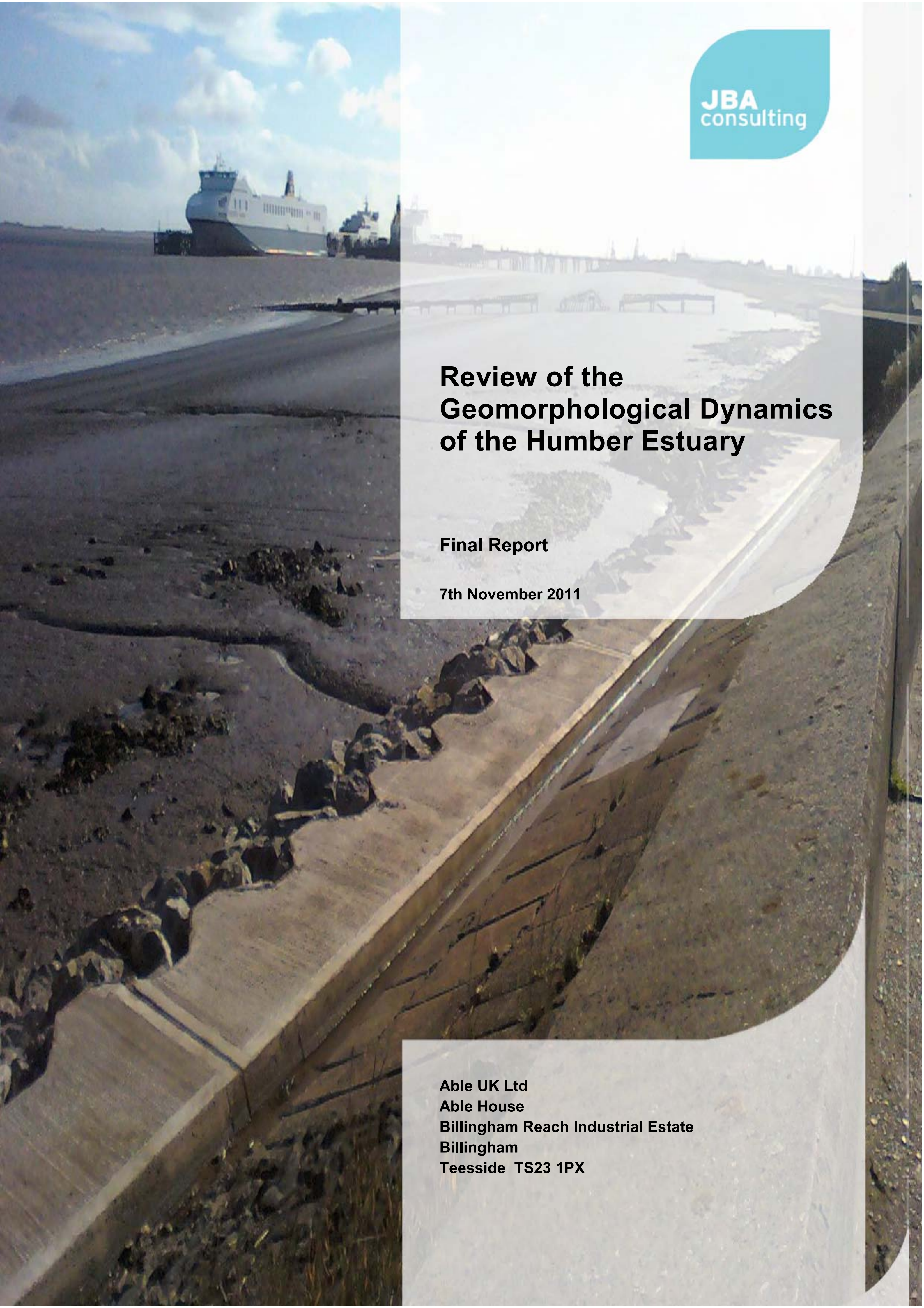
Annex 8.2

Review of the Geomorphological Dynamics of the Humber Estuary

(JBA Consulting)



Review of the Geomorphological Dynamics of the Humber Estuary

Final Report

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Revision History

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August 2011	Regulators & HR Wallingford comments addressed	Richard Cram
November 2011	Statements added following mitigation guidance	Richard Cram

Contract

This report describes work commissioned by Richard Cram, on behalf of Able UK. George Heritage of JBA Consulting carried out this work.

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Reviewed by .... Kevin Keating BEng MSc CEng MICE

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Purpose

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Executive Summary

This report summarises published studies concerned with the character and dynamics of the Humber Estuary, placing the contemporary Estuary in a long-term evolutionary context and detailing the drivers responsible for change in the Estuary today. It outlines the current magnitude of change and relates this to sediment transport processes with particular reference to suspended sediment. The overall dynamics are reviewed in the context of estuary habitats, considering their ability to respond to change.

It is clear from the review that the Humber Estuary is presently highly dynamic with submerged morphology change occurring throughout the Estuary. Freshwater inflows strongly influence dynamics in the Inner Estuary, the dynamics of the turbidity maximum affect the Middle Estuary and large scale general circulations impact on Outer Estuary morphology. The present restrictions on lateral development are imposing significant pressure on intertidal saltmarsh with mudflat development currently dominant. Managed realignment sites, promoting intertidal habitat development should help to mitigate against any local mudflat / saltmarsh loss although sedimentation rates and biotic colonisation appear variable.

The following key points emerged from the study:

- The morphology and habitat assemblage of the Humber Estuary is both varied and dynamic responding to process change over both long and short timescales.
- Overall the Estuary is in a dynamic equilibrium with morphological response keeping pace with gradual sea level rise. A fine balance exists between fluvial and marine inputs and sedimentation. Coarse sediment can be exported in the ebb-dominated channel with finer material accumulating on intertidal mudflats and moving upstream.
- Historic change is most notable in the area around Read's Island and across the Outer Estuary, with the consolidated boulder clays of the Middle Estuary promoting stability. However, change has been recorded across the entire Estuary and directional movement (consistent erosion or deposition) is not apparent across much of the Estuary, with areas frequently switching between a stable morphology, erosion and deposition. This is reflected in the variability in sub-tidal morphological maps produced for the estuary.
- The lack of accommodation space in the estuary, due to development, would suggest that mudflat development will dominate over salt marsh.
- Turbidity levels are generally high throughout the Estuary, particularly around the middle-upper estuary boundary.
- Freshwater flow volume variation is almost certainly influencing the dynamics of the upper Estuary.
- The influence of the 18.6 year Lunar Nodal Cycle is likely to be impacting on the general trend in sea level rise, further adding to the natural process variability across the Estuary.
- Local flow patterns and energy levels invoke morphologic response across intertidal areas promoting both erosion and deposition.
- The impact of the proposed quay on local sedimentation is likely to be one of enhanced deposition around the immediate structure. This is likely to develop as mudflat with only very marginal saltmarsh. Development is likely to take several decades to reach a dynamic equilibrium.
- Away from the proposed quay the combined impact of the development on intertidal and sub-tidal areas will be negligible in comparison with natural variation.
- The impacts of localised dredging and dumping appear to be insignificant when compared to the magnitude of sediment transport processes operating in the estuary with natural spatial and temporal variability dwarfing anthropogenic sediment redistribution.

ENVIRONMENTAL IMPACT ASSESSMENT IS AN ITERATIVE PROCESS. THE MODELLING WORK REPORTED IN THIS DOCUMENT RELATES TO A QUAY DESIGN THAT IS SIMILAR TO, BUT NOT THE SAME AS, THAT FOR WHICH AN APPLICATION FOR CONSENT IS SUBMITTED. IT IS THE PROFESSIONAL JUDGEMENT OF THE AUTHORS THAT THE SIGNIFICANCE OF THE IMPACTS IDENTIFIED IN THIS REPORT WILL NOT BE MATERIALLY DIFFERENT FOR THE SUBMITTED DESIGN AND THAT THE CONCLUSIONS OF THIS REPORT THEREFORE PROVIDE A SOUND BASIS FOR ANY PLANNING DECISION.

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1. Introduction and Contemporary Geomorphology

Purpose of the Report

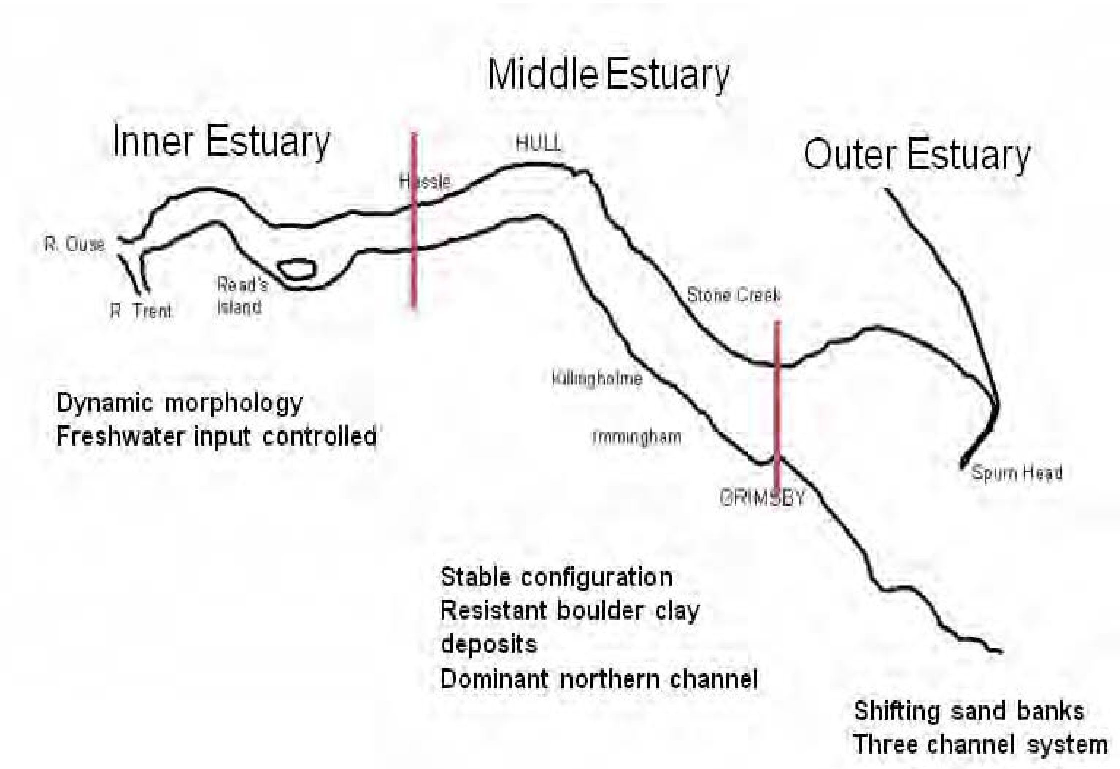
1.1 This document has been prepared in connection with the proposed quay development at Killingholme. The report summarises the findings of published research into the geomorphology and dynamics of the Humber Estuary looking at the evolution of the Estuary and reviewing the more recent historic change in response to natural and anthropogenic processes. Using the longer term data allows more recent changes in the Estuary to be placed in context, comparing magnitudes and locations of change against longer term trend and variability across the Estuary.

1.2 The report draws on the results from JBA Consulting's numerical modelling work, as reported in the "Modelling Studies" report (JBA 2011), and draws relevant conclusions based on the modelling work and previously reported evidence to determine the scale of any impacts on the range of relevant receptors present in the Estuary. Relevant receptors, and consultee concerns regarding them, are reported in the Modelling Studies report (JBA 2011).

General Geomorphic Structure of the Estuary

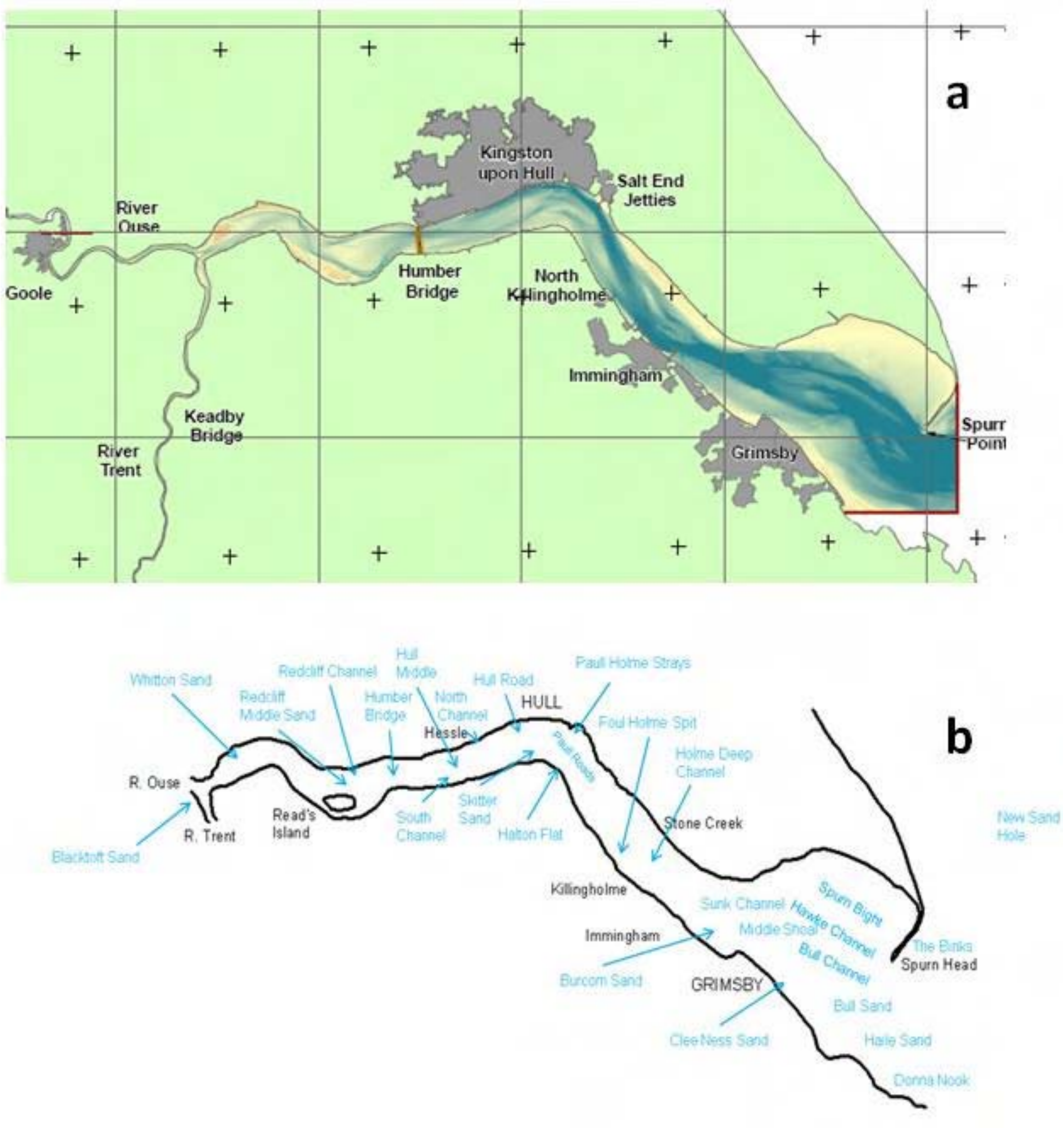
1.3 The Humber Estuary area described in this report extends from the confluence of the Rivers Ouse and Trent to the mouth at Spurn Point. The Inner Estuary of the Humber and the sheltered region behind Spurn spit are characterised by mudflats (Davidson *et al*. 1995) and extensive intertidal silty sandbanks. Reedbeds dominate through the Middle and Inner Estuary and saltmarsh is established along the north bank (Figure 1). Sand dunes have developed around Cleethorpes and eelgrass beds exist around Spurn Head. The gross geomorphology and setting of the Estuary is illustrated in Figure 2a and b and Appendix C.

