humberston Fitties; and 3) the concrete floodwall, which protects the Grainthorpe Haven tidal outfall. Elsewhere, there are natural or 'soft' defences such as the earth embankment that runs between Donna Nook and Saltfleet, the flood bank at Tetney Haven and the dunes at Horseshoe point.

6.7.3 Sediment Transport

Sources

The functioning of the Outer Humber is consistent with a typical macro-tidal estuary. Flows out of the estuary intersect the north to south transport pathways along the coast and prevent sediment from directly crossing the estuary mouth. The primary source of sand sized sediment to the outer estuary and banks is the Holderness cliffs, with additional contributions from the nearshore seabed and a relatively minor fluvial input of finer-grained sediment. It is estimated that 2.2 m^3 of fine sediment is transported into the estuary from offshore each year compared to around 0.3 Mm^3 from the rivers (SNSSTS2, 2002). Magnetic characterisation of the Humber river bed deposits by Cox (2002) found that 98% was composed of sediment derived from the Holderness coast with the remaining 2% of riverine origin. The frontage between Cleethorpes and Donna Nook receives annual inputs of 0.1 Mm^3 to 0.3 Mm^3 as sediment is moved across the mouth of the Humber.

Pathways

The main pathway for sediments entering this Behaviour Unit is across the mouth of the Humber. Sediments that are deposited in the vicinity of Donna Nook may be redistributed into the Humber Estuary by relatively weak longshore drift. However, there is the potential for short-term drift reversal during northerly storms and the loss of sediment from the system. Gravels and coarse sediments that move southwards from Holderness as bedload do not cross the Humber. However, isolated gravel deposits are known to exist offshore and these are also thought to have originated from Holderness (HR Wallingford *et al*, 2002).

Sinks

The Humber Estuary is a mature sediment sink for fine sediments and as such has limited capacity to accommodate large influxes of sediment, other than to keep pace with sea level rise. The main depositional areas are The Binks, Haile Sands and Donna Nook, which are estimated to contain around 80 Mm^3 of sediment.. The coastal dunes of north Lincolnshire are also a sink for wind blown sediments from Haile Sands Flats.

6.7.4 Beach Toe and Offshore Linkages

Beach Toe

As described in Section 6.7.1 Donna Nook is characterised by a wide, sandy foreshore. The EA bathymetric profile presented in Figure 6.24 shows that the inter-tidal zone is flat for almost 1 km from the shore and then shelves abruptly at around 1.2 km. There is a significant break in the slope at around -5 m ODN, which is located around 1500 m offshore. Based on this profile, it is concluded that the closure depth is around -5 m ODN.

Offshore linkages

Profile 5 Donna Nook north-east to New Sand Hole and Area 448 (Figure 6.25)

The profile extends for 25 km NE from Donna Nook and the nearshore sand flats out to New Sand Hole, extending along its length and beyond. From the coast to 13 km offshore the seabed is largely smooth. The coastal sand flats of Donna Nook and Haile Sand extend offshore at a low angle, reaching 10 m water depth on their seaward margin 7 km offshore, a gradient of 1 in 700. This seaward margin is sharply defined against the underlying glacial till, which is then exposed at the seabed over much of the rest of the profile until the south-westerly slope of New Sand Hole is reached 13 km offshore. The infill of New Sand Hole thickens from the flanks into the base of the feature and consists of sands and gravelly sands becoming sandwaves at the base with well-defined crests 8 m high in 30 m of water. These bedforms abruptly pinch out at 18 km along the profile in the base of New Sand Hole where the nature of the infill changes to thinner gravelly sands with intervening till exposures. Beyond New Sand Hole, the seabed is once again relatively flat in water depths of 14 m to 16 m.

Summary

Based on the available evidence from the EA bathymetric profile, and in particular the abrupt transition between the mobile sediments of the nearshore sandflats and the exposed glacial till described above, it is apparent that there is no direct interaction between the northern dredging areas and the north Lincolnshire coast. With the exception of Area 102 the dredging areas are all located seawards of the southerly sediment transport pathway described by Kenyon and Cooper (2005). It will still be necessary to determine whether changes to waves and tidal currents as a result of future dredging could alter the sediment transport pathways and indirectly affect the sediment supply to the north Lincolnshire coast.

6.7.5 Future Coastal Evolution

As described in the SMP2 for Flamborough Head to Gibraltar Point (Scott Wilson, 2009) the future evolution of the Outer Humber system is dependent upon the following:

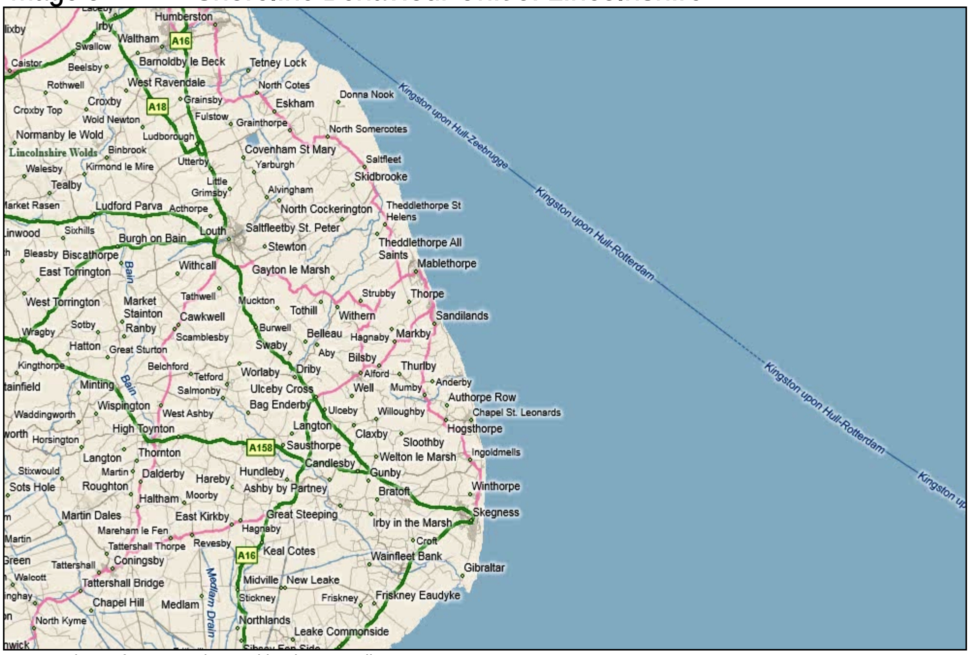
- The continued supply of sediment from Holderness;
- The geomorphology of Spurn Point and The Binks;
- Increased sediment demand within the Humber in response to sea level rise; and
- Maintenance dredging in the Sunk Dredge Channel.

As there is sufficient sediment held within the sand stores to maintain the system in the short- to medium-term (up to 100 years according to Townend and Pethick, 2002) there would almost certainly be a lag in the response time from the Outer Humber if the supply of sediment from Holderness were to decrease. Sea level rise in the Humber would increase sedimentation by around 0.3 Mm^3/year per 0.1 m increase in water level. However, despite this, the existing transport pathway across the Humber would not necessarily be affected.

Changes in the position or in the extent of the Spurn Peninsula and The Binks complex would almost certainly alter the sediment transport pathways and rates of sediment transfer into and across the Humber. Removal of the temporary sediment store in The Binks would reduce sediment transfers during storms and thus the overall input to the Lincolnshire coastline. The deposition of fine sand is likely to continue between Cleethorpes and Donna Nook in the medium-term at least. In the longer-term, deposition rates may decrease in response to increased sediment deposition within the estuary and changes to sediment pathways as described above.

6.8 Shoreline Behaviour Unit 5 - Lincolnshire

Image 5. Shoreline Behaviour Unit 5: Lincolnshire



©2010 Microsoft Corporation and its data suppliers

The coastline between Donna Nook and Gibraltar Point is east facing and is therefore exposed to the prevailing winds and waves from the north east. The frontage is predominantly composed of fine sand beaches overlying glacial till. The till is exposed in the inter-tidal zone along the coast and its surface forms a topographic high, which reaches a maximum elevation between Ingoldmells and Chapel St Leonards, creating a headland there (Scott Wilson, 2009). For the purposes of this discussion, the Lincolnshire coast is subdivided into four geomorphological components as described in the Shoreline Management Plan (Scott Wilson, 2009).

The north east coast of Lincolnshire as described previously consists of a wide, sandy inter-tidal zone that merges with the sub-tidal Haile Sands. These inter-tidal flats extend southwards to Mablethorpe. This area has been defined as the tidal ramparts of the Humber delta. The northern part of SBU 5 is characterised by extensive saltmarsh coverage. These marshes are composed of sandy silts and are sheltered from wave action by a nearshore bar. There is evidence that the marsh coverage has extended southwards during the past 20 years (Environment Agency, 2008) and further saltmarsh is observed at Gibraltar Point.

Wind blown, fine sand from the inter-tidal flats at Donna Nook has resulted in dune development, in some cases landward of the saltmarsh, as at Saltfleet. At the southern end of the frontage marsh and dune development is due to the sheltering effects of the nearshore banks at the entrance to The Wash.

The inter-tidal beaches between Saltfleet and Gibraltar Point comprise a thin veneer of sediment overlying glacial till. During storms, sediment may be stripped from the beach, exposing the till to erosion. This has led to a major beach nourishment programme that has been ongoing since 1994. This will be described in more detail in Section 6.8.4.

6.8.1 Sub Unit 1 - Donna Nook to Mablethorpe

The frontage is characterised by a wide, sandy inter-tidal zone that is linked to the sub-tidal sand flats by an array of banks and channels. Between Saltfleet and Theddlethorpe, much of the beach between MHWS and MHWN is covered by saltmarsh.

Accretion of both the inter-tidal and sub-tidal zone has been recorded between Donna Nook and Mablethorpe during the past 200 years (Halcrow, 2004) with a net accretion rate 2.3 m/year. Halcrow (2004) also notes the long term trend for foreshore steepening, which was also recorded by the EAduring the Anglian Coastal Monitoring Programme, which has been carried out since 1991 (Environment Agency, 2008).

As well as expanding seawards, analysis of beach profiles also shows a vertical accretion of the upper beach (Environment Agency, 2008). At low water, however, the sand beach is steepening as sediment is removed by wave action and with the marsh encroaching from the beach margin. The beach profile shown in Figure 6.26 shows that above MHWN the profile is flat and below this level, exhibits the ridge and channel features described previously.

Moving southwards along the frontage, the width of the inter-tidal flats decreases and they pinch out at Mablethorpe. To the north of Mablethorpe the beach has remained stable and the beach width and gradient have remained fairly constant during the 15 year monitoring period (Environment Agency, 2008). However, there has been a significant build up of sand at the toe of the dune system. The hinterland within Sub-Unit 1 is predominantly low-lying agricultural land with isolated settlements and large caravan parks at Saltfleet and Theddlethorpe. Expansion of the saltmarsh has been particularly rapid between Saltfleet and Theddlethorpe during the past 20 years. This has been linked by Pethick and Leggett, (1993) to the southward and eastward migration of the nearshore bar. This feature provides shelter from wave action at this location, thereby leading to a more benign, depositional environment.

6.8.2 Sub Unit 2 - Mablethorpe - Skegness

The 24 km stretch of coast between Mablethorpe and Skegness is characterised by fine sand beaches. Much of the surficial layer has been removed by contemporary hydrodynamic processes, leaving only a veneer of sand. It is considered that the offshore sediment supply, which benefits the beaches further to the north, ceases just to the north of Mablethorpe.

The coast has a convex outline and is east facing, increasing the exposure to the prevailing northerly and north easterly waves. The hinterland is predominantly low-lying agricultural land and large, urban settlements fronting the coast along with numerous caravan parks. Land levels are often below HAT and consequently the entire frontage is at risk from flooding (Blott and Pye, 2004).

In contrast to the northern Lincolnshire coastline, this frontage has a history of erosion that has been ongoing for thousands of years (Dugdale and Vere, 1993). Since 1890 the net erosion rate based on historic map analysis has been estimated to be approximately 1.3 m/year (Halcrow, 2003). In order to manage this erosion, and maintain a suitable standard of coastal defence, a major programme of beach nourishment was started in 1994. The Lincshore scheme monitors beach profiles and recharges those areas which do not meet threshold design criteria. Although the Lincshore scheme has offset the immediate problem of coastal erosion and beach lowering, export of sand from the system continues and thus ongoing maintenance is required. The Lincshore scheme will be discussed further in Section 6.8.4

The seaside town of Mablethorpe is at the northern boundary of this unit. The sand beach is fronted by a recurved promenade wall with additional rock armouring at the southern end of the town. The beach has a history of ongoing erosion and indeed, the first parish of Mablethorpe along with its church was lost to the sea during the Middle Ages (AA, 1984). Since the construction of the seawall there has been rapid erosion of the beach and the underlying glacial till along with associated foreshore steepening as the coast is prevented from 'rolling back'. This section of coast was first nourished in 1998 with around 61,000 m^3 of sand. The old timber groynes were buried during this operation thereby facilitating uninterrupted longshore transport to the south. Following the initial recharge the beach continued to erode although the profile shape remained fairly constant. Further nourishment was carried out in 2004 and 2006 to build up the mid-section of the profile but the general erosional trend has continued. Profile analysis carried out by the EA (EA, 2008) indicate that the greatest erosion rates are observed at around MSL and that the beach fill is distributed in a cross-shore direction both up the beach and towards low water. Based on the beach profiles presented in Figure 6.27 there has been very little change since 1995. However, this is most likely due to the recharge of the beach in 2006. This data does appear to show a slight onshore migration of Mablethorpe Bank, which lies around 1 km offshore and plays an important role in dissipating nearshore wave energy.

To the south of Mablethorpe at Sutton on Sea, the beach shows a continuous erosional trend in spite of regular nourishment. In particular the coast immediately to the south of Sandilands has been identified as an erosion hotspot (EA, 2008) and was nourished twice during 1997, receiving a total of around 0.65 Mm^3 sand. In spite of the continued erosion, the foreshore gradient has decreased between 1995 and 2008 resulting in a flatter, more dissipative profile (Figure 6.28).

The frontage at Anderby Creek is backed by a revetment. As shown in Figure 6.29 there are also small vegetated dunes indicating that the upper beach at least has remained stable over time. Indeed, the stretch of coast between Anderby Creek and Chapel St Leonards shows less variability that that to the north although the general trend is erosional and beach levels have been regularly 'topped up' since the late 1990s (EA, 2008). The erosion is concentrated around the low water mark, whilst the upper beach displays an accretionary trend.

Chapel St Leonards is a large village of private dwellings, interspersed with chalets and caravan parks that are protected by a concrete seawall. Chapel Point is a small promontory on an almost entirely straight coastline, which may have formed as a result of the exposed glacial till in the inter-tidal zone which creates a topographic high along this section of coast with the maximum elevation at this location (Scott Wilson, 2009). Chapel Point is protected by a stepped recurved seawall with rock armour at the toe. As shown in Figure 6.30 the beach shows an accretional trend, particularly around the low water mark. Downdrift from Chapel Point accumulation of sediment above the high water mark has led to vegetation growth during the past 15 years and the beach is shown to be accreting despite minimal recharge. Between Chapel St Leonards and Ingoldmells Point, the orientation of the coast changes slightly as the plan shape becomes more concave. The beach shows an accretionary trend, particularly around the low water mark. Previously this location was identified as an erosion hotspot as it was apparently a focal point for waves from the northeast (EA, 2004a) and was heavily nourished in 1995 and 1996 (EA, 2008). The beach received further nourishment in 2006.

Further to the south, towards Ingoldmells, the beach is less stable and requires more frequent maintenance with beach levels eroding back to a pre-nourishment profile within a few years. Vickers Point and Ingoldmells Point are protected with rock and concrete walls. Recent nourishment at Ingoldmells has buried the lower part of the wall (EA, 2008). However, analysis of EA beach profiles shows both considerable foreshore lowering and steepening between 1995 and 2008 (Figure 6.31).

The Lincshore scheme area ends south of Ingoldmells but surveys show that the beach receives some of the recharge sediment lost from beaches to the north. To the south of the Lincshore scheme the beach displays more annual and seasonal profile variability as expected from a natural beach. Between Ingoldmells and Skegness the beach is backed by a concrete seawall and there are timber groynes between Seathorne and Skegness (EA, 2008).

6.8.3 Sub Unit 3 Skegness to Gibraltar Point

The urban frontage of Skegness is protected by a concrete revetment and rock armour. This is fronted by a steep sand beach overlying glacial till (Scott Wilson, 2009). Based on monitoring carried out by the Environment Agency, the beach is generally stable although, as shown in Figure 6.32 there has been accretion of both the upper beach face and inter-tidal zone between 1995 and 2008 (EA, 2008). This Figure also shows a lowering of the beach seawards of the low water mark. Moving south from Skegness the hinterland becomes more rural comprising mainly agricultural land and a golf course. The backshore is characterised by an unconstrained, vegetated dune system, which is able to roll back in response to storms and rising sea levels.

The frontage between Skegness and Gibraltar Point is characterised by sand dunes, backed by saltmarsh that extends southwards into The Wash. The foreshore consists of fine to medium sand. Profile analysis indicates that the beach is accreting seawards with dune ridges forming as a result of previous profile migrations in response to storm events. There is also evidence of vertical accretion of up to the 2 m over 15 years (EA, 2008). The nearshore zone here is characterised by a complex arrangement of sand bars and channels that form the tidal ramparts of the ebb tide delta from the Boston Deep Channel in The Wash. The flat upper beach profile and complex nearshore bathymetry is shown in the profile presented in Figure 6.33. The Linkages between the beach and the nearshore features will be discussed further in Section 6.8.6. To the south of Gibraltar Point the marsh and dune system becomes more complex and is intersected by numerous creeks and dendritic channel systems. South of Wainfleet harbour the marsh is fronted by expanses of inter-tidal sand and mudflats that characterise the depositional environment of The Wash.

6.8.4 Coastal Defence and Management

The Lincolnshire beaches form only part of the coastal defence along this frontage and many of the urban areas are protected by a variety of sea defences. The Lincolnshire SMP identifies an 'embankment fronted by dunes' running from Donna Nook to Saltfleet. However, from Saltfleet to Mablethorpe, only the dune system is present. The 24 km of coastline between Mablethorpe and Skegness have been engineered with hard defence structures such as seawalls, revetments and rock armour, which protect around 20,000 ha of low lying hinterland. There are also a number of timber groynes along the frontage although many of these have been buried during the renourishment programme. The defences end at Skegness where the dune system resumes and continues to Gibraltar Point and beyond into The Wash.

The 1991 Sea Defence Study (Posford Duvivier, 1991) recommended a beach nourishment scheme in Lincolnshire and thus the section of coast between Mablethorpe and Ingoldmells is maintained through the Lincshore beach nourishment programme. It was hoped that the nourishment would stabilise the eroding beaches and offer a greater level of protection to the backshore defences. The EA Lincshore scheme started in 1994, in order to provide a 1:200 year standard of protection. Based on analysis of topographic surveys, Zwiers *et al*, (1996) estimated the nourishment volume between 1994 and 1995 was over 1,500,000 m^3. During the main period of nourishment from 1994 to 1998 over 6.21 Mm^3 of sand and gravel dredged from offshore in Licence Areas 107 and 440 was applied to the Lincolnshire coast. (EA, 2004a). Since 2010, Area 481 has been used to provide sand for the scheme. Lincshore was expected to complete in 1998 but still continues along various stretches of the frontage and the current scheme has a recommended strategy to continue for the next 50 years to 2055 (Halcrow, 2004).

Coastal defences along the Lincolnshire coastline are managed by the Environment Agency. The coast and flood defence policy as defined in the Shoreline Management Plan provides an indication of where investment will be made into protecting coastal assets over the next 100 years. For this frontage the policy is Hold the Line with the exception of Mablethorpe to Gibraltar Point where localised managed realignment could be considered in the longer term to increase defence sustainability.

6.8.5 Sediment Transport

Sources

The primary natural source of sediment to the Lincolnshire coastline is the sand eroded from the Holderness cliffs. It is also possible that sediment eroded from the Humber tidal delta as a result of historic land reclamation in the outer estuary could also have supplied sediment to this frontage (Scott Wilson, 2009). Cessation of reclamation in the early 20th Century combined with sea level rise increased the Humber tidal prism, providing additional sediment storage capacity at Donna Nook and Haile Sands, such that only small amounts of sediment are now supplied to the Lincolnshire coast.

The combined riverine output from the Humber Estuary provides only minor inputs (c. 0.1 Mm^3/year according to McCave, 1987) to the system. There is a further potential (but unsubstantiated) sediment source from the area offshore from the mouth of the Humber where the seabed till is of the Bolders Bank formation. Indeed, it is also widely believed that there is an offshore source of sediment to the Gibraltar Point sandflats (HR Wallingford *et al*, 2002). Finally, the Lincshore scheme represents an important although artificial source of sediment to the beaches between Mablethorpe and Ingoldmells.

Pathways

As described in Section 6.7.3, between 0.1 Mm^3 and 0.3 Mm^3 of sediment derived from the Holderness cliffs crosses the Humber and is deposited on the Lincolnshire coast each year. The majority of this is retained within the accreting sandflats between Donna Nook and Mablethorpe with a potential annual longshore transport rate of only 124,000 m^3 to the south. The SMP2 review of the Lincolnshire sediment system highlights some discrepancies between apparent accretion rates and potential supply from Holderness. This raises the possibility of multiple transport pathways across the Humber although there is no documented evidence to support this theory (Scott Wilson, 2009).

Inshore transport along the Lincolnshire coastline is predominantly wave driven and the net direction is southerly. However, sediment transport studies using drogues demonstrate that longshore sediment transport directions may be both northerly and southerly, with an apparent pivot point around the promontory at Ingoldmells. It is likely therefore that wave driven nearshore currents vary seasonally, annually and cyclically over longer periods.

Net flood tidal currents in the coastal zone to the west of 0°30' E move sediment in a predominantly southerly direction. This theory is supported by the interpretation of bedform asymmetry which indicates that sand is transported southwards and towards the coast (SNSSTS2, 2002). Hence sediment is likely to move onshore during peak tidal current flows in the near offshore zone and even more so during surge events. There is also a coupling between this and wave driven longshore drift, especially during periods of offshore winds. This sedimentary connection between the shore and the nearby offshore zone may provide a mechanism for sediment exchange between the coast and the nearshore banks such as Mablethorpe and Skegness Middle Sands, the latter of which has migrated almost 3 km to the south during the past 150 years (HR Wallingford *et al*, 2002).

As described in Section 5, offshore from 0°30' E bedform asymmetry suggests that the general transport direction is northerly despite this being contrary to the direction of strongest tidal flows.

Sinks

There are no substantial sinks within SBU5 other than at Donna Nook. Sediments transported along the Lincolnshire coast may be deposited on the wide, sandy foreshore and nearshore bar system at Gibraltar Point as numerical modelling suggests that only a small volume of sediment enters the Wash (HR Wallingford *et al*, 2002). This theory appears to be supported by accretion in this area since the start of the Lincshore scheme. Some sediment may also be moved offshore, across the Wash and into adjacent coastal units but the pathways and scale of transport are not well understood.

Immediately offshore from the Lincolnshire coast are the Mablethorpe and Skegness Middle Sands. Both these banks are reported to have extended southwards in recent years. Further offshore the Inner Dowsing Bank is composed of fine to medium sand.

6.8.6 Beach Toe and Offshore Linkages

Beach Toe

Estimations of the beach closure depth have been made using the bathymetric profiles measured by the Environment Agency. The profiles are presented in Figures 6.25 to 6.32 and Table 6.3 below provides an indication of the location of the beach toe.

Table 6.3 Beach Toe along Lincolnshire coast

Location	Beach Toe (m ODN)	Distance from Shore km
Donna Nook (profile facing east)	-5	1.5
Mablethorpe	-8	0.5
Chapel St Leonards	-6	0.5
Ingoldmells	-7	0.4

The estimated position of the beach toe presented in Table 6.3 highlight the difference between the northern part of the frontage, with its wide inter-tidal zone and healthy beach levels and the southern part, where the beaches are much narrower and are typically eroding.

Offshore linkages

Profile 6 Donna Nook south-east to Protector Overfalls and Area 197 (Figure 6.34)

This profile extends for over 25 km south-east from Donna Nook to dredging licence area 197 and to application Area 400, both located at or close to Protector Overfalls. Offshore from the sand flats which extend over 1.5 km from high water mark to low water mark and a further 1.5 km offshore at just below CD, the sea bed dips relatively steeply into a shore parallel channel 7 m deep, marking the inshore margin of Saltfleet Overfalls. Saltfleet Overfalls is an undulating series of low mounds of sand and gravel with localised megaripples separated by depressions floored with exposed glacial till or gravelly veneers. Water depths over the mounds are typically 2 - 5 m over 1 - 2 km whilst the intervening depressions extend to 12 m depth. An undulating sea bed 8 m to 13 m below CD with locally prominent but isolated sand waves extends offshore from Saltfleet Overfalls until at 19 km offshore a rise in the till surface draped with sand and gravel marks the location of Protector Overfalls. The sand and gravel here forms a lens 5 m thick with a well defined margin on the western flank of the Overfalls. The deposit thins to the east, becoming a sheet 1 m to 3 m thick extending for 1.5 km over the smooth till surface. Shallow dredge marks are apparent on the seabed in this locality, forming an undulating or corrugated bathymetry with a relief of up to 2 m over the sandy gravel sheet. This demonstrates the permanent nature of the dredged depressions since dredging has been taking place here since the early 1990's.

Beyond Protector Overfalls, the till surface dips to the east into 18 m of water where again sand and gravel lenses and sheets drape the till within application area 400. These consist of poorly sorted clean sandy gravel and are smooth on their surface except where sand bedforms are present. The sheets and lenses are relict, being immobile and having formed during deglaciation and during the early stages of marine transgression in the region. The separation of these sand and gravel deposits by intervening areas of till at seabed and by the mounds, channels and depressions inshore, demonstrates that these are isolated from the nearshore sands flanking the coast at Donna Nook. In addition, the consistent west - east orientation of sand bedform crests along this profile suggests a north-south tidal stream, further isolating the offshore sediments from the coastline.

Profile 7 Mablethorpe east-north-east to Protector Overfalls and Area 197 (Figure 6.35)
The beach and sand flats dip seaward to 8 m depth at 800 m offshore where they pinch out on the western margin of a shore parallel channel. Shallower waters immediately beyond the channel give way to a flat seabed deepening to only 5 m to 7 m out to 6 km offshore, locally characterised by sand waves and gravelly veneers. Low mounds of sand and gravel 2 m to 3 m thick with sandwaves separated by depressions mark Theddlethorpe Overfalls and the gently rising till surface leads over isolated sandwaves on till to Protector Overfalls and licence area 197 at 11 km offshore. The till is draped with a sheet of sand and gravel 1 m to 3 m thick over the licence area and this is separated from the inshore sand flats by till exposures and areas of deeper and shallower water. The stability of the sandy gravels is clear from their smooth profiles and low surface gradients, covering the pre-existing till surface. Mobile sand bedforms occur locally over the sandy gravels, for example on Protector Overfalls.

Profile 8 Ingoldmells Point east-north east to Inner Dowsing and Area 481 (Figure 6.36)
Extending over 25 km east-northeast from the Lincolnshire coast at Ingoldmells Point over Inner Dowsing Bank and towards the northern tip of Docking Shoal as it merges with the Wash Channel, this profile displays a contrast in character along its length. The smooth seabed of the inshore 11 km contrasts with the undulating offshore portion characterised by banks, sand waves and intervening deeps.

The sea bed gradient between the coast and the western part of the Wash Channel is almost flat, at approximately 1 in 650, with only isolated bedforms. Offshore, the seabed deepens to 33 m in the Wash Channel, cut into glacial till, before shoaling over the Inner Dowsing sandbank, lying just east of a pronounced rise in the till surface 13 km offshore. Inner Dowsing consists of a main sand ridge over 11 m thick flanked by sandwaves, lying less than 5 m below CD along the profile. Further offshore, 4 km of flat seabed with thin veneers gives way to sand bedforms in dredging Area 107, at the northern tip of Docking Shoal. At approximately 20 km offshore the seabed deepens over a till exposure to reach over 30 m CD where large sand waves infill a depression on the glacial till surface in dredging area 481. These sand waves are 11 m high with their pronounced crests lying in 20 m of water. Whilst the glacial till along the profile forms the offshore extension of the till found in Lincolnshire, the sand and gravel deposits lying on this late glacial surface are completely isolated from the coastline and inshore zone, being separated by depressions, banks, till exposures and veneers of sand and gravel.

Summary

The profile descriptions above highlight the complexity of the nearshore region in this area but based on the available evidence there do not appear to be any direct interactions between the dredging areas and the coast. However, as described in Section 6.8.5, there is an apparent mechanism for sediment exchange between the coast and the nearshore banks in this area. It will therefore be necessary to determine whether future dredging activities could indirectly affect cross-shore transport processes by altering the waves and tidal currents as well as potential direct impacts upon the features themselves.

6.8.7 Future Coastal Evolution

As described in the SMP2 for Flamborough Head to Gibraltar Point (Scott Wilson, 2009) there are four major drivers that will affect the future evolution of the Lincolnshire coast. These are:

- The continued supply of sediment from Holderness;
- The pathways and rates of sediment movement across the Humber;
- The continuation of accretion and sediment storage between Donna Nook and Mablethorpe; and
- The continuation of the Lincshore scheme.

The implications of sea level rise or decreasing supply from Holderness creating a potential sediment deficit in the Humber have been discussed previously. Whilst both have the potential to impact sediment supply to the Lincolnshire coastline, the effects would not become apparent in the short- or medium-term (< 100years).

A more immediate response to rising sea level along the Lincolnshire coast is likely to be continued or increased beach erosion and associated foreshore steepening leading to coastal squeeze along the defended sections of coast. Without the continuation of the Lincshore scheme beach erosion will accelerate in the short-term, resulting in the eventual failure of defence structures and an increased risk of flooding of the low lying hinterland.

Continued southwards migration of the nearshore banks (Mablethorpe and Skegness Middle Sand) may expose previously sheltered sections of the coast to increased wave action as well as altering nearshore sediment transport pathways.

The more stable southern part of the frontage, between Skegness and Gibraltar Point is likely to continue accreting, at least in the short-term and until such time as there is a dramatic reduction in sediment supply from the north and from offshore.

6.9 Shoreline Behaviour Unit 6 - North Norfolk

Image 6. Shoreline Behaviour Unit 6: North Norfolk

The North Norfolk SMP2 covers the area between Hunstanton at the entrance to The Wash and Weybourne to the east. For the purpose of this study, the eastern boundary has been extended to Cromer, which is the limit of the MAREA study area.

The North Norfolk coastal system is highly complex and comprises a discontinuous series of sand and gravel barriers fronting extensive marshes, dune systems and creek networks. The following sedimentary environments are present within SBU 5 (SMP2, 2009):

- Barrier and spit systems composed of gravel and coarse sand;
- Aeolian sand dunes;
- Chalk cliffs;
- Saltmarshes and inter-tidal muds;
- Inter-tidal sand flats with complex bedform and bar formations; and
- Tidal channel and creek systems.

The distribution of the various geomorphological features is controlled by the configuration of the chalk bedrock and the overlying glacial tills along with the contemporary hydrodynamic regime.

The North Norfolk coast receives tidal influences from both the north and south, which gives rise to significant differences in tidal range along the frontage. This also gives rise to complex tidal current patterns and variable flow speeds. As for the rest of the Humber MAREA study area, the North Norfolk coastline is exposed primarily to waves from the north and north-east. Due to the northerly orientation, the coast is largely sheltered from southerly waves.

6.9.1 Sub Unit 1 Old Hunstanton to Gore Point

The Hunstanton frontage is west facing and is backed by 20 m high cliffs of Cretaceous rocks comprising distinctive layers of impure limestone (the Red Chalk Formation) sandwiched between overlying white Chalk and underlying Carstone, a fine to coarse-grained sandstone (HR Wallingford *et al*, 2002), (Figure 6.37). The cliffs are fronted by a sand and shingle beach. The hinterland comprises the seaside resort of Hunstanton and further to the north the village of Old Hunstanton. These urban areas are surrounded by predominantly agricultural land. The cliff line declines between Hunstanton and Old Hunstanton and vegetated dunes then occur, fronted by a wide, sandy foreshore that is accreting at a rate of around 1 m to 2m/year (EA, 2007). Sediment movement across the beach is variable as sediment on the upper beach face is moved southwards by littoral drift whilst that on the lower foreshore is transported to the north by tidal currents (EA, 2007).

Moving northwards, the orientation of the coast changes to face north-west and ultimately almost due north. The hinterland is low-lying, mainly agricultural land. This small village of Holme-next-the-Sea is located around half a mile from the beach and the only other major coastal asset is the Hunstanton golf links. The coastal strip comprises a broad expanse of vegetated dunes fronted by a wide, sand and pebble beach, intersected with areas of saltmarsh and a complex array of inter-tidal sandbars and channels (Figure 6.37). Profile analysis undertaken by the EA, (2007) indicates that the beach is accreting at around 1.4 m/year.

Immediately to the west of Gore Point, which is the limit of the north-west facing section of the coast, the upper beach shows a general trend of accretion whereas at MSL, the trend is erosional, leading to considerable foreshore steepening during the past 15 years (EA, 2007). Gore Point constitutes a tidal delta as the flow from the tidal inlet crosses the inter-tidal zone and results in an interruption of the westerly drift as longshore currents are deflected offshore (SMP2, 2009). A pronounced lobe is formed in the lower inter-tidal zone by the tidal discharge from the inlet. This acts to shelter the upper shoreface from wave action. The tidal delta is typically characterised by a complex sandwave formation and the development of a marked ebb tide bar. Further tidal deltas are located at Thornham and Titchwell, immediately to the east of Gore Point. The inter-tidal zone at Gore Point is wide and sandy and the immediate hinterland is rural.

6.9.2 Sub Unit 2 - Brancaster Bay

To the east of Gore Point the coast is characterised by a fine sand beach, backed by dune ridges. The adjacent hinterland comprises both natural and reclaimed saltmarsh. Within the Thornham Harbour Channel profile analysis indicates erosion of around 2 m/year around the low water mark (EA, 2007).

The village of Titchwell is located approximately half a mile from the coast and is separated from the sea by the RSPB's Titchwell Marsh Reserve (AA, 1984). This comprises extensive saltmarsh and reed beds fronted by a shingle beach and was originally reclaimed for agriculture during the 18th Century. The defences were destroyed by a storm in 1949 and the land has since reverted to its original state (SMP2, 2009). The growth of the tidal delta following the breach resulted in progradation of the adjacent dunes, which locally reversed the erosional trend within Brancaster Bay. Profile analysis indicates that during the past 20 years the beach fronting the nature reserve has eroded at a net rate of 0.9 m/year. The profile has flattened slightly as the lower part of the profile has remained fairly stable.

At Brancaster the wide beach is backed by a large concrete seawall and extensive dunes front the marsh hinterland. Based on long-term monitoring undertaken by the Environment Agency, the dunes within Brancaster Bay have been rapidly eroded during the past decade although this is not apparent from the profiles presented in Figure 6.39, which show a stable upper profile. To the east of the beach road from Brancaster, the extensive inter-tidal zone is intersected by the Brancaster Harbour Channel. The beach is backed by a complex system of marsh and sandflats occupied by the Royal West Norfolk Golf Club. The villages of Brancaster Staithe and Burnham Deepdale lie adjacent to the marshes. The coast here is sheltered from wave action by Scolt Head Island but the inter-tidal shows a strong erosional trend of 4 m/year adjacent to the golf club (EA, 2007).

6.9.3 Sub Unit 3 Scolt Head Island

Scolt Head Island is one of the best examples of a barrier island to be found in the UK (EA, 2007). The morphology of the barrier is diverse, ranging from gravel ridges, sand and shingle beaches to sand dunes and saltmarsh. Scolt Island is thought to be transgressing landwards at rate of around 1 m/year (SMP2, 2009) as the barrier rolls back in response to storm events. Evidence of this is found in the washover fans, which can be found on the landward flanks of the barrier. The wide, flat inter-tidal zone, landward of the barrier and the steeper seaward face are clearly visible in the profiles presented in Figure 6.40. This also demonstrates that the seaward face has remained more or less stable during the past 16 years.

The barrier has also been experiencing accretion of around 2.5 m/year at the distal end of the spit during the past 1000 years. This is manifested as a westerly migration of the barrier and profile analysis also shows an accretionary trend (EA, 2007). The westward growth of Scolt Head may be attributable to westerly longshore drift that forms recurved laterals at the end of the spit (Vincent, 1979). However, other hypotheses have been put forward which will be explored further in Section 6.9.5. Conversely, the mid-section of the barrier is thought to be eroding at up to 2 m/year accompanied by a general steepening of the profile (EA, 2007). The eastern end of the barrier is stable.

6.9.4 Sub Unit 4 Burnham Overy to Wells-Next-the-Sea

This area is generally known as Holkham Bay. The small village of Burnham Overy Staithe lies adjacent to the coast and is fronted by the Overy Marsh. This is a complex arrangement of sandflats, marshes and creeks that have developed on either side of the tidal delta. The Gun Hill dunes are one of the few examples of multiple dune ridges along the North Norfolk coast. These mature ridges are colonised by a diverse dune flora. However, profile data shows that the beach fronting the dunes is eroding at a net rate of around 3.5 m/year and as dunes do not reform by roll over processes it is likely that the dune ridges are becoming narrower as offshore barriers move landwards.

Moving further east, the marsh and creek system is replaced by an extensive line of dunes known as the Holkham Meals. Large swathes of these have been forested with pine trees over the past 150 years. The hinterland behind the dunes is low lying agricultural marshland known as the Overy Marshes. This was the first strip of land to be reclaimed in North Norfolk, almost 400 years ago (AA, 1984). The entire coastline within this Sub-Unit forms part of the Holkham National Nature Reserve, which includes almost 10,000 ha of dunes, saltmarshes and beaches. In the middle of the frontage, Holkham Gap has a wide, sandy beach that shows variable rates of erosion and accretion, which may result from sandbars migrating onshore (EA, 2007).

The beach at Wells-Next-the-Sea consists of fine sand and a wide inter-tidal zone, which combines West Sands and Bob Halls Sands. This is intersected by a channel, which leads to Wells Harbour and forms the tidal delta. Based on the trend analysis undertaken by the Environment Agency, Wells beach is erosional, particularly along the upper foreshore (EA, 2007). However, this trend is not apparent in the beach profiles presented in Figure 6.41. In the vicinity of Wells lifeboat station the dune ridge is protected by a 170 m wire gabion revetment and timber apron.

6.9.5 Sub Unit 5 Wells Next the Sea – Blakeney

East of Wells lifeboat station the coast turns abruptly through 90˚ to face due east for approximately 1 mile. The harbour channel follows the line of the beach road, which is protected by an earth embankment. The town of Wells is fronted by a large expanse of saltmarsh and a wide, sandy inter-tidal flat that is up to 2.4 km wide. The western tip of the marsh is forested with pine trees. Profile analysis indicates a modest accretionary trend for this section of coast but less than 1km to the east beach levels are shown to be falling (EA, 2007).

The small village of Stiffkey is approximately 1 km from the coast. Like Wells, the coast is fronted by extensive saltmarsh - the Stiffkey Marshes - and up to 2 km of inter-tidal sandflats. The foreshore here is generally stable (EA, 2007). Moving further east, the coast is characterised by further saltmarshes that are intersected with creeks and tidal channels. The village of Marston and the small town of Blakeney lie adjacent to the coast, separated from each other by mainly agricultural land. The coast and marshes are in the lee of Blakeney Point barrier island and are therefore protected from wave action. A low sand/gravel ridge known as the Meols extends between Warham and Marston. This forms part of the framework within which the extensive saltmarshes have developed (SMP2, 2009).

Blakeney Point is an excellent example of a recurved spit. The barrier is over 9 km in length and is formed predominantly of a single shingle ridge with extensive dune and marsh development on the landward side (SMP2, 2009). The Blakeney harbour channel lies adjacent to the distal end of the spit and follows the same orientation as the feature itself. Like Scolt Head, Blakeney Point is undergoing both landward and westward migration. Beach profile analysis highlights this migration with the accretion at the end of the spit accompanied by erosion and steepening of the beach profile further to the east.

It has been suggested that the westerly migration of Blakeney Point is caused by the easterly transport of sand, which bypasses the major tidal deltas along the coast as episodic sandwaves. The easterly progression of these bedforms is interrupted by the spit and the sediment is then deposited at the western end of the spit (SMP2, 2009). Whilst this theory is unproven, it would help explain the abrupt change from shingle to sand at the western end of the barrier.

The shingle ridge continues westwards past the village of Salthouse and on towards Weybourne. The profile is fairly stable along this stretch of the coast although considerable beach lowering was recorded between 1995 and 2001 (Figure 6.42). This was remediated through a programme of shingle recycling up to 2006 and the erosion is not therefore visible in the profiles shown in Figure 6.42.

6.9.6 Sub Unit 7 Weybourne – Cromer

At Weybourne the character of the coast changes and the backshore marshes give way to eroding chalk and red sandstone cliffs fronted by a steeply shelving shingle beach (Figure 6.43). There is a break in the cliff line at the small fishing village of Sheringham. The beach here consists of shingle upper beach with a gently sloping sand foreshore that is protected by groynes. The cliffs rise again to the east of Sheringham. Further to the east, the beach at West Runton consists of a predominantly sandy foreshore and pebble backshore as shown in Figure 6.44. It is protected by groynes, a timber revetment and a concrete apron. Beach and nearshore bathymetric profiles are presented in Figure 6.44. These show that the cliffs, the flat inter-tidal and the nearshore region have remained remarkably stable between 1996 and 2007.

Cromer is located at the eastern boundary of the MAREA study area. Originally a small fishing port, Cromer is now a popular seaside resort with a fine sandy beach, scattered with shingle and shallow pools that are left exposed at low tide. The beach is groyned and the cliffs have been heavily engineered with both an upper and lower promenade. In the Middle Ages Cromer stood several kilometres inland and the original settlement of Shipden, along with a number of others along the former coast was destroyed by the sea and over time, Cromer became a coastal town (Weston and Weston, 1994).

6.9.7 Coastal Defences

North Norfolk District Council and the EA have responsibility for coastal defence and management along the North Norfolk coast. The current shoreline management policy is ‘Hold the Line’ for much of the frontage and No Active Intervention at Thornham, Titchwell and Stiffkey. Over half the defences along the North Norfolk Coastline are earth embankments or sea banks, with only isolated sections of hard defence such as seawalls and gabion revetments. There are groynes and various types of revetment at Sheringham, West Runton and Cromer.

6.9.8 Sediment Transport

Sources

The cliffs at Hunstanton are a source of sand-sized sediments to the coastline but much of the material released is transported into the Wash rather than northwards to feed the beaches of North Norfolk. Another source of sediment is the eroding glacial till cliffs between Weybourne and West Runton, which provide a variety of sediments including gravels, sands and muds in varying proportions. Sand typically accounts for 60% of the sediments with the gravel fraction making up a further 15% (SNSSTS, 2002). Burnham Flats and Docking Shoal lie offshore from the coast. These features represent an important sediment source to beaches in the east. Sediment appears to enter the nearshore system along Scolt Head Island.

Pathways

The predominant longshore transport pathways and sediment sources along the North Norfolk coast are not clearly defined. The East Coast processes review carried out for the Futurecoast project (Halcrow 2002) states that the net longshore transport direction is from east to west with annual littoral drift rates of 70,000 m^3 and 40,000 m^3 at Blakeney and Holme, respectively (ABPmer, 2002). This observation is supported by the westward accretion of Scolt Head Island and Blakeney Point Spit. Similarly, SNSSTS2 concluded that at the eastern end of the frontage, sediment from the eroding cliffs is transported westwards. Conversely, seabed indicators and numerical modelling study evidence presented elsewhere in SNSSTS2, and the Coastal Habitats Management Plan (CHaMP), show that the primary transport pathway is from west to east with the majority of sediment derived from Burnham Flats and Docking Shoal. Data collected by BGS indicates that offshore (below -7 m ODN), sediment is transported from west to east whilst the littoral drift along Scolt Head is from east to west.

The CHaMP concludes that the opposing transport directions can be related to the variable hydrodynamic conditions. For example, sediments are transported westwards along the beach face during high frequency, low magnitude events. This transport pathway typically involves only small volumes of sediment, and primarily serves to redistribute sediment along the coast. Conversely during storm conditions, a strong north to south pathway develops across Burnham Flats and Docking Shoal, which moves large volumes of sediment onshore. During these events, sediment is transported in an easterly direction and deposited in the tidal delta along the coast. Sediments are sorted by wave and tidal action and are then transported westwards towards the Wash, noting that the material may be deposited and re-eroded many times along the way, indicating a number of smaller transport pathways within this highly complex system (SNSSTS2, 2002).

Sinks

The primary sinks for material are the barrier islands and marsh/flat systems that exist along this coast. Both Scolt Head and Blakeney have been extending westwards and are also migrating landwards under rising sea levels. Over time, the barriers will merge with the Norfolk plateau to the south and the sink will be lost. Sandy sediments are currently lost from this sink to the west to be eventually deposited in the Wash and there is also evidence of offshore transport movement during onshore wind conditions.

6.9.9 Beach Toe and Offshore Linkages

Beach Toe

The bathymetric profiles measured by the EA have been used to estimate the position of the beach toe. The profiles are presented in Figures 6.38 to 6.44 and Table 6.4 below provides an indication of the location of the beach toe. However, it is important to recognise that the North Norfolk coast has a highly complex morphology, which results in highly variable beach and nearshore profiles. The estimates of the beach toe should therefore be applied with caution and in conjunction with an awareness of the nearshore variability at each location.

Table 6.4 Beach closure depth along North Norfolk coast

Location	Closure Depth (m ODN)	Distance from Shore (km)
Brancaster	-6	1.4
Scolt Head	-6	0.7
Wells next the Sea	-8	2.1
Salthouse	-4	0.2
West Runton	-5	0.2

The variability of the beach toe as presented in Table 6.4 reflects the complexity of the beach and nearshore region. The relatively narrow, shingle beaches at the western end of the frontage contrast sharply with the wide flat inter-tidal areas fronting the beaches further to the east. The steeply shelving beach face seawards of Scolt Head is also apparent from the profile data.

Offshore linkages

Profile 9 Scolt Head, near Brancaster, north to Docking Shoal and Area 481 (Figure 6.45)

A single geophysical profile was taken from the North Norfolk coast. This extends from Scolt Head, near Brancaster, north to Docking Shoal and Area 481. Moving seawards from the coast, the nearshore slope dips to 8 m depth in Brancaster Road, then rising gradually to Burnham Flats over 3 km offshore. Burnham Flats is a sheet of sands and gravelly sands 4 m to 6 m thick on till, thickening further towards Docking Shoal at 18 km offshore. Bedforms on the sheets display crests orientated north-northwest to south-southeast. At 22 km along the profile, bedforms become more pronounced, being 3 m to 4 m high in dredging area 107. The seabed north from the coast remains at 5 m to 6 m below CD over much of the length of the profile, only dipping into deeper water at 26.5 km offshore. Here the surface of the glacial till dips southwards to over 30 m water depth towards the Wash Channel. Overlying sandwaves with sharply defined crests characterise Area 481 at the northern limit of Docking Shoal. These display northwest to southeast trending crests and southerly orientated lee faces. At 32 km offshore the sandwaves diminish in height and merge with a smooth seabed north to the end of the profile. The extensive sand sheet of Docking Shoal and Burnham Flats isolates the dredging areas from the North Norfolk coastline.

Summary

Based on the estimation of beach closure depth, the complex nearshore bathymetry and the large distance between the dredging areas and the coast, direct interactions are unlikely. However, it will be necessary to determine whether changes to the waves and tidal currents as a result of future dredging affect either the morphology or sediment transport processes on Burnham Flats as this could indirectly affect sediment supply to the North Norfolk coast.

6.9.10 Future Coastal Evolution

During the next 100 years, the main changes to the North Norfolk coast will result from relative sea level rise. Given the general nature of the western part of the frontage with its wide inter-tidal areas and mature marshland it is unlikely that there will be any dramatic increase in flood risk in the short- to medium-term. To the west, the shingle beaches are narrower but based on the profile analysis presented above are generally stable. Where the beach is backed by dunes and marshes, the shingle ridge will be able to roll back naturally as sea levels rise.

Between Weybourne and Cromer the beach is backed by cliffs and is therefore constrained. Over time the beach is likely to become narrower and steeper, potentially exposing the cliffs to increased wave energy and erosion.

The barrier islands at Scolt Head and Blakeney Point are shown to be migrating landwards over time. This is expected to continue in the future and the spits will eventually merge with the coast resulting in dramatic changes to longshore sediment transport processes. This is not expected to occur within this short- to medium-term.

7. Other Sea Uses

In addition to characterising the coastal and offshore environments within the MAREA study area, it is also necessary to consider human interventions such as conservation and other human activities that have the potential to affect or be affected by dredging. The following sections provide an overview of the various conservation designations in the study area and identify other anthropogenic activities that may produce ‘in-combination’ effects that require further consideration in the subsequent impact assessment.

7.1 Conservation Designations

The UK supports a wide variety of species and habitats, ranging from cold water coral reefs to saltmarshes and mountain summits. A key policy tool for conserving them all is the designation and management of protected sites; areas of land, inland water and the sea that have special legal protection to conserve important habitats and species. There are a number of different types of conservation and protected areas, each of which addresses the different priorities of the three key pieces of UK conservation legislation, namely:

- The European Habitats Directive (1992);
- The European Wild Birds Directive (1979); and
- The Wildlife and Countryside Act (1981).

An overview of the different designations that apply to marine and coastal environments is provided in Table 7.1 below.

Table 7.1 UK Marine and Coastal Conservation Designations

Designation	Abbreviation	Legislation	Scale
Special Area of Conservation	SAC	European Habitats Directive (92/43/EEC)	European
Special Protection Area	SPA	European Wild Birds Directive 2009/147/EC)	European
Ramsar Site	Ramsar	Convention on Wetlands of International Importance	International
Sites of Special Scientific Interest	SSSI	Wildlife and Countryside Act (1981)	National
National Nature Reserve	NNR	Wildlife and Countryside Act (1981)	National
Marine Nature Reserve	MNR	Wildlife and Countryside Act (1981)	National
Marine Conservation Zone	MCZ	The Marine and Coastal Access Act (2009)	National
Recommended Reference Area	rRA	The Marine and Coastal Access Act (2009)	National
Marine Protected Area	MPA	European Marine Strategy Framework Directive (2008)	European

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 designations and National designations are shown in Figure 7.1. These include five SACs, one Candidate SAC, five SPAs and four Ramsar sites along with numerous coastal SSSIs, rMCZs and rRAs. Those sites of most relevance to the present study are described in more detail below and the remainder are summarised in Table 7.2.

Humber Estuary SAC and SPA

The designated features of the Humber Estuary SAC are estuaries, mud and sand flats not covered by seawater at low tide. The majority of the site comprises inter-tidal mudflats and sandflats, saltmarsh, lagoons and the various river channels These features support a number of internationally important populations of breeding and overwintering birds, for which the SPA designation is given. The boundaries of the Humber Estuary also coincide with the boundaries of the Humber Estuary Ramsar site.

The Wash and North Norfolk Coast SAC and SPA

The Wash and North Norfolk Coast SAC and SPA comprise over 100,000 ha of tidal estuaries, marine habitats and saltmarsh. The SAC has been designated in order to provide protection for the following primary features:

- Sandbanks, which are slightly covered by seawater at all times;
- Mudflats and sandflats not covered by seawater at low tide
- Large, shallow inlets and bays;
- Reefs;
- Salicornia and other annuals colonising mud and sand;
- Atlantic salt meadows;
- Mediterranean and thermo – Atlantic halophilous scubs;
- Common seal.

The Wash and North Norfolk's diverse coastal habitats support a number of important breeding and overwintering bird populations, for which the SPA designation is given. The SPA boundaries also coincide with those of the Ramsar sites.

Inner Dowsing, Race Bank and North Ride Candidate SAC

The Inner Dowsing, Race Bank and North Ridge site is located off the south Lincolnshire coast in the vicinity of Skegness, and extends eastwards and northwards from Burnham Flats on the North Norfolk coast. The site 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. Water depths are generally shallow and mostly less than 30 m below chart datum. The area encompasses a wide range of sandbank types (banks bordering channels, linear relict banks, sinusoidal banks with distinctive 'comb-like' subsidiary banks) and biogenic reef of the worm Sabellaria spinulosa. The group of banks within the Wash Approaches are generally between 15 km to 20 km long and 1.5 km to 3 km wide. They arise from the basal layers by 7m to 12m with crest heights generally less than 5 m BCD. The sedimentary component of the banks is fine to medium sands (Cooper *et al*, 2008).

Abundant *Sabellaria spinulosa* agglomerations have consistently been recorded within the boundary of the cSAC. Survey data indicate that reef structures are concentrated in certain areas of the site, with a patchy distribution of crust-forming aggregations across the site. The main areas of *S. spinulosa* reef are found along the Lincolnshire coast south of Skegness at Lynn Knock and Skegness Middle Ground (south-east part of the site); just north of Docking Shoal bank; and associated with the southern edge of Silver Pit (in the northern area of the site) (JNCC, undated).

Whilst the effects of dredging on designated features will be considered elsewhere in the MAREA, the information will be derived from the physical processes assessment. The present study will therefore make reference to the various site described above when drawing conclusions as to the significance of any changes to the hydrodynamic or sedimentary regime.

Table 7.2 Designated Conservation Sites within the Humber MAREA

Designation	Site Name
SAC	Flamborough Head
	Humber Estuary
	Wash and North Norfolk
	Saltfleetby – Thleddlethorpe Dunes and Gibraltar Point
cSAC	Inner Dowsing, Race Bank and North Ridge
	North Norfolk Sandbanks and Saturn Reef (on edge of study area)
SPA	Humber Estuary
	Gibraltar Point
	The Wash
	North Norfolk
Ramsar	Humber Estuary
	Wash and North Norfolk
	Gibraltar Point
OSPAR MPAs	Flamborough Head
	Humber Estuary
	Wash and North Norfolk
SSSI	Withow Gap – Skipsea (Holderness)
	Dimlington Cliff (Holderness)
	Humber Estuary
	Sea Bank to Clay Pits (Lincolnshire)
	Chapel Point to Walla Bank (Lincolnshire)
	Gibraltar Point
	The Wash
	North Nofolk Coast
Recommended Reference Areas (rRA)	RA1: North Norfolk Mussel Beds
	RA2a&b: Seahorse Lagoon and Arnold's Marsh
	RA3: Glaven Reed Bed
	RA4: Blakeney Marsh
	RA5: Blakeney Sea Grass Beds
	RA6: Dog's Head Sandbank
	RA7: Seahenge Peat and Clay
	RA8: Wash Approach

7.2 Potential In-Combination Activities

Many anthropogenic activities are carried out within the Humber MAREA study area in addition to aggregate dredging. Some of these also affect the physical environment either temporarily or permanently and could either be affected by or interact with aggregate dredging to produce an overall larger change to the physical processes. The various 'other seabed users' within the Humber Region have been identified using information on Marine Spatial Planning. These are presented in Figure 7.2 and are summarised below.

Capital and Maintenance dredging is carried out for navigational purposes and for port and harbour developments. By definition, this practice alters the water depth and seabed topography, which may in turn affect the propagation of waves and tidal currents towards the coast. Within the study area maintenance dredging is only carried out within the Humber Estuary and in the small harbours along the North Norfolk coast. Consequently there is no possibility that the effects of offshore aggregate dredging could combine with those resulting from maintenance dredging to produce an overall greater impact on the coast and this will not therefore be considered within the impact assessment.

Sediments dredged from harbours and navigation channels are sometimes disposed at sea. This activity is very tightly controlled and disposal is only permitted in certain locations. Sediments dredged from the Humber are generally disposed within the confines of the estuary but there are a number of other disposal grounds in the study area as shown on Figure 7.2. The potential effects of disposal include a temporary increase in local suspended sediment concentrations and sediment deposition. This could potentially interact with the turbid plumes produced during aggregate dredging. However, based on Figure 7.2, this is not likely to occur and therefore offshore disposal does not require further consideration within the impact assessment.

Certain types of commercial fishing, such as beam trawling, disturbs seabed sediments, locally increasing turbidity, which could potentially combine with the turbid plumes produced during aggregate dredging to create an overall larger impact. Commercial fishing grounds are presented on Figure 7.2 and this shows that although there is overlap between commercial fishing and aggregate extraction areas, there is unlikely to be any measurable 'in-combination' effects from the two activities.

The construction of coastal defences, including beach nourishment often leads to changes in nearshore waves, currents and sediment transport patterns. Further modification to the waves as a result of aggregate dredging could exacerbate the problem. However, as Coastal Impact Studies are carried out to ensure that dredging does not induce unacceptable wave height changes, this is unlikely to be an issue. Therefore it is not necessary to assess the combined effect of aggregate dredging and coastal defence schemes.

Figure 7.2 shows there are 11 offshore windfarms in varying stages of development, some of which are located very close to existing aggregate licence and application areas. Wind turbines have the potential to permanently alter the surrounding waves and currents as well as producing temporary increases in suspended sediment concentrations during the construction phase. Although all proposed offshore windfarm developments are subject to detailed physical processes impact assessments, consideration of potential 'in-combination' effects are typically very high level. As there is now a lot of information on the effects of both windfarms and aggregate dredging within the public domain, it will be possible to develop a more informed judgement on the potential interaction between the two activities in the Humber Region. This will be undertaken as part of the impact assessment.

Finally, the seabed in the study area is crossed by numerous cables and pipelines. As more offshore windfarms are constructed, the number of cables will increase as the export cables are brought onshore. Cables are typically buried and consequently only affect physical processes during installation. Although pipelines are surface laid, they do not have a major effect on tidal currents or sediment transport and therefore 'in-combination' effects between this infrastructure and aggregate dredging is unlikely. Of greater importance is the potential effect of aggregate dredging on cables and pipelines that pass close to or lie within a licence area. However, this issue would be addressed at EIA stage and will not be discussed further within the present study.

8. Concluding Remarks

The information presented in this report provides a high level overview of the geological, hydrodynamic and sedimentary processes responsible for the formation, maintenance and evolution of the Humber Region. The report also provides a detailed description of the coastal environment and key interest features of relevance to the present study. The overall aim of this exercise was to identify the receptors and impact pathways to be considered in the cumulative assessment of dredging effects. The mechanisms by which aggregate dredging can change the hydrodynamic and sedimentary regime are:

- Direct removal of the seabed;
- Changes to tidal current speeds and flow patterns;
- Changes to inshore wave height and direction; and
- Indirect changes to sediment transport rates and pathways.

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 12 km from the nearest landfall. Based on the available evidence there are no direct interactions between these areas and the coast, but it will still be necessary to determine whether changes to the hydrodynamic or sedimentary regime will propagate into the nearshore region. With this in mind, the receptors and impact pathways that will be considered in the cumulative impact assessment are presented in Table 8.1.

Table 8.1 Physical processes receptors and impact pathways

Receptor	Impact Pathway
Holderness Coast	Changes to north easterly waves
Spurn Point	Changes to easterly waves
The Binks	Changes to northeast and easterly waves
	Interruptions to the southerly 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 Topographic Features	Changes in sediment transport resulting from changes in changes to the hydrodynamic regime.

9. Bibliography

AA, 1984. An Illustrated Guide to Britain's Coast

ABP R&C, 1996. Southern North Sea Sediment transport Study: Literature Review & Conceptual Sediment Transport Model. R.546.

ABP, 2001. Futurecoast – East Coast Processes Review: Flamborough Head to North Foreland. Report No 919 for the Halcrow Group.

ABPmer, Met Office and POL, 2008. Atlas of UK Marine Renewable Energy Resources: Atlas Pages. A Strategic Environmental Assessment Report, March 2008. Produced for BERR. Report and associated GIS layers available at: http://www.renewables-atlas.info/

ABPmer, 2008. Humber Gateway Offshore Wind Farm: Coastal Processes Baseline Assessment. Commissioned by Environmental Resources Management. R.1332.

ABPmer, 2008. Conceptual Understanding of Spurn. ABP Marine Environmental Research Ltd, Report No. R.1483

ABPmer, 2008. Atlas of UK Marine Renewable Energy Resources: Technical Report. Commissioned by the Department for Business, Enterprise & Regulatory Reform. R.1432.

ABPmer, 2010. Humber CCS Pipeline Project – Volume 1: Main Report. R.1598.

Balson, P.A, Tragheim, D.G. and Newsham, R., 1998. Determination and prediction of sediment yields from recession of the Holderness coast, Eastern England. Proceedings of the 33rd MAFF Conference of River and Coastal Engineers, July 1998.

Balson, P., 1999. The Holocene coastal evolution of eastern England: evidence from the offshore Southern North Sea. Proceedings of 4th International Symposium Engineering Science of Coastal Sediments, pp. 1284-1294.

Balson, P.A, and Philpott, S.L, 2004. Sediment sources, sinks and pathways at the mouth of the Humber Estuary. British Geological Survey Report CR/04/159.

British Geological Survey, MES, Vista, University of Birmingham, Guardline Environmental 2011. Humber Regional Environmental Characterisation. Report prepared for the MALSF and English Heritage. BGS Open Report, OR/10/54

Blott, S. and Pye, K. 2004. Morphological and sedimentological changes on an artificially nourished beach, Lincolnshire, UK. J Coastal Research 20, 214-233

Bowden, K.F., 1983. Physical oceanography of coastal waters. Ellis Horwood Limited, Chichester. 302pp.

Cooper, W.S., Townend, I.H., and Balson, P.S., 2008. A Synthesis of Current Knowledge on the Genesis of the Great Yarmouth and Norfolk Bank Systems. Marine Estate Research Report to the Crown Estate: OSR 06 06.

Cox, 2002. Report on Mineralogical Tracers. UEA/CEFAS Report.

Defra, 2006. Flood and coastal defence appraisal guidance FCDPAG3 economic appraisal. Supplementary note to operating authorities - climate change impacts. October 2006

Donovan DT. 1973. The Geology and Origin of the Silver Pit and Other Closed Basins in the North Sea. Proceedings of the Yorkshire Geological Society 39(13): 267-293.

Dugdale, R. E., & Vere, A., 1993. Saving Lincolnshire's beaches. East Midland Geographer 16 (1), pp. 31-32.

Eisma and Kalf, 1979. Distribution and particle size of suspended matter in the Southern Bight of the North Sea and the eastern Channel. Netherlands Journal of Sea Research, Vol. 13, 298-324.

Environment Agency 2004a. Lincshore 2005 to 2010 PAR Volume 1, Strategy For Approval. Report to Environment Agency, Anglian Region, Peterborough. Halcrow, Swindon.

Environment Agency., 2007. Technical Note for the East Midlands Management Plan; Tidal Flood Risk Issues along the Lincolnshire Coast.

Environment Agency, 2007. Anglian Coastal Monitoring Programme – North Norfolk.

Environment Agency, 2008. Anglian Coastal Monitoring Programme – Lincolnshire

Environment Agency, 2008. The Humber Flood Risk Management Strategy, March 2008.

Environment Agency, 2009. North Norfolk Shoreline Management Plan(2)

Eurosion, undated. Holderness Case Study. Eurosion Project

Evans, C.D.R., Crosby, A., Wingfield, R.T.R., James, J.W.C., Slater, M.P. and Newsham, R. 1998. Inshore seabed characterisation of selected sectors of the English coast. British Geological Survey Technical Report WB 98/45

Flather, R.A. and Davies, A.M., 1978. On the specification of meteorological forcing in numerical modelling for North Sea storm surge prediction, with application to the 2 to 4 January 1976. Deutsche Hydrographische Zeitscrift, Ergangunsheft, Reihe, Nr15.

Halcrow, 2002. Futurecoast [CD-ROM] produced for DEFRA, with BGS, ABP MER Ltd., Queen's University of Belfast and University of Plymouth.

Halcrow, 2004. Lincshore Sea Defence Strategy. Mablethorpe to Skegness.

Harrison, D J. 1992. The marine sand and gravel resources off the Humber. Offshore Geology Series, British Geological Survey Technical Report WB/92/1.

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.

Kenyon NH. 1970. The origin of some transverse sand patches in the Celtic sea. Geological Magazine 107: 389-394

Kenyon, N.H., and Cooper, W.S., 2005. Sand banks, sand transport and offshore wind farms.

Komar, P.D., 1999. Beach Processes and Sedimentation (Second Edition). Prentice Hall, 544pp

Lowe et al, 2009. UK Climate Projections Science Report: Marine and Coastal Projections. June 2009.

McCave, I.N., 1987. Fine sediment sources and sinks around the East Anglian Coast (UK). Journal of the Geological Society of London. 144, 149-152.

Pethick, J. S., and Leggett, D., 1993. The geomorphology of the Anglian coast. In R. Hillen and H J Verhagen (eds.) Coastlines of the Southern North Sea. American Society of Civil Engineers, 52-64. .

Posford Duvivier, 1991. Mablethorpe to Skegness Sea Defences Strategy Study. Report to National Rivers Authority, Anglian Region, Peterborough. Posford Duvivier, Peterborough, 164 pp.

Pratt, I. 1995: The storm surge of 21February, 1993. Weather 50(2): p42-48.

Pringle A W 1985. Holderness coast erosion and the significance of ords. Earth Surface Processes and Landforms, 10, 107-124

Pugh, D.T. 1987: Tides, surges and mean sea level: a handbook for engineers and scientists. J. Wiley & Sons, 472pp.

Scott Wilson, 2009. Flamborough Head to Gibraltar Point Shoreline Management Plan (2).

Southern North Sea Sediment Transport Study (SNSSTS), 2002. Phase 2, Sediment Transport Report. Appendix 11 Report on Southern North Sea Longshore sediment transport. Report EX4526, Report for Great Yarmouth Borough Council. HR Wallingford.

Townend, I. and Pethick, J. 2002. Estuarine flooding and managed retreat. Phil Trans Roy Soc Lond A. 360, pp 1477-1495

UKCP, 2009. UK Climate Projections – Sea level Rise. http://www.ukcip.org.uk/ukcp09/

Valentin, H. 1954. Der landverlust in Holderness, Ostengland von 1852-1952. Erde 6: 296-315

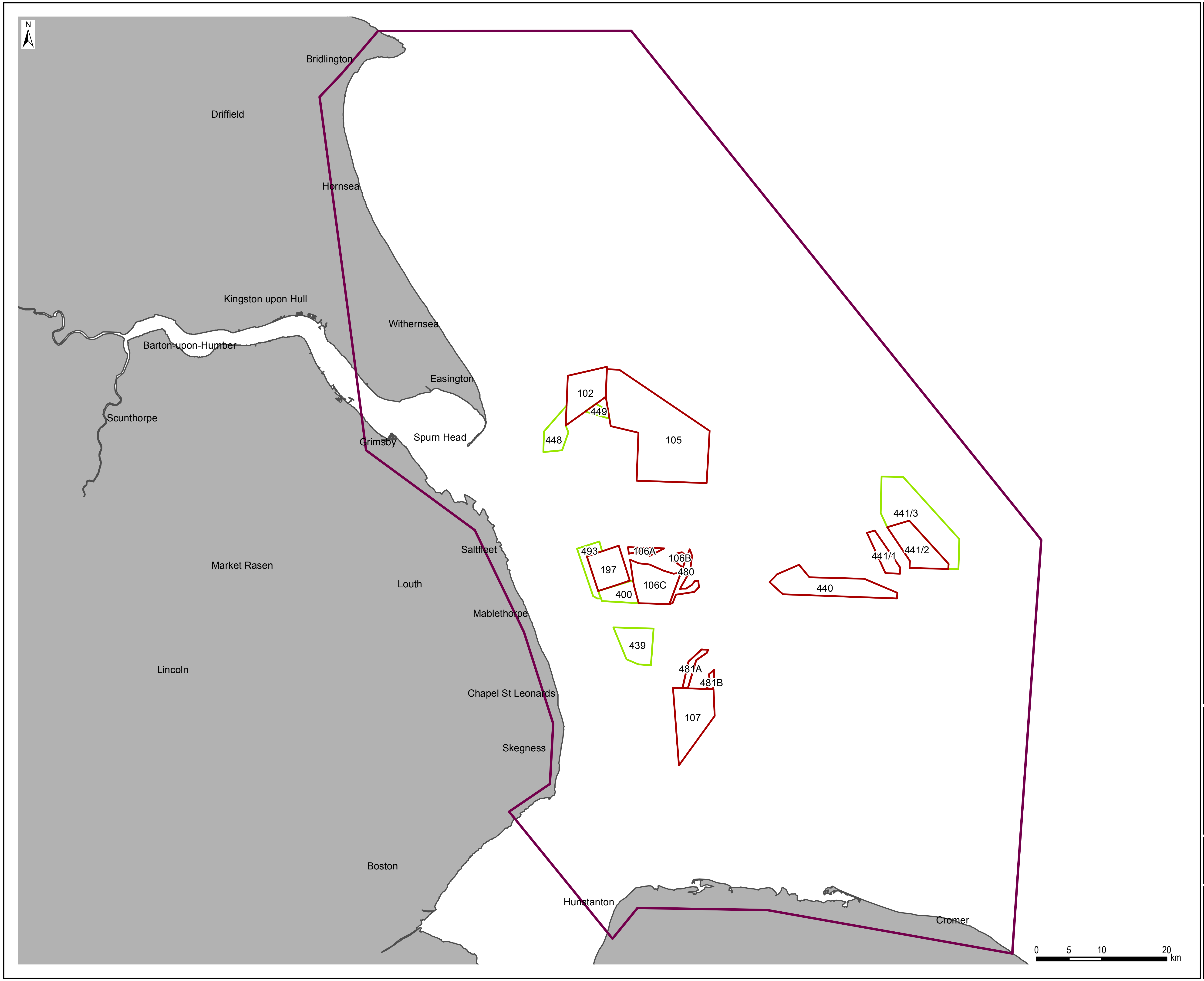
Vincent, C. (1979) Longshore sand transport rates: a simple model for the East Anglian coast. *Coastal Engineering* 3, 113-136.

Weston and Weston, 1994. Claimed by the Sea. Wood Green Publications. 88pp

Wingfield, R. and Evans, C., 1998. The significance of the shoreface ramp for coastal development: Holderness, eastern England, UK. Proceedings of Littoral '98.

Zwiers, M., Dales, D. & Lunt, H., 1996. Mablethorpe to Skegness beach nourishment: Is it working? Partnership in Coastal Zone Management (Eds.) J. Taussik & J. Mitchell. Samara Publishing, Cardigan. Pp. 631-637.