Figure 1. Estuary zonation and characteristic processes along the Humber.



1.4 Four main seabed facies are present; mobile sediments, till, featureless gravel / coarse sand and featureless sands. Mega-rippled mobile sand sediments are widespread around the mouth (Balson and Philpott 2004). The dominantly sub-tidal facies occurring across the Estuary is sandy, however, these sediments comprise a significant fine fraction potentially causing them to behave as cohesive deposits (ABPmer 2004).

Figure 2. Contemporary channel and bar morphology of the Humber Estuary.



Long-Term Estuary Setting

1.5 The Humber lies in an area of complex solid and superficial geology, which can be simplified into three groups – the pre-Quaternary, the glacial (or Quarternary) and Post Glacial (or Holocene). Upstream of the Humber Bridge the Estuary represents an older estuary system formed in the last interglacial period (120,000 to 80,000 years BP) with the Estuary mouth at this time being located close to the current bridge. Downstream of this point the Estuary is more recent in geological terms, the channel having been formed in immediate post glacial times as melt water cut down through glacial till deposits. During the post glacial period of sea level rise the former river channel underwent marine transgression and was subject to estuarine sedimentation. Within the Inner Humber the presence of the underlying chalk has been a key factor in controlling the extent of the earlier proto-Humber mouth, the extent of the most recent (Devensian) ice incursion from the North Sea and the formation and release of waters from the Inner Humber Lake, which led to the cutting of the Middle and Outer Humber channel. In the Outer Humber, the presence of boulder clay deposits, both beneath the surface and as outcrops provides a geological constraint which influences the form of the channel and the position of the some of the sandbanks such as Clee Ness Sand and intertidal areas such as Spurn Bight as well as Spurn Point peninsular at the mouth.

1.6 The last 12,000 years comprising the Holocene period represents a time of infilling of the sedimentary basin created by ice during the last glaciation. Thick sequences of boulder clay and alluvium were deposited over the chalk and resistant morainic deposits continue to control gross estuary shape (forcing the channel to bend) around Hull (Townend & Whitehead 2003). The majority of the sediments laid down during the Holocene are of marine origin (Rees *et al*. 2006) reflecting a general transgression of the sea inland.

1.7 The infilling of the sedimentary basin following the last glaciation was initially very rapid with rates between 350,000 and 450,000 m^3 per annum estimated for the Newland and Butterwick Suites deposited between 7000 and 6000 years before present (BP). The moraine at Hull was breached during this period extending the Estuary upriver. Sedimentation rates fell to between 350,000 and 250,000 m^3 per annum through to 3400 years BP (as evidenced by the saltmarsh deposits of the Garthorpe Suite). A period of channel migration associated with comparatively low rates of sedimentation (250,000 m^3 per annum) followed between 3400 and 1400 years BP before renewed saltmarsh development up to 300 years BP. Channel incision and reducing sedimentation rates have dominated the record between 300 years BP and present. The recorded pattern is strongly associated with the availability of accommodation space as sea levels rose. This variability is not unusual in estuarine settings reflecting the long-term dynamic nature of these environments. It would appear that the morphodynamics of the Humber Estuary is strongly controlled by the accommodation space available during sea-level rise. The ability of the Estuary to extend laterally, creating a shallow topography, encourages channel stability and saltmarsh development. In contrast, restricted expansion encourages channel migration and mudflat development (Metcalfe *et al*. 2000). The lack of accommodation space in the Estuary due to development would suggest that mudflat development will dominate over salt marsh.

1.8 Sedimentological evidence suggests that the Estuary mouth has undergone considerable changes throughout the Holocene. The present spit is likely to be a relatively recent development consisting of surficial aeolian sands over eroded muds to the north and aeolian sands over more extensive gravels to the south. More importantly a gravel shoreline is suggested for the north shore prior to 6500 years BP. It was the development of a gravelly barrier beach to the north which first protected the Inner Estuary, allowing mudflats to develop. The partial erosion of this feature following landward migration of the Estuary leaves the northern stretch of the present spit susceptible to adjustment (Balson & Philpott 2004).

1.9 Analysis of 3500 borehole logs distributed throughout the Humber Estuary (Rees 2006) reveal a remarkable uniformity of marginal sequence sediments after around 6000 years BP with deposits dominated by mud (85%) and much smaller proportions of gravel and sand (5% and 10%, respectively). Across the entire estuary fill, the proportion of mud increased steadily to around 80% between 6000 and 4000 years BP where it remains constant until the present day. This apparent overall uniformity disguises some significant local spatial variation, with the area around Spurn Bight showing a recent loss of mud to sand and gravels over the last 1000 years and muds increasing around Read's Island at the expense of gravels. Read's Island, Foulholme, Sunk Island and Spurn Bight have exhibited some responsiveness over the last 2000 years suggesting that the shorter term changes described below are at least in part a function of natural processes in the area.

Estuary Geomorphology and Ecology

1.10 The Humber Estuary Special Area of Conservation (SAC), as designated under the Habitats Directive, qualifies due to the presence of the following Annex I habitats as listed in the EU Habitats Directive together with their sub-habitats:

- Estuaries
  - Saltmarsh
  - Intertidal mudflats and sandflats
  - Sub-tidal sediments
- Coastal lagoons
- Atlantic salt meadows
  - Low to mid marsh
  - Mid to upper marsh
  - Transitional zones
- *Salicornia* and other annuals colonising mud and sand
  - Annual *Salicornia* saltmarsh
  - *Suaeda maritima* saltmarsh
- Mudflats and sandflats not covered by seawater at low tide (intertidal mudflats and sandflats)
  - Intertidal gravel and sand
  - Intertidal muddy sand
  - Intertidal mud
  - Eelgrass beds
- Sandbanks which are slightly covered by seawater all the time (sub-tidal sandbanks)
  - Sub-tidal gravel and sands
  - Sub-tidal muddy sands

1.11 The contemporary habitat distribution is illustrated in Figure 3. The morphology supports a variety of habitats including; coastal lagoons, fixed dunes with herbaceous vegetation, Atlantic salt meadows, embryonic shifting dunes, dunes with mudflats and sandflats not covered by seawater at low tide, sandbanks which are slightly covered by sea water at all times and shifting dunes along the shoreline.

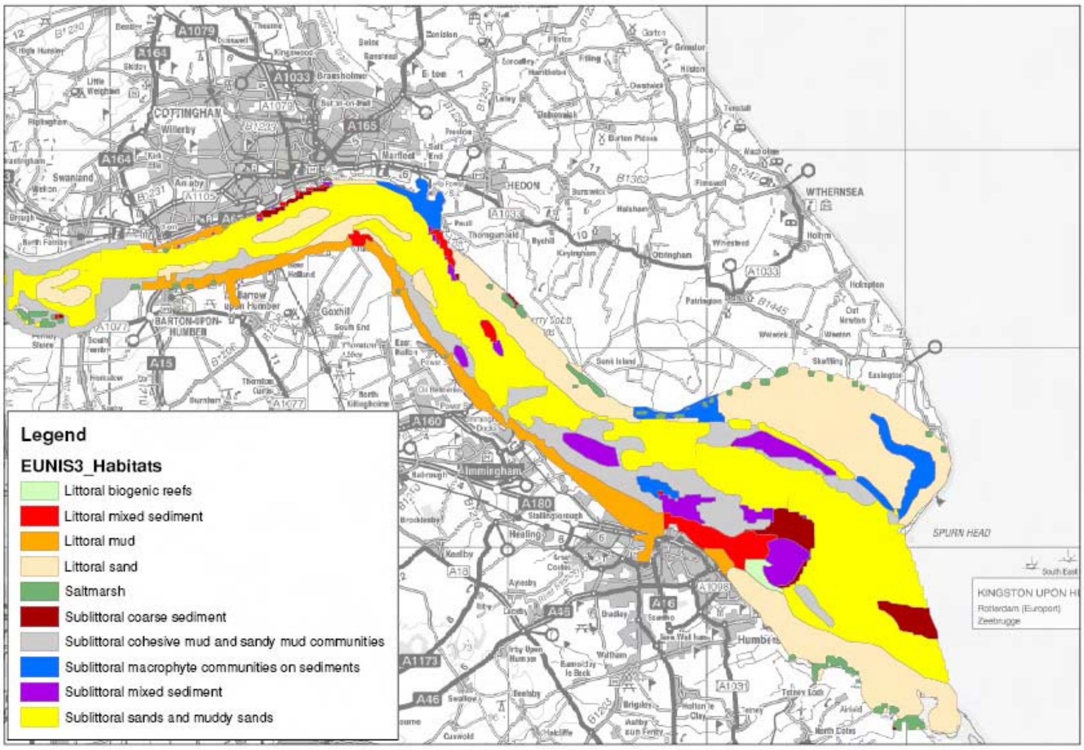
1.12 Considerable change has been recorded for the habitats across the Estuary following the coastal warping of the 1700s. In particular Hessle Middle and Skitter Sands have declined around Reeds Island and the area along the Hull foreshore has eroded (Cutts *et al*. 2008). Hawkings Point west of Spurn Bight has also displayed intertidal habitat loss after the closure of the navigable North Channel (Pethick 1990). Estimates of habitat change (Table 1) showing general loss are provided by Cutts *et al*. (2008).

Table 1. Habitat loss in the last 200 years across the Humber Estuary (ha). After Cutts *et al* (2008).

Location	Mud	Sand	Saltmarsh	Dune	Reed	Lagoon	Subtidal
Inner	225		110		420	20	
Middle	1700	300	200		50		20
Outer	690	400	110				10

Coast	400	600	100	100			
TOTAL	3015	1300	520	100	470	20	30

Figure 3. The contemporary habitat distribution across the Humber Estuary (after Hemmingway *et al*. 2008).



1.13 The main sub-tidal sandbanks occur in the Outer Estuary east of Grimsby consisting of steep banks of sediment over flat or sloping sand plains. In a few areas strong tidal currents have exposed glacial boulder clay gravels and cobbles with occasional tide swept sand veneers. All of these features are strongly linked with the fauna of the Estuary (Table 2).

Table 2. Principal morphology – ecology associations in the Humber Estuary (Source: Allen *et al*., 2003)

Morphology	Species Association	Sensitive Locations
Strand-line pebbles and sand	Talitrus saltator	Spurn, Cleethorpes
Embryonic shifting dunes	Hippophae rhamnoides	
Upper shore medium and fine sand	Polychaetes	Outer Estuary (South bank) and some at Spurn
Mid to lower shore clean mobile fine and medium sand	Nephtys cirrosa, Scolelepis squamata and Amphipods	Extensive: Spurn Bight and Cleethorpes to Donna Nook
Littoral (intertidal) gravels and	Lanice conchilega	Cleethorpes eastwards

sands Tide-swept mid to lower shore poorly sorted sand		
Littoral (intertidal) muddy sands Upper to mid shore muddy fine sand	Arenicola marina and bivalves	Cleethorpes to Donna Nook
Mid shore sandy mud	Macoma balthica and Cerastoderma edule	Extensive in Outer Estuary, Spurn Bight and Cleethorpes eastwards
Upper to mid shore mud	Scrobicularia plana	Part of Spurn Bight, South Bank
Extensive Variable salinity lower shore mud	Nephtys hombergii and Caulleriella (Tharyx) killariensis	Ubiquitous in middle and Outer Estuary
Low salinity mid to lower shore mud	Hediste diversicolor, Heterochaeta costata, Tubificidae spp. and Corophium volutator	Middle to Upper Estuary, on the South Bank
Sublittoral sandy mud	Scoloplos armiger and Phoronis muelleri	Middle-Outer Estuary
Sublittoral mud	Nephtys hombergii and Phoronis muelleri	Outer Estuary
Nearshore mud	Macoma balthica	
Sublittoral mud/clay and sandy mud	Polydora sp., Aphelochaeta sp., Pygospio elegans, Corophium and Tubificoides spp.	Outer Estuary
Sublittoral mixed muddy substrata	polychaetes, crustaceans and ascidians	Middle and Outer Estuary

General Controls and Behaviour

1.14 In general, shallow zones of the Estuary are composed of silt, whilst the bed of the channel is sandy, Foul Holme Spit consists of sandy gravel and the deep channel adjacent to Immingham has patchy gravels and some bedrock. Hull Roads and Paull Roads have similar patches of bedrock. Palaeo spit deposits exist offshore to the north helping to protect Spurn Head and considerable volumes of finer material exist as offshore sandbanks (ABP Marine Environmental Research Ltd 2009).

1.15 The Estuary has been split into three regions (Townend *et al*. 2000), their character and extent are briefly described below (see Figure 1):

- The Inner Humber between Trent Falls and the Humber Bridge.

  Characterised by extensive intertidal banks composed of sands and silts including Redcliff, Middle Sand, Winteringham, Barton Ness Sand and Hessle. This is the most dynamic region with strong dynamic links to freshwater flows from the rivers Ouse and Trent. In the Inner Estuary the channels around Read's Island have exhibited considerable dynamism switching from close to the island to a more northern position, possibly in response to freshwater flows from the rivers Ouse and Trent (Townend *et al*. 2000). Gameson (1982) reports stabilisation of the channel since the construction of training walls in the River Trent in the mid 1930's.

- The Middle Humber from the Humber Bridge to Grimsby.

  A relatively stable region of the Estuary characterised by resistant boulder clay deposits. Intertidal banks have a stable configuration. The Middle Humber has a slightly more stable configuration with a dominant northern channel and an ephemeral channel along the southern shore. The Halton Middle channel then forms the main channel. The deep stable central channel between Immingham and Grimsby is formed in boulder clay deposits and is presently resistant to erosion allowing a stable ledge to form to the south supporting the Pyewipe mudflats.

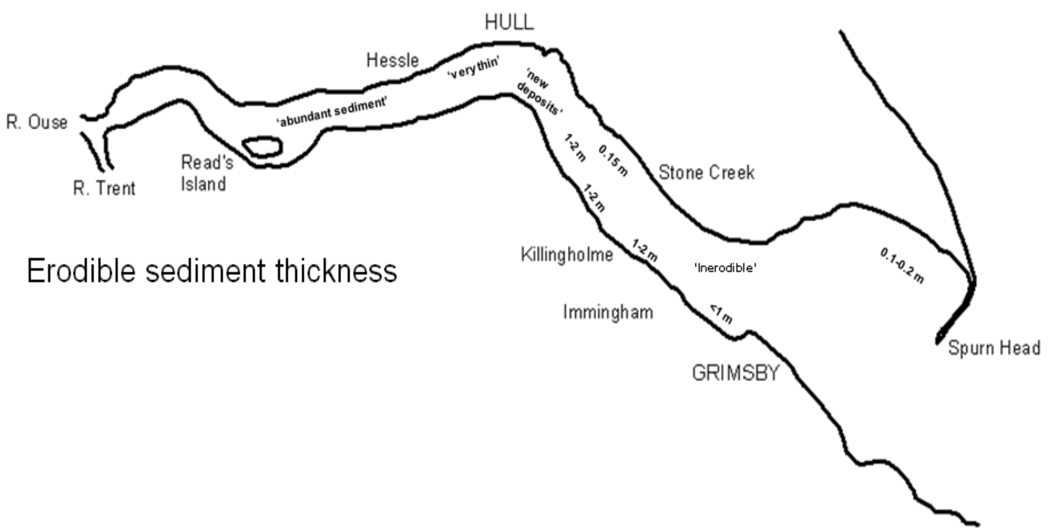
- The Outer Humber extending from Grimsby to Spurn Point.

  A dynamic region of shifting sandbanks. The Outer Humber has a three channel system (the Haile, Bull and Hawke channels) with the Hawke Channel artificially extending across Middle Shoal as the Sunk Dredged Channel. Outer Estuary boulder clays form non-erodible areas partially controlling flows and sedimentation patterns. The areas around Spurn Head and Donna Nook have undergone significant change (Balson & Philpott 2004). Large-scale sediment sinks are present, including gravels across The Binks and New Sand Hole and sands and muds over Donna Nook and Haile Island. Shifting sandbanks across the Estuary mouth also represent a significant sediment store.

1.16 The dynamic nature of the Estuary is also illustrated by the interaction that exists between the various bank systems in the Inner and Middle Humber. For example, the migration of channels in the Inner Humber region releases sand, which forms banks off Barton and New Holland in the Middle Humber. In addition, there is an exchange of sediment between Barton Ness Sand and Skitter Sand in the Middle Humber.

1.17 Continued erosion is ultimately controlled by the thickness of the Holocene sediments which is generally not limiting vertically with deposits exceeding 5 metres across much of the Estuary and extending to 20 metres across the Inner Estuary (ABPmer 2004). However, consolidated boulder clays are widespread and are presently resistant to general erosion by contemporary estuarine processes placing a lower limit on potential erosion (Figure 4).

Figure 4. Thickness of erodible sediments under present estuary conditions (after ABPmer 2004).



1.18 Several morphologic maps have been produced for the Estuary and each is subtly different from the other reflecting both survey variation and shifting sediment patterns. Typically, much of the Estuary is covered in sand and muddy sand with areas of sandy mud and mud around Killingholme, Immingham and across Spurn Bight. Isolated basal boulder clay and gravels are exposed at several locations across the Estuary including Bull Channel, around Spurn Head and close to Immingham.

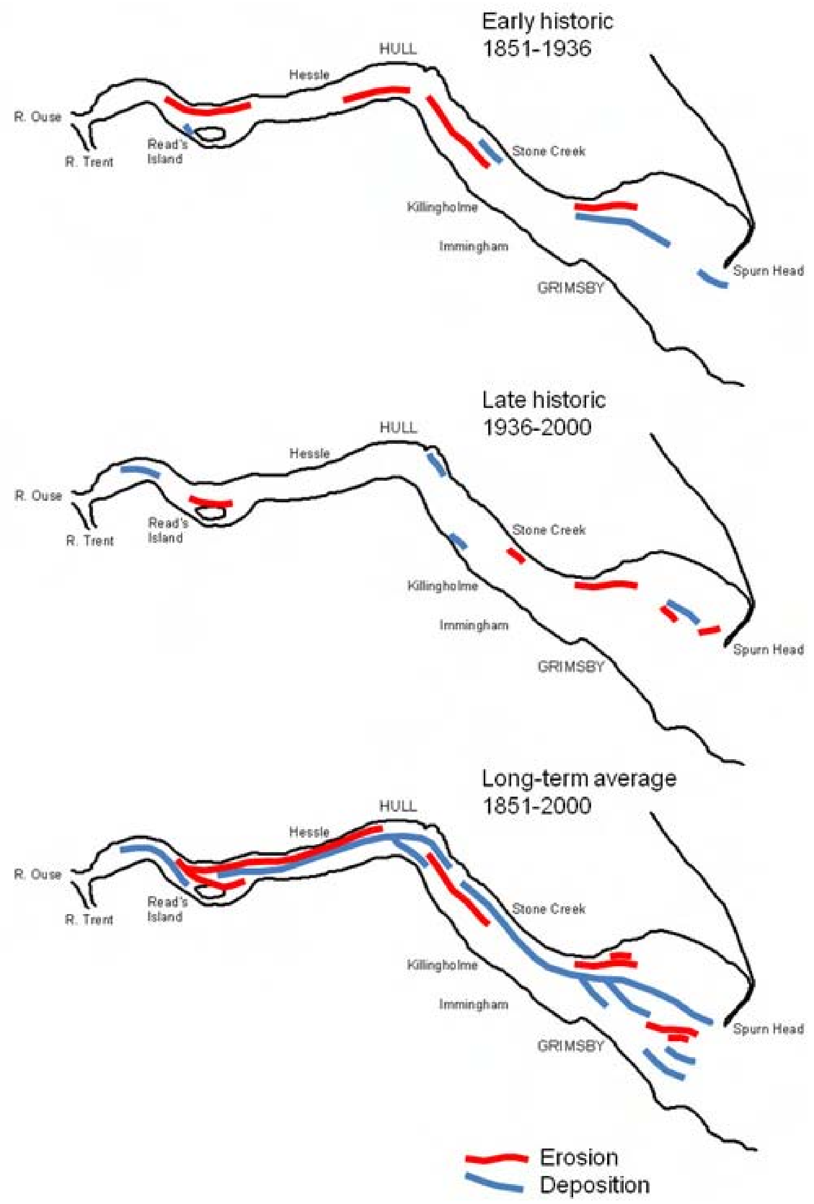
1.19 This dynamism, over short and longer timescales, will be reviewed in more detail in later sections and the implications for assessing the impact of the proposed quay will be discussed. The Estuary may be seen to have evolved over the long term, since the end of the last ice age, in response to rising sea levels and isostatic rebound. More recent natural and anthropogenic drivers have resulted in estuary response over historic time (the past 150 years) and a number of studies have also shown that local change may be more rapid in the short-term in response to lower magnitude changes to the system drivers.

2. Recent Estuary Change

More Recent Estuary Development - General Dynamics

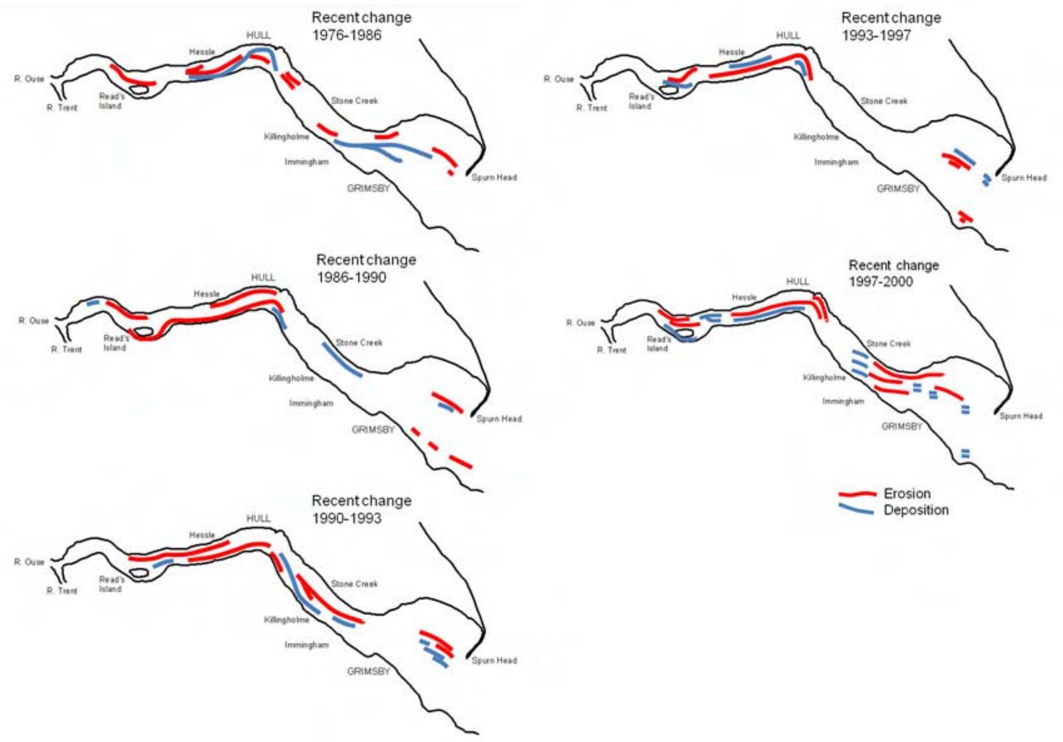
2.1 Quantitative volumetric change analysis of bathymetric data for the Humber Estuary has been undertaken between 1851 and 2000 (ABPmer 2004). The study revealed general accretion between 1851 and 1936 particularly around Grimsby Middle, Middle Shoal, Foul Holme Sand and in the vicinity of Read's Island. Since 1936, however, the trend has been towards erosion and sediment loss. The Inner Estuary is most dynamic, changing through channel migration and sediment shoaling. These changes are broadly summarised in Figure 5, constructed from visual analysis of historic bathymetric survey data.

Figure 5. Historic change recorded for the Humber Estuary.



2.2 More recent morphologic activity, surveyed over the last 35 years (Figure 6) has been greatest around Read's Island with notable channel creation and abandonment between 1976 and 2000 (van Ormondt and Roelvink 2004). This behaviour has been linked to freshwater discharge variation. Further down the Estuary a channel has intermittently formed and infilled to the south of Hull Middle, similarly Middle Shoal has shown erosion and deposition.

Figure 6. Summary of recent historic change measured for the Humber Estuary.



More Recent Estuary Development - Sedimentation and Infill Rates

2.3 During more recent times covered by the historic record (1850 – present) the estuary has maintained a dynamic equilibrium with sedimentation keeping pace with relative sea level change (Table 3). The trend in sea level change in the Humber Estuary between 1920 and 2000 amounts to around 1.8 mm per annum (Townend *et al*., 2007) although estimates vary slightly. Estimates of historic infill rates (Table 2) indicate that sedimentation is broadly in line with sea level rise (Townend & Whitehead 2003), although there is some evidence of local sediment losses since the 1930s (ABPmer 2004). The Estuary has been shown to exhibit a balance between fluvial and marine sedimentation; coarse sediment is generally exported in the ebb-dominated channel influencing the sediments there, with finer material accumulating on intertidal mudflats and moving upstream (Townend & Whitehead 2003). The general equilibrium follows from rising sea-level increasing over-depth in the Estuary thereby creating or enhancing tidal asymmetry in favour of flood dominance and net import of fine marine sediments for deposition.

Table 3. Average annual estuary infill rates and sea level change for the Humber (Townend & Whitehead 2003).

Location	Minimum rate (mm/annum)	Maximum rate (mm/annum)	Mean rate (mm/annum)
Estuary wide	2.6	6.6	
Intertidal zone	1.93	3.45	2.69
Sub-tidal zone	0.65	3.17	1.91
Sea level rise	1.7	4.5	3.1

2.4 Morphological measures of tidal asymmetry suggest that the Estuary as a whole has become more flood dominant over the last 150 years, however, this is mostly attributable to the area up-estuary of the Humber Bridge, since downstream of Hull there has been an increase in ebb dominance.

2.5 Changes to intertidal areas have been calculated and the following general statements can be made concerning local estuary dynamics. The Outer Estuary north shore displayed a significant loss of intertidal area around 1950, increasing since that date but with local variation potentially linked to the nodal tidal cycle. The Outer Estuary south shore also shows a significant loss of intertidal area around 1950, continuing to decline with no discernable link to the nodal tidal cycle. The Middle Estuary response has been more variable locally but with a general decrease between 1936 and 1985 increasing thereafter. Significant factors responsible for the temporal and geographical variation include the nodal tidal cycle and differential wave exposure. Errors in change estimation and interpretation are likely due to the distribution of the data and coverage is particularly sparse and temporally variable across intertidal areas including Spurn Bight.