Figures

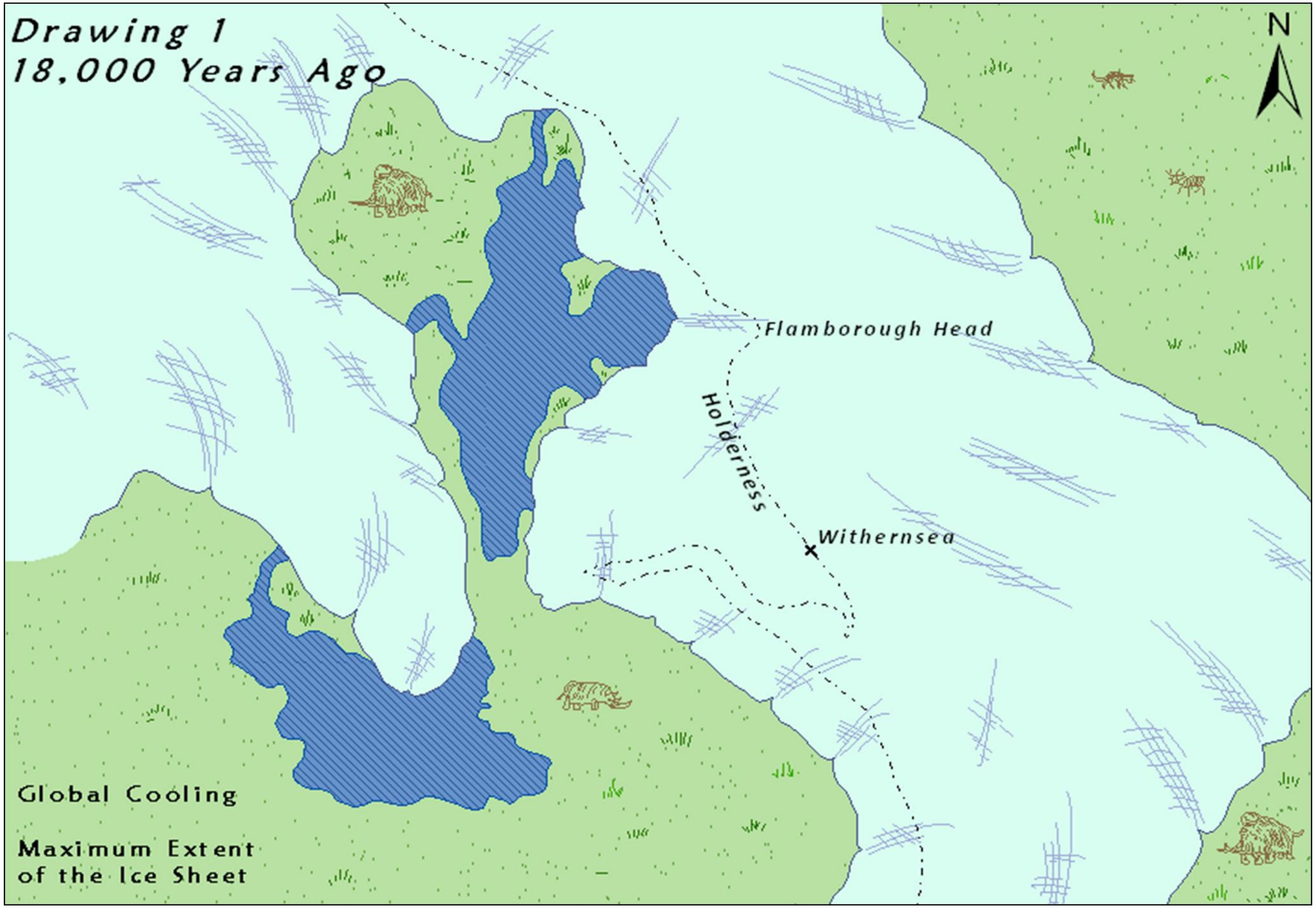


Date	By	Size	Version
Aug 11	NJG	A3	2
Projection	WGS84 UTM31		
Scale	1:540,000		
QA	MCE		
3965 - fig_1.1_StudyArea.mxd			
Produced by ABPmer Ltd			

ABP mer marine environmental research

Humber MAREA Study Area and Licence Areas

Figure 1.1



Date	By	Size	Version
Aug 2011	MCE	A4	2
QA		NJG	

3965–Fig 2.1 Geological Processes 18kBP.pdf

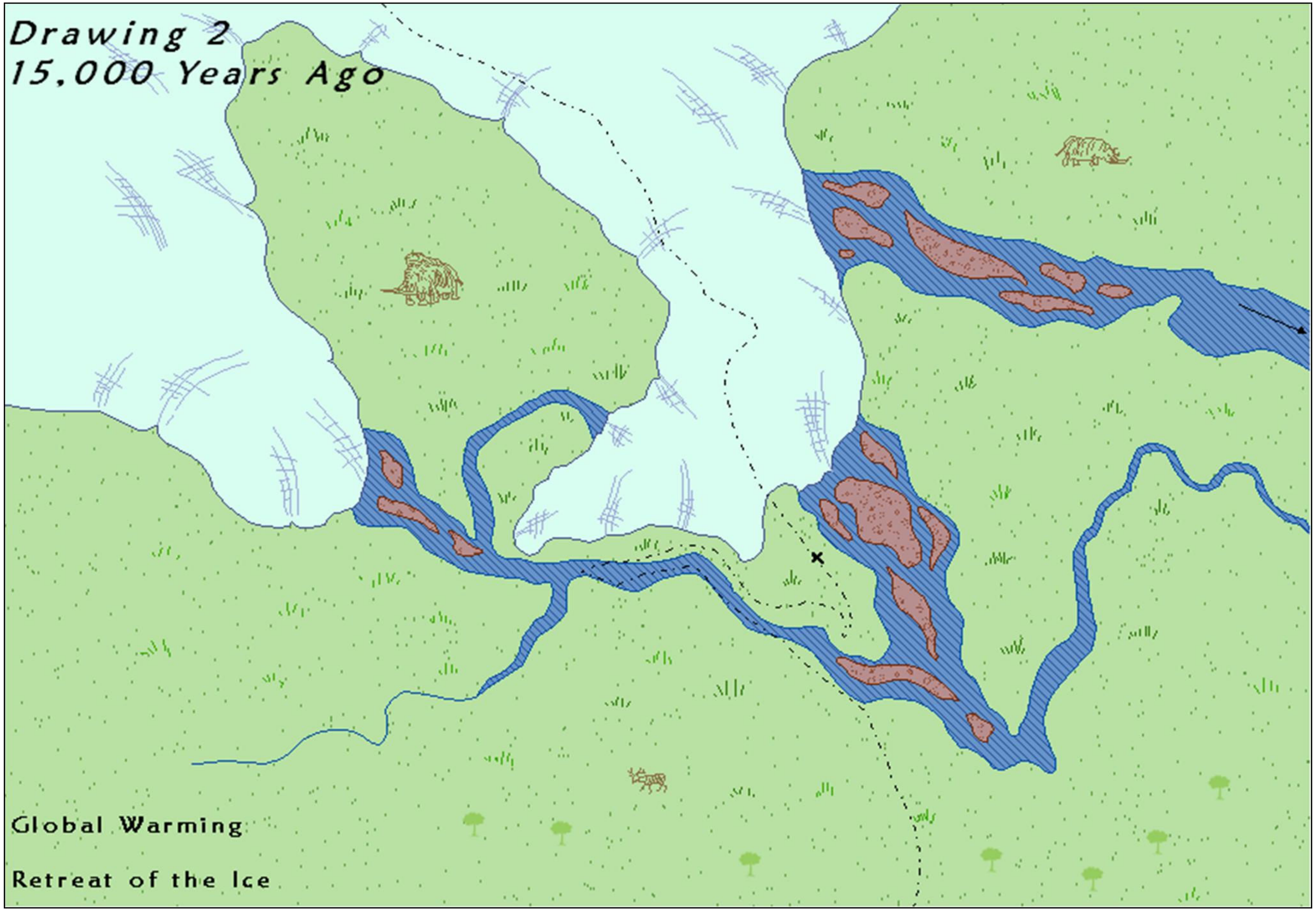
Produced by ABPmer Ltd

Data Sources: Courtesy of Tarmac Marine Dredging Ltd

marine environmental research

Geological Processes - 18,000BP

Figure 2.1



Date	By	Size	Version
Aug 2011	MCE	A4	2
QA		NJG	

3965–Fig 2.2 Geological Processes 15kBP.pdf

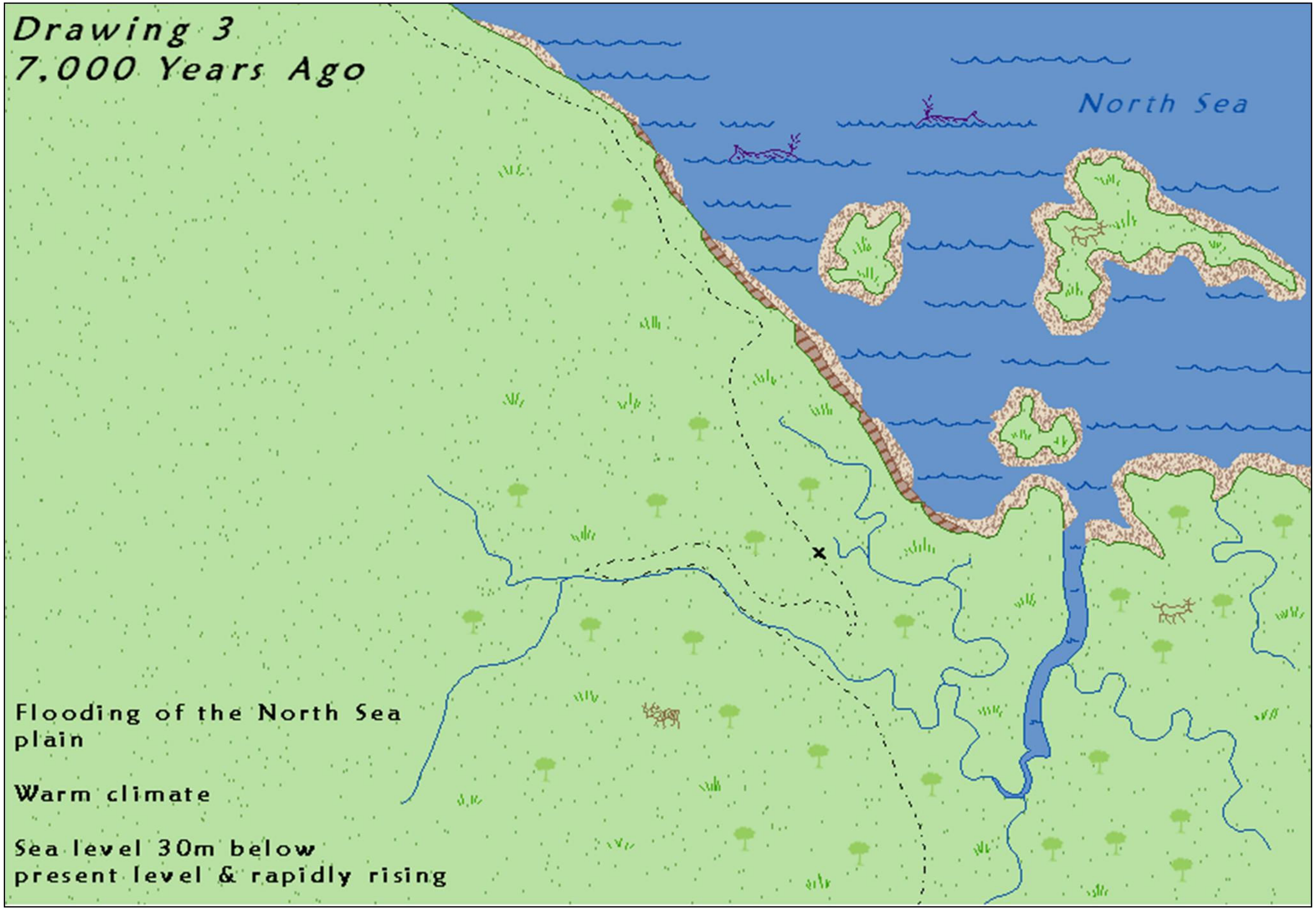
Produced by ABPmer Ltd

Data Sources: Courtesy of Tarmac Marine Dredging Ltd

ABP mer marine environmental research

Geological Processes - 15,000BP

Figure 2.2



Date	By	Size	Version
Aug 2011	MCE	A4	2
QA		NJG	

3965–Fig 2.3 Geological Processes 7kBP.pdf

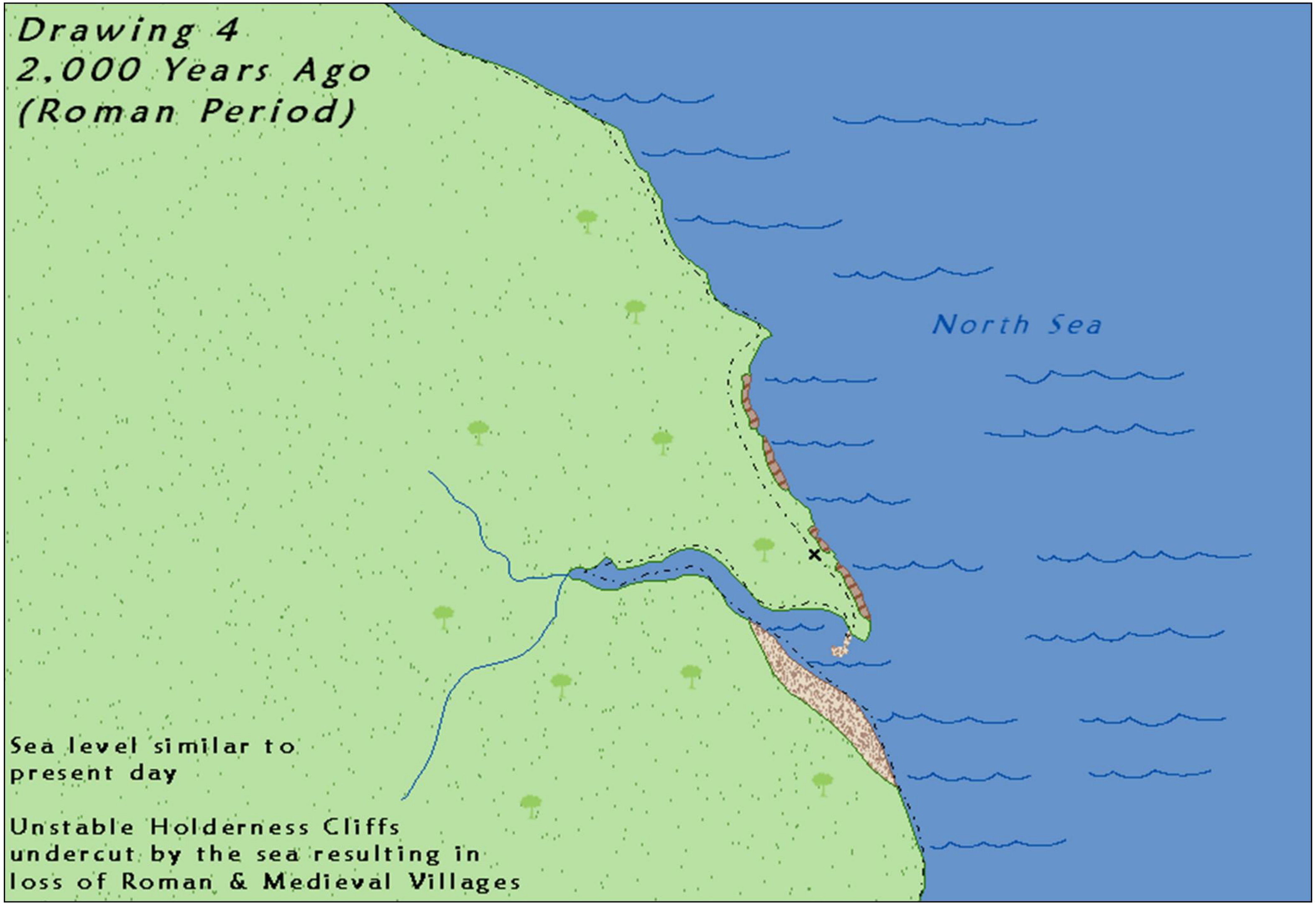
Produced by ABPmer Ltd

Data Sources: Courtesy of Tarmac Marine Dredging Ltd

ABP mer
marine environmental research

Geological Processes - 7,000BP

Figure 2.3



Date	By	Size	Version
Aug 2011	MCE	A4	2
QA		NJG	

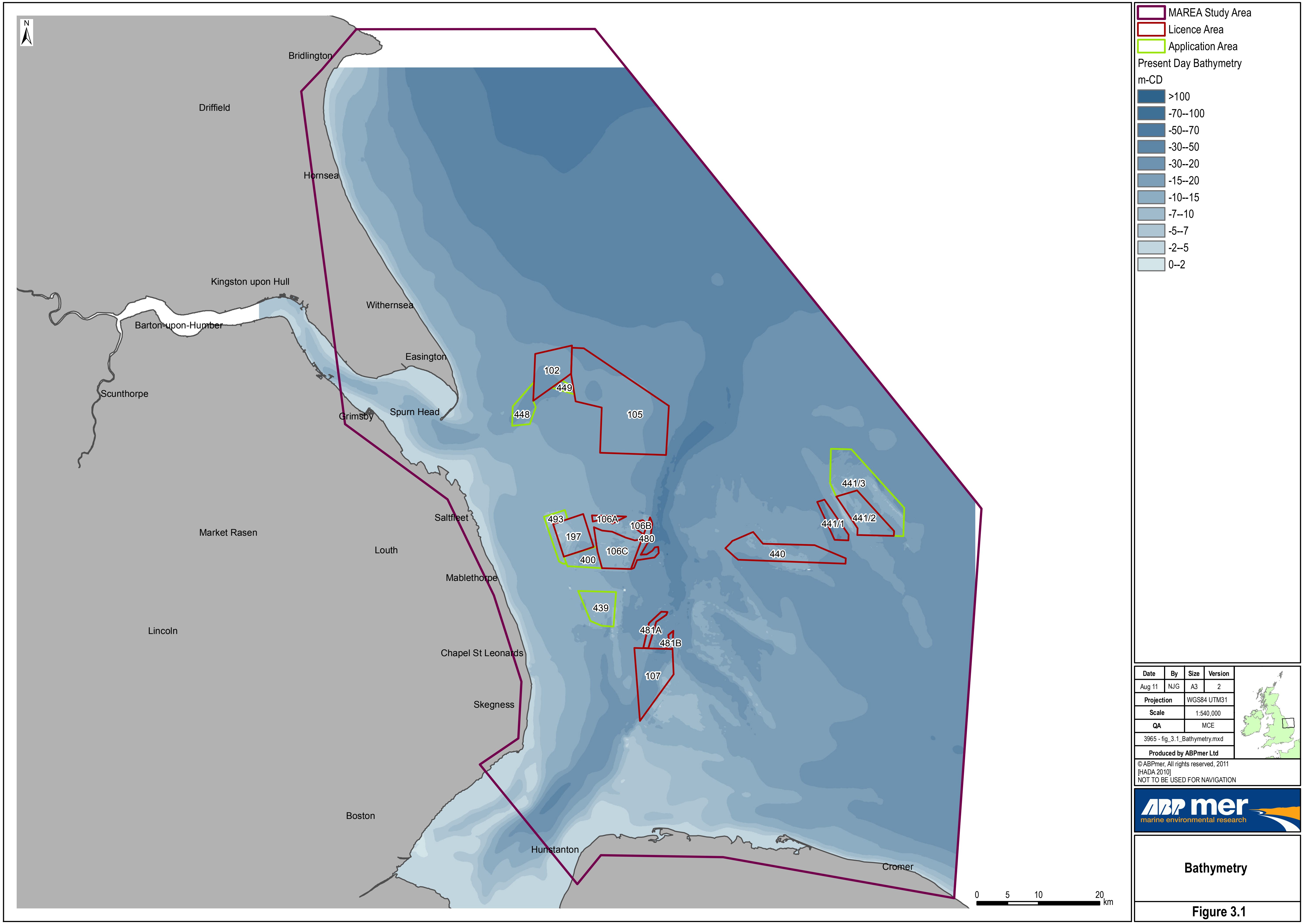
3965–Fig 2.4 Geological Processes 2kBP.pdf

Produced by ABPmer Ltd

Data Sources: Courtesy of Tarmac Marine Dredging Ltd

Geological Processes - 2,000BP

Figure 2.4

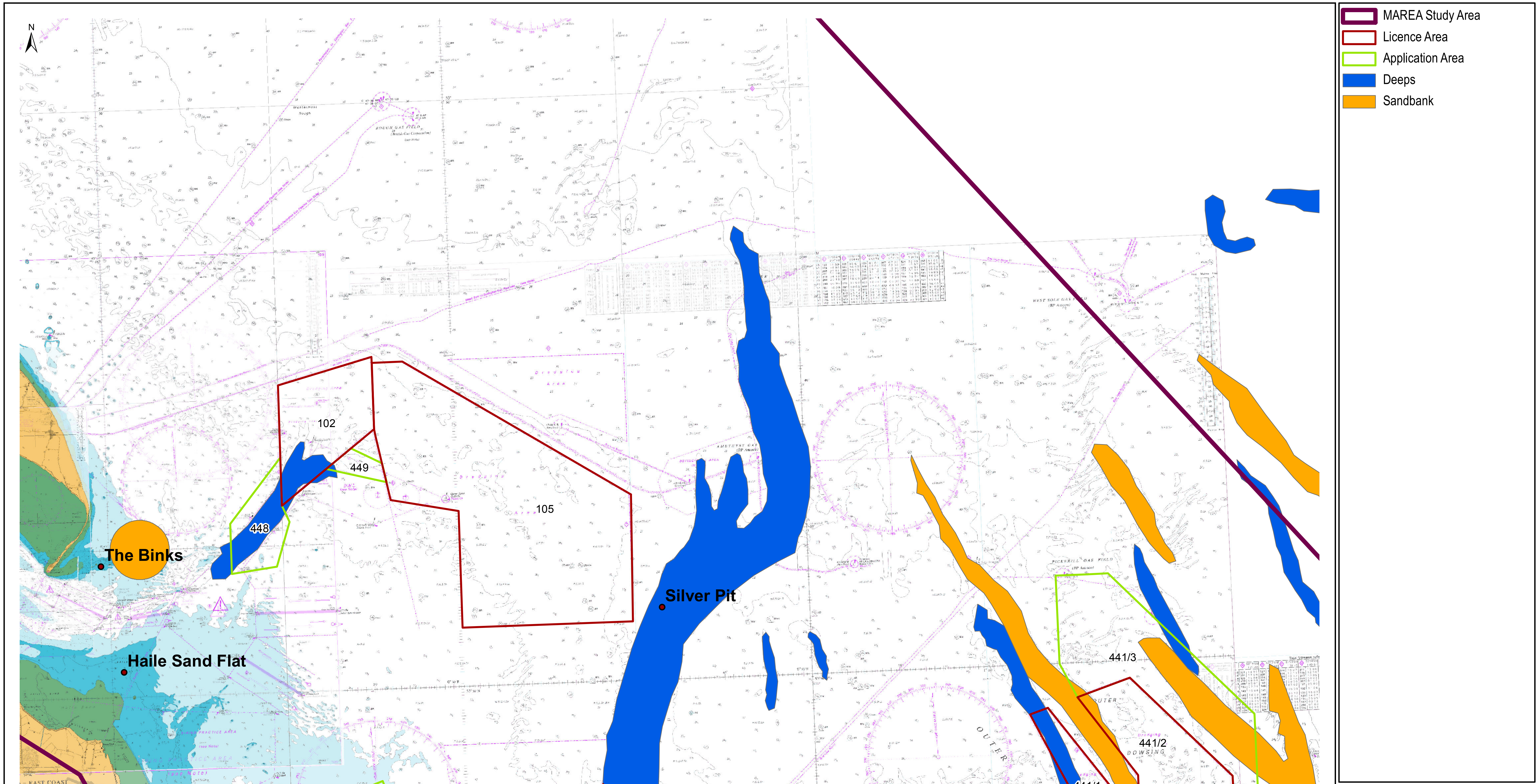


Date	By	Size	Version
Aug 11	NJG	A3	2
Projection		WGS84 UTM31	
Scale		1:540,000	
QA		MCE	
3965 - fig_3.1_Bathymetry.mxd			
Produced by ABPmer Ltd			

ABP mer
marine environmental research

Bathymetry

Figure 3.1



Date	By	Size	Version
July 11	NJG	A3	1
Projection		WGS84 UTM31	
Scale		1:247,374	
QA		NMW	

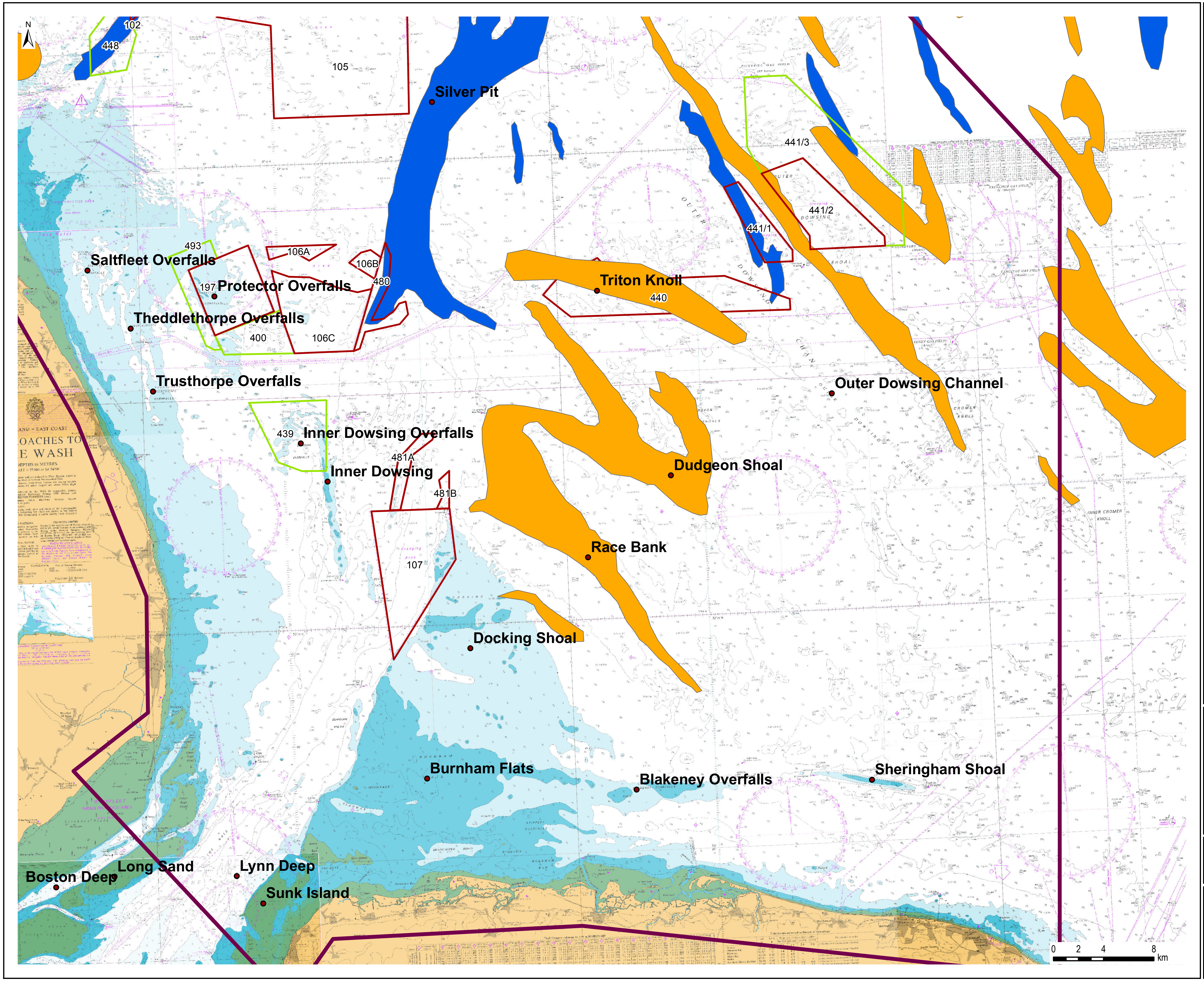
3965 - figure_AllSandbanksa.mxd

Produced by ABPmer Ltd

ABP mer
marine environmental research

Humber MAREA Sandbanks

Figure 3.2a



MAREA Study Area
Licence Area
Application Area
Deeps
Sandbank

Date	By	Size	Version
July 11	NJG	A3	1
Projection		WGS84 UTM31	
Scale		1:280,154	
QA		NMW	

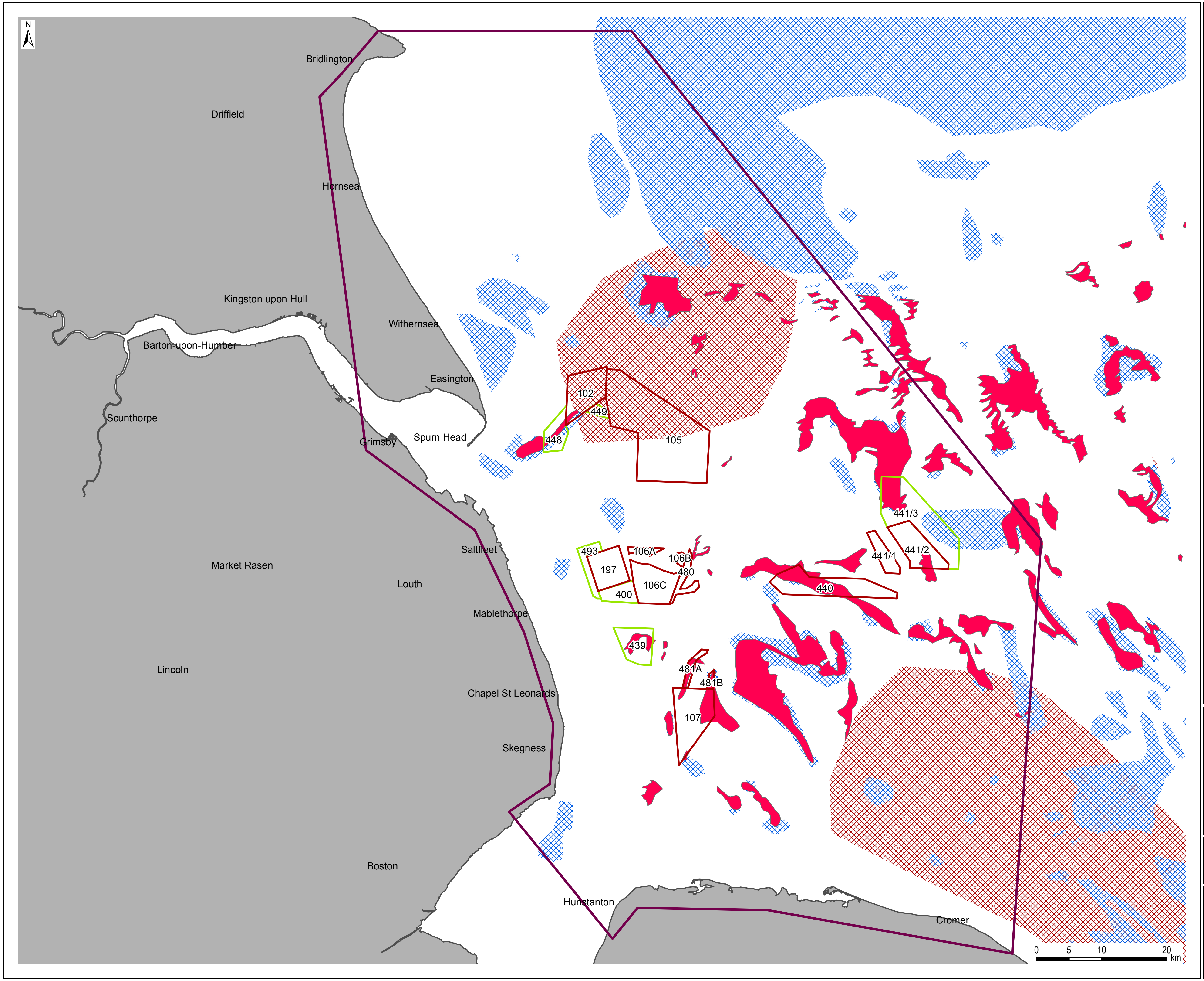
3965 - figure_AllSandbanksb.mxd

Produced by ABPmer Ltd

ABP mer
marine environmental research

Humber MAREA
Sandbanks

Figure 3.2b



MAREA Study Area
Licence Area
Application Area
Sandwaves
Sand Wave Field
Sand Ribbon Field

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

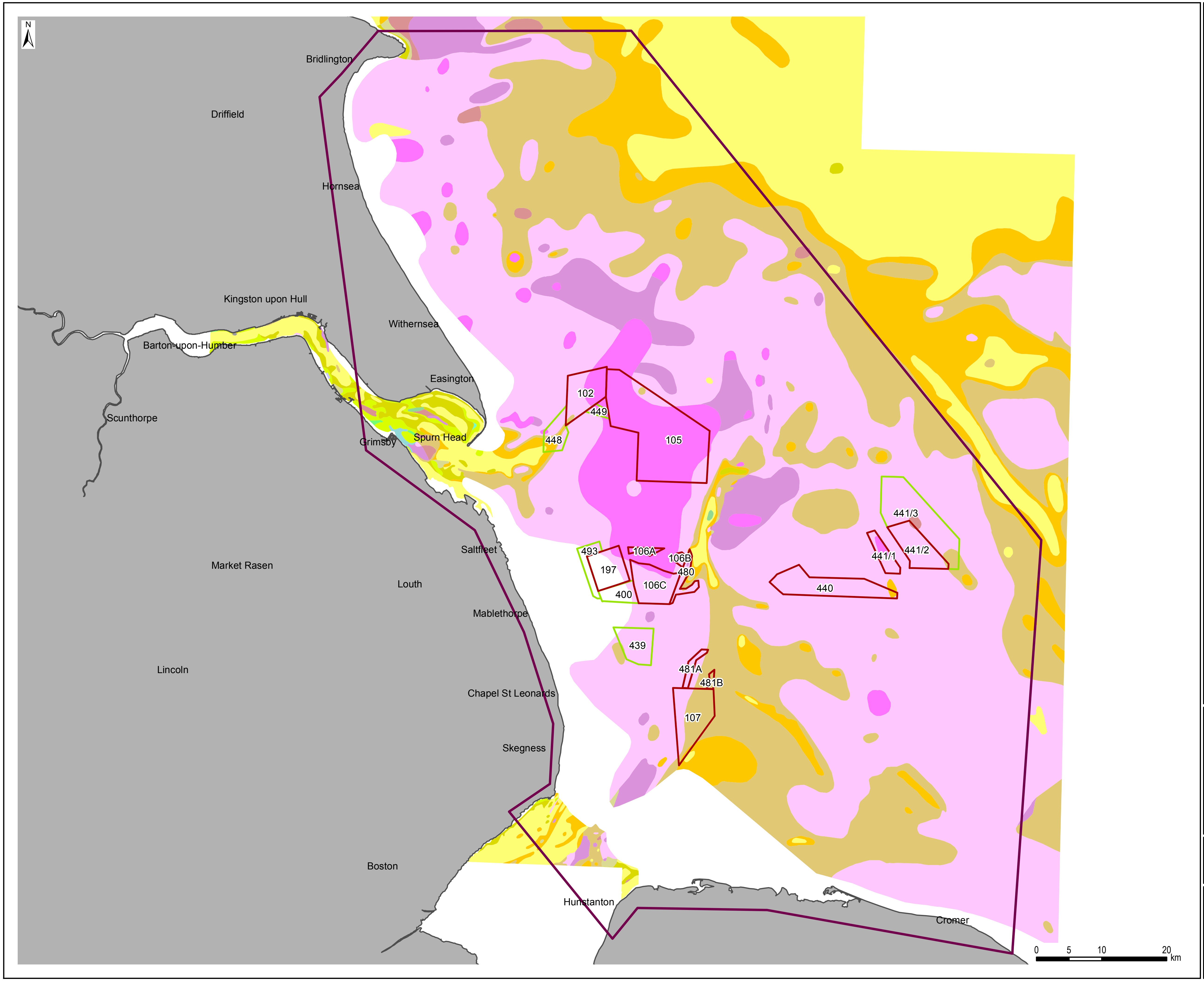
3965 - Fig_3.3 Mobile Bedforms.mxd

Produced by ABPmer Ltd

ABP mer
marine environmental research

Mobile Bedforms

Figure 3.3



MAREA Study Area
Licence Area
Application Area
Mud
Sand
Gravel
Rock
Sandy Mud
Slightly Gravelly Mud
Slightly Gravelly Sandy Mud
Gravelly Mud
Muddy Sand
Slightly Gravelly Sand
Slightly Gravelly Muddy Sand
Gravelly Muddy Sand
Gravelly Sand
Muddy Gravel
Muddy Sandy Gravel
Sandy Gravel

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

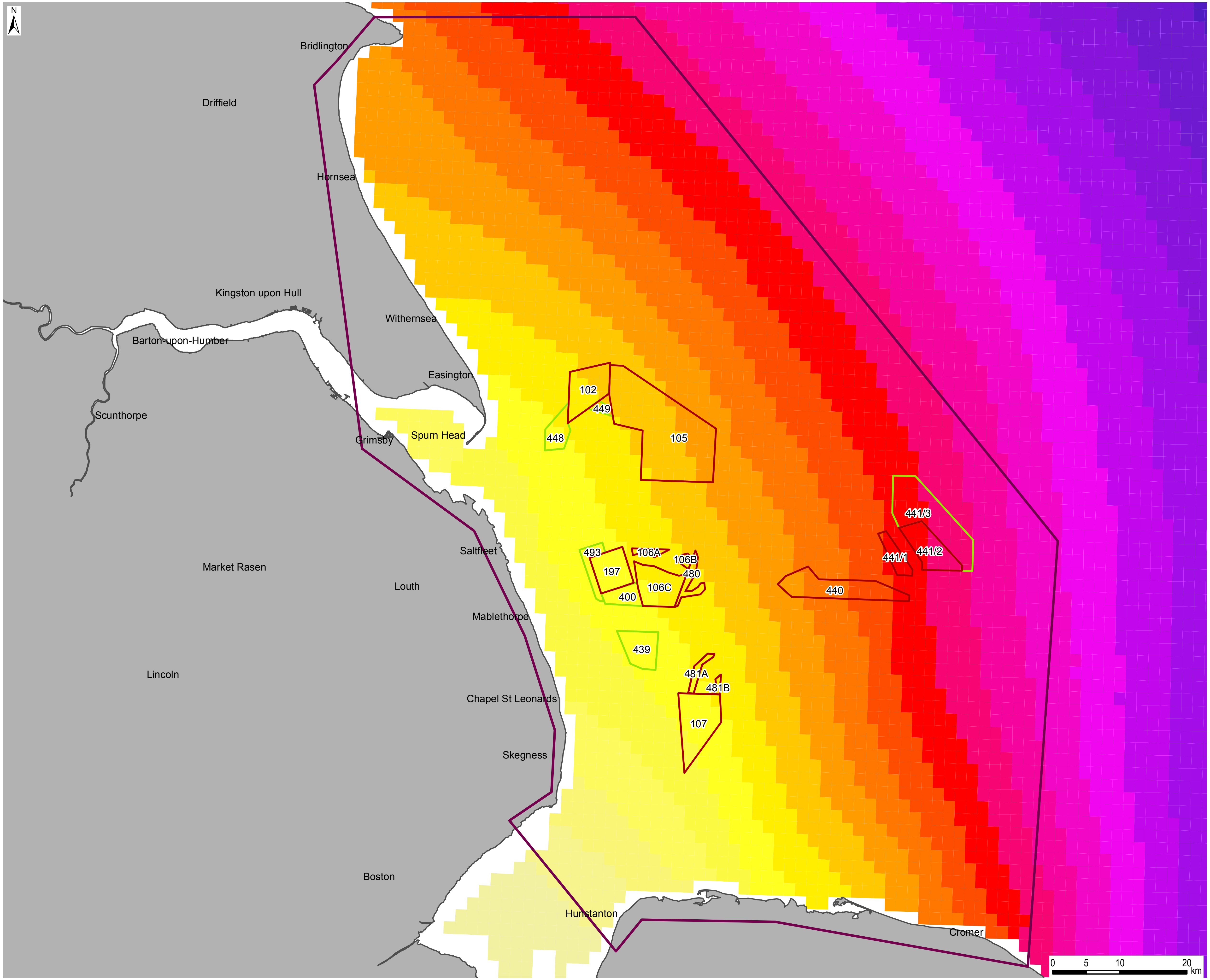
3965 - Figure_3.4 Surficial seds.mxd

Produced by ABPmer Ltd

ABP mer
marine environmental research

Surficial Seabed Sediments

Figure 3.4



MAREA Study Area
Licence Area
Application Area

Mean Spring Tidal Range (m)