2.6 The Summary of Geomorphology studies (Environment Agency 2004) reports a loss of 485 ha of intertidal area from the Middle Estuary over the last 50 years whilst The Humber Coastal Habitats Management Plan (CHaMP) (Black and Veatch 2005) reports losses of 535 and 530 ha of Middle Estuary intertidal area in a similar period. More recently (ABPmer 2009) indicate a progressive reduction in intertidal extent of the inner part of the Middle Estuary on the south bank with a decrease of 97ha (-14.7%) in 2002 and in 2005 and 2007 reductions of 216ha and 268ha relative to 2000 due to a reduction in size of Barton Ness Sand and Skitter Sand.

2.7 Mean tidal levels are increasing throughout the estuary. Spurn Head data show a 2.3 mm rise per annum, rising to 3.4 mm at Immingham. The spring tidal range at Spurn is 5.7 m reducing to 2.8 m during neap tides. This increases inland up to the Humber Bridge before starting to reduce. Upstream of the Humber Bridge the estuary is becoming increasingly flood dominant. Downstream of the Humber Bridge, ebb velocities exceed flood velocities by up to 20% and a counter-clockwise current is known to operate (ABP Marine Environmental Research Ltd 2009). The Inner Estuary has become more flood tide dominated over the last 150 years in contrast to the Outer Estuary which is now slightly more ebb tide dominated. As a result there has been increased erosion around Grimsby and enhanced accretion rates along the Inner Estuary (ABP Marine Environmental Research Ltd 2009).

Morphologic Change

2.8 Intertidal areas are generally said to be accumulating fine sediment whilst sub-tidal areas are exporting sandy material. Analysis of aerial photographic records between 1976 and 1995 (Table 4) show a small increase in salt marsh coverage (ABP Research 1996)

Table 4. Alteration (gain or loss in hectarage) in salt marsh across the Humber Estuary between 1976 and 1995 (ABP Research 1996).

Estuary location	1976 (ha)	1995 (ha)	Change (ha)	% Change (ha)
Inner	168	226	+58	35.5
Middle	64	67	+3	4.7
Outer	357	333	-24	-6.7
Total	590	627	+37	4.3

2.9 Sedimentation may also be influenced by the variation in tidal range linked to the 18.6 year nodal tidal cycle and other longer term factors. This is a potentially very significant driver for change. A tide level fluctuation of only 0.1 m (2% of the average tidal range) can effectively offset the effect of sea-level rise in causing sedimentation.

2.10 The sediments deposited in the Sunk Dredged Channel between 1969 and 1993 were dominated by silts, this then changed to a more sandy material with occasional silt episodes. This variation has been linked with winter flushing of sandy sediments from upstream by freshwater flows and has been linked to grain size coarsening at other depositional sites downstream. There appears to be some correlation between peak freshwater discharge and limiting deposition rates through the Sunk Dredged Channel with increased flows preventing sediment accumulation. ABP Research & Consultancy Ltd (1993) concluded that this amounted to 15,000 m^3 of material for every 1 m^3/s change in the mean monthly freshwater discharge.

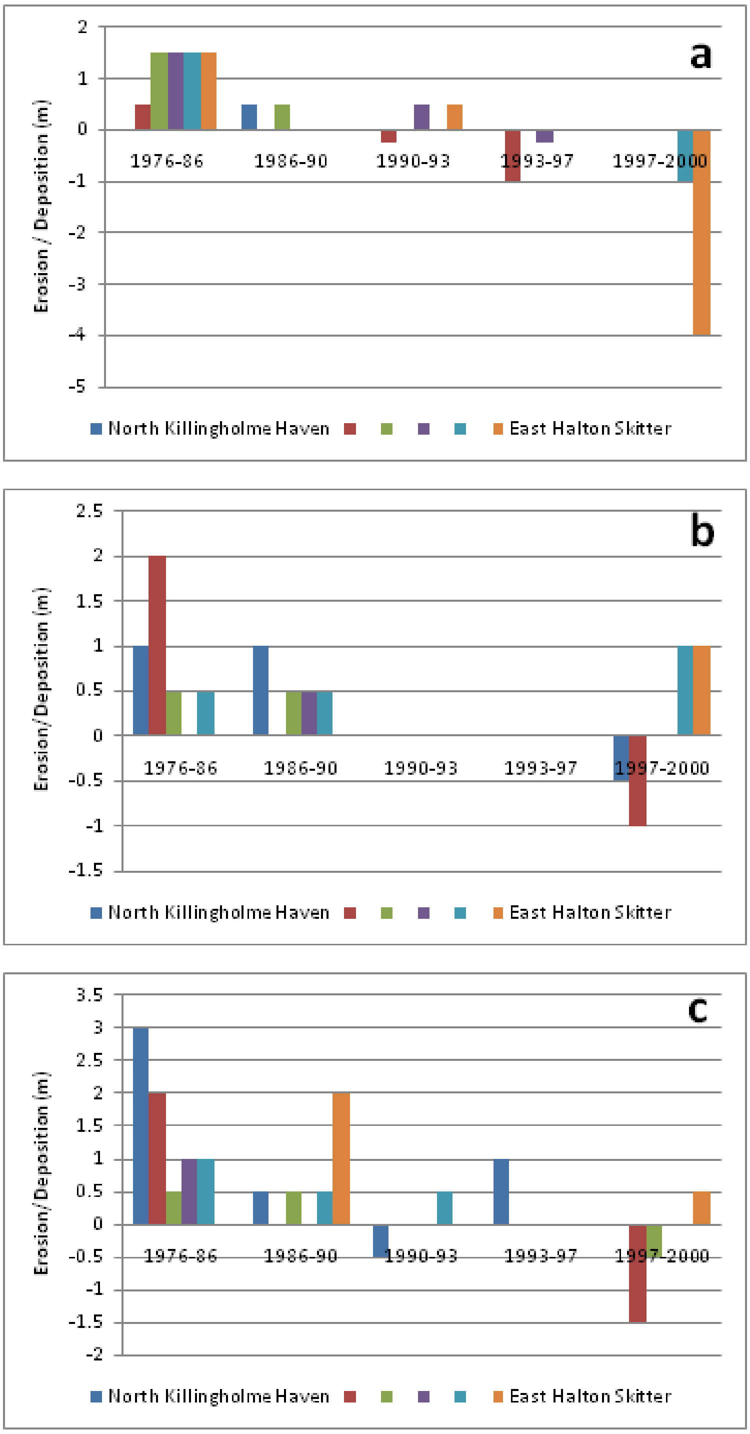
2.11 A large scale dynamic link exists between erosion and deposition of material in the Estuary with material eroded in the vicinity of Read's Island subsequently deposited as sandbanks in the upper Middle Humber around Barton upon Humber and New Holland. A similar exchange exists between Skitter Sand and Halton Flat (ABP Marine Environmental Research Ltd 2009).

2.12 Changes to bed elevation at monitoring sites across Grimsby Middle and Middle Shoal show a shorter 10 – 12 year cycle of erosion and deposition with overall bed elevation change ranging between ±1 – 1.5 m, incorporating annual variability of between 0.2 – 0.5 m ranging up to 1.0 m. Fine very mobile sands and silts exist seaward of Grimsby moving around in response to wind, wave, tidal surge and freshwater events and sediment supply variability. Sediment thickness reduces towards the estuary mouth and morphologic variability is related to the configuration of the Hawke, Bull and Haile channels. There appears to be a cycle of change with a dominant Haile channel associated with a reduced Middle Shoal and a deeper Bull channel developing in response to an eastward extension of the Middle Shoal. Erosion and deposition can alter sediment thickness by up to 3 m and the cycle is apparent both before and after dredging of the Sunk Deep Channel commenced (ABP Marine Environmental Research Ltd 2009).

2.13 This dynamic variability is strongly apparent from a detailed review of the historic bathymetric survey data carried out as part of this study. Change is both extensive and highly variable in nature across the entire Estuary. Trends in morphologic change are most apparent around Read's Island, elsewhere continuous erosion or deposition is rare with most areas switching between stability, erosion and deposition. This extreme spatial variability is highly significant in terms of estuary dynamics suggesting that much of the Estuary morphology is dynamic. It is likely, therefore, that the present ecology is adapted to this variability.

2.14 A detailed review of the bathymetric change maps presented in Van Ormondt and Roelvink (2004) for the period 1976 - 2000 (Figure 7) illustrates the extreme dynamic nature of the Estuary bed local to Killingholme. General deposition in the 1970s has been replaced by more limited and variable change. Rates as high as half a metre of change have been recorded annually but this is more generally around 0.05 to 0.1 m per annum.

Figure 7. Recorded change across the intertidal mud flat at Killingholme based on bathymetric survey data, (a) 450 m offshore, (b) 250 m offshore, (c) 100 m offshore.



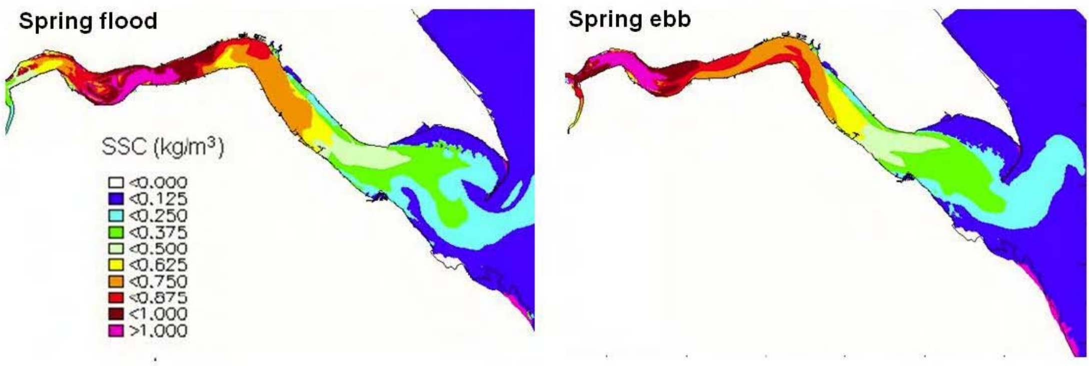
3. Short-Term System Response

Turbidity

3.1 Turbidity levels in the Estuary are high (Figure 8). Suspended sediment concentrations in the Inner and Middle Estuary are generally in excess of 200 mg/l, reducing in the Outer Estuary (Boyes and Elliot 2006). More general figures of suspended sediment concentrations in the Estuary are reported mean values ranging from 330 mg/l during neap summer tides rising to 1200 mg/l for winter springs (British Transport Docks Board 1970).

3.2 The estuarine turbidity maximum is a strong feature of the Humber Estuary with concentrations of suspended matter around 50 g/l in the upper estuary. This turbidity maxima shifts between Hull and Selby according to the seasons (Uncles *et al*. 1998) and in relation to the freshwater flow, shifting down Estuary in response to increased winter discharge. Flood tide dominated advection of suspended sediment creates the potential for high rates of sedimentation in the Upper Estuary (Uncles *et al*. 2006). There appears to be no discernable influence from the lunar tidal cycle (Uncles *et al.* 1998).

Figure 8. Spring tide suspended sediment concentration across the Humber Estuary ((kg/m^3 equivalent to mg/l) (after Boyes and Elliot 2006).



Sediment transport

3.3 Net landward (up estuary) transport of fine sediment occurs if the time integrated low water slack velocities exceed the time integrated high water slack velocities, this is the case for the first 80 km of the Estuary. It also generally occurs where the time-integrated tidal flood velocities exceed the time integrated tidal ebb velocities (ESTPROC/rapport 2004). Large scale influences on sediment transport have been identified (GeoSea Consulting 1990) with a general counter clockwise circulation pattern influencing Foul Holme Spit in the Middle Humber and an independent clockwise circulation around the Middle Shoal within the Outer Humber. Density driven currents linked to the Coriolis force allow marine processes to dominate along the north bank whilst fluvial influence is greater along the south bank. Down-estuary transport of intertidal mud was reported for both sides of the Estuary.

3.4 The Humber Estuary has relatively shallow depths of easily erodible material along the northern and southern shorelines with the exception of the area in the vicinity of Killingholme. The dominantly sub-tidal facies occurring across the Estuary is sandy, however, these sediments comprise a significant fine fraction potentially causing them to behave as cohesive deposits (ABPmer 2004). Critical flow speeds of 0.25 to 0.3 m/s leading to erosion have been recorded across the lower Spurn Bight muds corresponding to critical shear stresses of around 0.35 N/m^2. These are exceeded only during short periods across the largest spring tides delivering suspended sediment to the upper mudflat. Locally the sediment delivery process is influenced by wind activity generating waves and altering shear stresses which may enhance or subdue sediment supply (Black 1998).

Morphologic change

3.5 The fundamental controls on local sediment dynamics in intertidal zones has been defined by Le Hir *et al*. (2000) as water depth, current speed and wave activity with sediment delivery to mudflats linked to transport by shallow high velocity sheets of water. Once delivered the ebb tide is then incapable of re-suspending the deposited sediment (Black 1998).

3.6 Spring tides mark a potential depositional maximum as they have the most sediment available for deposition, particularly around the area of maximum turbidity in the Middle Estuary. In contrast local erosion is governed principally by local current speed and intensity of wave action (Le Hir *et al*. 2000). In general, however, the potential for greater erosion is moderated by high levels of suspended sediment (Mitchell *et al.* 2003).

3.7 Local variation in erosion and deposition has been recorded over short-term timescales. A study of the local sediment dynamics across Blacktoft bank revealed greater variability across the mid-bank surface compared with the upper bank which has been attributed to increased inundation time and stronger currents. More generally, intertidal mudflat development shows a seasonal pattern with summer accumulation linked to decreased storminess and wave intensity, biostabilisation and subaerial stabilisation processes. There is evidence of relatively rapid (annual) variation in grain size composition across intertidal mudflat areas with the deposits across the Middle Estuary becoming increasingly silty between 1998 and 1999 before becoming sandier during 2000 and 2001 and slightly more silty between 2002 and 2004. Interestingly, the infaunal response was equally rapid with tubificid worms being replaced by ragworms as grainsize increased (Boyes and Allen 2007), suggesting that the ecology is adaptable to frequent morphological and sedimentological variation.

3.8 A reanalysis of the recent bathymetric survey data (1976-2000) has been undertaken for this study. It reveals an extremely dynamic morphology over this short time period with change apparent across almost the whole of the Estuary. Of particular note is the continued lack of any substantive directional change with the majority of areas continuing to switch between short-term stability, erosion and deposition suggesting a dynamic template for the ecology. Visual analysis of historic aerial photographs of the estuary (Appendix A) reveal a general stability in mudflat and saltmarsh distribution since the 1940s. However, movement of the deeper channels close to the shore has resulted in local changes to the drainage pattern off of some mudflat areas.

General Anthropogenic Influence

3.9 On average 7.3 million cubic metres of sediment are dredged annually based on figures between 1960 and 1994 often with more than 5 million cubic metres coming from the Sunk Dredged Channel. Townend and Whitehead (2003) have calculated that this represents a probable loss of 800 tonnes of sediment per tide rising to 1100 tonnes per tide due to the Sunk Dredged Channel and represents only a tiny fraction of the 1.2 million tonnes of sediment estimated to be in suspension in the Estuary. Modelling of the Estuary indicates that the direct impact of sediment removal as a result of dredging can be considered to be negligible when compared with the natural variability in the system from, wave effects and tidal processes linked to the nodal tidal cycle. Suspended sediment concentration increases by between 5 and 10 mg/l on peak tides (0.5 – 1% of background levels). Similar increases in sand fraction suspended sediment concentration have also been reported (ABP Marine Environmental Research Ltd, 2009). Often fine sediment arisings, deposited at the disposal sites, are reworked (deposited on neaps and re-eroded on springs) with eventually 48% of silt and 44% of sand being assimilated back into the estuarine sediment transport system.

3.10 Monitoring of the bathymetry at the deposit sites shows them to be dynamic, however, no directional change in terms of prolonged erosion or deposition has been detected (ABP

Marine Environmental Research Ltd 2009). Local scale directional morphologic response has also been reported across intertidal areas. The 80 hectare managed realignment site at Paull Holme Strays recorded high spatial variability in sedimentation rates. Clays and silts were the dominant deposited sediment size. Rates of change varied around ±0.05 m across the area with more localised accumulation zones of up to 0.1 m - 0.15 m locally over a 4 month monitoring period in the winter of 2003-2004 (Mazik *et al.* 2007). Monthly variability of ±0.02 m was reported. Monitoring of daily sediment exchange rates (Mitchell *et al.* 2003) across Blacktoft Bank revealed alternating erosion and deposition of between 30 and 50 mm, with accumulation being extremely sensitive to wind speeds.

3.11 Bund construction has also affected the Saltend mudflats enhancing accretion and leading to increased drying time and a change to infaunal assemblages. This declines to negligible levels around 1 km downstream (Boyes and Allen 2007). Annual sedimentation rates between 2000 and 2006 varied considerably across the monitored site ranging from 0.12 - 0.15 m across lower and mid mudflat to 0.025 m across higher areas.

3.12 Whilst the general review of aerial imagery shows the majority of the intertidal areas along the Middle and Outer Estuary appear stable in terms of the proportion of mudflat and saltmarsh present (Appendix A), a review of the aerial photographs around Cherry Cobbs Sands Bank west of Stone Creek shows that the mudflats are affected by an ephemeral offshore channel which appears to infill and reform across the area (Appendix A). The dynamics of this feature is investigated in detail in the compensation site dynamics report (Black and Veatch 2011). ABPmer (2009) suggest that the intertidal area for the south bank in the Outer Estuary decreased by 138ha (10.5%) from its 2000 baseline value.

3.13 Saltmarsh development associated with natural and anthropogenic influence around the Humber shows a general stability, with saltmarsh restricted to very low energy areas (Appendix B). Where coastal defences are restricting lateral estuary expansion, saltmarsh growth is severely restricted. This situation is found at the proposed quay site and strongly suggests that any new sedimentary units will develop as mudflats with only a small chance of long-term (decadal) development of linear saltmarsh in the lowest energy areas. This was reviewed using the shear stress outputs. Areas prone to fine sediment deposition have been determined based on the following assumptions:

- Sedimentation will occur during slack water conditions where shear stresses drop below 0.2 N/m^2
- Deposited sediment will only be re-suspended where maximum shear stresses exceed 0.5 N/m^2

To put these values of bed shear stress in to context, in general, for most muddy (silt and clay) sediments in marine environments, the threshold for the initiation of bedload transport ranges from 0.5 to about 5 N/m^2 (Brown *et al.*, 2005). During periods of slack water, areas where the bed shear stress drops below 0.2 N/m^2 will typically experience fine sediment deposition (Ormondt and Roelvink, 2004).

3.14 The area along the Immingham Waterfront has been analysed for average bed level changes between 1920 and 1999. The analysis showed that in an area adjacent to the jetties there has been an accretionary trend since around 1925, increasing markedly in rate between 1965 and 1985. Thereafter, rates have slowed and there may be evidence for a deepening phase from the end of the 1990's. Conversely, the outer section of the main channel showed rapid accretion of up to about 2 m, from 1920 to the 1950/ 1960's. Since then the general trend has been erosional. The analysis of average bed level changes near Immingham show variations of the order of 0.5 m to 1.0 m for successive 5-year intervals. Over the longer-term, from 1920 to 1999, changes are greater, with bed levels varying over a range of 2 to 3 m, approximately (ABP Research 2000).

3.15 Volumetric analysis of historical data undertaken for the whole Immingham Waterfront section indicates there was overall sub-tidal accretion to the mid 1950's followed by general erosion to present. Over the intertidal, the data indicated erosion to the mid 1930's followed by rapid accretion or stability, although some erosion is evident near the base of the seawalls. Around North Killingholme substantial cross-sectional change has taken place since the 1920's, generally in-filling of the deep channel on the southern side of the Estuary, leading to a more stable estuary form. ABPmer (2009) show a reduction in intertidal area along the south bank in 2007 relative to 2000 (18ha).

4. Geomorphological Impacts of the Development

4.1 Long-term geomorphological impacts of the potential quay development are difficult to predict. However, the minimal sea level impacts predicted, coupled with the rapid decline in flow influence away from the quay suggests that there will be no discernable impact on the present long-term pathway for the wider Estuary (refer to the associated "Modelling Studies" report (JBA 2011)).

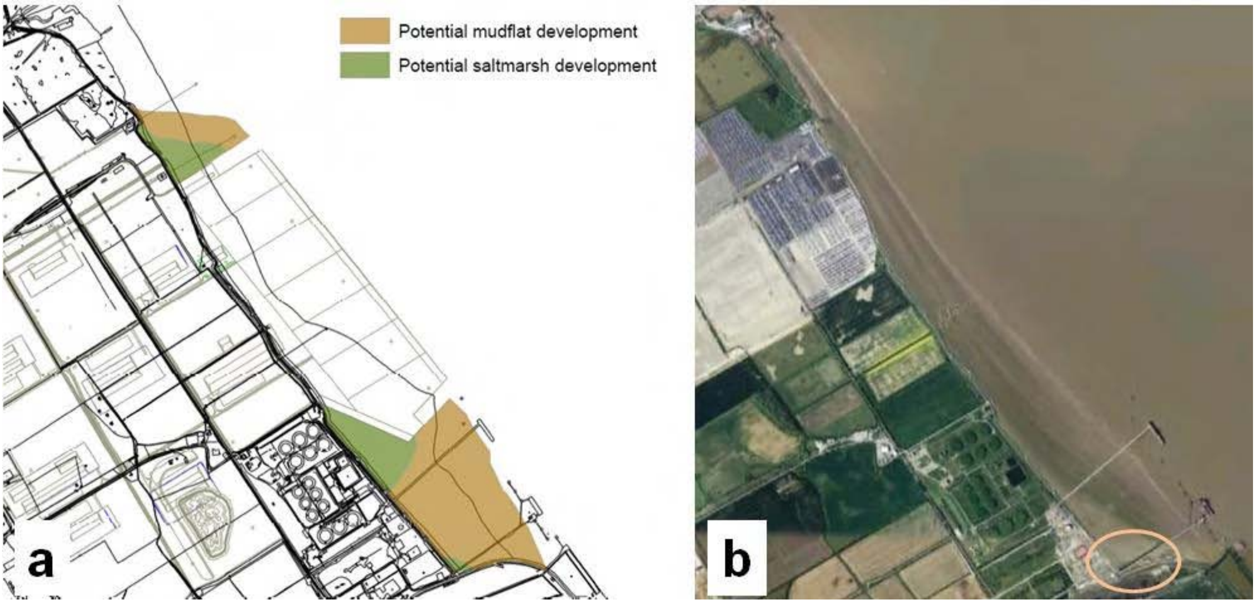
4.2 Estuary morphological units away from the immediate environs of the quay will be unaffected by the development, this includes submerged gravel areas in the channel off of Killingholme. The results of the hydrodynamic modelling suggest that changes to intertidal area and composition will also be negligible when viewed against the impact of continued sea level rise in the Estuary. As such no major morphologic change is likely and the general character of mudflat and saltmarsh areas will be maintained following the development.

4.3 Overall Estuary morphology and morphodynamics will continue to be controlled by wider, Estuary processes (both natural and anthropogenically influenced) and, provided compensation sites mitigate against direct loss of habitats caused by the footprint of the quay, the Water Framework Directive objectives for the Estuary will not be compromised from a hydromorphological perspective. It is essential here that compensation sites are more than adequate to offset the predicted loss of habitats.

However, dynamic change can be expected to occur which may cause a local shift in morphologic pattern. Local development of intertidal mudflat and limited saltmarsh will occur adjacent to the development. Direct loss of intertidal and sub-tidal morphologies will be compensated for elsewhere in the estuary.

4.4 Shear stresses in the vicinity of the proposed quay are likely to lead to sedimentation with deposition predicted to the north and south of the structure. Navigation is likely to restrict deposition around the front of the quay and mudflat development is likely to dominate. Extreme low energy zones may, however, show limited saltmarsh development (Figure 9a). Lidar data across the site reveal embryonic salt marsh development close to the South Killingholme jetty (Figure 9b) with deposits around 0.4 m above the general mud flat level. Other potential salt marsh areas can be expected to develop to this height over several decades. This rate of change has been found elsewhere across the Estuary, evidence of intertidal morphologic development associated with man made structures (section 3.10) confirms that this will be a slow process.

Figure 9. Potential sedimentation around the proposed quay development (a) differentiated into mudflat and salt marsh, (b) present elevated sedimentation close to South Killingholme Jetty (circled).



4.5 Exposed boulder and cobble areas along the shoreline to the north of the proposed development (Figure 10) may be subject to change either through burial by silt local to the development or increased exposure further towards North Killingholme Pits. These features appear to be a mixture of natural (Figure 10a) and man made sediments (Figure 10b). The former being remnant glacial deposits and the latter being material emplaced to mitigate against erosion close to the revetted sea walls. If necessary the man made features could be reconstructed elsewhere along the shore.

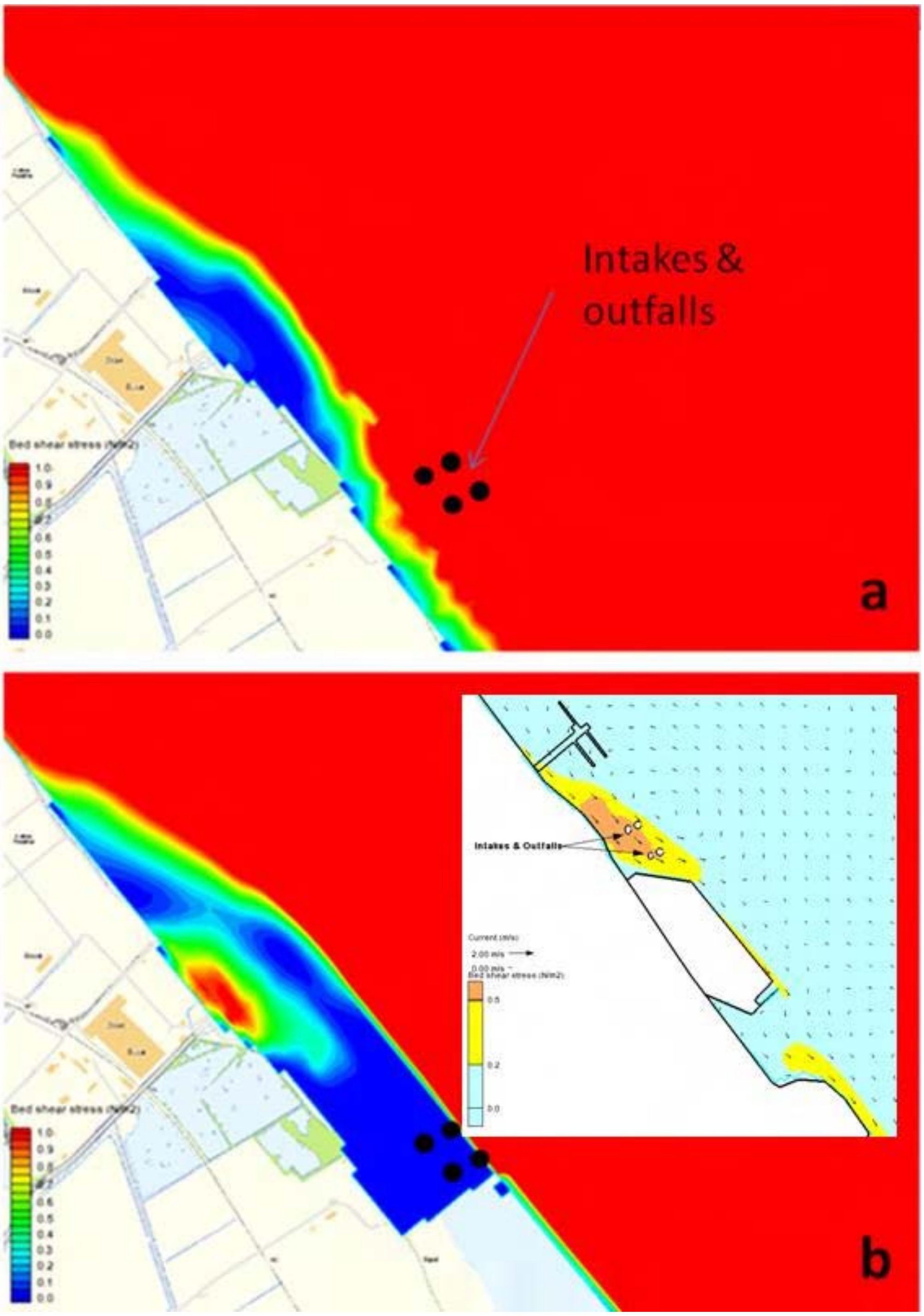
4.6 The zone of influence of the proposed quay declines to the north, with slackwater shear stresses exceeding the 0.2 N/m^2 upper limit for fine sediment deposition. Shear stress modelling results (ignoring any associated bathymetric change) reveal an increase in peak levels as a result of the quay development (Figure 11). This coincides with a recirculation zone which develops either side of slackwater. As such the North Killingholme Pits foreshore will not be subject to enhanced sedimentation except potentially at the southern end of the reserve.