- 6.30 - 6.50
- 6.10 - 6.30
- 5.90 - 6.10
- 5.70 - 5.90
- 5.50 - 5.70
- 5.30 - 5.50
- 5.10 - 5.30
- 4.90 - 5.10
- 4.70 - 4.90
- 4.50 - 4.70
- 4.30 - 4.50
- 4.10 - 4.30
- 3.90 - 4.10
- 3.70 - 3.90
- 3.50 - 3.70
- 3.30- 3.50
- 3.10 - 3.30
- 2.90 - 3.10
- 2.70 - 2.90
- 2.50 - 2.70
- 2.30- 2.50
- 2.10 - 2.30
- 1.90 - 2.10

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

3965 - Fig_4.1_Spring_TidalR.mxd

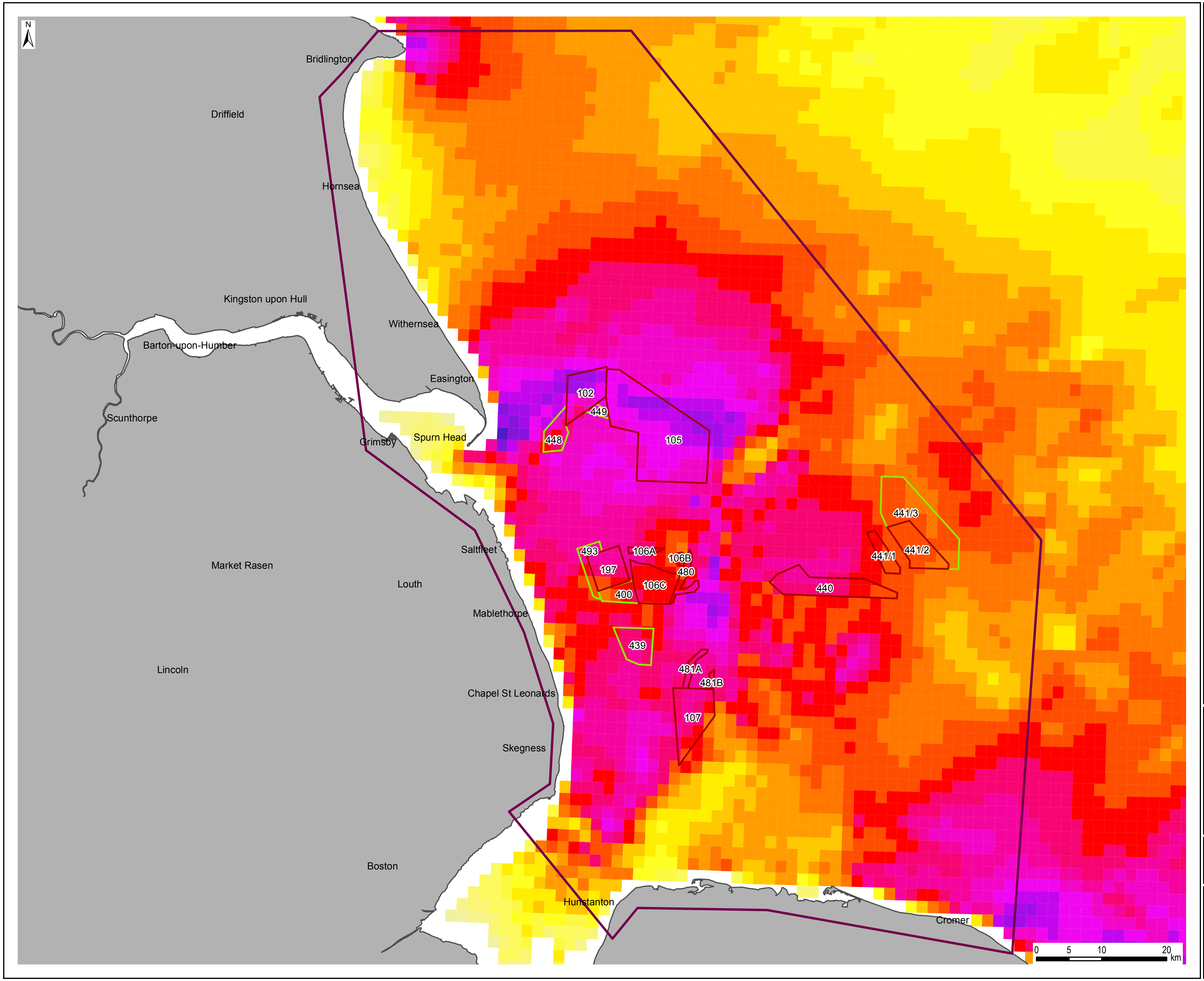
Produced by ABPmer Ltd

[Data extracted from the Offshore Renewables Atlas]
NOT TO BE USED FOR NAVIGATION

ABP mer
marine environmental research

Mean Spring Tidal Range

Figure 4.1



MAREA Study Area
Licence Area
Application Area

Mean Spring Peak Current
- 1.79 - 1.92
- 1.68 - 1.78
- 1.59 - 1.67
- 1.52 - 1.58
- 1.45 - 1.51
- 1.38 - 1.44
- 1.31 - 1.37
- 1.24 - 1.30
- 1.17 - 1.23
- 1.10 - 1.16
- 1.03 - 1.09
- 0.96 - 1.02
- 0.89 - 0.95
- 0.82 - 0.88
- 0.76 - 0.81
- 0.69 - 0.75
- 0.62 - 0.68
- 0.56 - 0.61
- 0.48 - 0.55
- 0.37 - 0.47
- 0.28 - 0.36
- 0.21 - 0.27
- 0.12 - 0.20

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

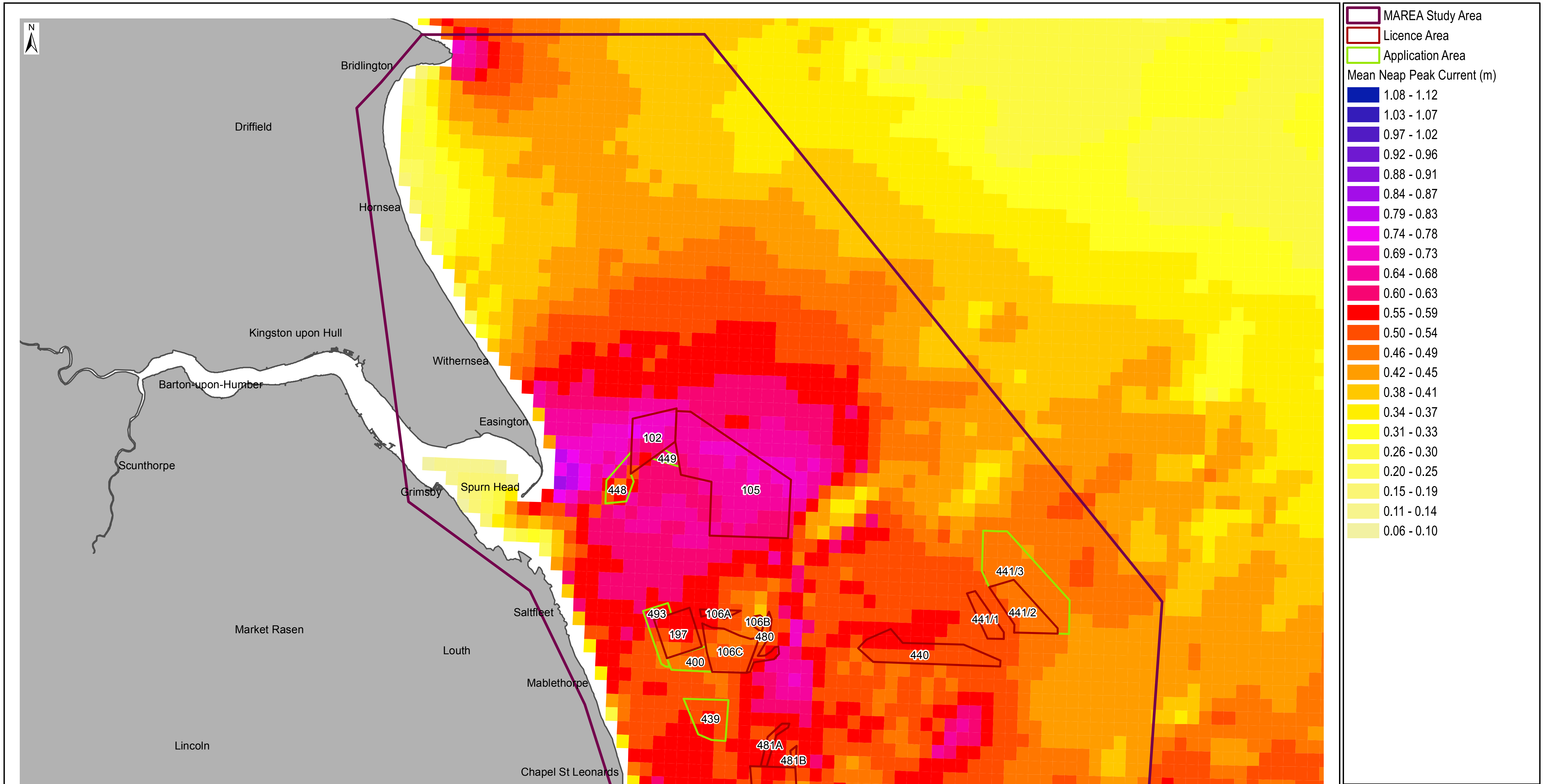
3965 - Fig_4.2_Spring_TidalC.mxd

Produced by ABPmer Ltd

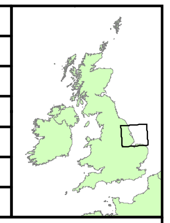
ABP mer marine environmental research

Spring Tidal Currents

Figure 4.2



Date	By	Size	Version
Aug 11	NJG	A3	2
Projection		WGS84 UTM31	
Scale		1:540,000	
QA		MCE	
3965 - Fig_4.3_Neap_Currents.mxd			
Produced by ABPmer Ltd			



[Data extracted from the Offshore Renewables Atlas]
NOT TO BE USED FOR NAVIGATION

ABP mer marine environmental research

Neap Tidal Currents

Figure 4.3

Date	By	Size	Version
July 2011	MCE	A4	3
QA		NJG	

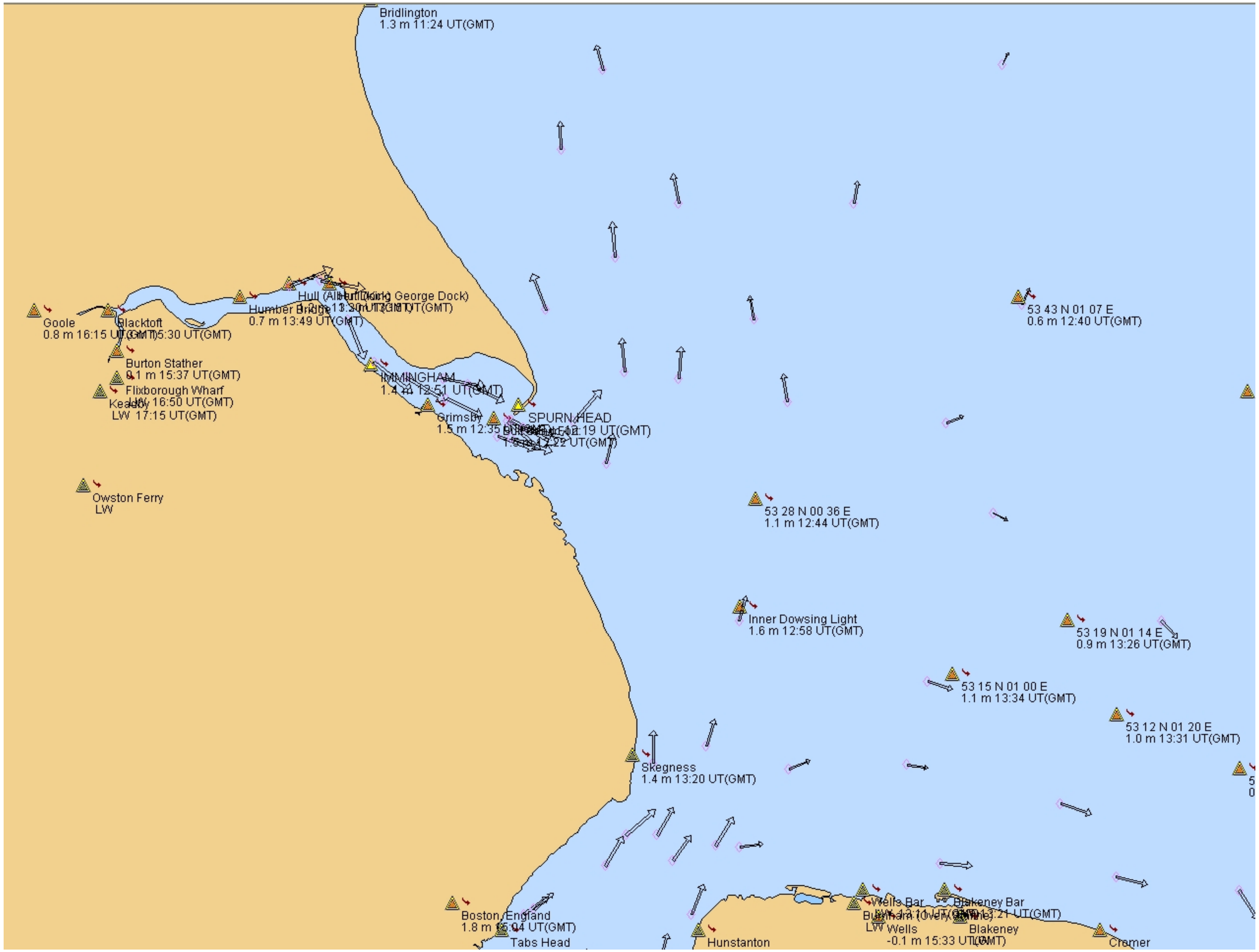
3965–Fig 4.4 Geological Processes 2kBP.pdf

Produced by ABPmer Ltd

Data Sources: TotalTide

Tidal Flows - Flood

Figure 4.4



Date	By	Size	Version
July 2011	MCE	A4	3
QA		NJG	

3965–Fig 4.5 Tidal Flows Ebb.pdf

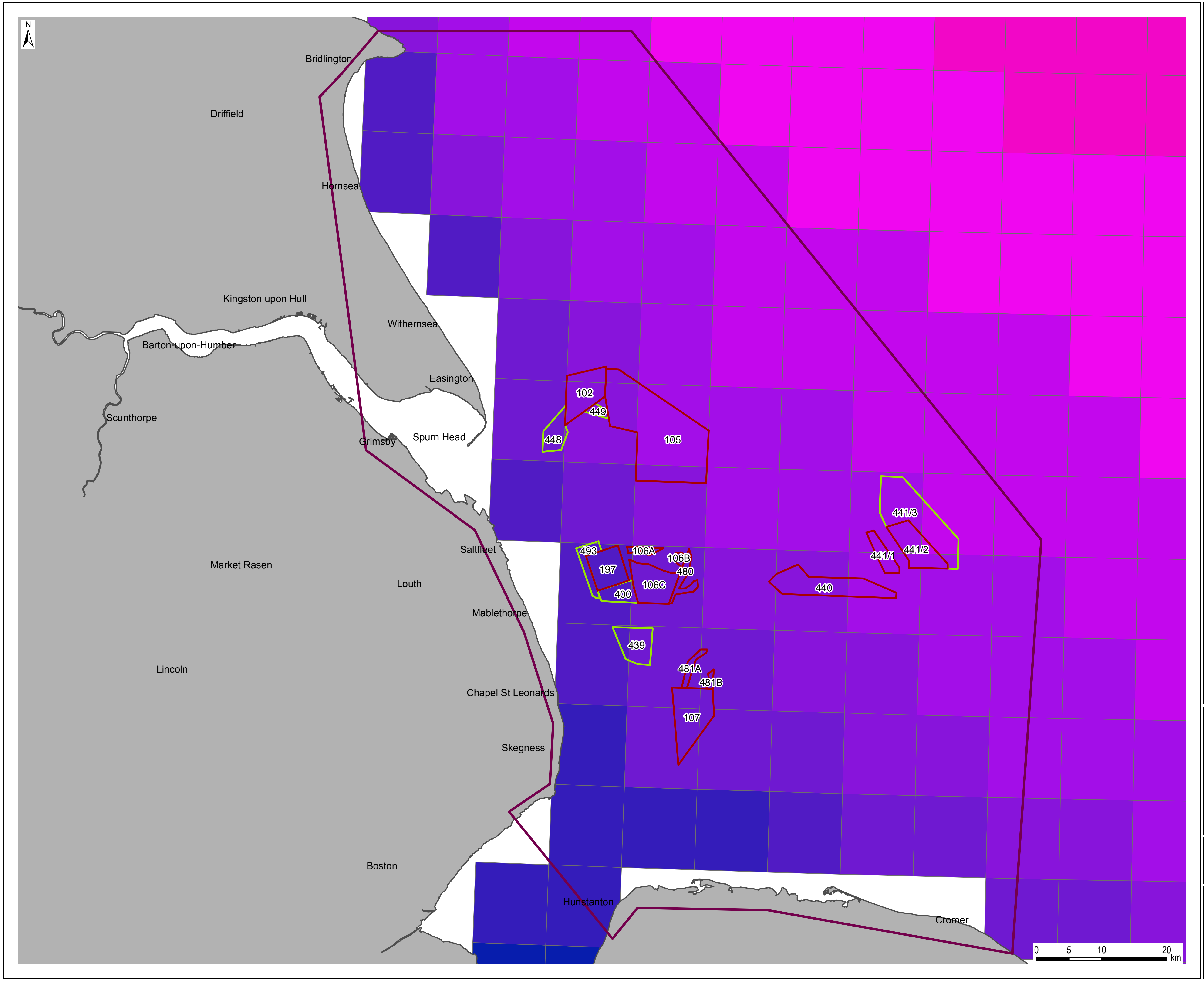
Produced by ABPmer Ltd

Data Sources: TotalTide

marine environmental research

Tidal Flows - Ebb

Figure 4.5



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

3965 - Fig_4.6_Annual Wave_C.mxd

Produced by ABPmer Ltd

[Data extracted from the Offshore Renewables Atlas]
NOT TO BE USED FOR NAVIGATION

ABP mer
marine environmental research

Annual Wave Climate

Figure 4.6

MAREA Study Area
Licence Area
Application Area
Bed load parting
SNS transport vectors
Bed load transport
Longshore transport
Dominantly tidal
Surge

Date	By	Size	Version
Aug 11	NJG	A3	3

Projection	WGS84 UTM31
Scale	1:540,000
QA	MCE

3965 - fig_5.1_SedTransPaths.mxd

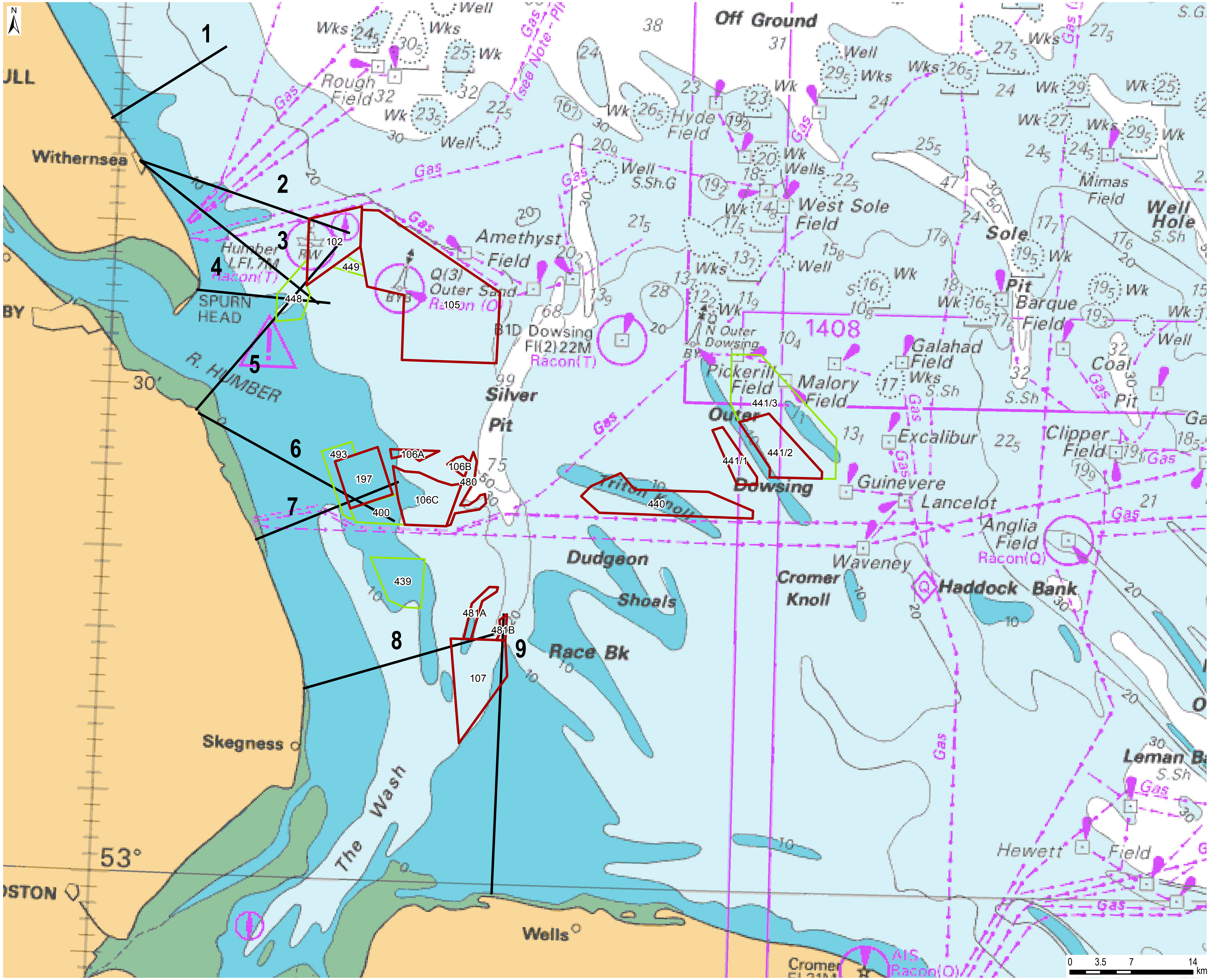
Produced by ABPmer Ltd

[After Kenyon and Cooper; Seazone Licence 042009.005]
NOT TO BE USED FOR NAVIGATION

ABP mer
marine environmental research

Bedload Sediment Transport Pathways

Figure 5.1



Licence Area
Application Area
Cross Sections

Date	By	Size	Version
Aug 11	NJG	A3	1
Projection		WGS84 UTM31	
Scale		1:412,923	
QA		NMW	

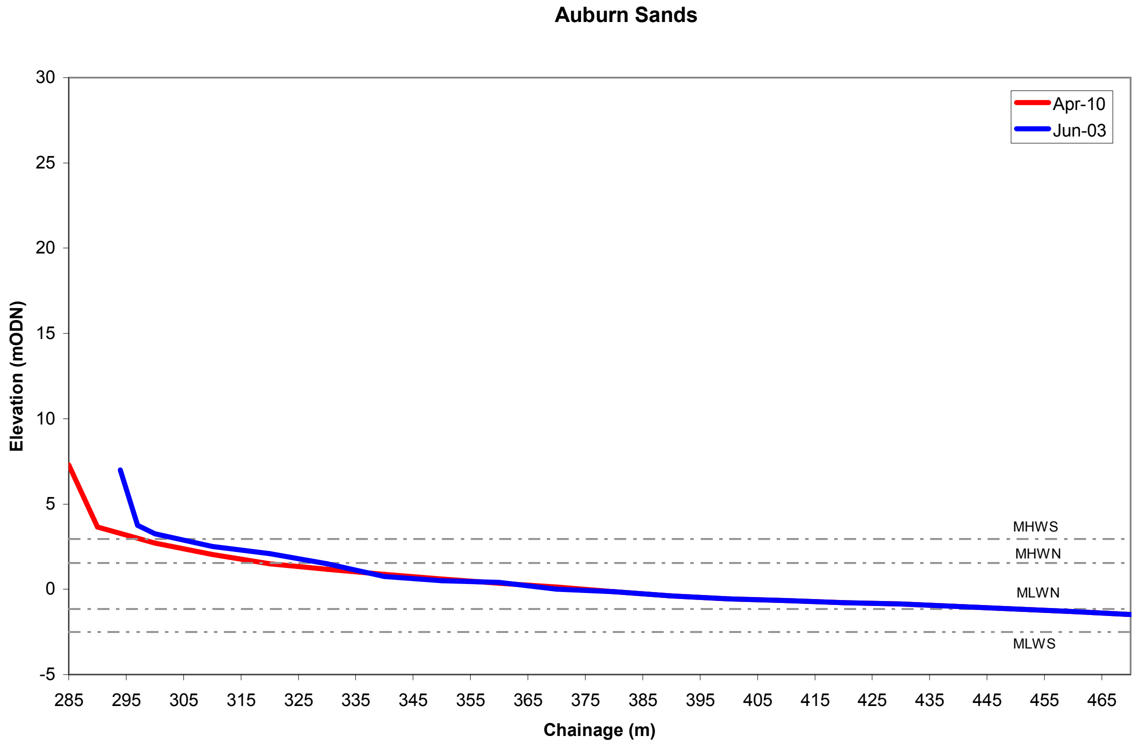
3965 - fig_6.1_Surficial_Seds.mxd

Produced by ABPmer Ltd

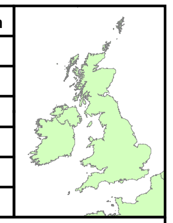
ABP mer
marine environmental research

Location of Cross Sections

Figure 6.1



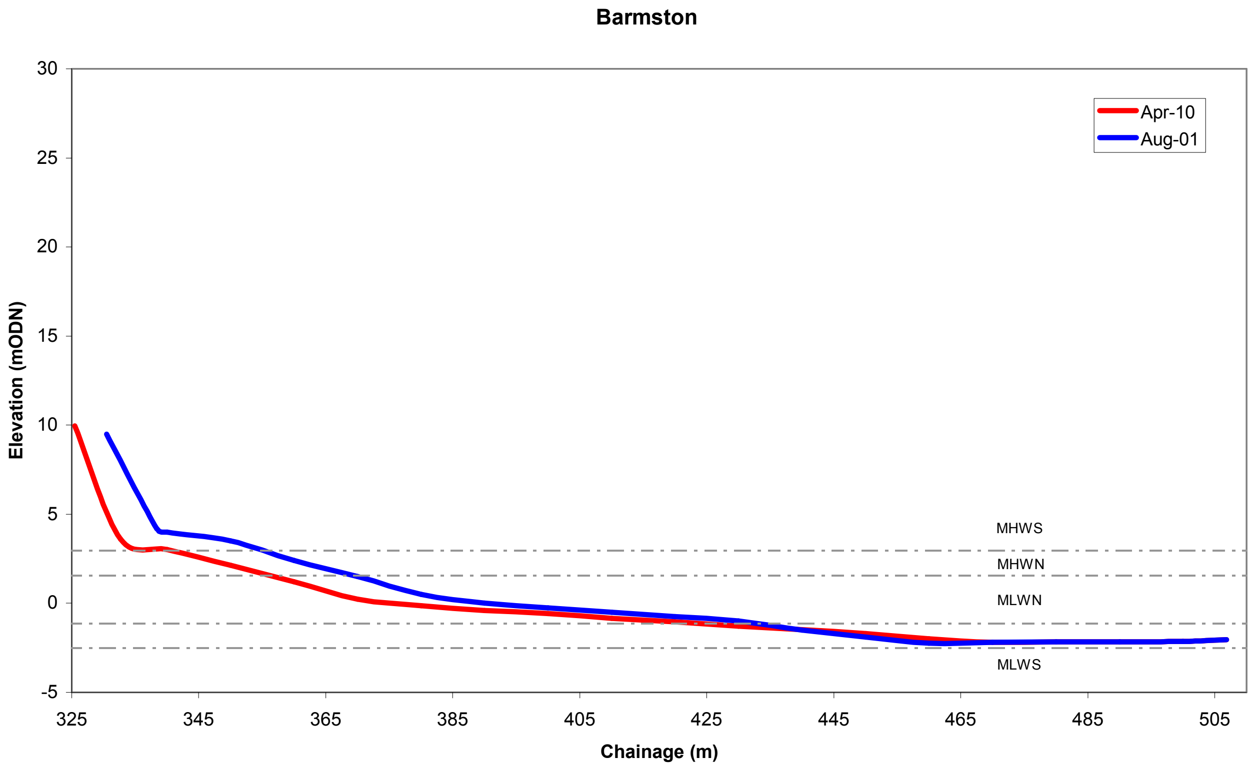
Date	By	Size	Version
Jun 11	NJG	A3	1
Projection		WGS 84 UTM31	
Scale		1:6,000	
QA		FMM	
3965 - fig_6.2_Auburn Sands.mxd			
Produced by ABPmer Ltd			



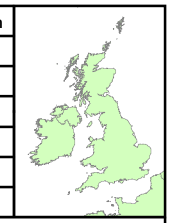
ABP mer
marine environmental research

Auburn Sands

Figure 6.2

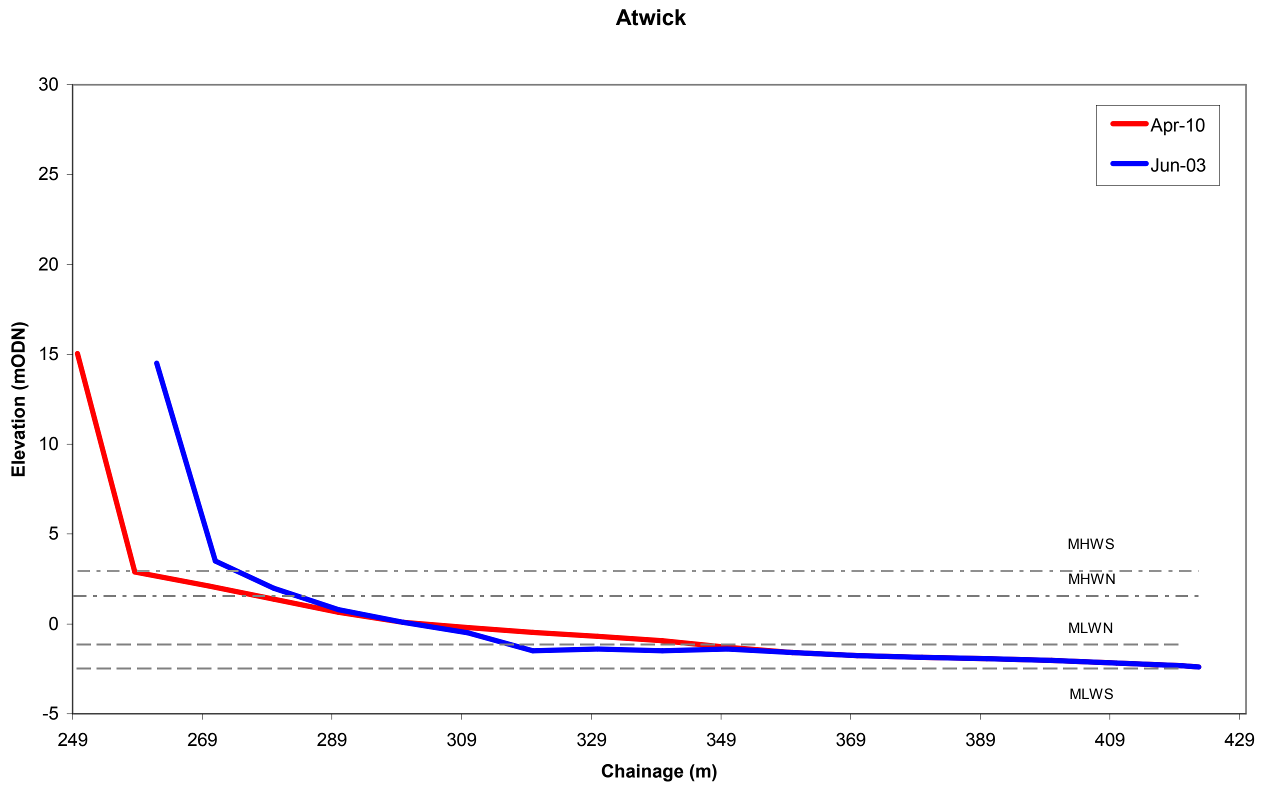


Date	By	Size	Version
Jun 11	NJG	A3	1
Projection		WGS 84 UTM31	
Scale		1:6,000	
QA		FMM	
3965 - fig_6.3_Barmston.mxd			
Produced by ABPmer Ltd			

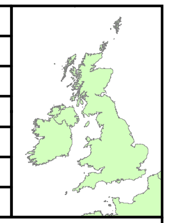


Barmston

Figure 6.3



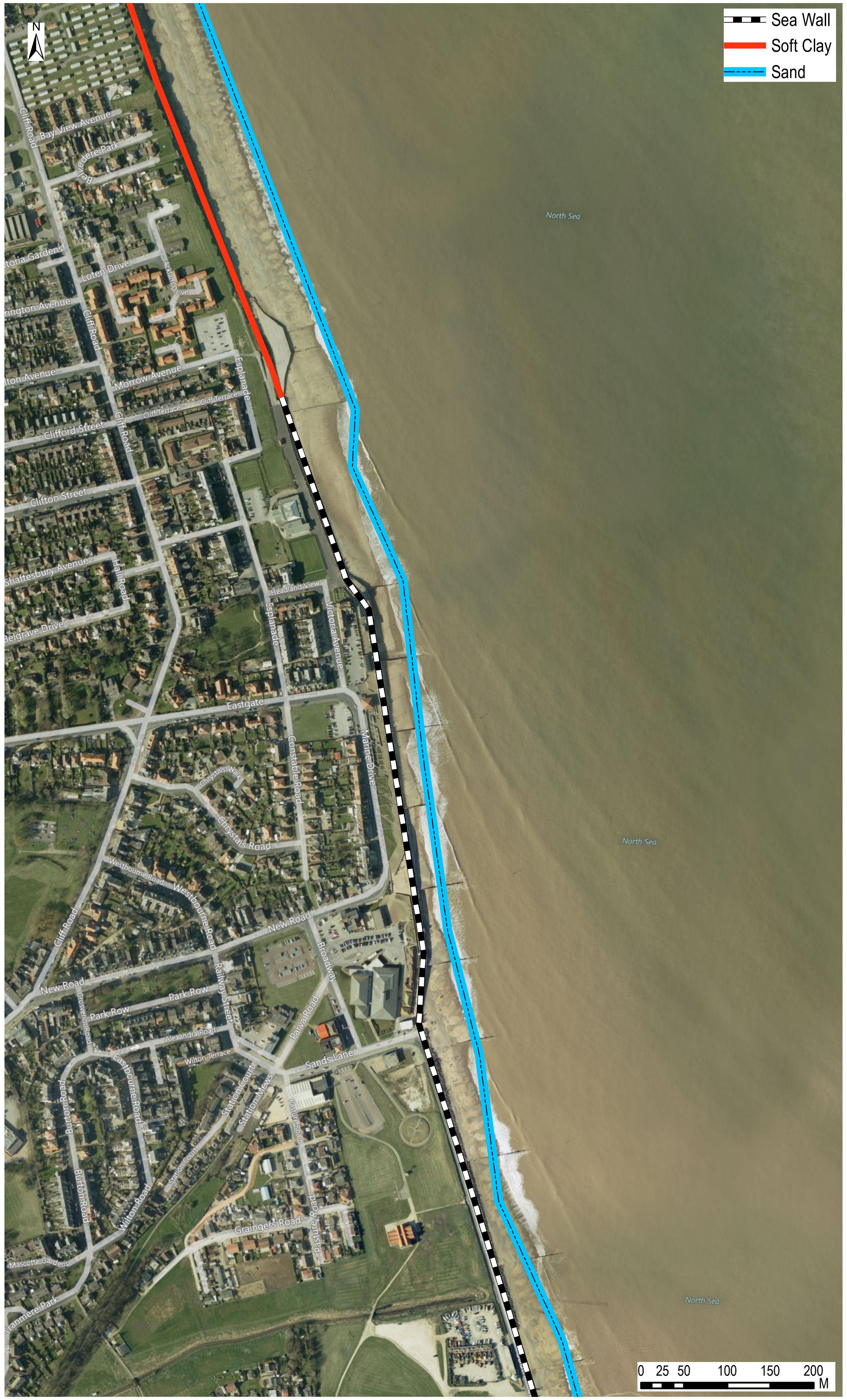
Date	By	Size	Version
Jun 11	NJG	A3	1
Projection		WGS 84 UTM31	
Scale		1:6,000	
QA		FMM	
3965 - fig_6.4 Atwick.mxd			
Produced by ABPmer Ltd			