4.7 The change to the shear stress pattern locally suggests that the Centrica intake and outfall should not be affected. The EON power station intake and outfall does, however, look likely to suffer sedimentation. Further quay refinement modelling has been undertaken, and the impact of the quay geometry changes on erosion and deposition are detailed in the associated "Modelling Studies" report (JBA 2011)). This effect may be heightened during dredging operations.

4.8 The recirculation pattern on the rising tide at the HST leads to increased shear stress near the foreshore around North Killingholme Pits. This is revealed as an elevated shear stress zone (red) in Figure 11b. It is, therefore, unlikely that siltation will increase here, but rather that there is the potential for erosion. The Humber Work Boats are also based at the coastline at this location. The potential for erosion along the intertidal area should not impact upon their shipping operations, and may reduce the need for maintenance dredging.

Figure 10. Exposed gravelly mud along the Killingholme foreshore.

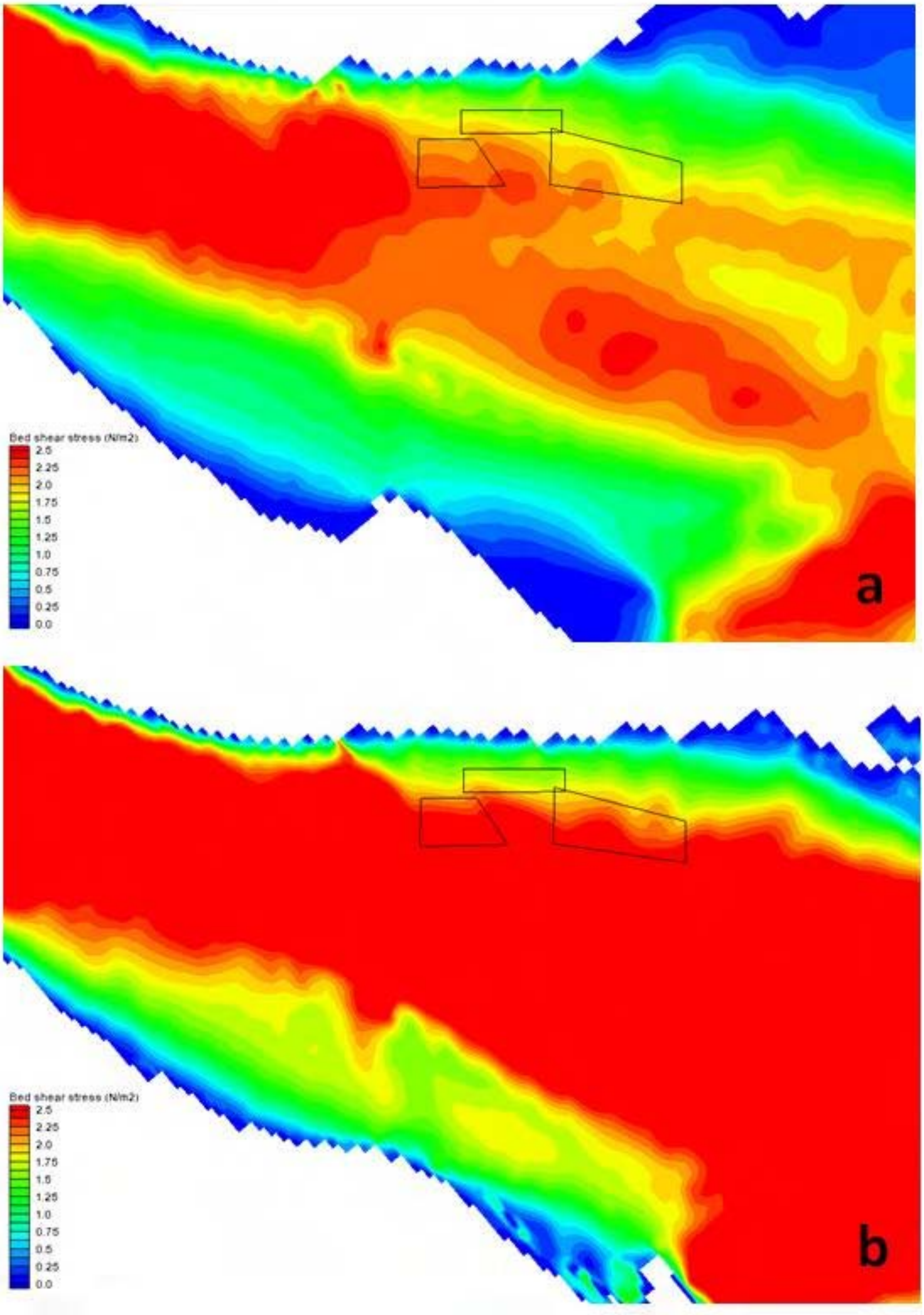
Figure 11. Changed shear stress patterns in the vicinity of North Killingholme Pits caused by the quay development, (a) Present conditions, (b) with quay. Inset details flow pattern highlighting recirculation zone.



4.9 Across the Estuary at Stone Creek the altered hydrodynamics created by the compensation area in the vicinity of Cherry Cobbs Sands may result in morphologic adjustment. An analysis of historic mapping across the site (Black and Veatch 2011) shows the area to be naturally quite dynamic with Foul Holme Sand varying in extent and connectivity to the foreshore. ABPmer (2009) state that over the period 2000 - 2007, Foul Holme Spit has migrated northwest from its detached position to rejoin Paull Sand from 2005 onwards. Historic aerial photographic evidence from the site also reveals that a creek has formed and been destroyed across the mudflats. This issue is referred to in more detail in the report on the mitigation site (Black & Veatch 2011).

4.10 Disposal of arisings from the capital dredge programme will not lead to significant morphological change as shear stresses in the vicinity of the disposal site are insufficient to break up and transport the highly cohesive glacial sediments (Figure 12). Sediments derived from the maintenance dredge programme are to be deposited at licensed sites subject to monitoring and increases in suspended sediment concentration at these sites will quickly be dwarfed by background levels. Natural variability on suspended loads will be greater than the increases due to disposal of dredged material. Refer to the associated Modelling Studies report (JBA 2011) for further supporting information.

Figure 12. Modelled shear stress levels across dredge disposal sites, (a) peak high water spring flood flow, (b) peak high water spring ebb flow.



5. Summary

5.1 It is clear from the review above that the Humber Estuary is presently highly dynamic with submerged morphology change occurring throughout the Estuary. Freshwater inflows strongly influence dynamics in the Upper Estuary; the dynamics of the turbidity maximum affect the Middle Estuary and large-scale general circulations impact on Outer Estuary morphology. Additionally, many anthroprogenic factors have altered the Estuary morphology and processes, in particular the present restrictions on lateral development are imposing significant pressure on intertidal saltmarsh with mudflat development currently dominant. Managed realignment sites should help to mitigate against saltmarsh loss, however, the likely alteration to the morphology at the proposed quay site will impact on other smaller features such as the exposed muddy gravels and mitigation for the loss of these features will be necessary.

5.2 The following key points emerged from the study:

- The morphology and habitat assemblage of the Humber Estuary is both varied and dynamic responding to process change over both long and short timescales.
- Overall the Estuary is in a dynamic equilibrium with morphological response keeping pace with gradual sea level rise. A fine balance exists between fluvial and marine inputs and sedimentation. Coarse sediment can be exported in the ebb-dominated channel with finer material accumulating on intertidal mudflats and moving upestuary.
- Historic change is most notable in the area around Read's Island and across the Outer Estuary, with the consolidated boulder clays of the Middle Estuary promoting stability. However, change has been recorded across the entire Estuary and directional movement (consistent erosion or deposition) is not apparent across much of the Estuary, with areas frequently switching between a stable morphology, erosion and deposition. This is reflected in the variability in sub-tidal morphological maps produced for the Estuary.
- The lack of accommodation space in the estuary, due to development, would suggest that mudflat development will dominate over salt marsh.
- Turbidity levels are generally high throughout the Estuary, particularly around the Middle-Upper Estuary boundary.
- Freshwater flow volume variation is almost certainly influencing the dynamics of the Upper Estuary.
- The influence of the 18.6 year Lunar Nodal Cycle is likely to be impacting on top of the general trend in sea level rise, further adding to the natural process variability across the Estuary.
- Local flow patterns and energy levels invoke morphologic response across intertidal areas promoting both erosion and deposition. This is particularly likely at the compensation site where creek formation will occur.
- The impact of the proposed quay on local sedimentation is likely to be one of enhanced deposition around the immediate structure. This is likely to develop as mudflat with only marginal saltmarsh. Development is likely to take several decades to reach a dynamic equilibrium.
- Away from the proposed quay the combined impact of the development on intertidal and sub-tidal areas will be negligible in comparison with natural variation.
- The impacts of localised dredging and dumping appear to be insignificant when compared to the magnitude of sediment transport processes operating in the Estuary with natural spatial and temporal variability dwarfing anthropogenic sediment redistribution.

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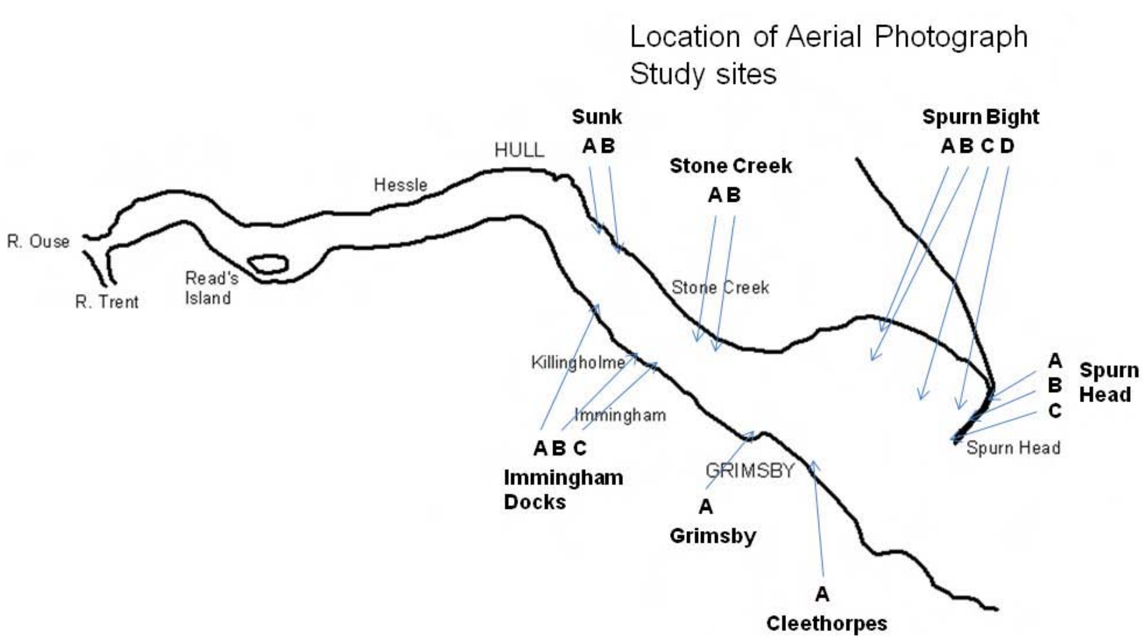
Appendices

A. Morphological change evidenced from aerial photographs of the Humber Estuary 1945 – 2010.

Visual study based on limited historic photographic evidence around the Estuary.



A.1 Immingham Docks

OS/62/96 093 1st September 1962 - 84-70-070 3681 28th October 1970

Cohesive mudflats show no morphological change.

84-70-048 28th October 1970 – TGT339/90 005 18th August 1990

No observable change to monotonous mudflats.

Exit channel from tributary morphologically stable.

A.2 Cleethorpes

OS/64252 27th October 1964 – 37-76-217 6th June 1976 – 054 196 6th May 1988 – Bing Maps 2010

Nearshore dune / saltmarsh vegetation stable between 1964 and 1976, extended slightly through to 1988. Continues to develop through to 2010.

Highly mobile sand ribbons offshore. Major ribbon sandbank seen in 1976 persists through to 1988. Destroyed by 2010.

A.3 Grimsby Docks

106G/UK849 6063 28th September 1945 – V58/RAF/2111.1 127 18th February 1957 – MAL/59402 75253 29th September 1959 – OS/62/96 4028 1st September 1962 – 56-70107 & 109 18th July 1970 – Bing Maps 2010

Major mudflat with incised primary sinuous off-bar drainage channel exhibiting a very stable sinuous planform to 1970, lost by 2010 as a result of change to drainage on land. Local drainage network similarly stable. Saltmarsh configuration stable through to 1970, now a car park.

Exposure of bedrock across upper mudflat apparent by 2010.

A.4 Immingham

OS/62/96 48 1st September 1962 – TGT339/90 053 – Bing Maps 2010

Development of offshore sandbar which persists through to 2010.

Generally stable expanse of sandy and mudflats, creation of new outflow caused development of sub-linear channel perpendicular to the coast.

4042 2083 29th April 1947 – 06-76-210 1st March 1976 – Bing Maps 2010

Largely undifferentiated mudflat, minor disruption to the edge of the saltmarsh near the jetty.

Minor expansion of marsh further down estuary accelerating through to 2010

A.5 Stone Creek

4060 4030 21st September 1946 – 4042 2078 29th April 1947 – 06-76-216 1st March 1976 – TGT834/328R95 032 19th August 1995 – Bing Maps 2010

Initial well differentiated saltmarsh and upper and lower mudflat area with stable local drainage network. Stable configuration persists through 1976 and 1995. Saltmarsh persists in 2010.

Deep major offshore channel developed/dredged to the west.

0111 3rd February 1953 – TGT834/328R95 030 19th August 1995

Poorly differentiated but wide nearshore drainage channel close to shore with minor local drainage into the channel. Additional larger mudflat drainage channels running parallel to the shore.

Development of a deeper channel very close to the shore associated with very strong well developed offshore drainage across the mudflat.

A.6 Sunk

4062 6033 21st September 1946 – 0116 3rd February 1953 – 32-73-056 1973 – Bing Maps 2010

Presence of coherent largely undisrupted saltmarsh grading into mudflats in 1946 with a sinuous principal inshore drainage channel and deeper larger nearshore channel, maintained through 1953. Sinuosity in this channel reduces through to 1973 but other morphology remains stable.

Marsh area shows reduction by 2010.

Potentially some vegetation community change?

RU.420 6711 60 & 62 17th March 1942 – 541/170 3197 21st September 1948 – OS/66/222 260 19th August 1966 – 07-76-161 25th February 1976 – TGT360A92S 003, 004 & 005 26th May 1992

Original offshore sub-parallel braided sub-channels draining mudflats. Major offshore isolated mudflat with what appears to be a major largely infilled channel covered in braided channel network.

Largely undifferentiated mudflats persist through 1966.

Slow sedimentation and associated vegetative development in lee of shoreline spur structures continuing through to 1992.

Major change to the local drainage pattern linked to a deeper channel between the nearshore mudflat and offshore isolated mudflat with sub-parallel drainage channels perpendicular to the shore.

A.7 Spurn Bight

69-420 168 24th August 1969 – 37-76-080 6th June 1976 – TGT834/328R95 048

Very minor changes to the intertidal supratidal boundary with isolated vegetation patches remaining stable.

69 420 170 24th August 1969 – 37-76-078 6th June 1976 – 82 133 010A 29th May 1982 – TGT834/328R95 046 19th August 1995

Saltmarsh drainage network is extremely stable throughout, tributary channel straightens after construction of sluice between 1969 and 1978.

Minor extension to saltmarsh to the west of the tributary post 1978.

Possible vegetative assemblage alteration with lighter patches extending between 1976 and 1995.

4014 21st September 1946 – 3060 29th April 1947

Local mudflat drainage patterns extremely stable with only very minor migration of local meanders.

A.8 Spurn Head

3007 21st September 1946 – 77-22 244 6th July 1977

Sand megaripples give way to mudflats to the north. Distinct sand – mud boundary maintained throughout (two levels possibly corresponding to neap tide high and low water mark).

Dendritic drainage north off of the mudflat maintained.

Loss of meandering sub-channels in favour of braided channels possibly linked to mudflat steepening.

BR174 773 24th March 1941 – 22-77-890 6th July 1977 – TGT 355A94 004 13th June 1994

Spurn Head megaripples in lee of spit maintained.

Beach sands maintained.

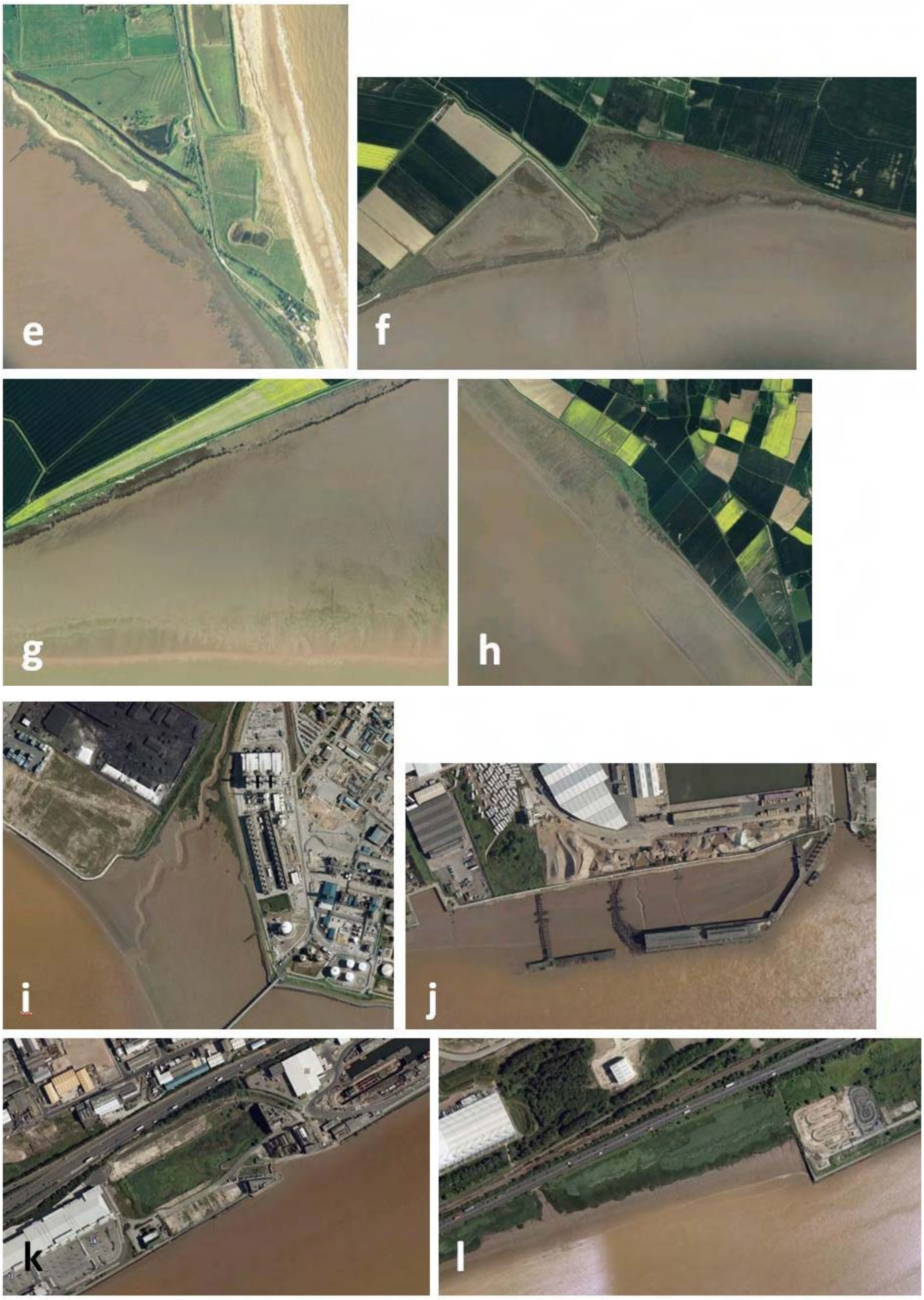
TGT355A94 009 13th June 1994 – TGT834/328R95 128 19th August 1995

Patchy Inner Estuary saltmarsh is maintained.

Offshore Inner Estuary mega-ripples show local dynamism

B. Aerial photographs of saltmarsh around the Humber Estuary.


a
b
c
d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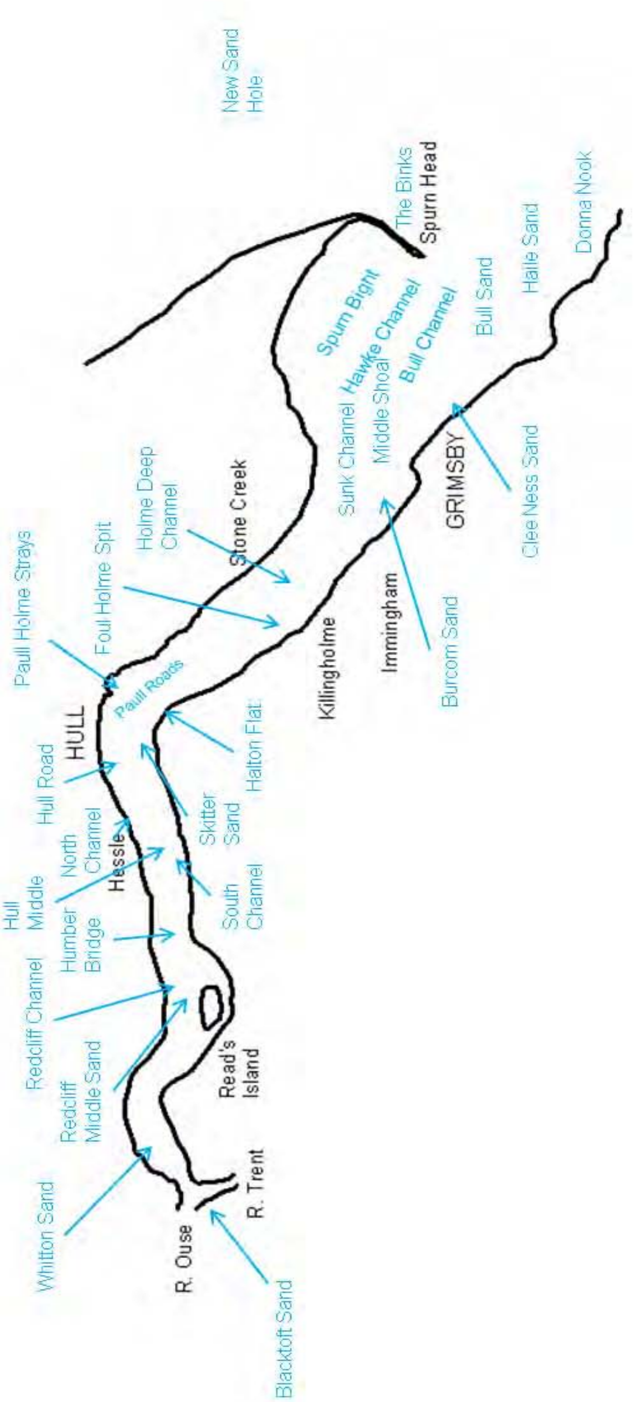
C. Location map



D. Record of responses to regulator comments

This annex contains comments on the original report and details the changes made to address these (bold text). Italicised bold text received from Black and Veatch.

MMO Response

Thank you for consulting the Marine Management Organisation (the MMO) on the Humber Geomorphology Report.

In considering this report, we have consulted with the Centre for Environment, Fisheries and Aquaculture Science and the MMOs district Marine Officer for the Humber. Their comments have been incorporated into this letter.

The review presents the Humber Estuary as a complex and highly turbid environment that is in dynamic equilibrium. Most sectors of the estuary show no directional trends. Given the high natural variability in the system, many impacts of the proposed development may be undetectable.

The response of the intertidal areas adjacent to the proposed development are largely assessed using the bed shear stress (skin friction) results presented in the Modelling chapter, and setting these changes in the context of the wider estuarine natural variability. Wave modelling, including investigation of wave reflection from the quay, is used, but the results do not appear be included in the calculations of bed shear stress, which is particularly relevant in intertidal areas where wave motion is important to erosion (e.g., Le Hir, 2000 and Section 3.5). If this is not considered important, it should be stated and backed up with evidence. Otherwise the assessment of erosion/accretion due to the development should include wave (natural and reflected) induced shear stress. The additional impact of the reflected waves off the proposed structure on the intertidal area should also be assessed and reported in the Environmental Statement (ES).

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The Modelling report defers comments on erosion/accretion patterns to the Geomorphology report, however the report seems general and reports only briefly on the anticipated impacts. The erosion predicted at the Humber Work Boats site (Section 5.35; Modelling) is not mentioned in the Geomorphology chapter. Please provide the erosion patterns and the forms of mitigation anticipated if this is not considered to be a positive impact within the final ES.

The recirculation pattern on the rising tide at the HST leads to increased shear stress near the foreshore around North Killingholme Pits. Therefore, there is unlikely to be an increase in siltation here, but rather the potential for erosion. Humber Work Boats are based at the coastline at this location. The potential for erosion along the intertidal area should not impact upon their shipping operations, and may reduce any maintenance dredging required. This is reported on in section 4.8.

The Geomorphology report is light on information concerning the compensatory realignment. Although the shoreline in the Cherry Cobb realignment area is discussed in Chapter 8.1, this document was unfinished at the time of reading and did not consider the impacts of coastal realignment. Realignment has also not been assessed in any great detail in the Geomorphology chapter. However, this chapter should detail the expected impacts of the realignment, drawing on experiences from other realignments, including the Paull Holme Strays coastal realignment, which is in the same part of the estuary and the same side of the estuary as the proposed compensatory realignment.

The dynamics of the Estuary shoreline in the Cherry Cobb realignment area has been the subject of a separate detailed study by Black and Veatch (Black & Veatch 2011). Reference is made to this document in section 4.10.

Regarding the habitat, specific actions to be taken in the compensatory coastal realignment to ensure like-for-like habitat substitution should be detailed in full in the ES For example, in the case of salt marshes sediment chemistry appears to be critical to project success.

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Section 2.1 states that "general accretion between 1851 and 1936 particularly around Grimsby Middle, Middle Shoal, Foul Holme Sand and in the vicinity of Read's Island. Since 1936, however, the trend has been towards erosion and sediment loss.". In contradiction, Figure 5 appears to show erosion dominating in the 1851-1936 period. Please provide a full justification for the comments made or make appropriate amendments.

Figure 5 is a generalisation of the bathymetric survey data and does show accretion around Grimsby Middle, Middle Shoal, Foul Holme Sand and in the vicinity of Read's Island, additionally it picks up some erosion in other areas not specifically commented on by ABPmer (2004) and reviewed in section 2.1. It is argued that at this level of generalisation there is no major contradiction.

Section 3.12: "Most areas are stable in terms of the proportion of mud flat to salt marsh". This statement does not identify whether these areas are growing or declining, or whether there are any areas of erosion in the bed levels. Please expand.

The historic aerial photographic coverage for the Estuary is extremely patchy (Appendix A). As such the statements in 3.12 are qualitative in nature and accurate estimates of habitat change using this source of data would be patchy and inaccurate. The assessment method is able to report on general stability based on local planform change alone and cannot be extrapolated up.

Section 3.13: Assumptions regarding deposition and erosion shear stresses require justification/evidence

Additional text has been added to 3.13 to justify the source of the threshold values.

Sections 3.14 and 3.15 mention important data/evidence. For ease of understanding, quantification and to visualise spatial aspects, these data should also be given in graphical form, for example, a time-series of erosion/accretion maps. Additional discussion on where the accretionary area is located, how large it is, what the rates of change are, what the spatial variability in bed level changes mentioned are and whether all of the changes are within the 0.5 – 1 m range.