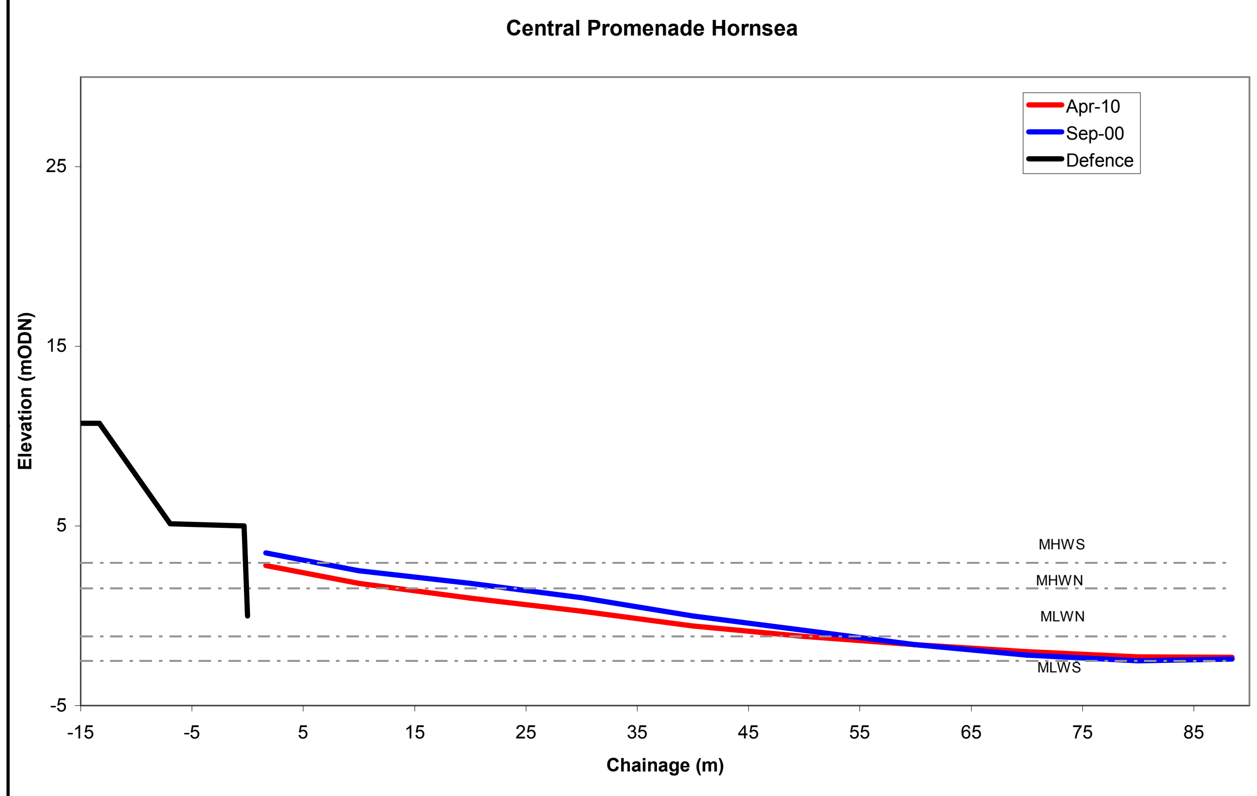


ABP mer
marine environmental research

Atwick

Figure 6.4



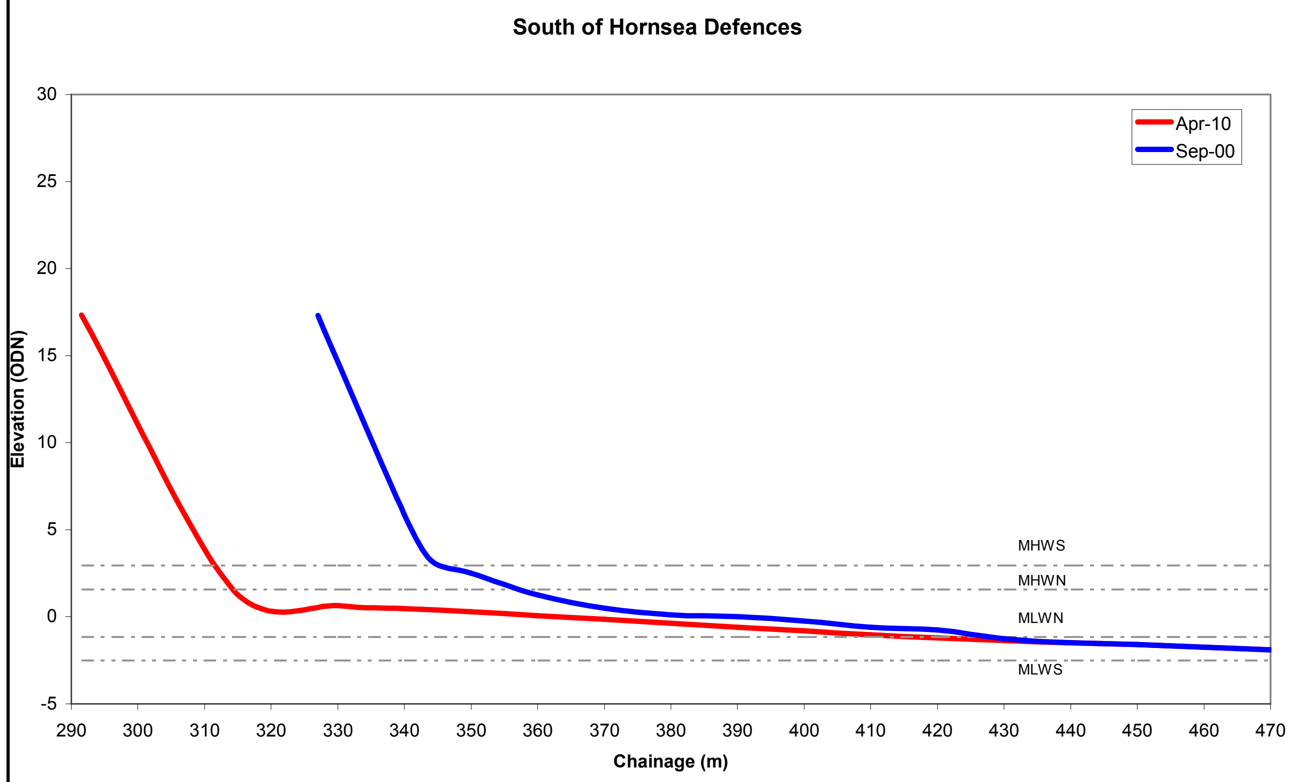


Date	By	Size	Version
Jun 11	NJG	A3	1
Projection	WGS 84 UTM31		
Scale	1:6,000		
QA	FMM		
3965 - fig_6.5_Hornsea.mxd			
Produced by ABPmer Ltd			

ABP mer
marine environmental research

Hornsea

Figure 6.5



Date	By	Size	Version
Jun 11	NJG	A3	1
Projection		WGS 84 UTM31	
Scale		1:6,000	
QA		FMM	

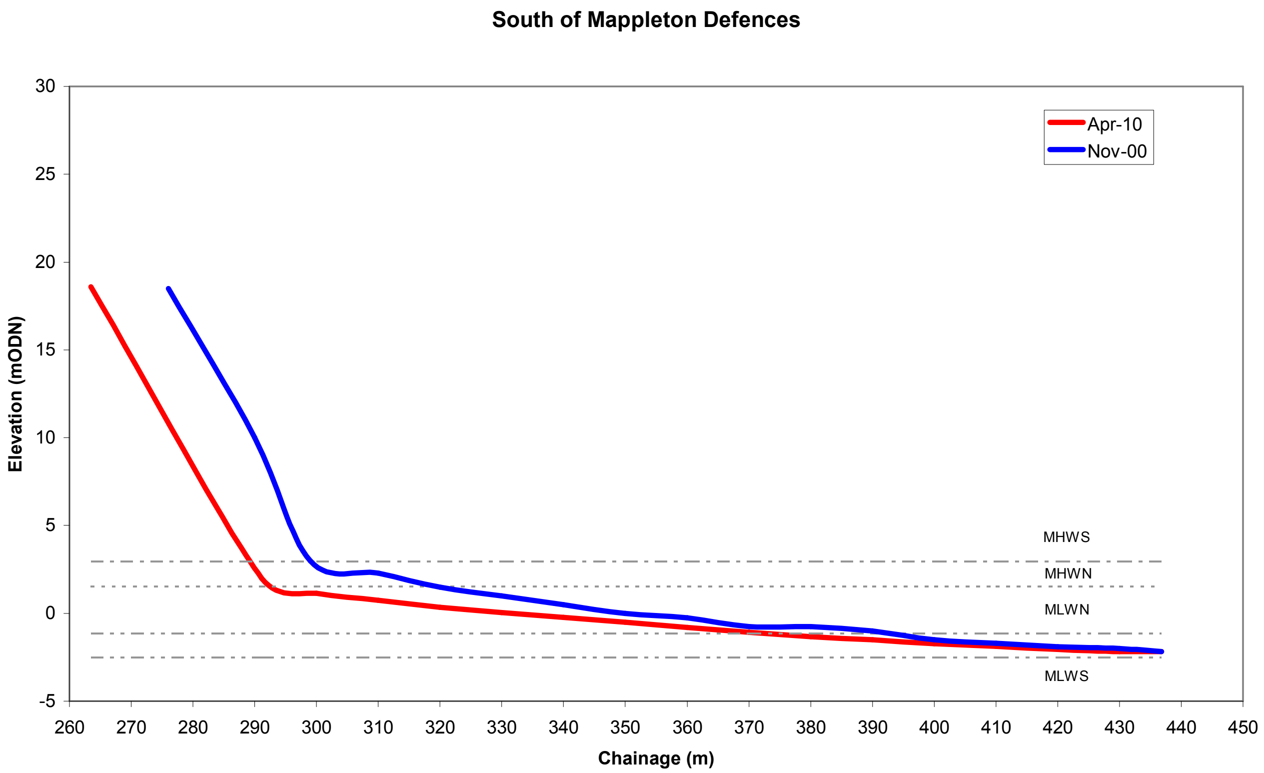
3965 - fig_6.6_South of Hornsea.mxd

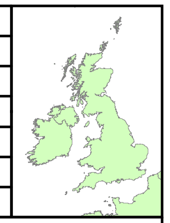
Produced by ABPmer Ltd

ABP mer
marine environmental research

South of Hornsea Defences

Figure 6.6



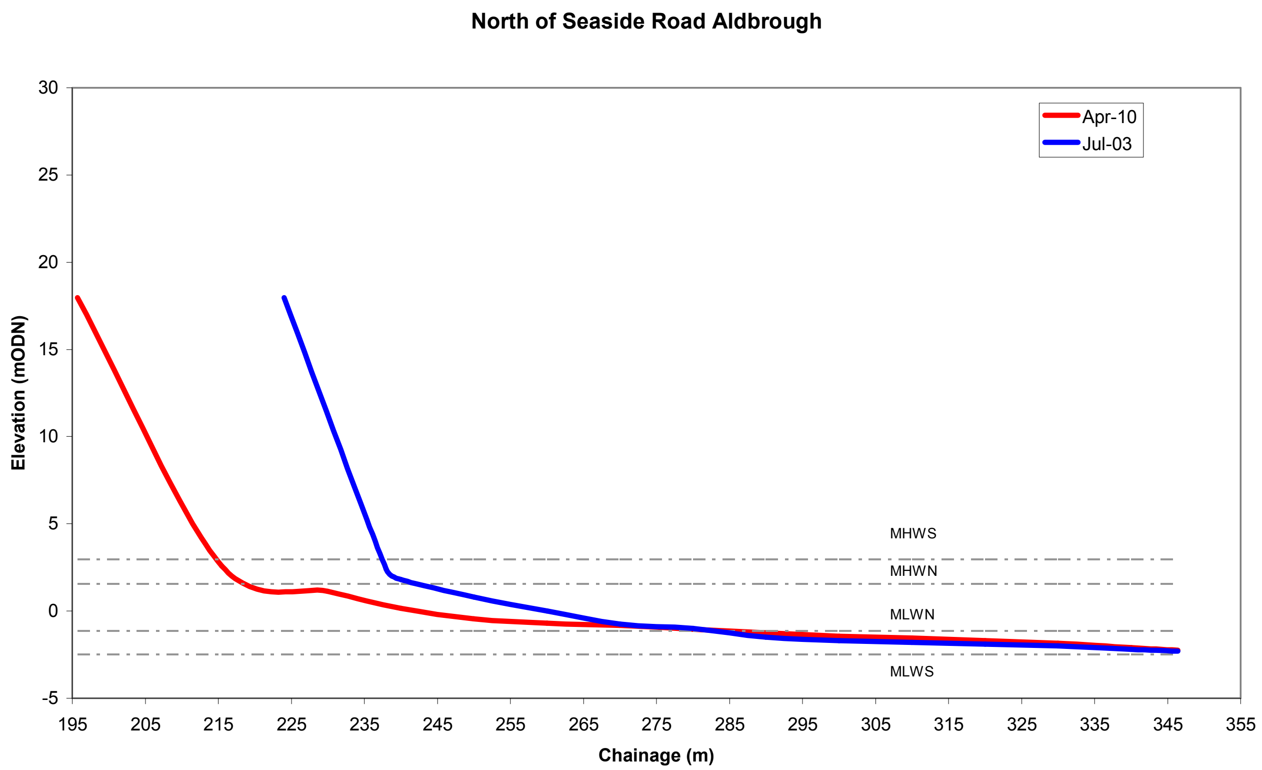


Date	By	Size	Version
Jun 11	NJG	A3	1
Projection		WGS 84 UTM31	
Scale		1:6,000	
QA		FMM	
3965 - fig_6.7_SouthofMappleton.mxd			
Produced by ABPmer Ltd			

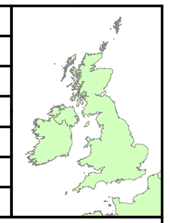
ABP mer
marine environmental research

South of Mappleton Defences

Figure 6.7



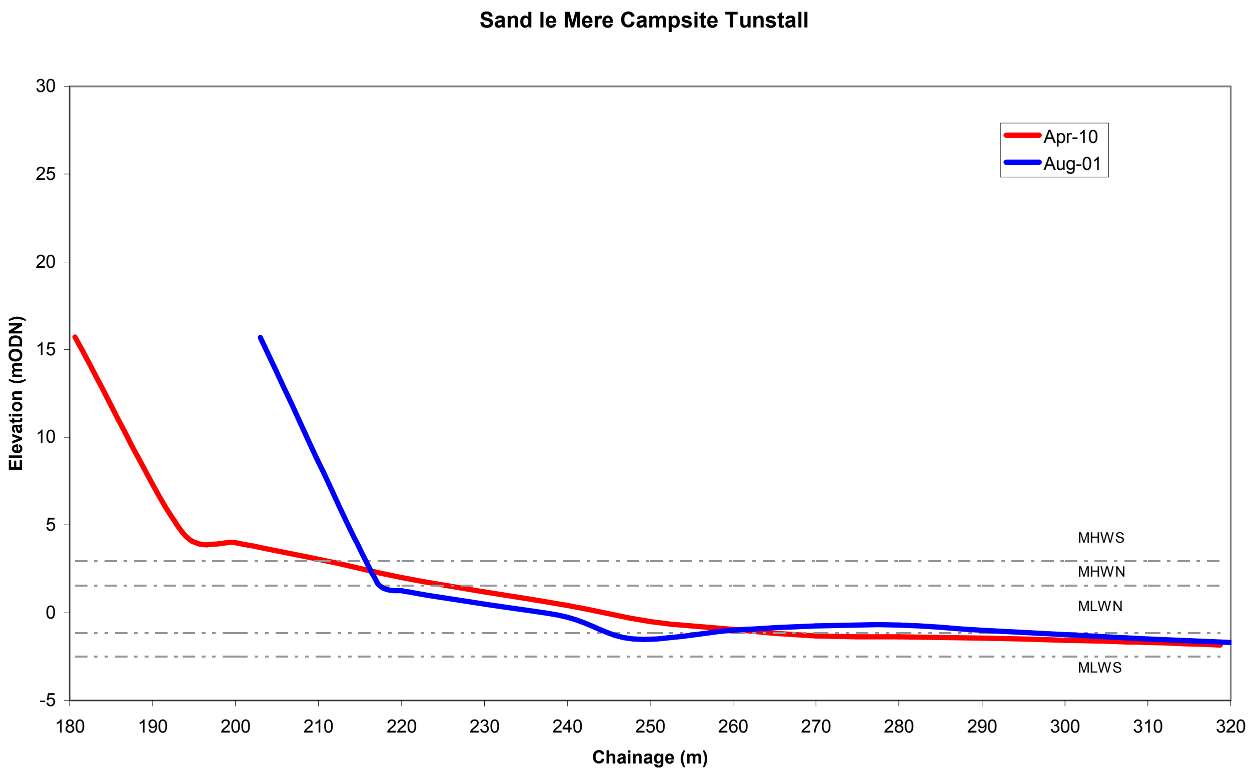
Date	By	Size	Version
Jun 11	NJG	A3	1
Projection	WGS 84 UTM31		
Scale	1:6,000		
QA	FMM		
3965 - fig_6.8_Aldbrough.mxd			
Produced by ABPmer Ltd			



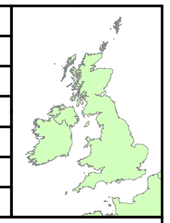
ABP mer marine environmental research

Aldbrough

Figure 6.8



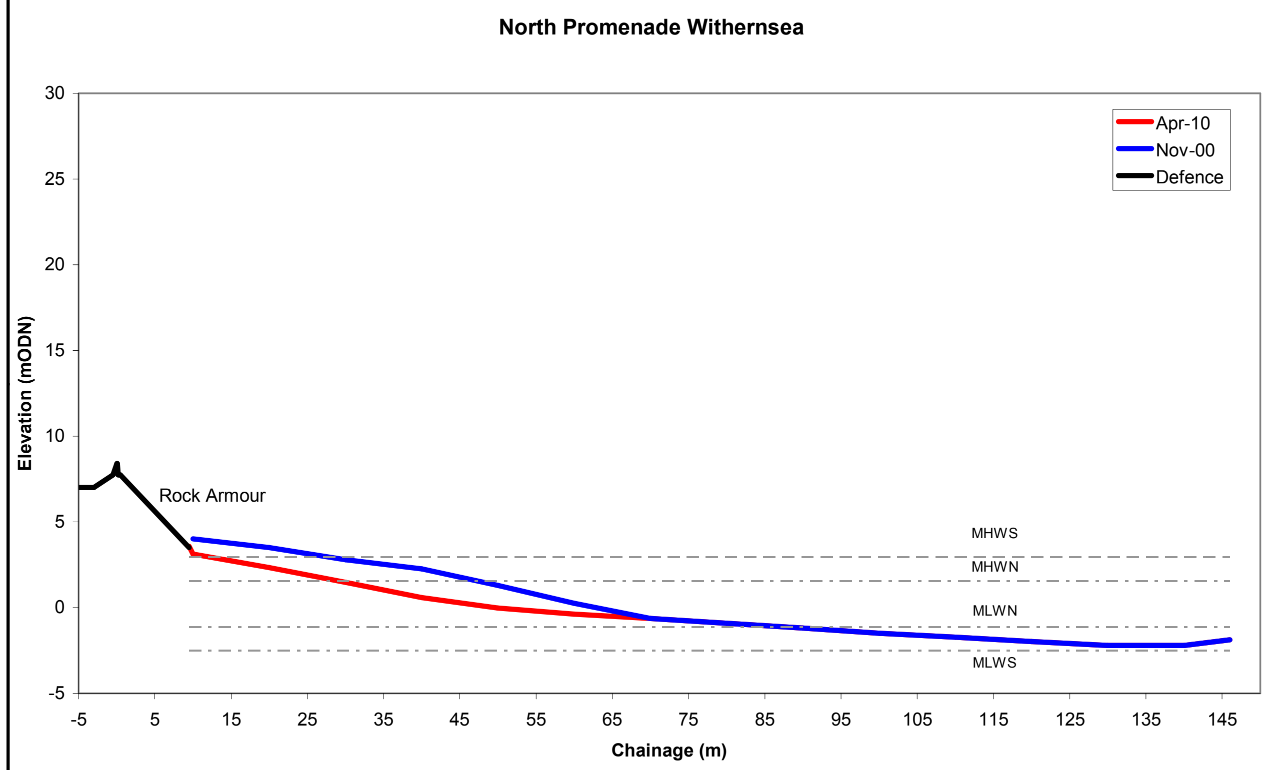
Date	By	Size	Version
Jun 11	NJG	A3	1
Projection		WGS 84 UTM31	
Scale		1:6,000	
QA		FMM	
3965 - fig_6.9_Tunstall.mxd			
Produced by ABPmer Ltd			



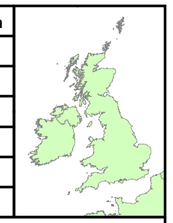
ABP mer
marine environmental research

Tunstall

Figure 6.9



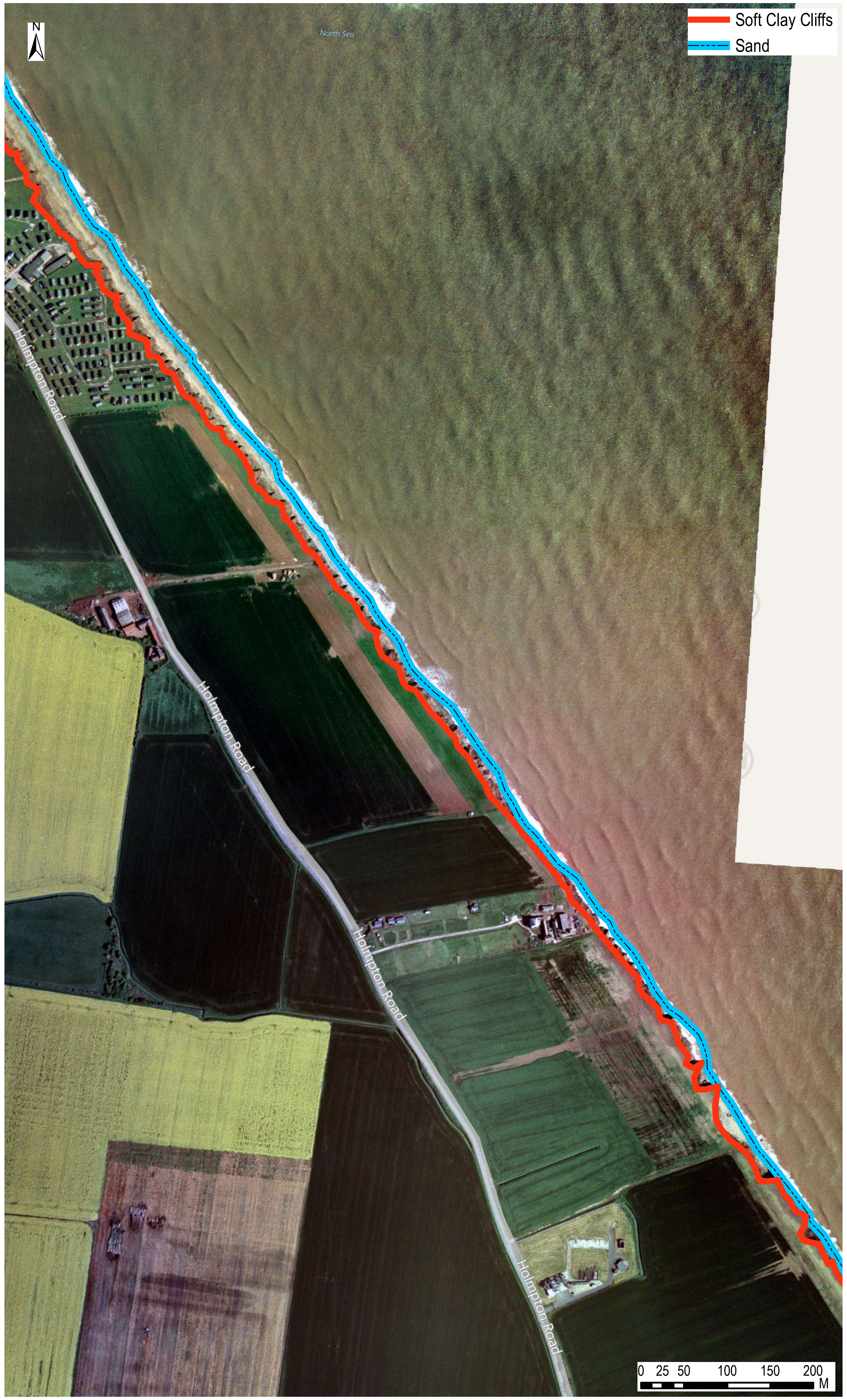
Date	By	Size	Version
Jun 11	NJG	A3	1
Projection	WGS 84 UTM31		
Scale	1:6,000		
QA	FMM		
3965 - fig_6.10_Withernsea.mxd			
Produced by ABPmer Ltd			

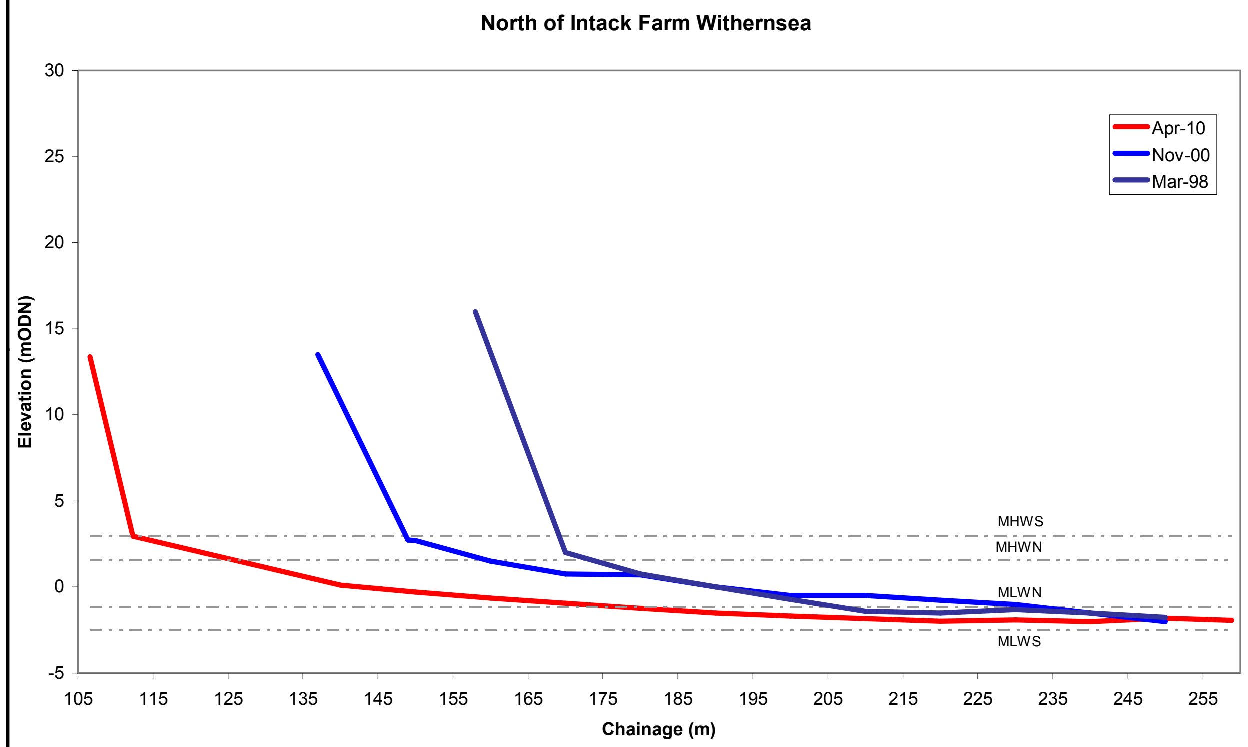


ABP mer
marine environmental research

Withernsea

Figure 6.10





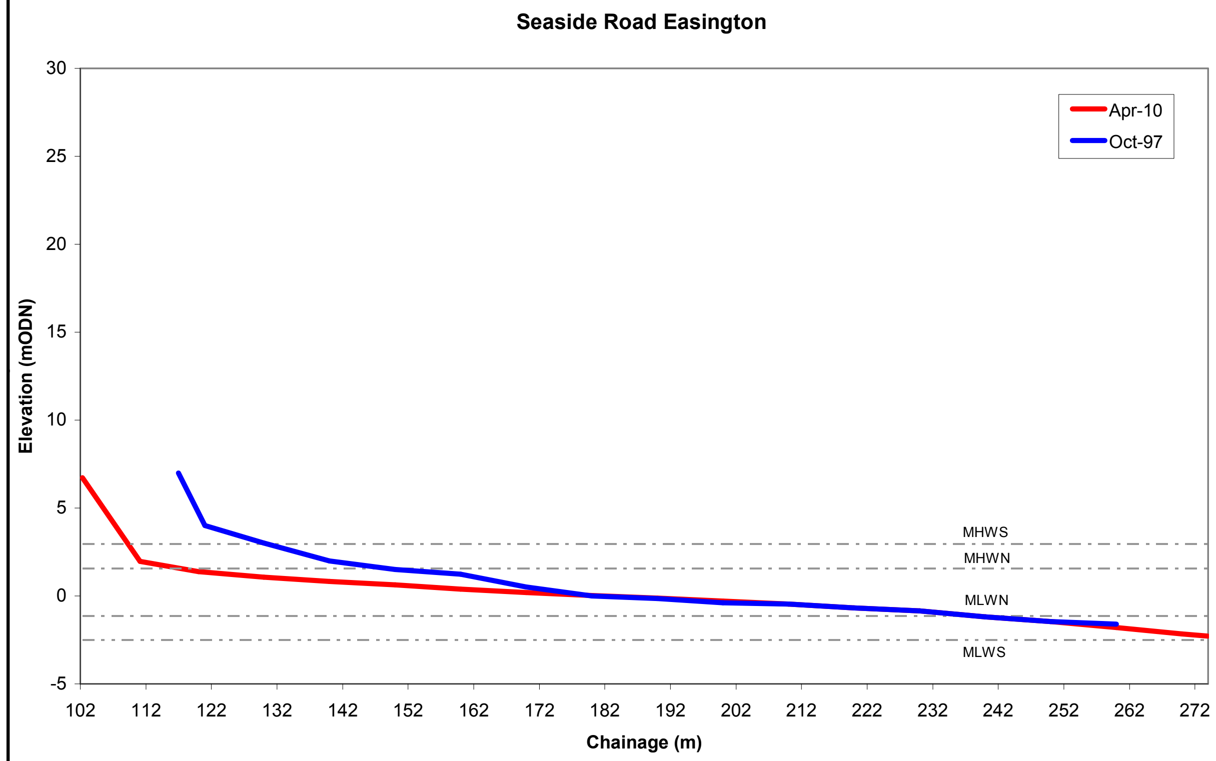
Date	By	Size	Version
Jun 11	NJG	A3	1
Projection		WGS 84 UTM31	
Scale		1:6,000	
QA		FMM	
3965 - fig_6.11_South of Withernsea.mxd			

Produced by ABPmer Ltd

ABP mer marine environmental research

South of Withernsea Defences

Figure 6.11



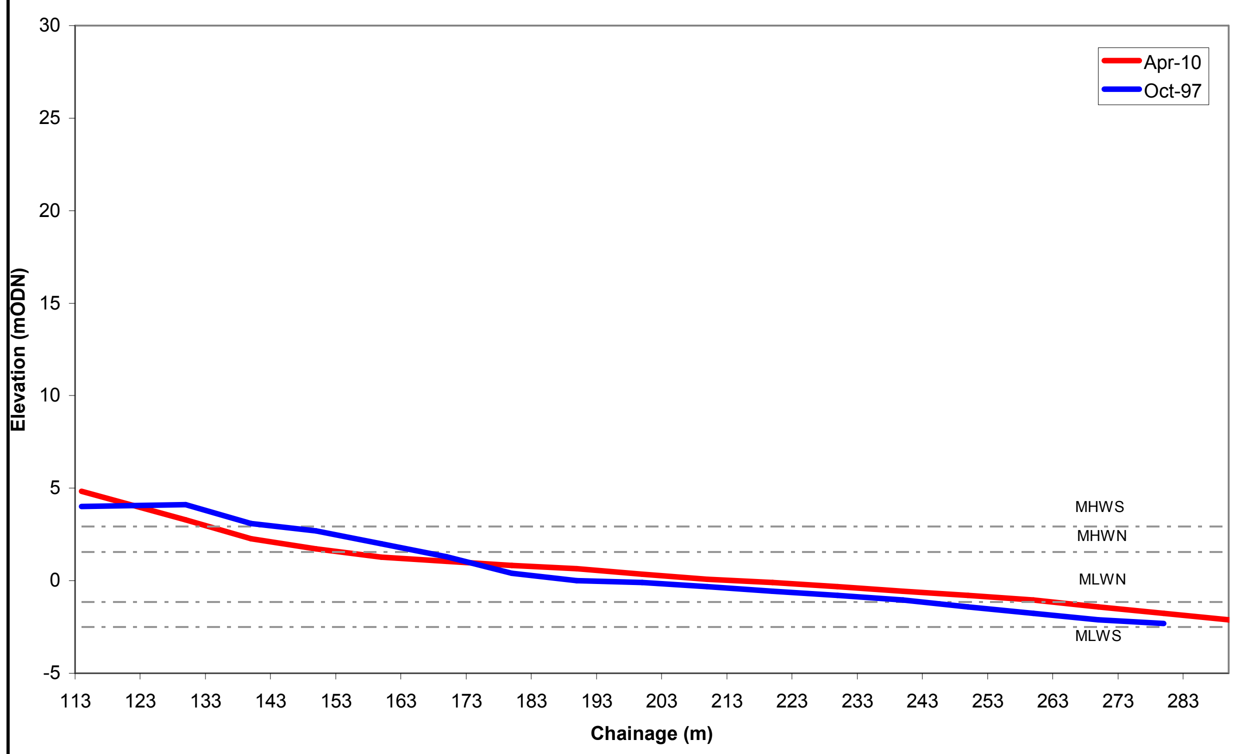
Date	By	Size	Version
Jun 11	NJG	A3	1
Projection	WGS 84 UTM31		
Scale	1:6,000		
QA	FMM		
3965 - fig_6.12_Easington.mxd			
Produced by ABPmer Ltd			

ABP mer
marine environmental research

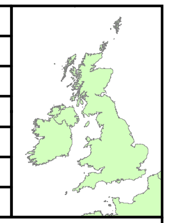
Easington

Figure 6.12

North End of Kilnsea Lagoon



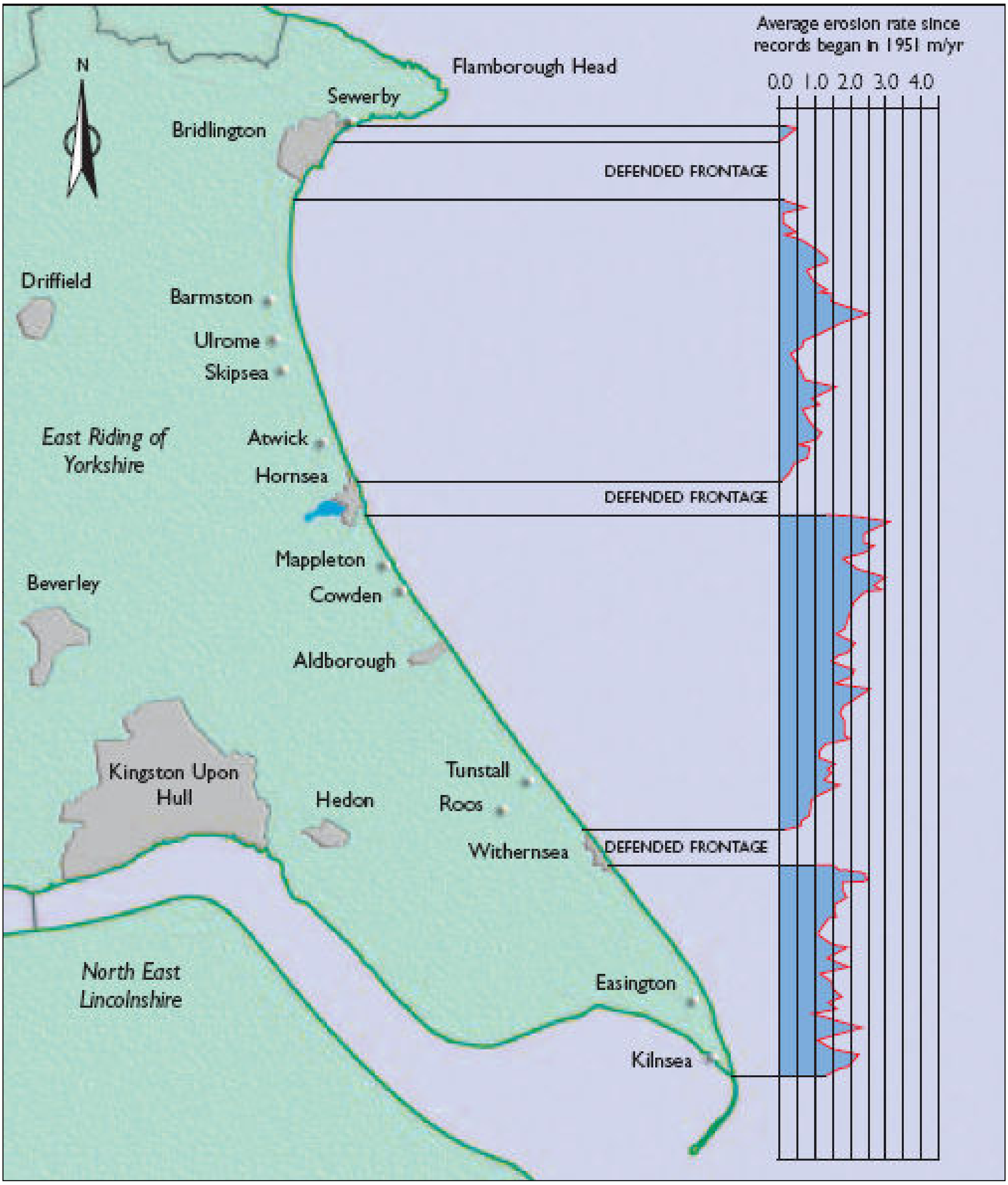
Date	By	Size	Version
Aug 11	NJG	A3	2
Projection		WGS 84 UTM31	
Scale		1:6,000	
QA		FMM	
3965 - fig_6.13_Kilnsea.mxd			
Produced by ABPmer Ltd			



ABP mer
marine environmental research

Kilnsea

Figure 6.13



Date	By	Size	Version
Aug 11	NJG	A4	2
Projection		N/A	
Scale		1:90,000	
QA		FMM	
3965 - figure_6.14_cliffrecess.mxd			
Produced by ABPmer Ltd			

ABP mer
marine environmental research

Summary of Cliff Recession Since 1951

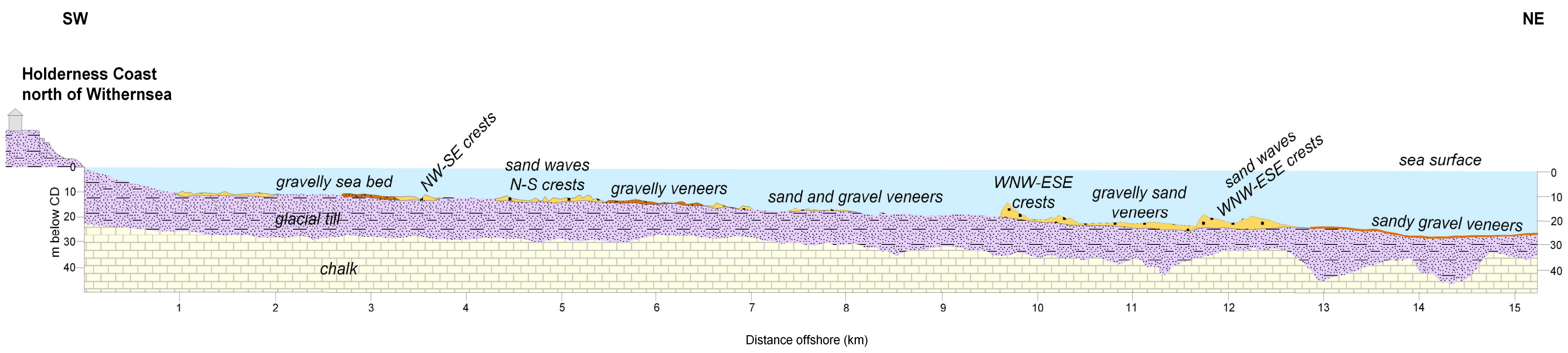
Figure 6.14

Date	By	Size	Version
July 11	NJG	A4	1
Projection		N/A	
Scale		1:90,000	
QA		FMM	
3965 - figure_6.15_lostvillages.mxd			
Produced by ABPmer Ltd			

ABP mer marine environmental research

Villages Lost to Erosion | **Figure 6.15**

Profile 1: Holderness coast and north east 15km



Date	By	Size	Version
July 11	NJG	A4	1
QA		FMM	

3965 – Figure6.16Profile1.ppt

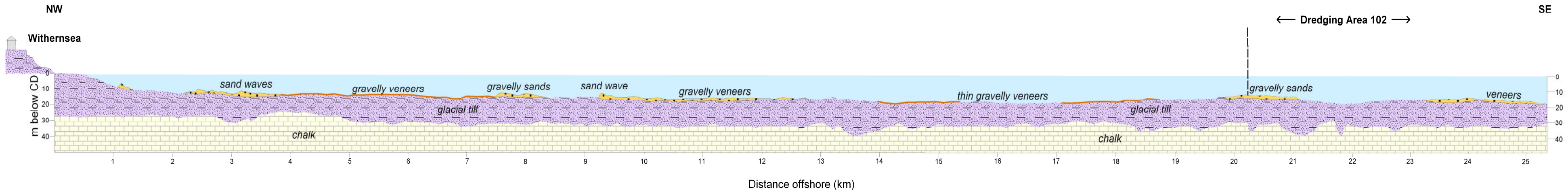
Produced by ABPmer Ltd

ABP mer
marine environmental research

Subtidal profile 1

Figure 6.16

Profile 2: Withernsea east south east to Dredge Area 102



Date	By	Size	Version
July 11	NJG	A4	1
QA		FMM	

3965 – Figure6.17 Profile2.ppt

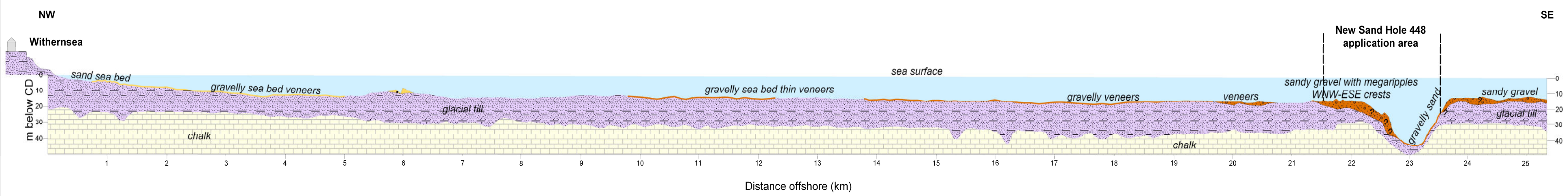
Produced by ABPmer Ltd

ABP mer marine environmental research

Subtidal profile 2

Figure 6.17

Profile 3: Withernsea south east to New Sand Hole and Area 448



Date	By	Size	Version
July 11	NJG	A4	1
QA		FMM	

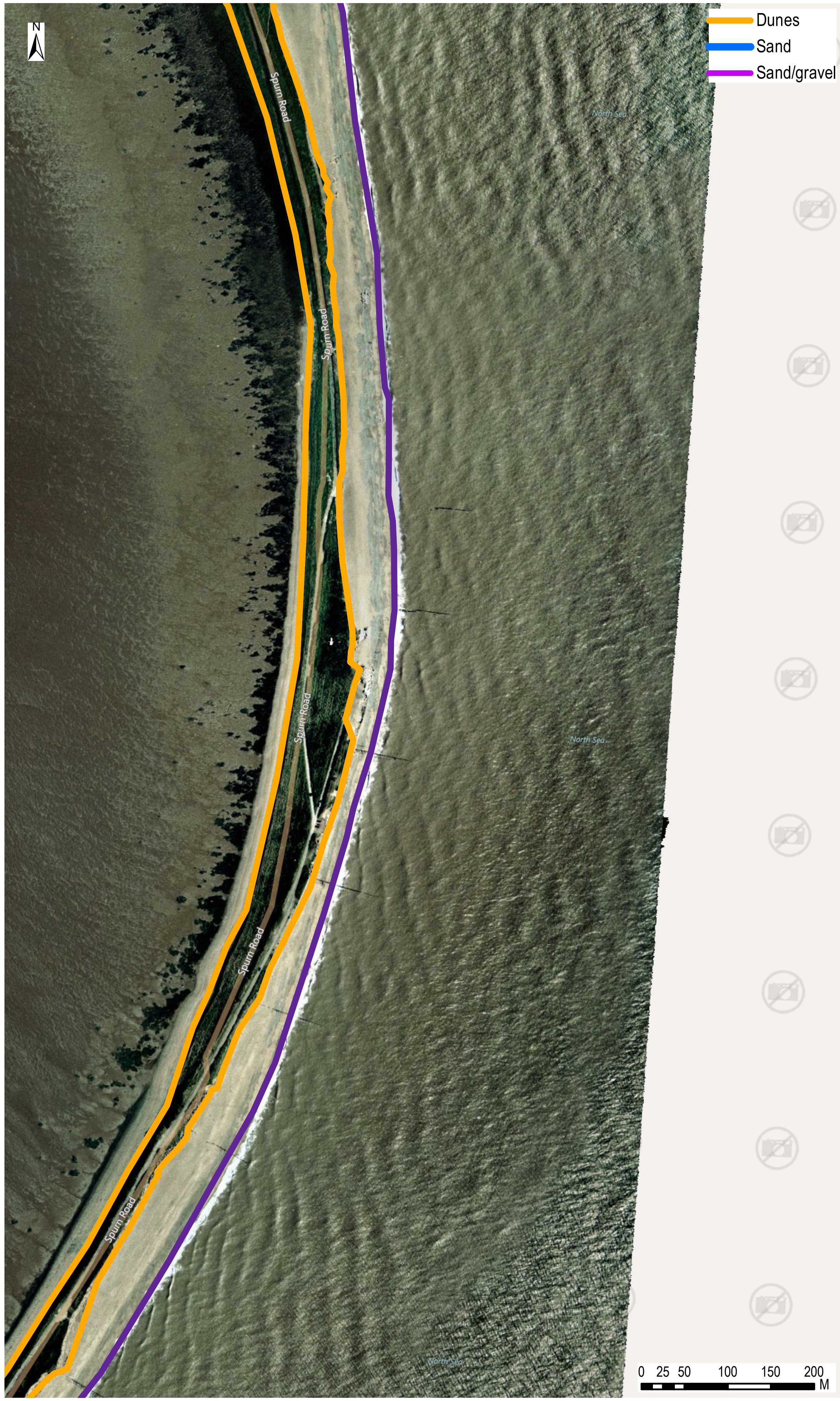
3965 – Figure6.18 Profile3.ppt

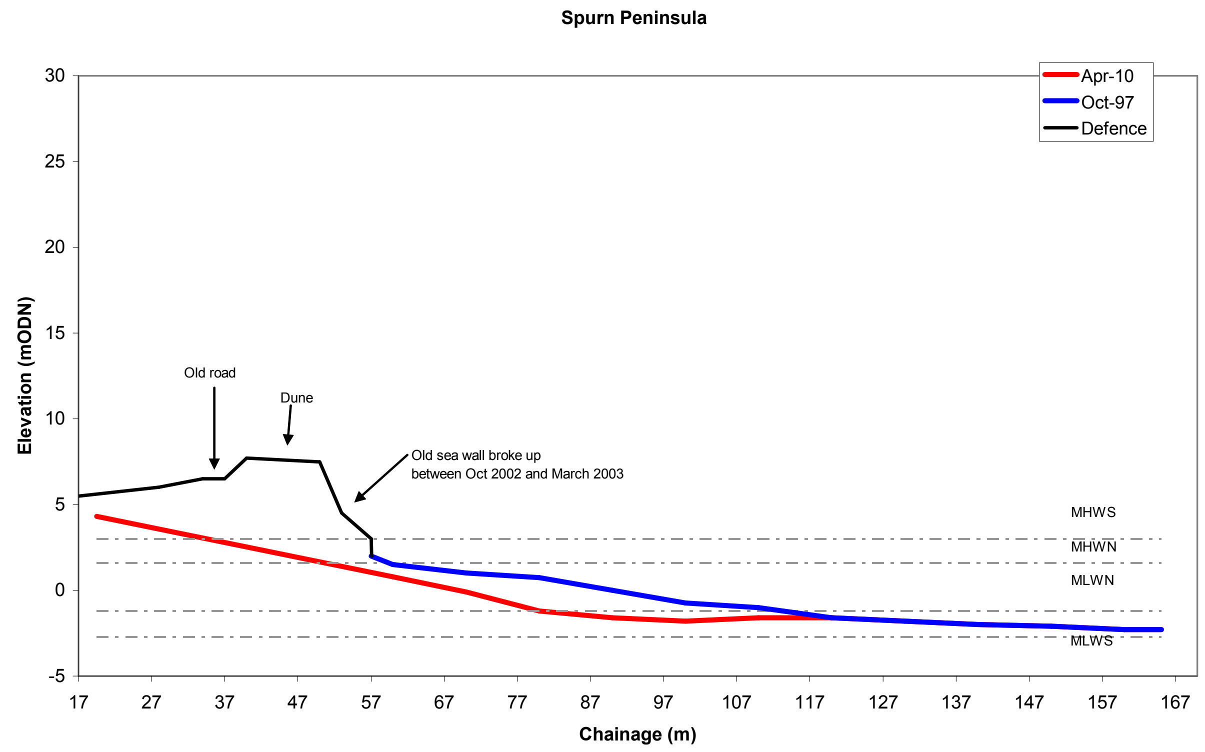
Produced by ABPmer Ltd

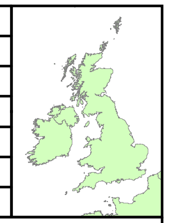
ABP mer marine environmental research

Subtidal profile 3

Figure 6.18





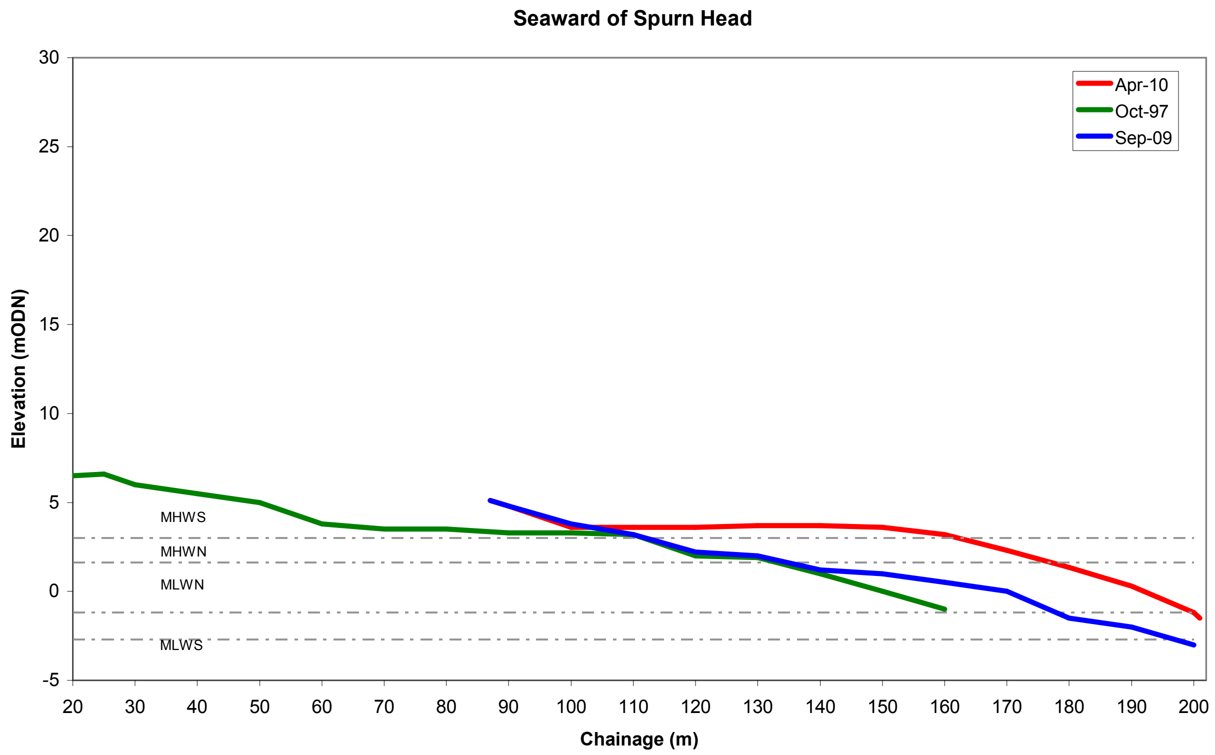


Date	By	Size	Version
Jun 11	NJG	A3	1
Projection		WGS 84 UTM31	
Scale		1:6,000	
QA		FMM	
3965 - fig_6.19 Spurn_Pen.mxd			
Produced by ABPmer Ltd			

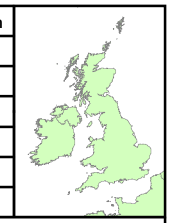
ABP mer
marine environmental research

Spurn peninsula

Figure 6.19



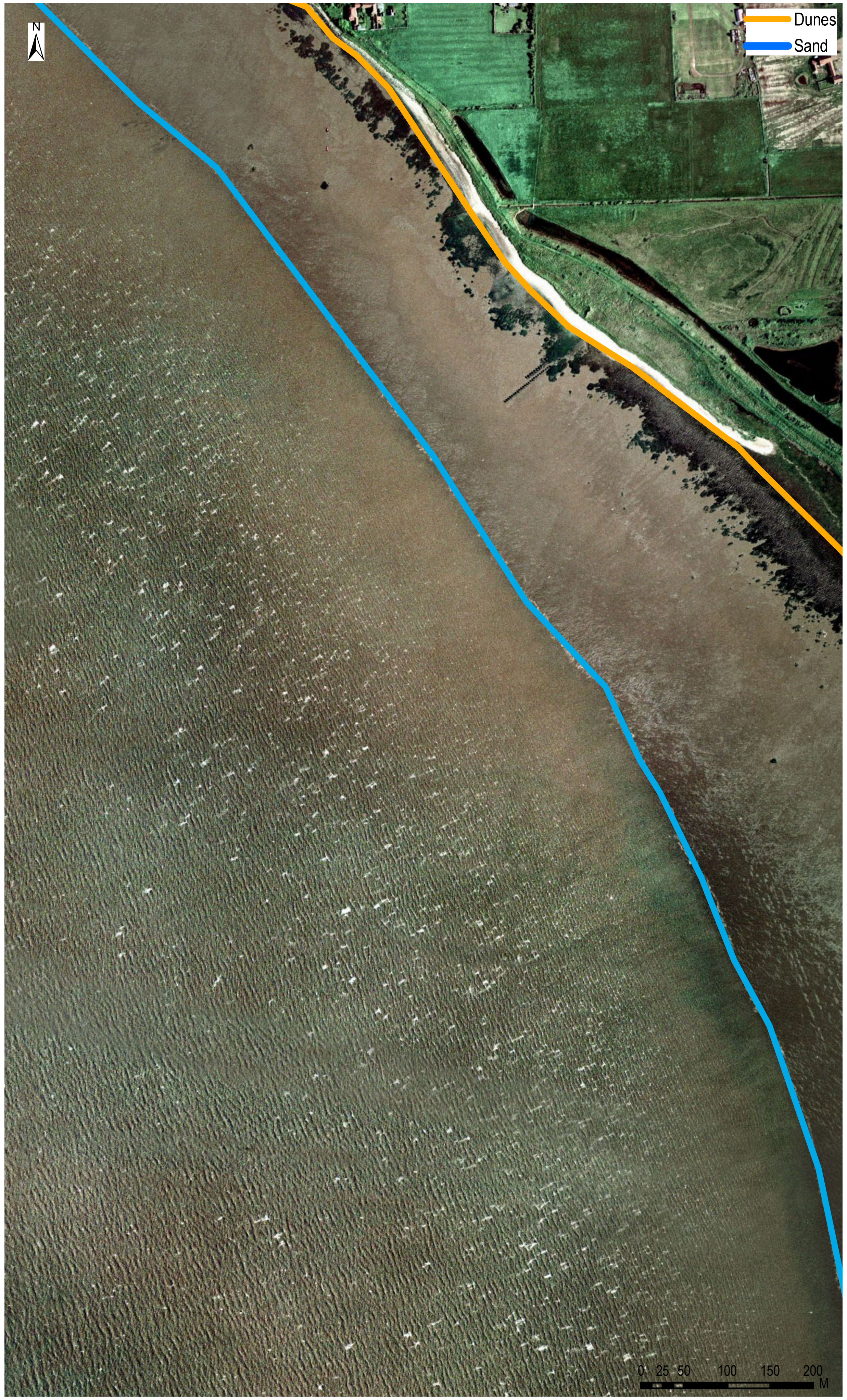
Date	By	Size	Version
Jun 11	NJG	A3	1
Projection		WGS 84 UTM31	
Scale		1:6,000	
QA		FMM	
3965 - fig_6.20 Spurn_Point.mxd			
Produced by ABPmer Ltd			

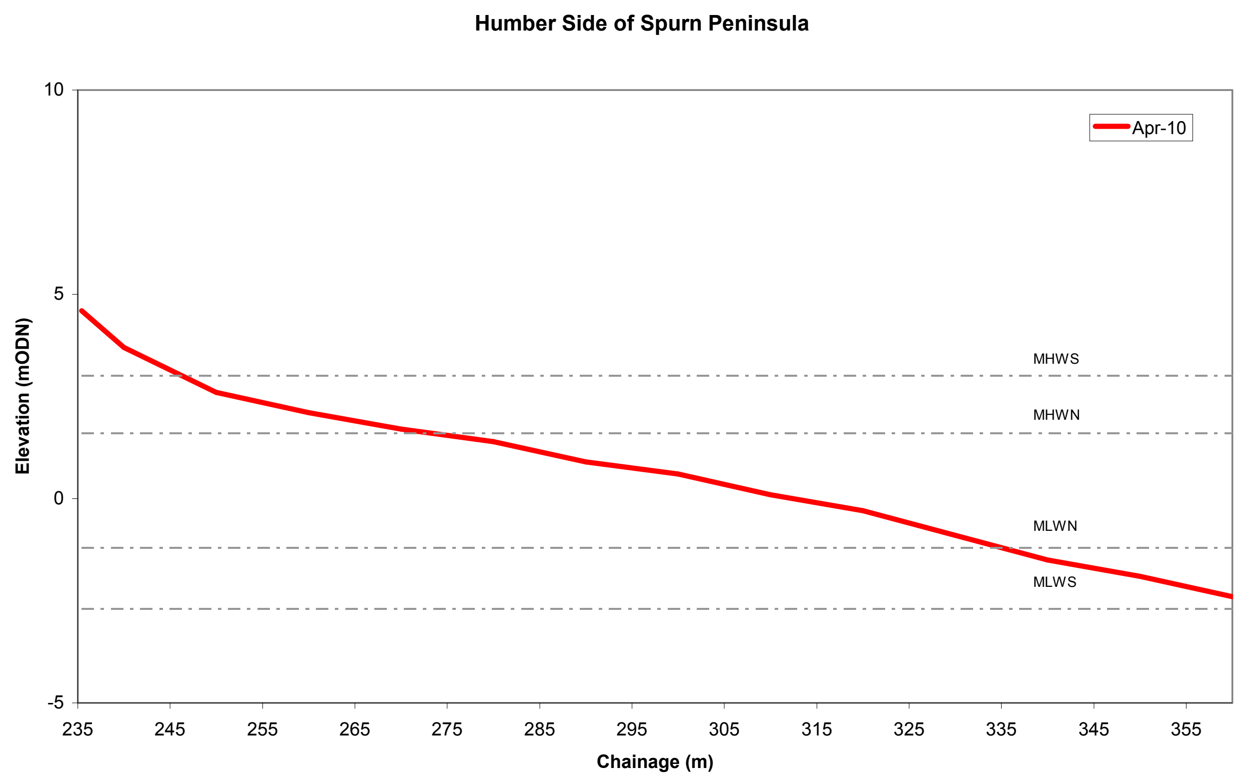


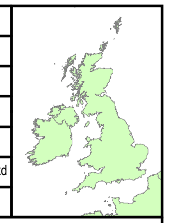
ABP mer
marine environmental research

Spurn point

Figure 6.20





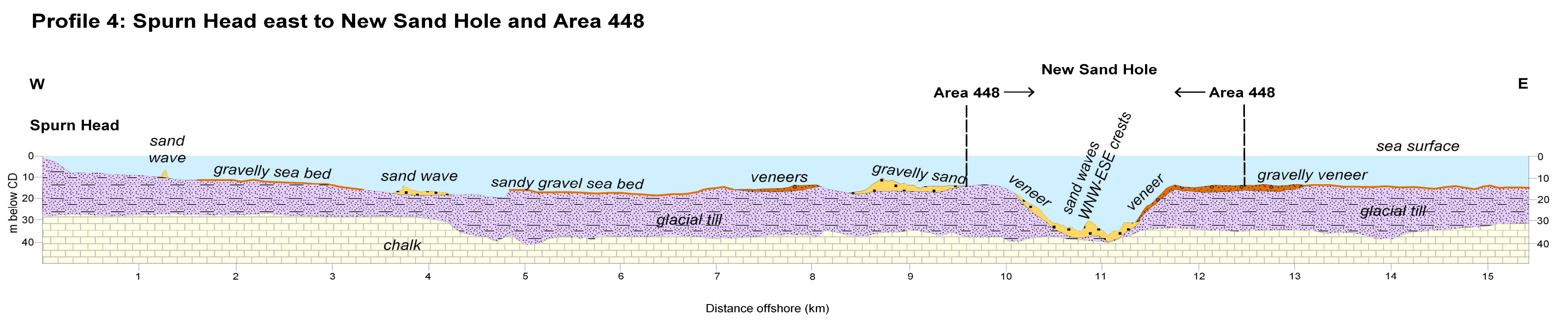


Date	By	Size	Version
Jun 11	NJG	A3	1
Projection		WGS 84 UTM31	
Scale		1:6,000	
QA		FMM	
3965 - fig_6.21 Humber_Spurn Head.mxd			
Produced by ABPmer Ltd			

ABP mer
marine environmental research

Humber side of Spurn Head

Figure 6.21



Date	By	Size	Version
July 11	NJG	A4	1
QA		FMM	

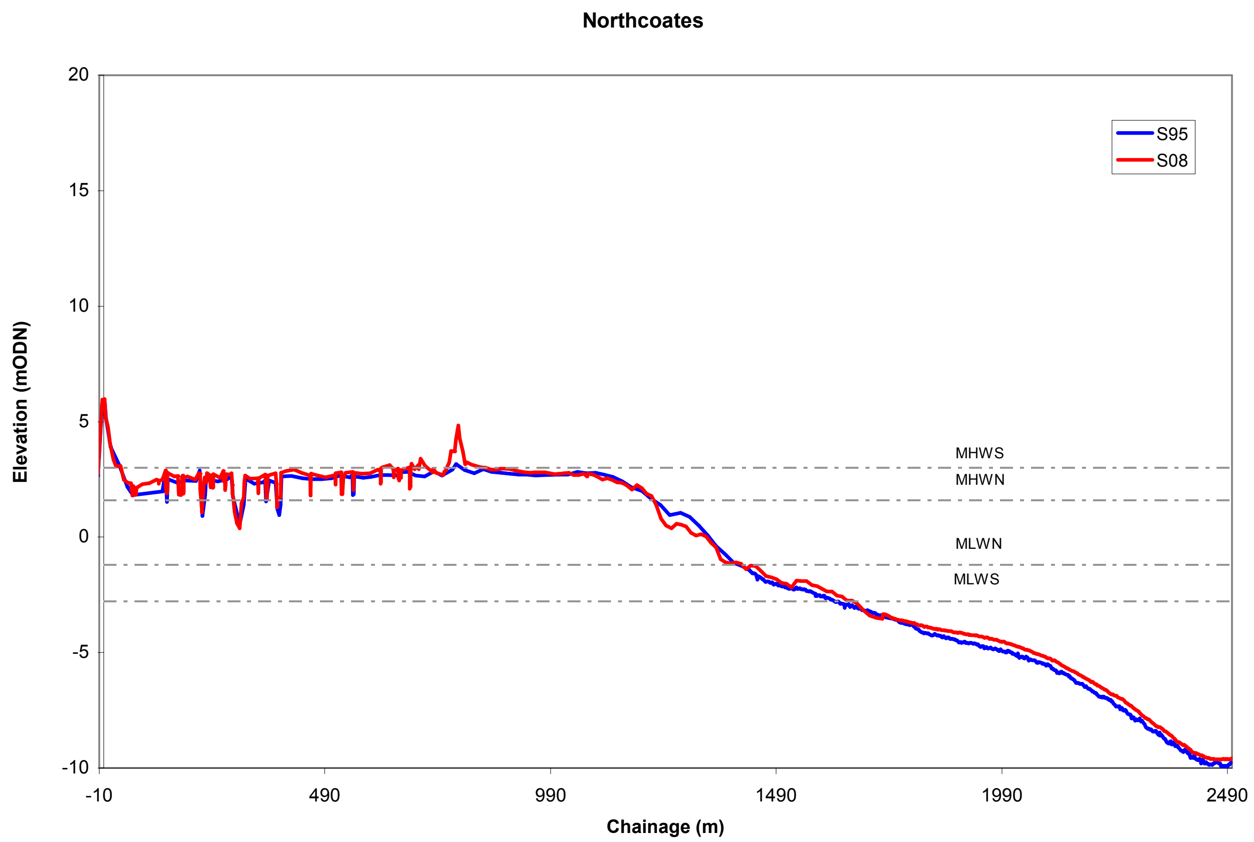
3965 – Figure6.22Profile4.ppt

Produced by ABPmer Ltd

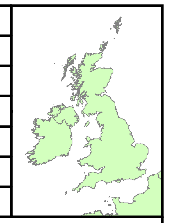
ABP mer marine environmental research

Subtidal profile 4

Figure 6.22



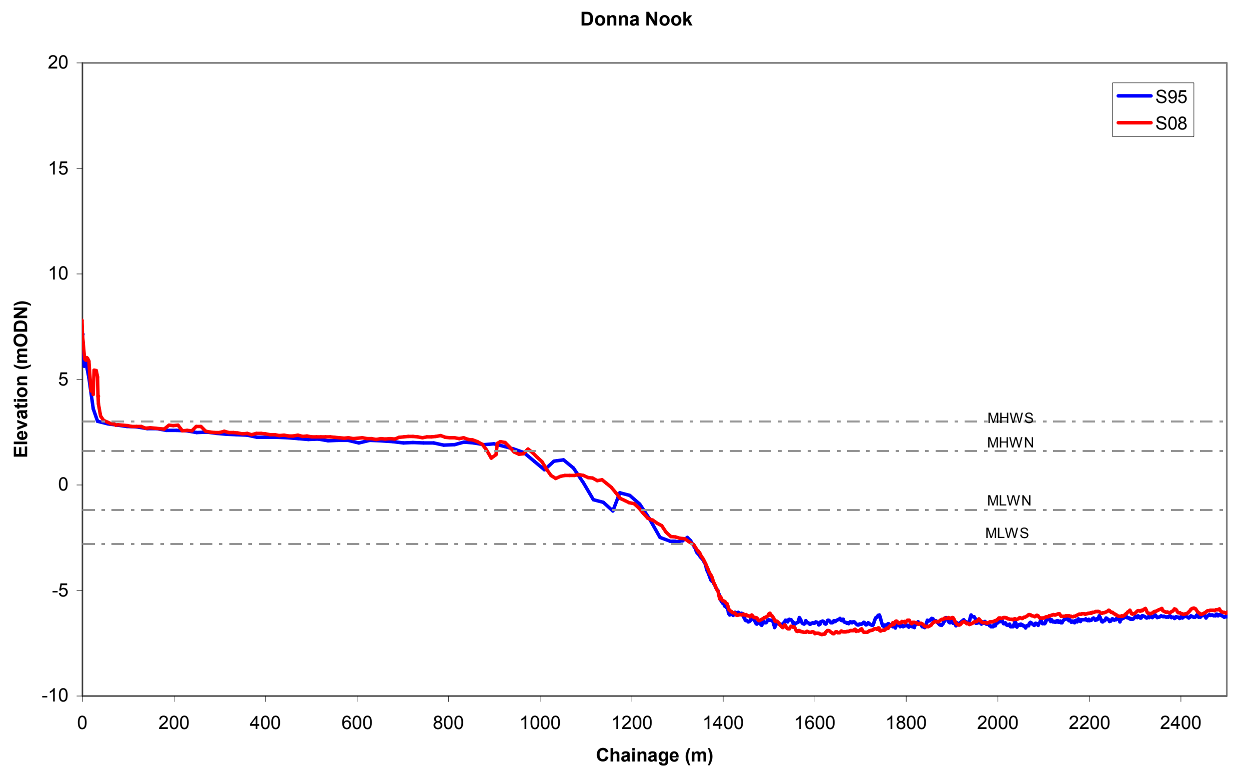
Date	By	Size	Version
Jun 11	NJG	A3	1
Projection		WGS 84 UTM31	
Scale		1:20,398	
QA		FMM	
3965 - fig_6.23_Northcoates.mxd			
Produced by ABPmer Ltd			



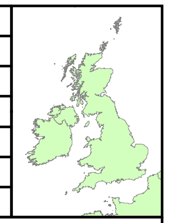
ABP mer
marine environmental research

Northcoates

Figure 6.23



Date	By	Size	Version
Jun 11	NJG	A3	1
Projection		WGS 84 UTM31	
Scale		1:12,000	
QA		FMM	
3965 - fig_6.24_DonnaNook.mxd			
Produced by ABPmer Ltd			

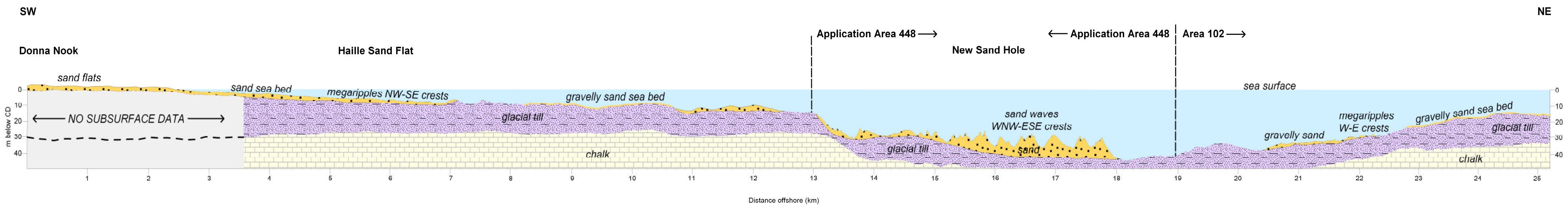


marine environmental research

Donna Nook

Figure 6.24

Profile 5: Donna Nook north east to New Sand Hole and Area 448 & 102



Date	By	Size	Version
July 11	NJG	A4	1
QA		FMM	

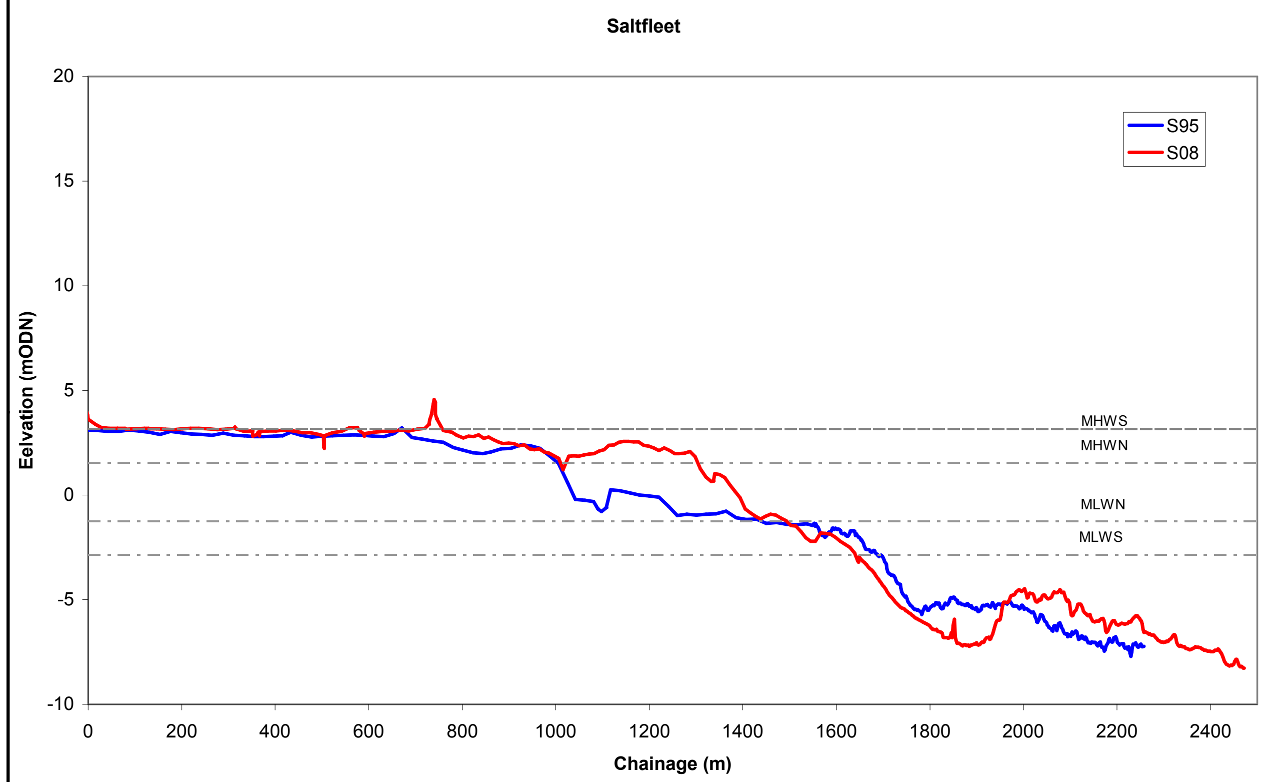
3965 – Figure6.25Profile5.ppt

Produced by ABPmer Ltd

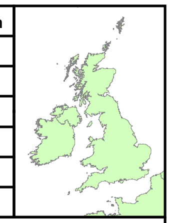
marine environmental research

Subtidal profile 5

Figure 6.25



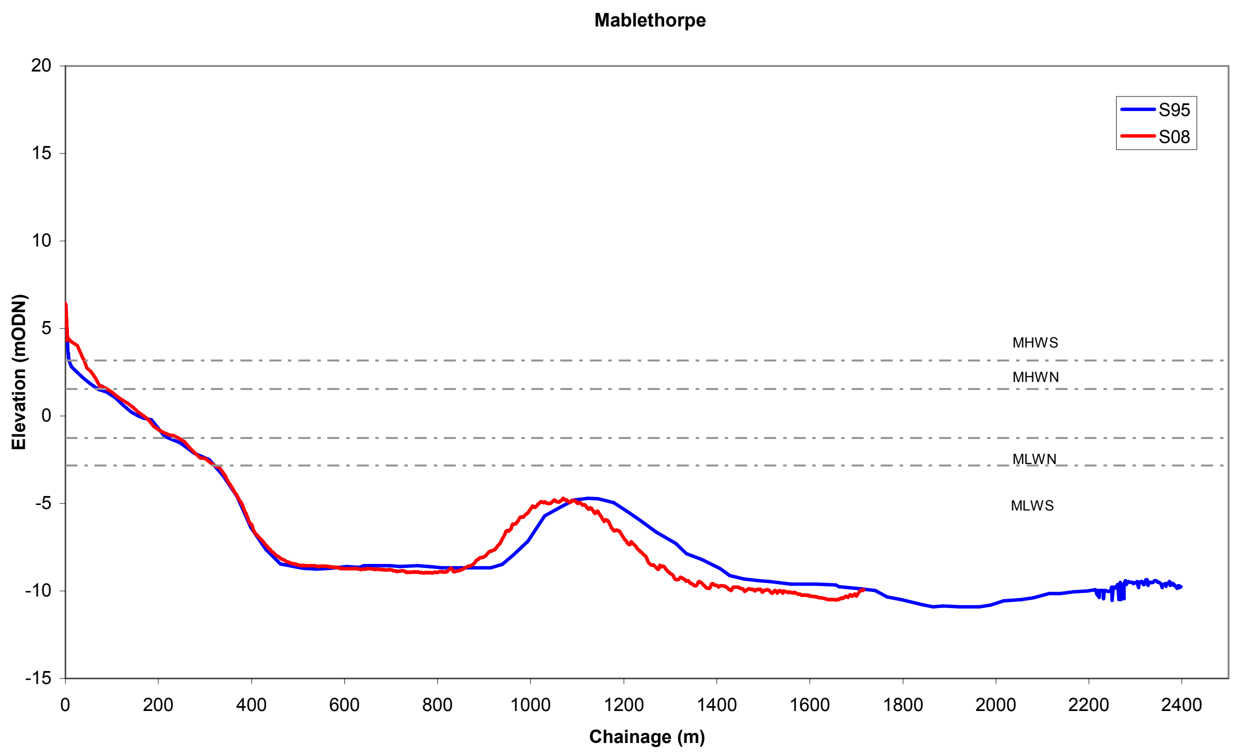
Date	By	Size	Version
Jun 11	NJG	A3	1
Projection		WGS 84 UTM31	
Scale		1:12,000	
QA		FMM	
3965 - fig_6.26_Saltfleet.mxd			
Produced by ABPmer Ltd			



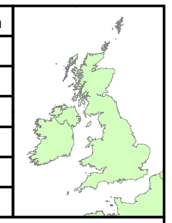
ABP mer
marine environmental research

Saltfleet

Figure 6.26



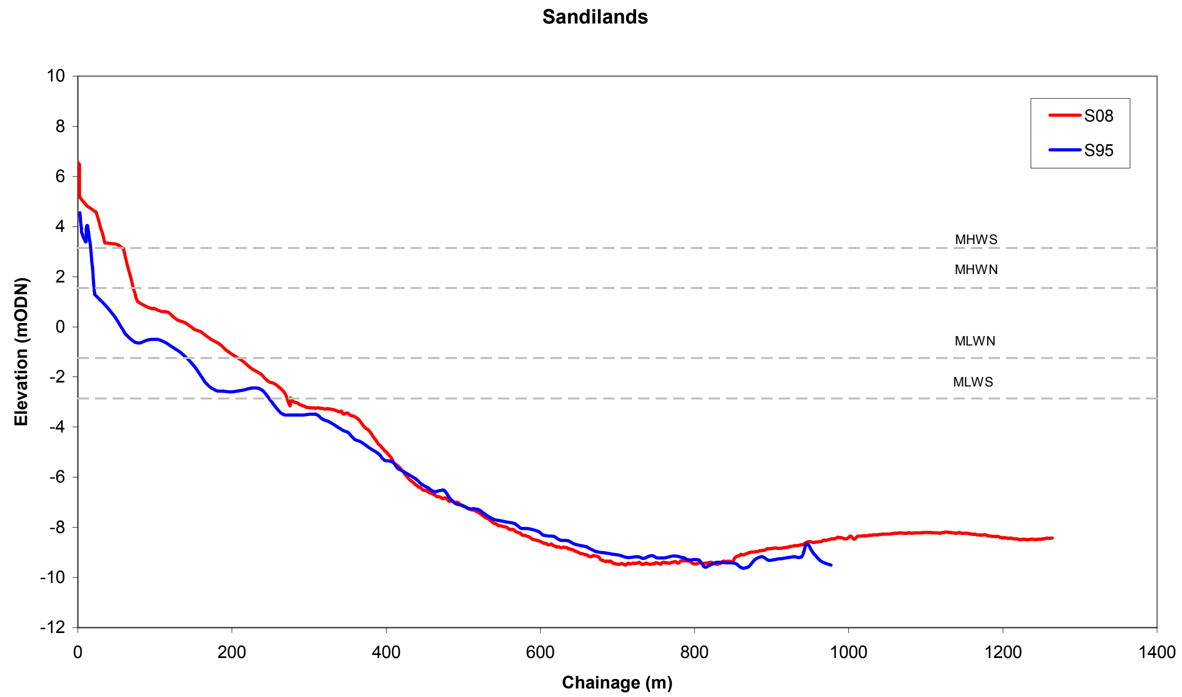
Date	By	Size	Version
Jun 11	NJG	A3	1
Projection	WGS 84 UTM31		
Scale	1:12,000		
QA	FMM		
3965 - fig_6.27 Mablethorpe.mxd			
Produced by ABPmer Ltd			



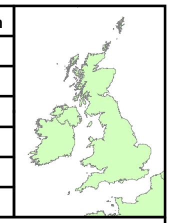
ABP mer
marine environmental research

Mablethorpe

Figure 6.27



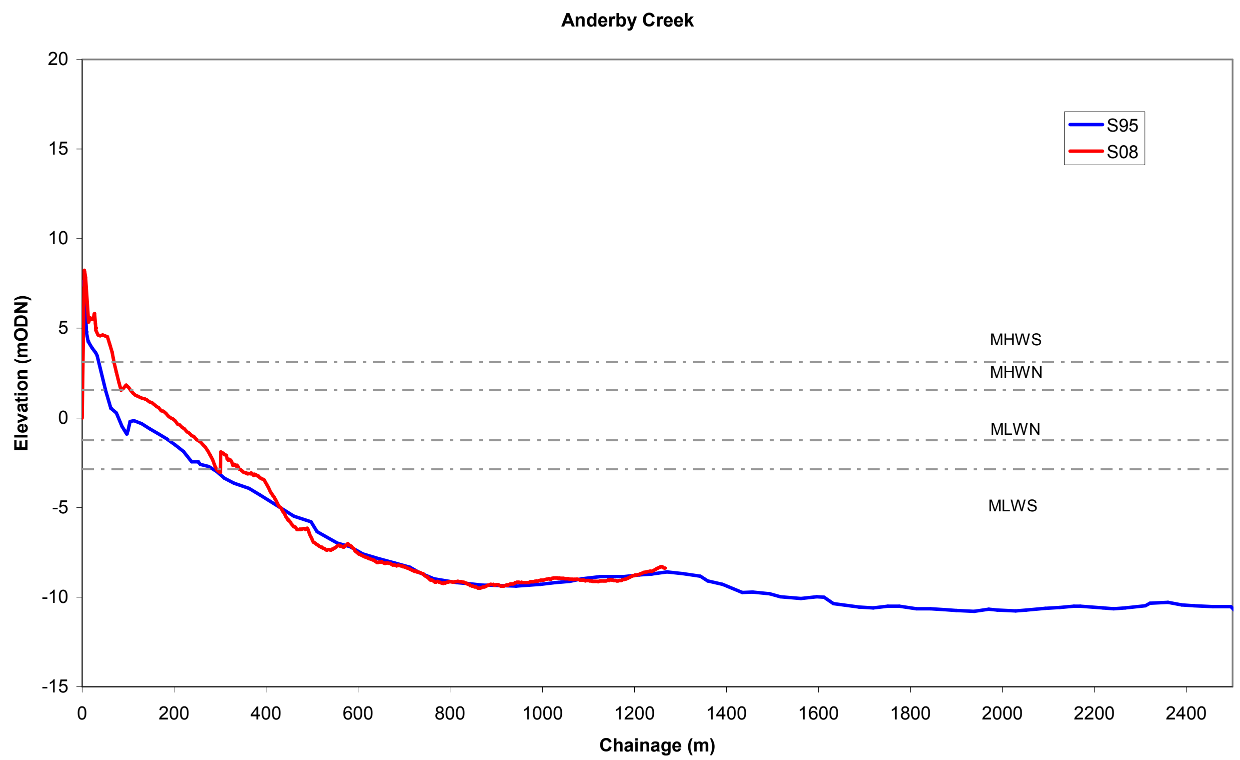
Date	By	Size	Version
Jun 11	NJG	A3	1
Projection	WGS 84 UTM31		
Scale	1:12,000		
QA	FMM		
3965 - fig_6.28_Sandilands.mxd			
Produced by ABPmer Ltd			



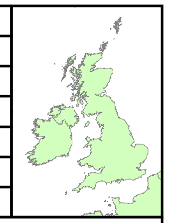
ABP mer
marine environmental research

Sandilands

Figure 6.28



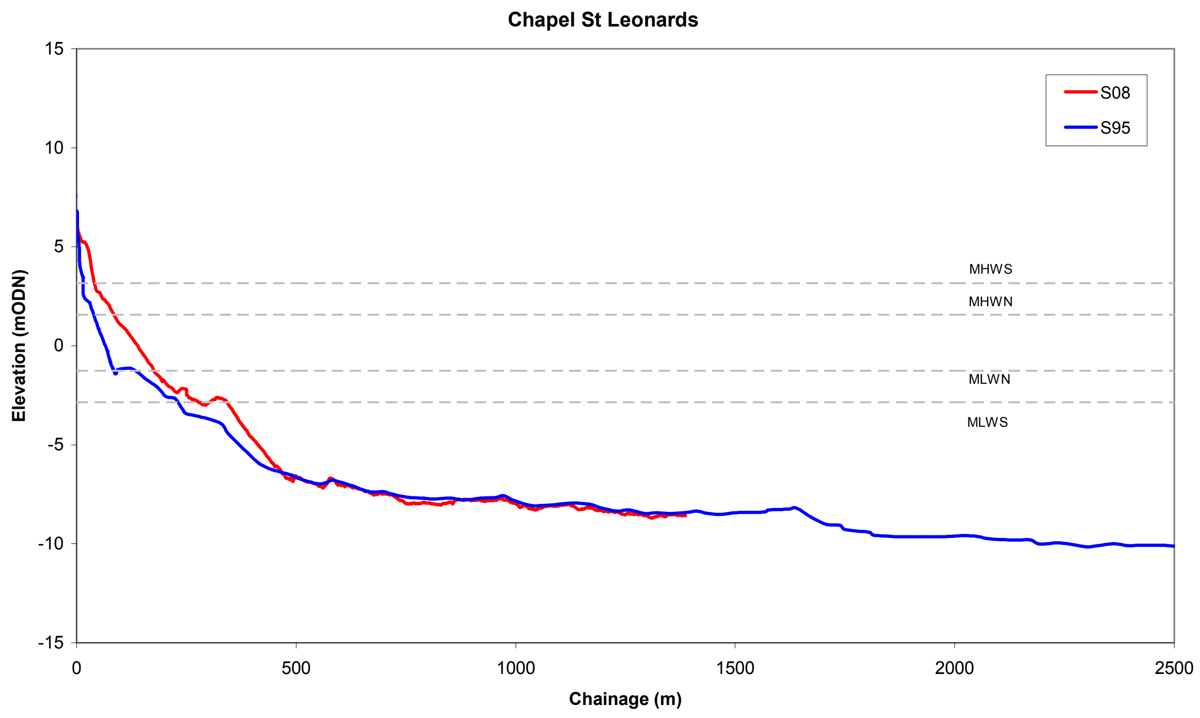
Date	By	Size	Version
Jun 11	NJG	A3	1
Projection		WGS 84 UTM31	
Scale		1:12,000	
QA		FMM	
3965 - fig_6.29_AnderbyCreek.mxd			
Produced by ABPmer Ltd			

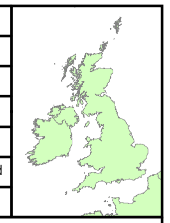


ABP mer marine environmental research

Anderby Creek

Figure 6.29

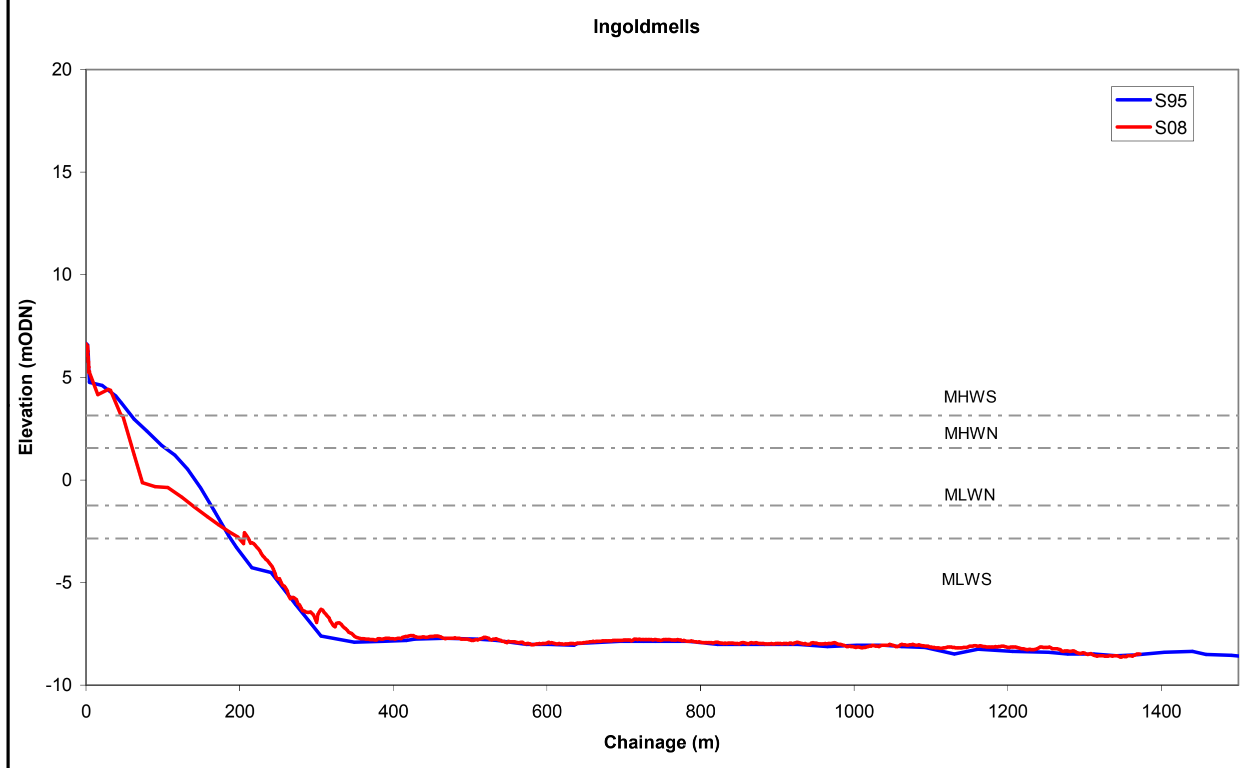




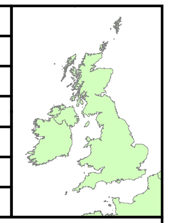
Date	By	Size	Version
Jun 11	NJG	A3	1
Projection		WGS 84 UTM31	
Scale		1:12,000	
QA		FMM	
3965 - fig_6.30_ChapelStLeonards.mxd			
Produced by ABPmer Ltd			

Chapel St Leonards

Figure 6.30



Date	By	Size	Version
Jun 11	NJG	A3	1
Projection		WGS 84 UTM31	
Scale		1:12,000	
QA		FMM	



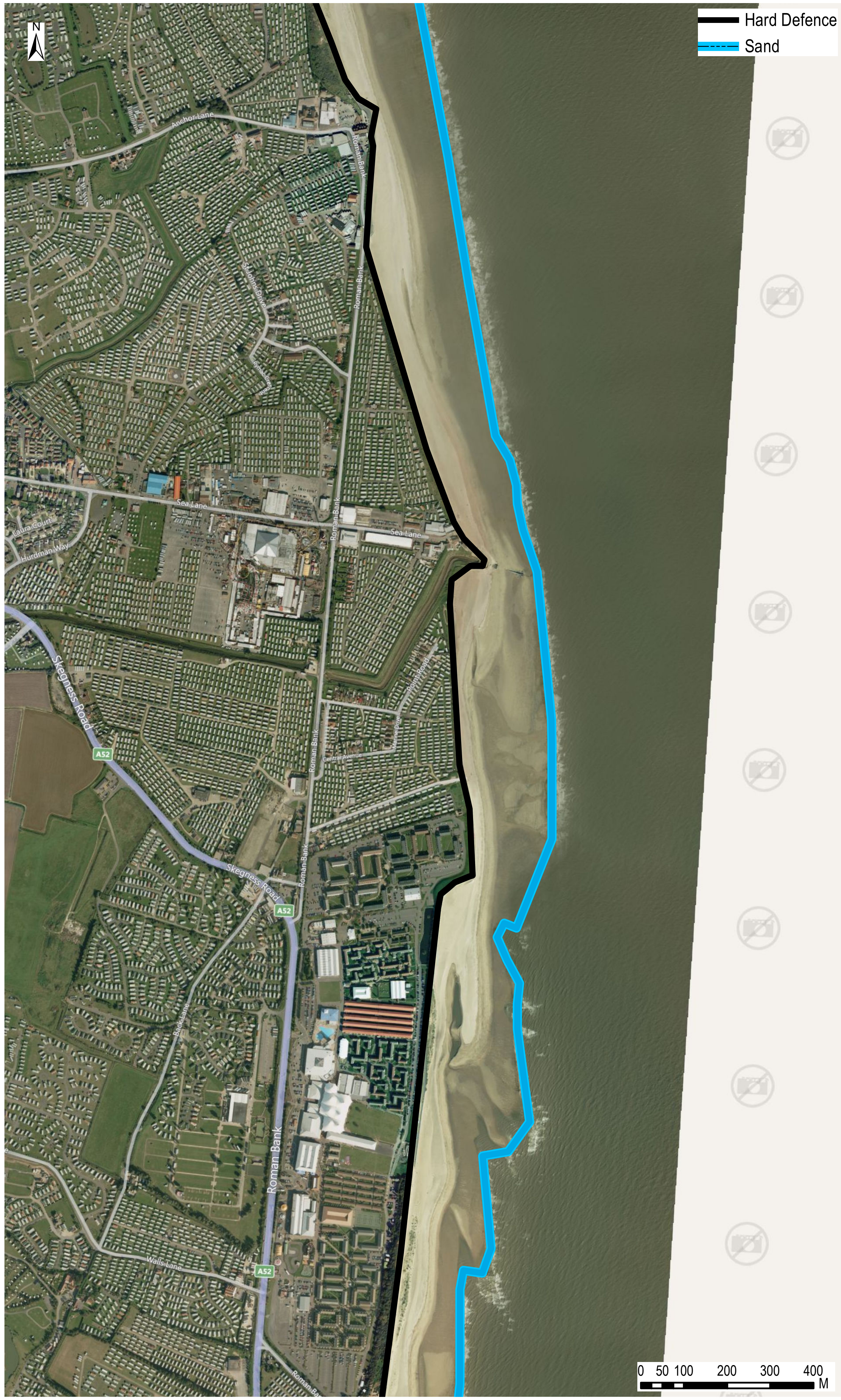
3965 - fig_6.31_Ingoldmells.mxd

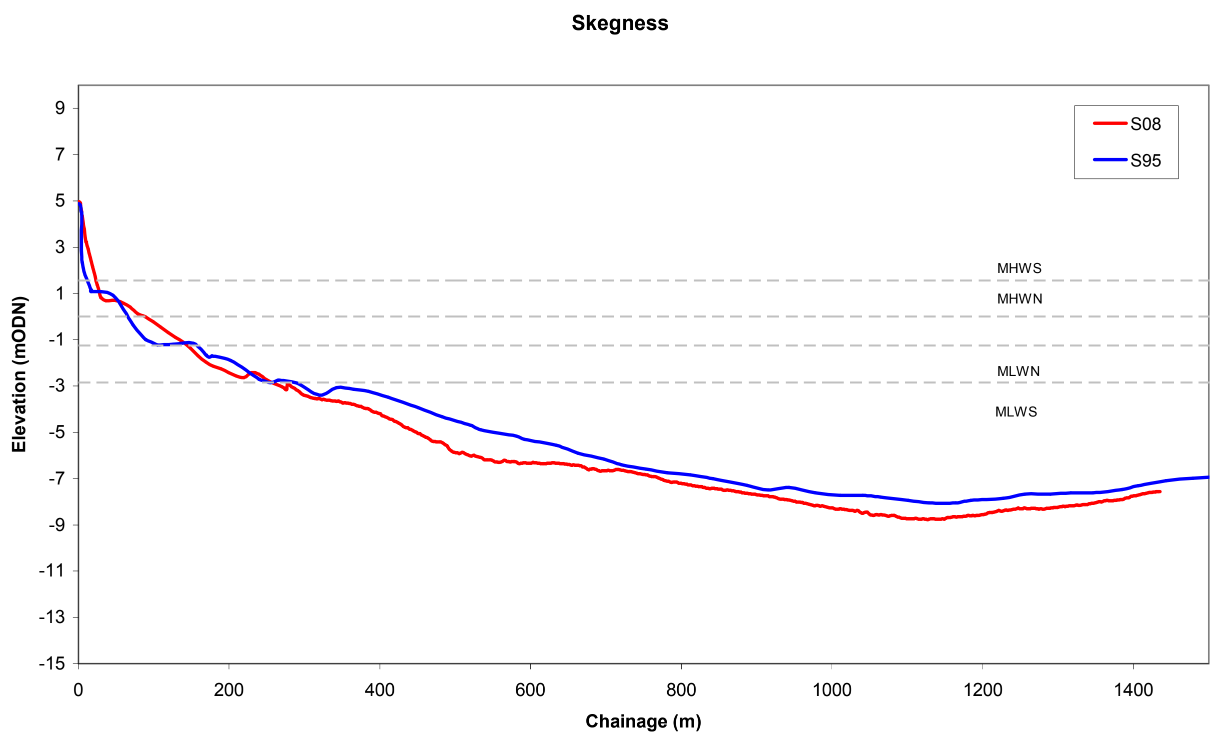
Produced by ABPmer Ltd

ABP mer marine environmental research

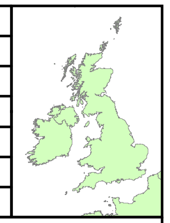
Ingoldmells

Figure 6.31





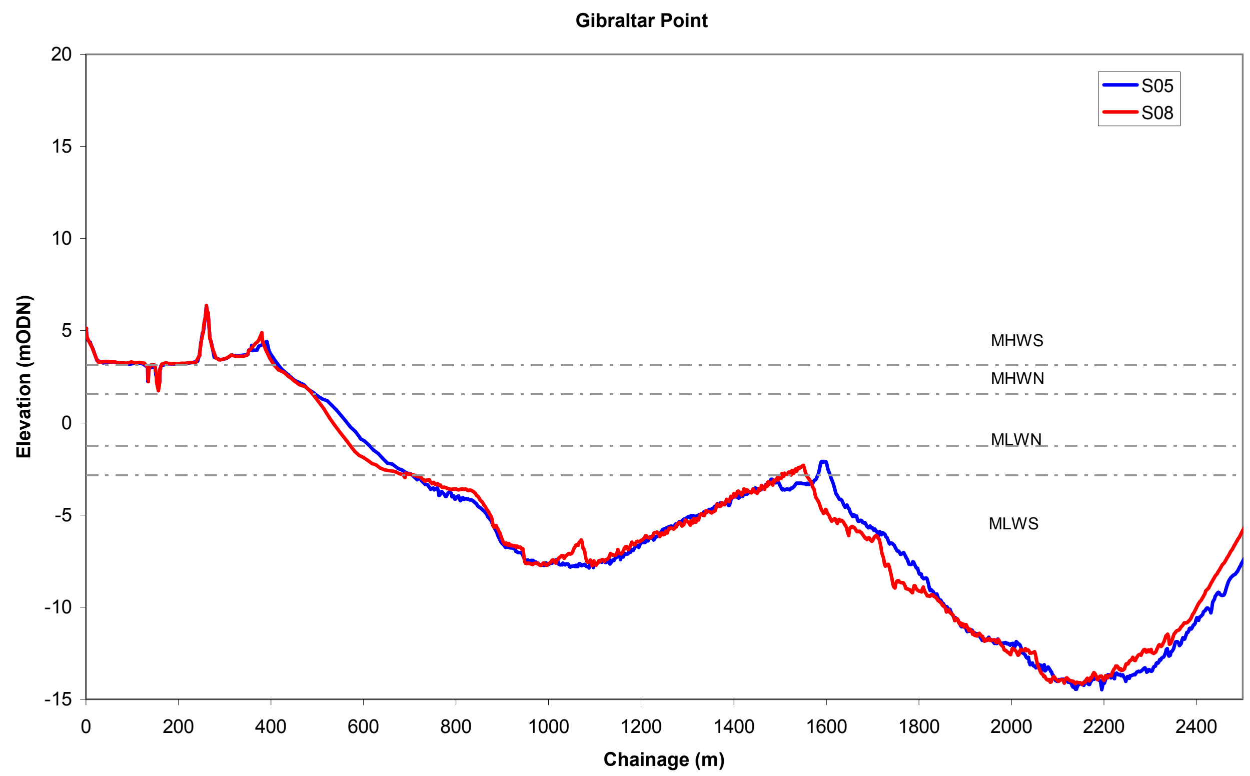
Date	By	Size	Version
Jun 11	NJG	A3	1
Projection		WGS 84 UTM31	
Scale		1:12,000	
QA		FMM	
3965 - fig_6.32_Skegness.mxd			
Produced by ABPmer Ltd			

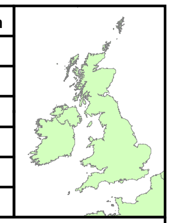


ABP mer
marine environmental research

Skegness

Figure 6.32





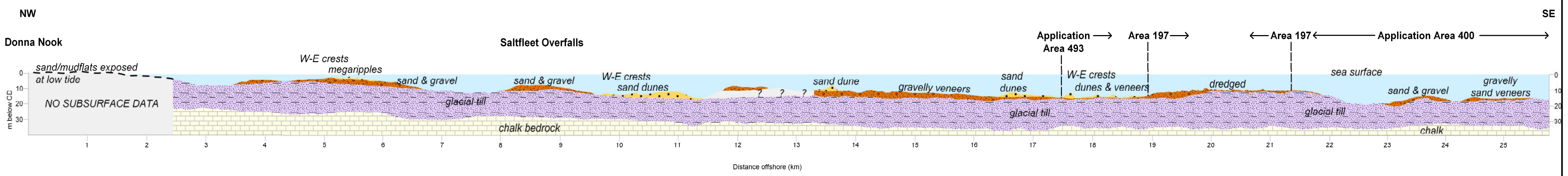
Date	By	Size	Version
Jun 11	NJG	A3	1
Projection	WGS 84 UTM31		
Scale	1:12,000		
QA	FMM		
3965 - fig_6.33 GibralterPt.mxd			
Produced by ABPmer Ltd			

marine environmental research

Gibralter Point

Figure 6.33

Profile 6: Donna Nook south east to Protector Overfalls, Area 197 and Area 400



Date	By	Size	Version
July 11	NJG	A4	1
QA		FMM	

3965 – Figure6.34Profile6.ppt

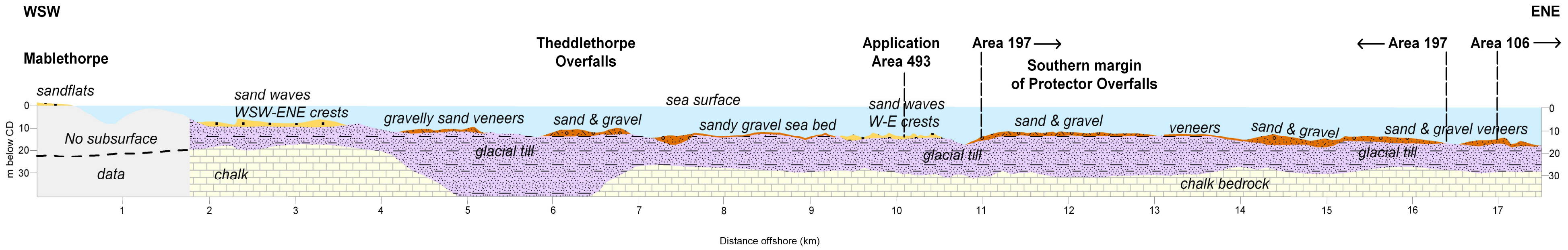
Produced by ABPmer Ltd

ABP mer marine environmental research

Subtidal profile 6

Figure 6.34

Profile 7: Mablethorpe ENE to Protector Overfalls, Area 493 & 197



Date	By	Size	Version
July 11	NJG	A4	1
QA		FMM	

3965 – Figure6.35Profile7.ppt

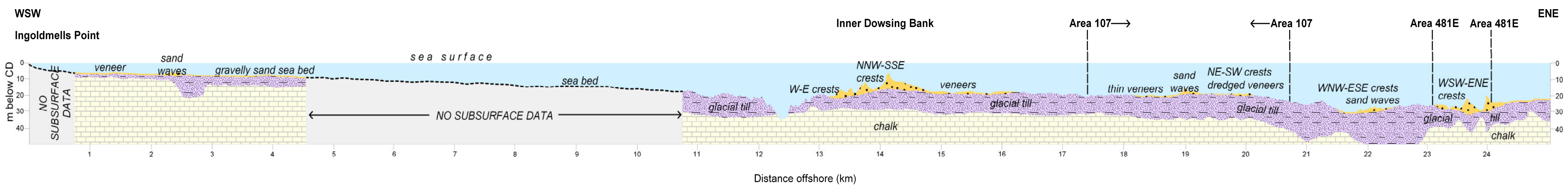
Produced by ABPmer Ltd

ABP mer marine environmental research

Subtidal profile 7

Figure 6.35

Profile 8: Ingoldmells Point ENE to Inner Dowsing and Area 481



Date	By	Size	Version
July 11	NJG	A3	1
QA		FMM	

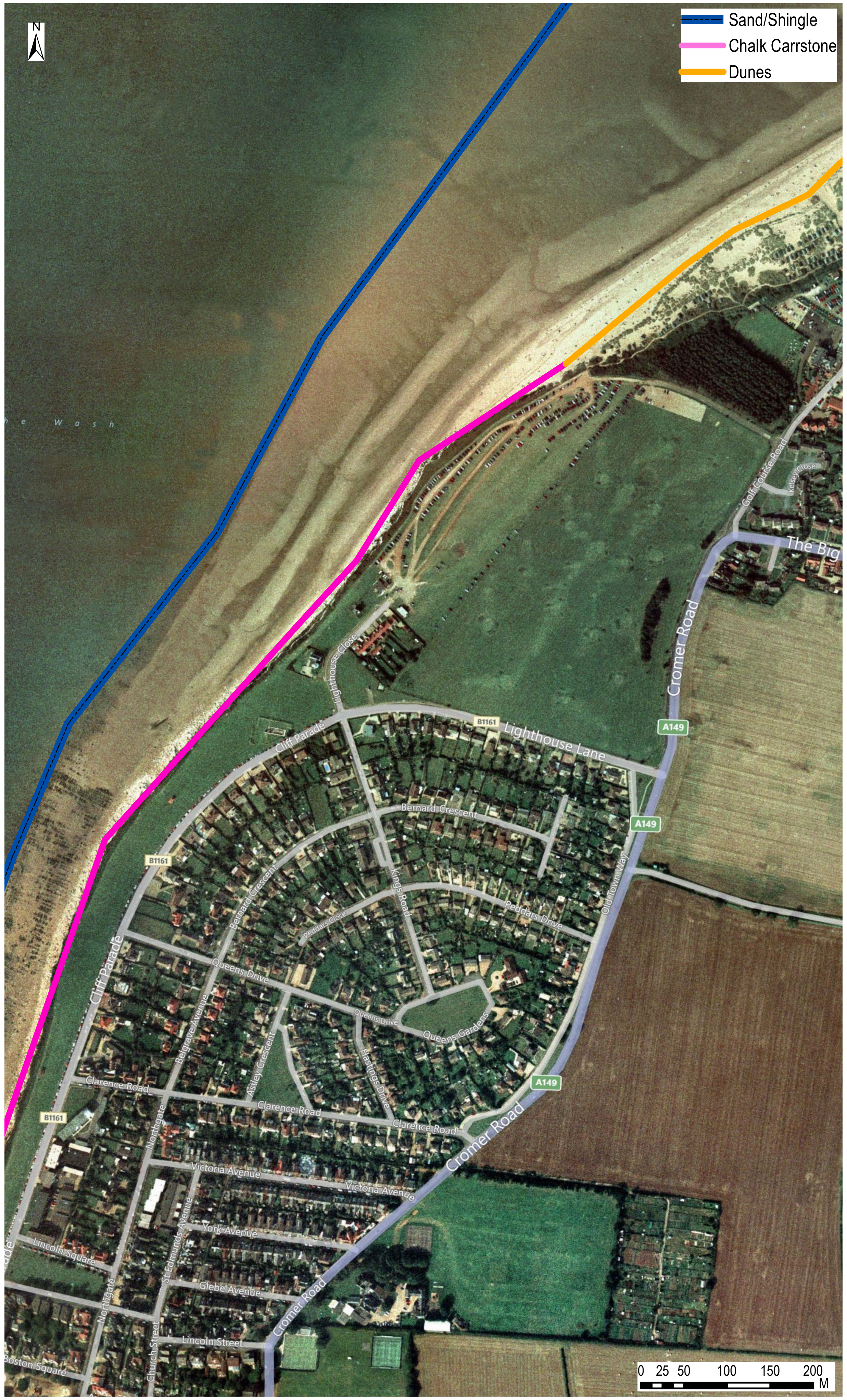
3965 – Figure6.36Profile8.ppt

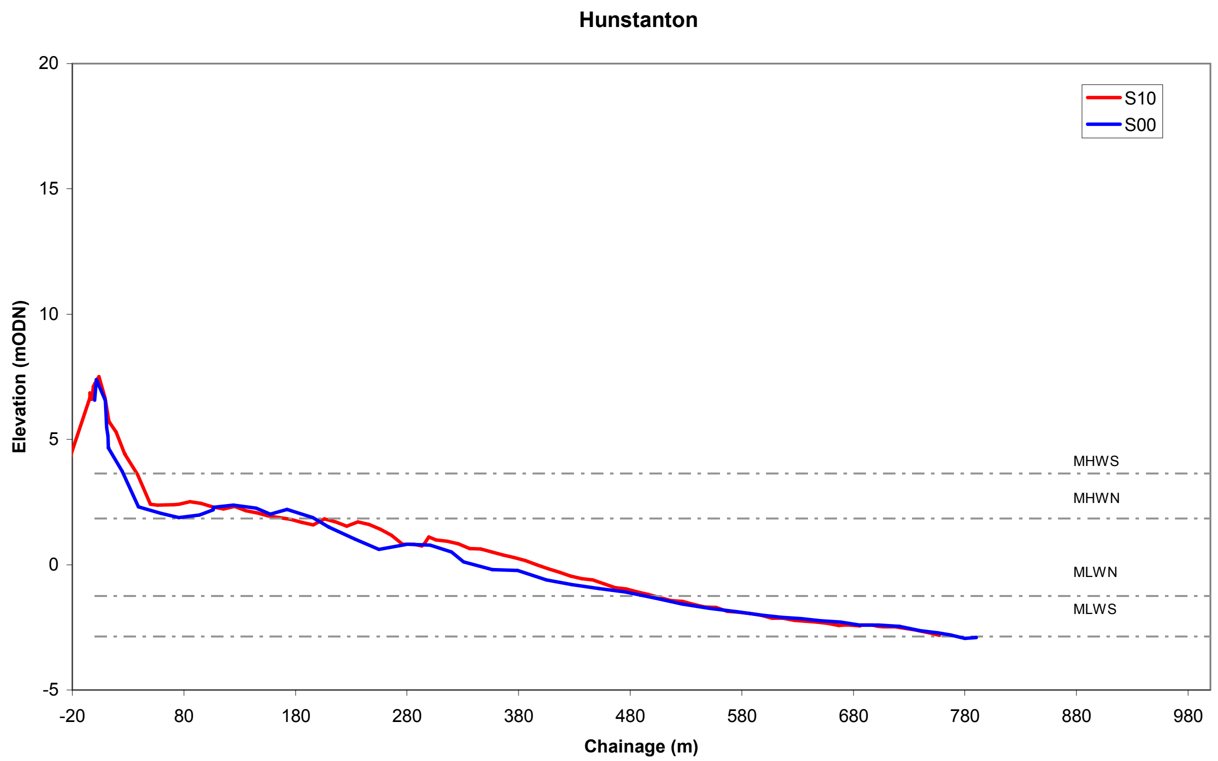
Produced by ABPmer Ltd

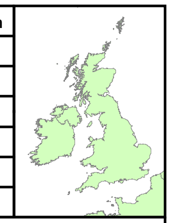
ABP mer marine environmental research

Subtidal profile 8

Figure 6.36





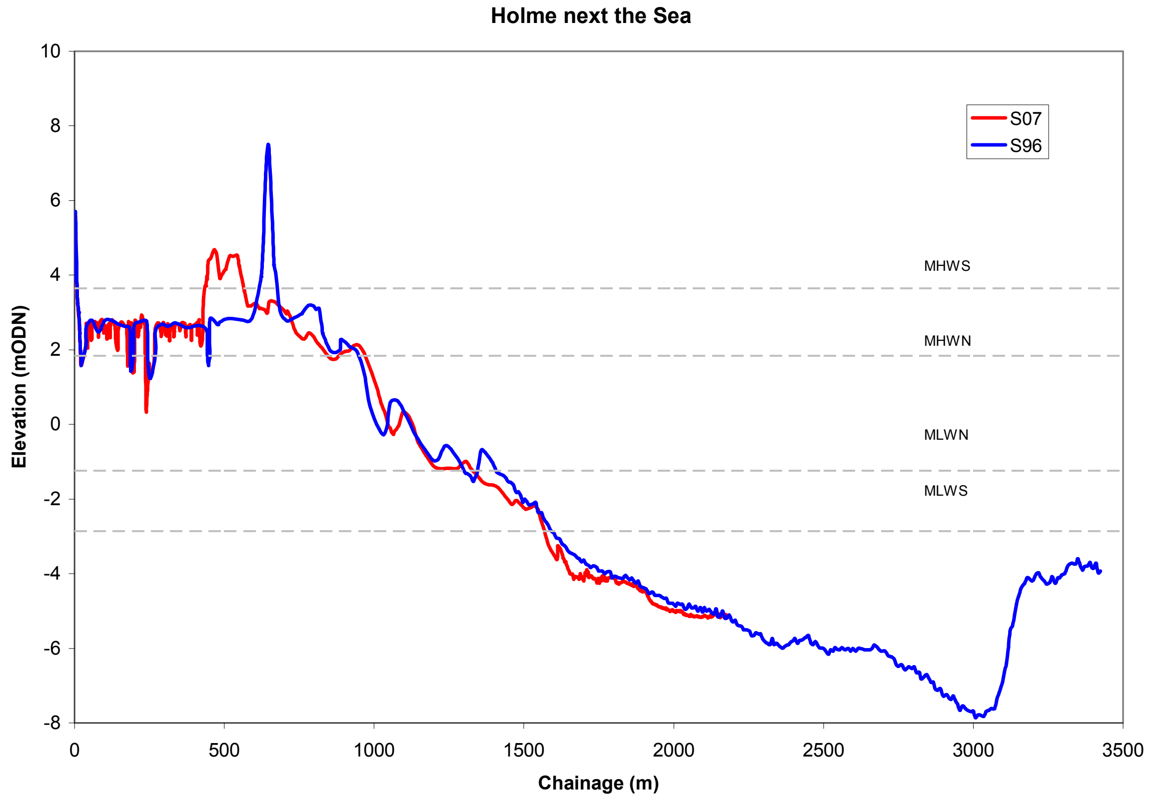


Date	By	Size	Version
Jun 11	NJG	A3	1
Projection		WGS 84 UTM31	
Scale		1:6,000	
QA		FMM	
3965 - fig_6.37 Hunstanton.mxd			
Produced by ABPmer Ltd			

ABP mer
marine environmental research

Hunstanton

Figure 6.37

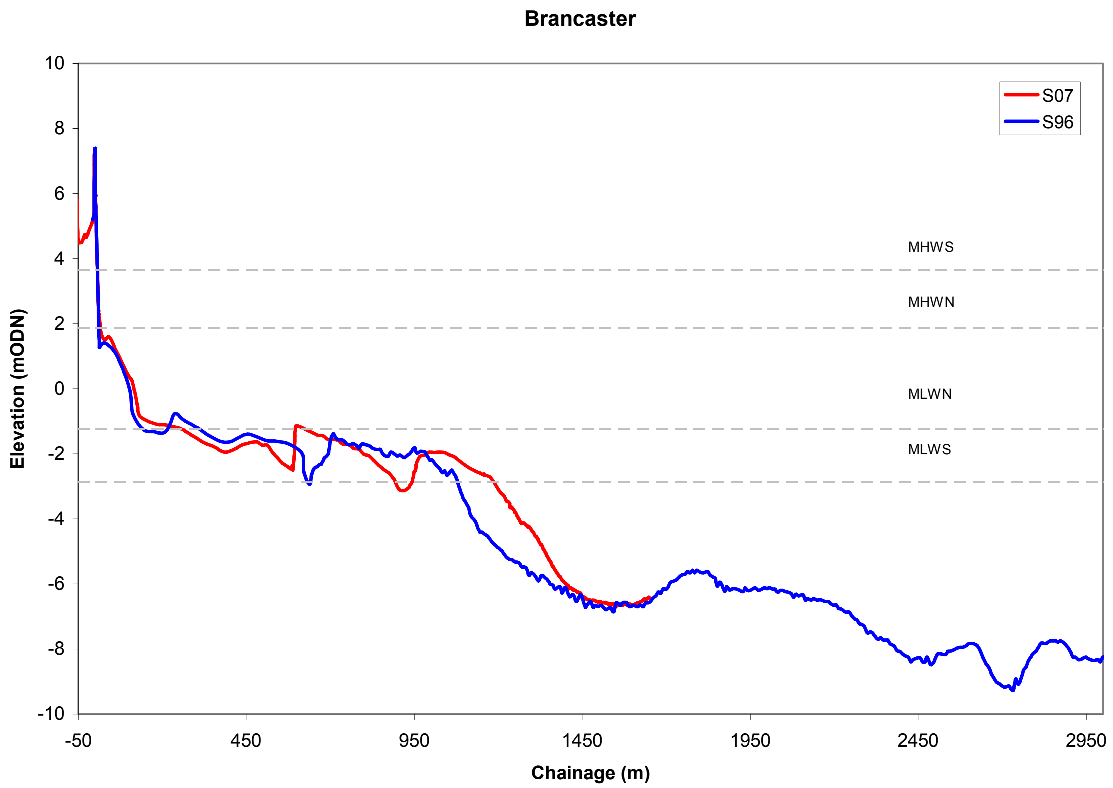


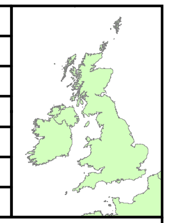
Date	By	Size	Version
Jun 11	NJG	A3	1
Projection		WGS 84 UTM31	
Scale		1:6,000	
QA		FMM	
3965 - fig_6.38 Holme-Next-the-Sea.mxd			
Produced by ABPmer Ltd			

ABP mer
marine environmental research

Holme Next the Sea

Figure 6.38



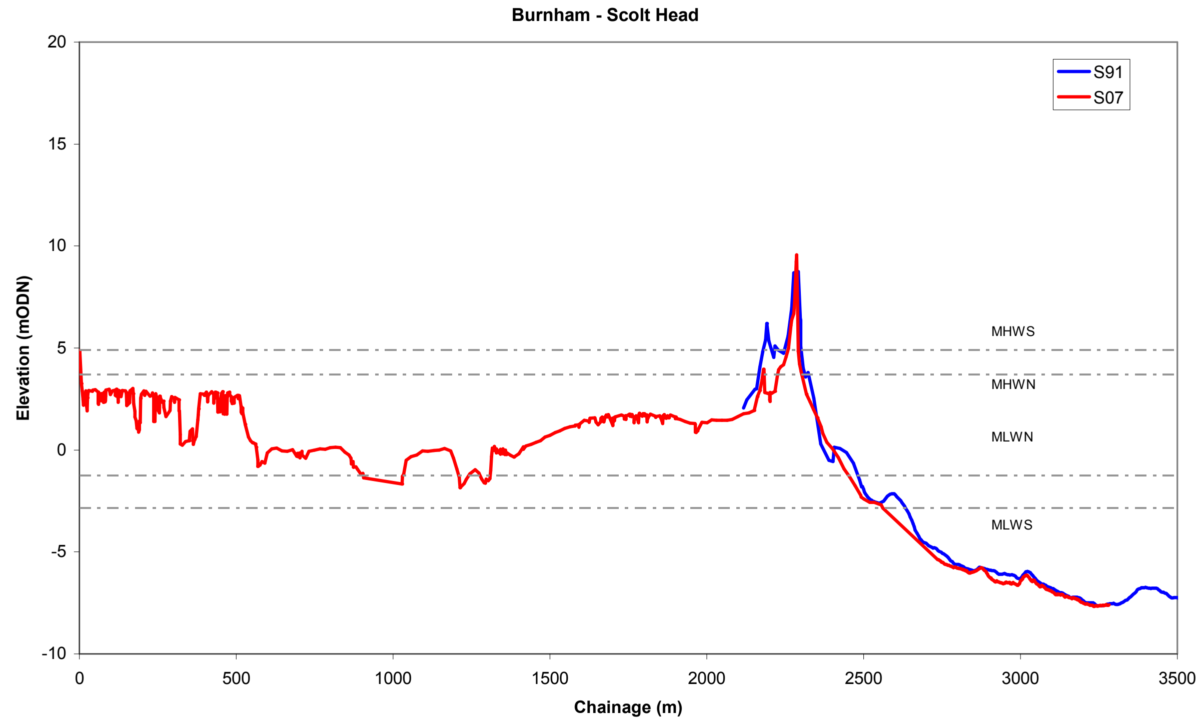


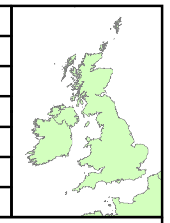
Date	By	Size	Version
July 11	NJG	A3	1
Projection		WGS 84 UTM31	
Scale		1:12,000	
QA		FMM	
3965 - fig_6.39 Brancaster.mxd			
Produced by ABPmer Ltd			

ABP mer
marine environmental research

Brancaster

Figure 6.39



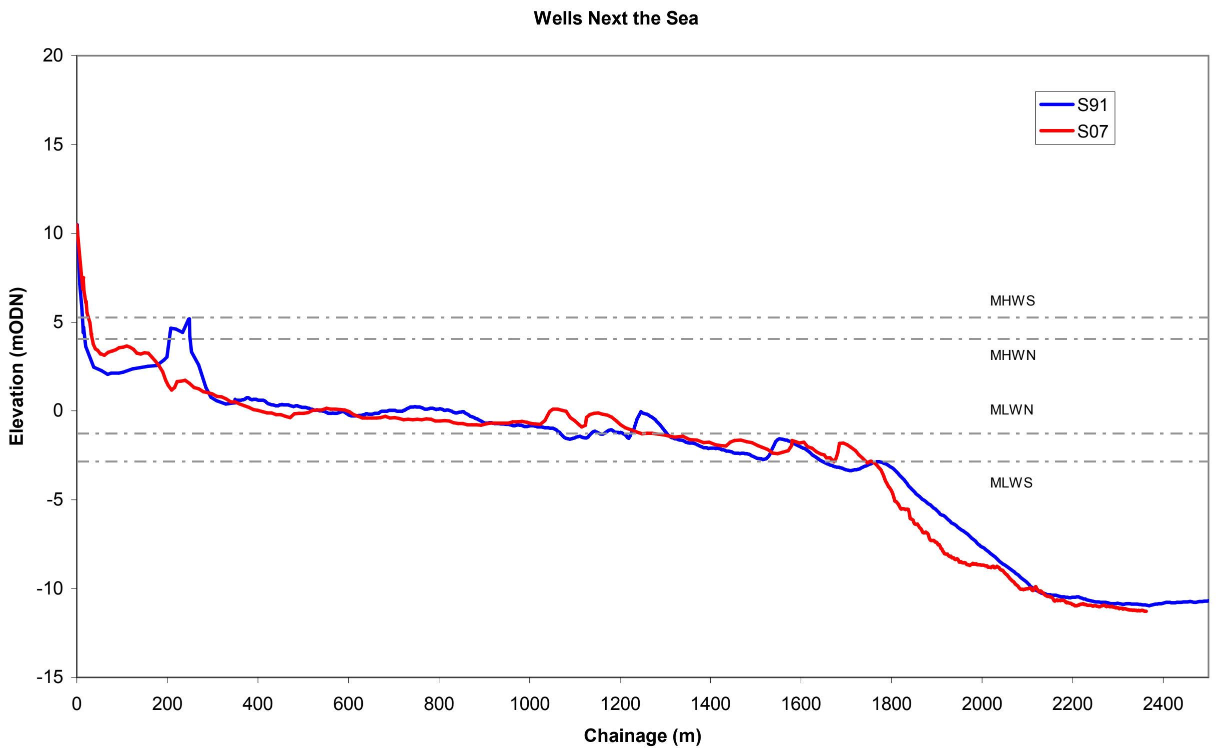


Date	By	Size	Version
Jun 11	NJG	A3	1
Projection		WGS 84 UTM31	
Scale		1:12,000	
QA		FMM	
3965 - fig_6.40 Scolt.mxd			
Produced by ABPmer Ltd			

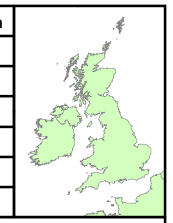
ABP mer
marine environmental research

Scolt Head Island

Figure 6.40



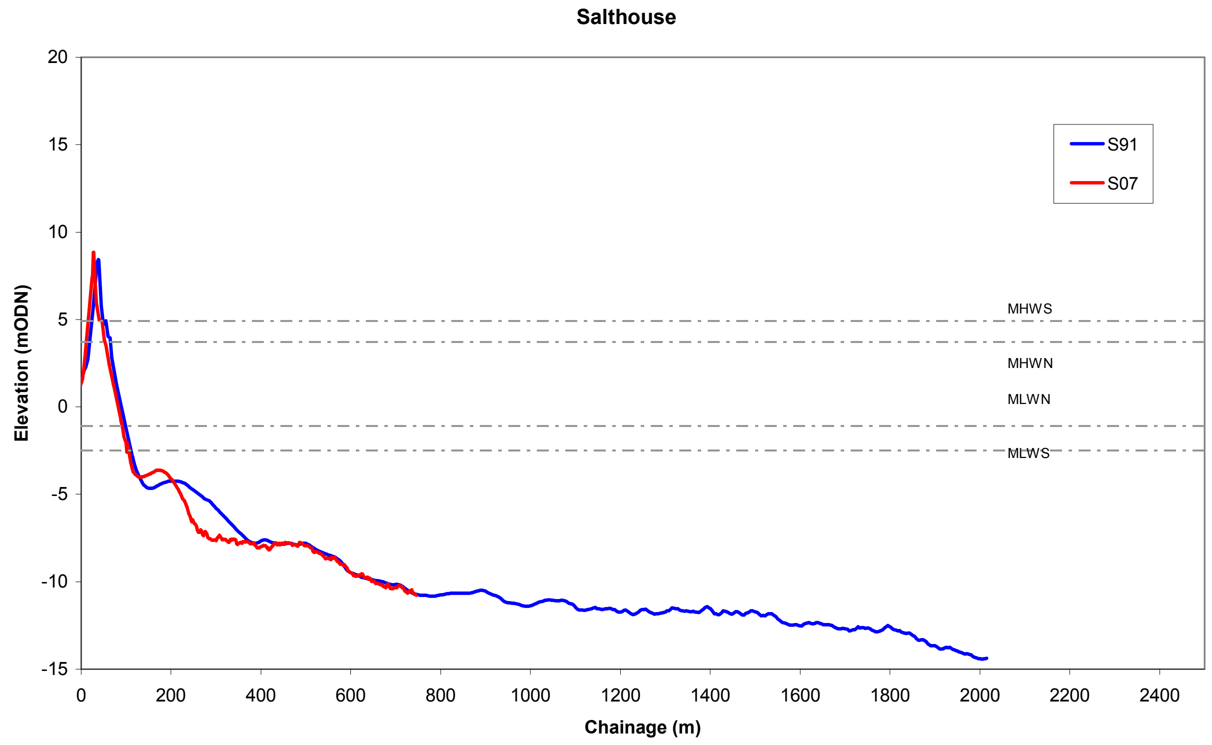
Date	By	Size	Version
Jun 11	NJG	A3	1
Projection	WGS 84 UTM31		
Scale	1:12,000		
QA	FMM		
3965 - fig_6.41 WellsnextheSea.mxd			
Produced by ABPmer Ltd			



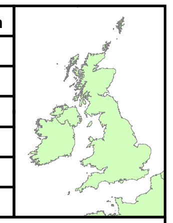
ABP mer marine environmental research

Wells Next The Sea

Figure 6.41



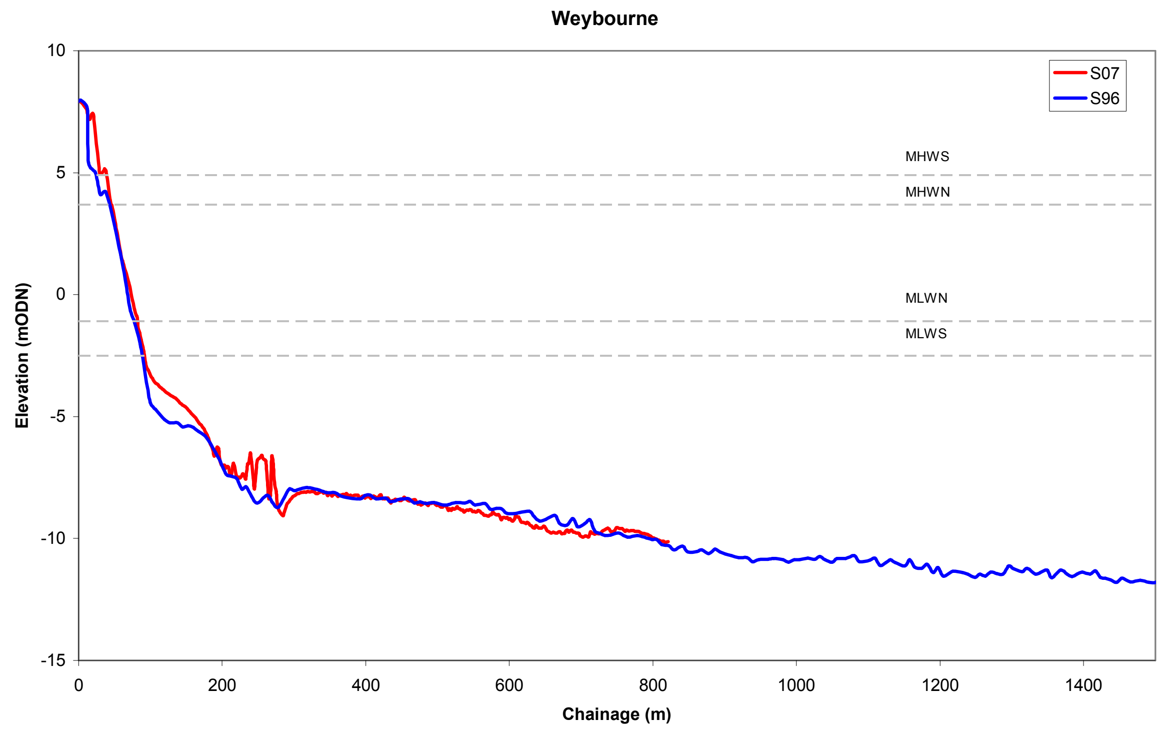
Date	By	Size	Version
Jun 11	NJG	A3	1
Projection		WGS 84 UTM31	
Scale		1:6,000	
QA		FMM	
3965 - fig_6.42 Salthouse.mxd			
Produced by ABPmer Ltd			

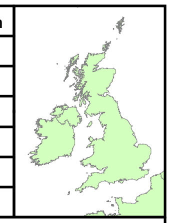


ABP mer
marine environmental research

Salthouse

Figure 6.42



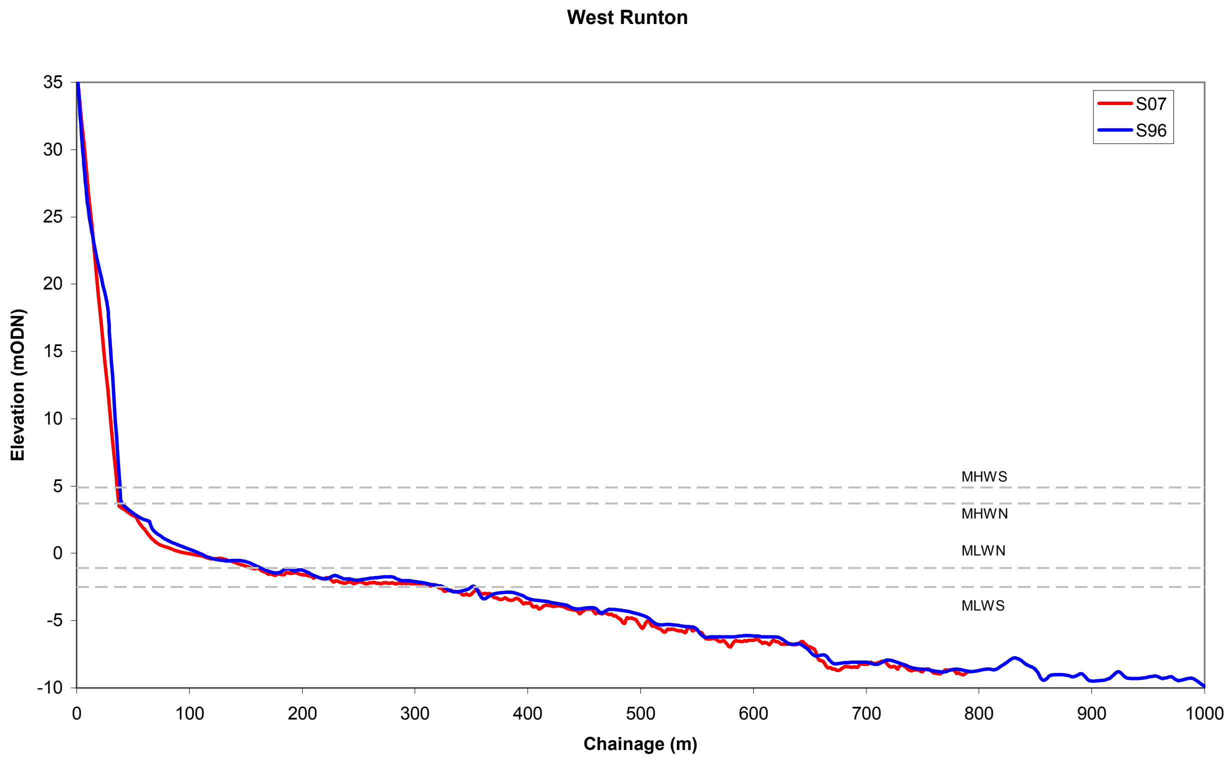


Date	By	Size	Version
Jun 11	NJG	A3	1
Projection		WGS 84 UTM31	
Scale		1:6,000	
QA		FMM	
3965 - fig_6.43 Weybourne.mxd			
Produced by ABPmer Ltd			

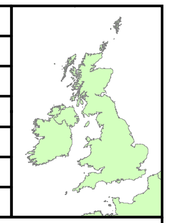
ABP mer
marine environmental research

Weybourne

Figure 6.43



Date	By	Size	Version
Jun 11	NJG	A3	1
Projection		WGS 84 UTM31	
Scale		1:6,000	
QA		FMM	
3965 - fig_6.44 West Runton.mxd			
Produced by ABPmer Ltd			

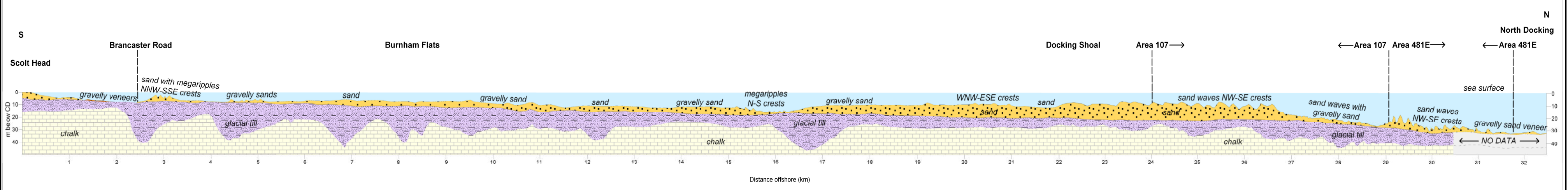


ABPmer marine environmental research

West Runton

Figure 6.44

Profile 9: Scolt Head, near Brancaster, north to Docking Shoal and Area 107 & 481



Date	By	Size	Version
July 11	NJG	A4	1
QA		FMM	

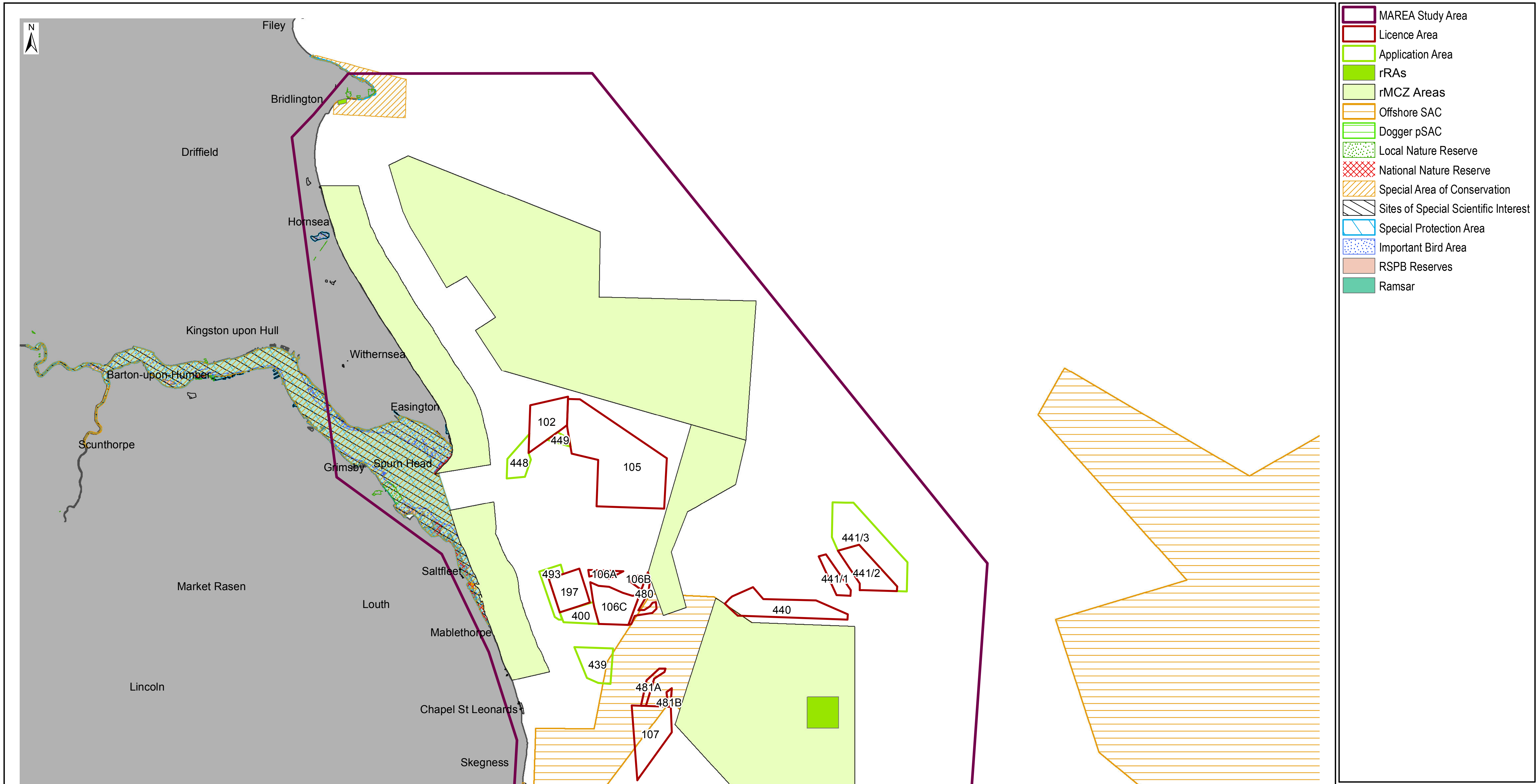
3965 – Figure6.45Profile9.ppt

Produced by ABPmer Ltd

marine environmental research

Subtidal profile 9

Figure 6.45



Date	By	Size	Version
Aug 11	NJG	A3	2
Projection		WGS84 UTM31	
Scale		1:623,518	
QA		FMM	

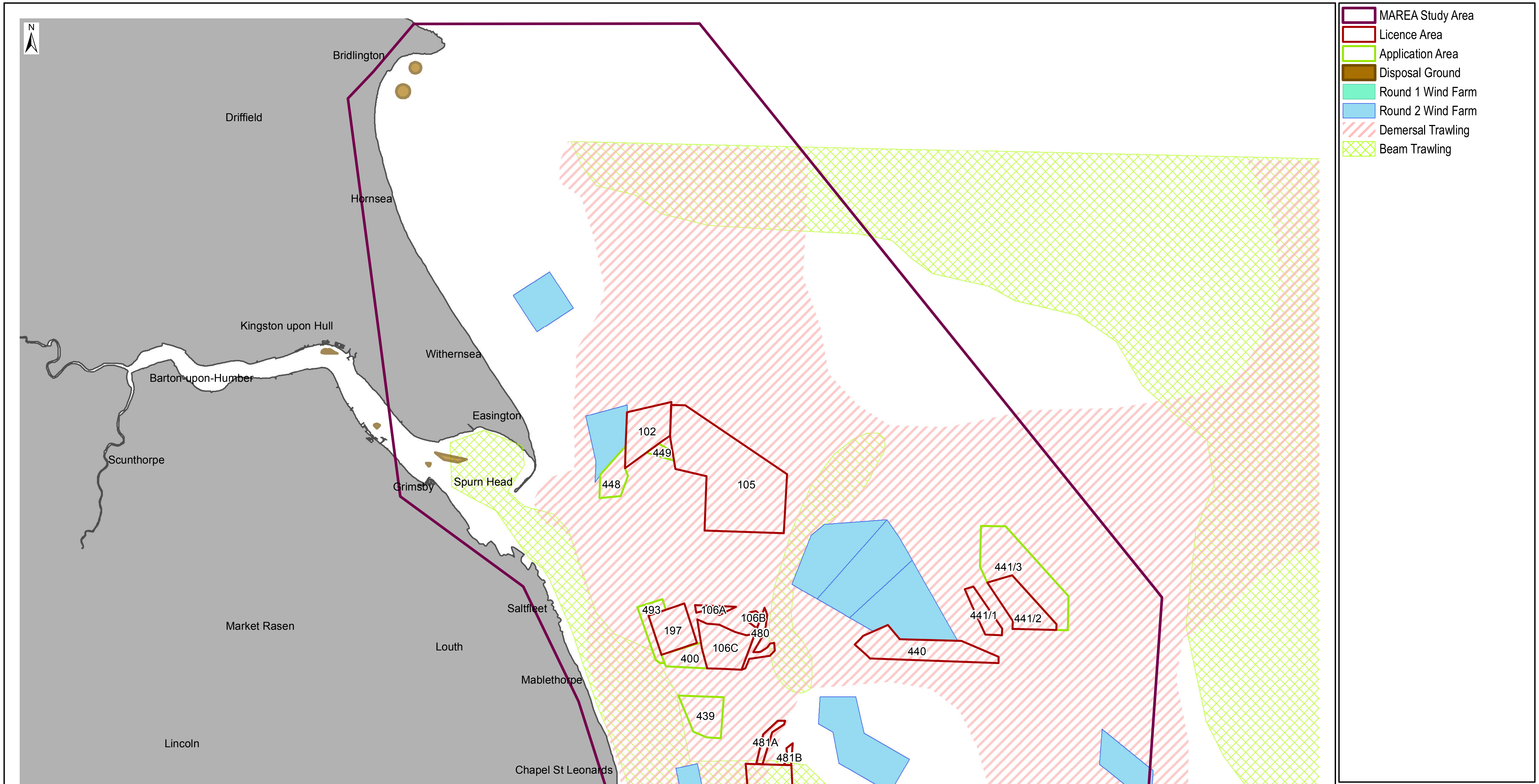
3965 - fig7.1_Env_designations.mxd

Produced by ABPmer Ltd

ABP mer
marine environmental research

Environmental Designations

Figure 7.1



Date	By	Size	Version
Aug 11	NJG	A3	1

Projection	WGS84 UTM31
Scale	1:532,689
QA	FMM

3965 - fig7.2_Commercial.mxd

Produced by ABPmer Ltd

ABP mer marine environmental research

Commercial Activities

Figure 7.2

ABP Marine Environmental Research Ltd (ABPmer)
Suite B, Waterside House, Town Quay, Southampton, Hampshire SO14 2AQ

T +44 (0)23 8071 1840
F +44 (0)23 8071 1841
E enquiries@abpmer.co.uk

www.abpmer.co.uk

Creating sustainable solutions for the marine environment