Section 5.2: The second to last bullet point “Away from the proposed quay the combined impact of the development on intertidal and sub-tidal areas will be negligible in comparison with natural variation.” This statement is lacking evidence or citation of evidence elsewhere in the ES. This needs to be provided in the final ES.

This is a summary statement and draws from evidence presented in section 4. In particular paragraph 4.1 reviews the predicted hydraulic changes as a result of the proposed development and refers to the modelling report (JBA 2011) where greater detail is presented.

It would be helpful if SSC units were consistent (kg/m3 and mg/L used).

The equivalence has been stated in the caption to figure 5.

Section 4.8: The outfalls discussed are not shown on diagrams. Reference made to another report.

These are now included in Figure 9

Section 5.2, fifth bullet: it is unclear whether this is a general statement or made with reference to the proposed development.

This is a reemphasis of the general situation in the Estuary.

The various components of the draft ES for the Humber Marine Energy Park have arrived as separate chapters, which has made an assessment difficult as linked chapters are not always all present during each review. This document is well organised and formatted and appears to be complete, although it is more brief than expected concerning the section on the Geomorphological Impacts of the Development.

This has increased following the suggested changes above.

Future consultation reports and the ES must address the comments made in this minute, and previous advice, and detail how they have been taken into account. A reference document of some kind in the annex may be appropriate. If any issues raised are not addressed or are scoped out then we would like to see detailed reasoning and justification as to why.

This appendix forms the reference document for the changes made.

Natural England Response

Thank you for consulting Natural England on the geomorphological information. These comments are based on the information provided in those documents forwarded to us by Jonathan Monk on 19 May. It is given without prejudice to any advice Natural England may offer in accordance with our statutory roles under the Conservation of Habitats and Species Regulations 2010 and the Infrastructure Planning (Environmental Impact Assessment) Regulations 2009. Formal comments will be provided following consultation on the full Environment Statement and the Habitat Regulations Assessment.

General overview comments

Both the "Geomorphological Dynamics" and "Modelling Studies" reports are thorough scientific documents that contain high quality work that is written up in a logical, informative and straight-forward manner. The only apparent omission is in linking some of the historic land reclamation in the estuary to the geomorphological change that has occurred.

There are however two areas in the "Geomorphological Dynamics" report where findings have not been fully developed into the understanding.

First, there is mention of an overall 'dynamic equilibrium' claimed to be observed over the period 1850 – present (i.e. morphological response keeping pace with sea-level rise). However, there is a later statement that "since 1936 the trend has been towards erosion and sediment loss" (page 8). Are these statements compatible? Does the more recent historic change reflect a change in state or rate of change and, if so, what is the driving cause of this?

The report quotes two studies (ABPmer 2004 and Townend & Whitehead 2003) which have come to slightly different conclusions. Reference is made to the ABPmer work

alongside the Townend & Whitehead 2003 study in section 2.3 to provide additional information beyond their study. Such apparent contradiction is inevitable when making general statements about whole Estuary behaviour. The overall message is one of morphology change keeping pace with sea-level rise but with considerable local spatial and temporal variability in erosion and deposition everywhere across the Estuary.

Second, this report refers to "cycles of change" (stability-erosion-deposition) in certain areas of the estuary, but does not really get to the bottom of their triggers. Similarly, the assessment of bed level changes in front of the Immingham Waterfront appears to suggest subtidal accretion to the mid-1950s and erosion since, with intertidal erosion to the mid-1930s and accretion or stability since. The reasons for, or implications of, these changes are not discussed in the report, despite potentially being of high relevance due to the proximity of Immingham to the proposed development at Killingholme.

Reference is made in section 2.12 to the study by ABP marine Environmental Research ltd (2009) which identified potential 'cycles' in the gross morphology of the Outer Estuary. No triggers have been suggested as these 'cycles' relate to large-scale migration of the principal submarine channels in this part of the Estuary. More local changes around Killingholme have also not been attributed to any clear triggers. Again the overall intention is to highlight the inherent stochastic behaviour of the channel bed locally with erosion or deposition remaining unpredictable. This is now emphasised through a quantitative analysis of mapped bathymetric change presented by Van Ormondt and Roelvink (2004) which reveals major local variability in bed level change since the mid 1970s.

It is noted that the compensation site has been modelled using a more detailed model grid by Black & Veatch using Tuflow. It is a little confusing why a detailed local model grid could not have been built into the estuary wide model developed by JBA Consulting, and why there was a change of model type, Clear explanation and justification of why this has been carried out is needed.

The modelling approaches were developed separately by JBA Consulting and Black and Veatch in agreement with ABLE UK.

We are concerned by the extremely high siltation rates predicted in the vicinity of the dredged areas associated with the proposed development. Additionally, the sediment transport model "fails to predict the likely long term increased accumulation in the intertidal area adjacent to the quay" - the reason for this is not given and more information on why this has not been predicted is needed.

An additional addendum to the modelling report concentrates on the sediment dynamics in the vicinity of the proposed quay and statements on potential sedimentation rates derived from across the Estuary are given in sections 3.9-3.15.

Black & Veatch appear to have taken rather a strange approach (presumably dictated by absence of suitable measured data) whereby they have taken output from JBA Consulting's model as input on their boundary conditions and then also used output from JBA Consulting's model for verification purposes. Despite this, there are some notable differences in outputs, especially in relation to flow velocities which are stated to "arise from the different grid resolution of the two models". An explanation of these differences should be provided.

Para 3.2.2 of Annex 32.2 (Hydraulic model set up) has been expanded to clarify why different grid resolution can affect results. New sentence added 'This leads to the many detailed model cells within each larger Humber model cell having different bed levels because the detailed model picks up greater detail from the bathymetry that is

common to both models.' There is considerable discussion in the text on the reasons for the differences that were found between the two models. We are not sure what can usefully be added to this discussion. The report notes the good agreement at 5 out of 7 sites for both velocity magnitude and direction and considers the issues that might affect agreement at other sites. We consider the overall conclusion that 'the reasonably good agreement between the results provides confidence in the reliability of the detailed model for predicting the effects of the development' is a fair and valid assessment.

The "Geomorphological Dynamics" report 'parked' the issue of changes to the estuary due to the compensation scheme, for the Black & Veatch work to pick up in more detail. However, this work mainly focused on within site changes and did not discuss sufficiently the wider scale changes/impacts, which needs to mainly cover the fronting foreshore and, potentially, the subtidal. The issues of changes to the wider estuary due to the compensation scheme will need to be assessed and reported.

Suggest issues relating to the local geomorphology of Foul Holme Sand and the Compensation Site are only discussed in the B&V reports eg foreshore evolution report. The wider effects of the compensation site are already included within the JBA modelling and these should be specifically mentioned as being included in the JBA modelling and geomorphology reports. B&V have added section 2.5 Far Field effects of the Compensation Site to Annex 32.4. This states 'The modelling described in this report is restricted to the effects within the Compensation Site and on the adjacent intertidal foreshore of the Humber estuary including Cherry Cobb Sands Creek and Foul Holme Sand. Any more distant effects of the Compensation Site are considered implicitly in the modelling of 'the Project' in Annex 8.1.'

In para 32.1.1 the following text has been added '... including distant effects of the development of the Compensation Site as an integral part of the whole Project are covered in Chapter 8' to clearly indicate where such impacts are assessed.

Some bed level changes are predicted in the vicinity of the new quay approach ±0.4 – 0.5m according to the modelling plots, when simulated over an 18 day period. This is a very high rate of change over such a short time and has not really been discussed in the report, leaving it to the reader to draw these values from the figure. This information needs to be clearly reported within the text, other information in figures which show important changes also need to be clearly explained within the text.

This statement refers to Figure 28 in the JBA modelling report. This work is reported on but has been superseded by additional local modelling work. An addendum has been included in the revised document detailing the modelled shear stress variation around several proposed quay design options and these are fully reviewed in terms of potential erosion and deposition around the site.

The sediment transport model does not seem to predict erosion in the area within the recirculation zone (on a flood tide) in the wake of the quay and this does not seem to have been discussed in the "Geomorphological Dynamics" report. This should be included.

Data on the intertidal morphology were absent from the sediment transport model and no predictions of change were made in the recirculation zone. The links between the shear stress predictions and the recirculation zone is made clear in a revised section 4.6 and on Figure 9 which now incorporates a flow pattern inset.

Based on the work presented, there will be local impacts associated with this scheme in relation to:

· Increased potential for siltation (and associated maintenance dredging/ disposal) at Eon and Centrica intakes/outfalls, the approach channel to Humber Sea Terminal (HST), South Killingholme Oil Jetty, Immingham Gas Jetty, Humber International Terminal and Immingham Bulk Terminal, and also at the new berths themselves. Estimates of the increase in annual maintenance dredge volume associated with this development are very high.

An addendum has been included in the revised JBA modelling report detailing the modelled shear stress variation around several proposed quay design options and these are fully reviewed in terms of potential erosion and deposition around the site. Figure 7 has been added to the report to demonstrate the recorded rates of change for the Killingholme foreshore illustrating local changes ranging up to +_ 0.5 m per annum but more generally at 0.05 - 0.1 m per annum. The new data help to contextualise the predicted change to the foreshore following the quay development.

· Increased potential for erosion of the foreshore fronting North Killingholme Pits and the new compensation site.

An addendum has been included in the revised JBA modelling report detailing the modelled shear stress variation around several proposed quay design options and these are fully reviewed in terms of potential erosion and deposition around the site. Section 4.4 and Figures 7 and 8 have been updated to provide further local context and evidence of sedimentation rates and morphological development in the vicinity of the proposed quay.

Some key factors which must be assessed are;

· The issue of the work not having been carried out for the lifetime of the project

· Assessment of the impacts of the realignment on the wider estuary (not just the compensation site itself).

This issue is already covered in the JBA modelling report and perhaps this fact should be highlighted. B&V modelling report will highlight JBA reports as location where far field effects are assessed.

Specific comments on individual documents:

Review of the Geomorphological Dynamics of the Humber Estuary

Page 3 Section 1.7 states "It would appear that the morphodynamics of the Humber Estuary is strongly controlled by the accommodation space available during sea-level rise. The ability of the estuary to extend laterally, creating a shallow topography, encourages channel stability and saltmarsh development. In contrast, restricted expansion encourages channel migration and mudflat development (Metcalfe *et al*. 2000). The lack of accommodation space in the estuary due to development would suggest that mudflat development will dominate over saltmarsh." This suggests that this development will further exacerbate this problem over the long term thereby leading to mudflat creation (short term) and ultimately a lack of intertidal space.

Section 1.7 refers to the overall Estuary state, the proposed quay will narrow the Estuary locally and results in a slight increase in the overall velocity across the channel. This has been assessed as having a negligible impact on the morphodynamics of the Estuary when compared with the present observed spatial and temporal variation. The proposed quay will impact locally and potential morphologic response is set out in chapter 4.

Page 10, Section 2.5 states "The Outer Estuary north shore displayed a significant loss of intertidal area around 1950, increasing since that date but with local variation potentially linked to the nodal tidal cycle. The Outer Estuary south shore also shows a significant loss of intertidal area around 1950, continuing to decline with no discernable link to the nodal tidal cycle. The Middle Estuary response has been more variable locally but with a general decrease between 1936 and 1985 increasing thereafter." But later on the document says "Intertidal areas are generally said to be accumulating fine sediment whilst sub-tidal areas are exporting sandy material. Analysis of aerial photographic records between 1976 and 1995 (Table 3) show a small increase in saltmarsh coverage (ABP Research 1996)" This second statement needs to make clear which portion of the estuary is showing accumulation; clearly the earlier statement says the outer estuary is showing loss of intertidal areas, also table 3 appears to show that much of the gain is in the inner estuary which is not highlighted in the text. Natural England is also aware that the Environment Agency's work shows that the middle estuary is losing habitat – up to 10ha per year, which is contradictory to the statement in section 2.5.

Again the issue here is one of scale and generalisation. The report notes the general process of intertidal fine sediment accumulation and sub-tidal sand transport and details measured changes to intertidal habitats (Table 3). Reported habitat change from differing studies reveals some inconsistency in change areas and rates as would be expected.

Page 13, section 3.8 notes that "Visual analysis of historic aerial photographs of the estuary (Appendix A) reveals a general stability in mudflat and saltmarsh distribution since the 1940s." Again as in the point above consistency is needed throughout the report on discussing changes.

This reports on a visual assessment conducted as part of the study which has found contrasting results. These are however based on limited photographic coverage. This is reported in Appendix A.

Page 13, section 3.9 states "Often fine sediment arisings, deposited at the disposal sites, are reworked (deposited on neaps and re-eroded on springs) with eventually 48% of silt and 44% of sand being lost." Explaining where this is lost to would be beneficial (i.e. lost from the disposal site to elsewhere in the estuary, moved out of estuary)?

The word 'lost' is misleading here and has been replaced by assimilated into the general suspended sediment transport process.

Page 14, section 3.12 "a review of the aerial photographs around Cherry Cobb Sands Bank west of Stone Creek shows that the mudflats are affected by an ephemeral offshore channel which appears to infill and reform across the area (Appendix A)." Over how long a time period does this occur?

This issue is addressed in the B&V geomorphology report of the foreshore evolution. Suggest para is deleted or reworded to point to annex 32.1 (B&V geomorphology report)

This paragraph has not been deleted as it is a finding from the aerial photograph analysis. Reference is made to the B&V geomorphology report for more information.

Page 14, section 3.14 "The area along the Immingham Waterfront has been analysed for average bed level changes between 1920 and 1999." Although we welcome this long term dataset, it is missing data up to the present day (i.e. over 10 years of data), why has this not been assessed?

These data were analysed from the Delft 3D modelling report (Van Ormondt, M. & Roelvink, D. 2004). As such the data available only extended through to 2000.

Page 15, section 4.2 “The results of the hydrodynamic modelling suggest that changes to intertidal area and composition will also be negligible when viewed against the impact of continued sea level rise in the estuary. As such no major morphologic change is likely and the character of mudflat and saltmarsh areas will be maintained following the development.” Effects caused by plans or projects are not natural change and the likely significance of their effects on the system must therefore be considered independently of any natural change observed due to natural processes.

Agreed but the data suggest that additional impact over and above that affecting the current Estuary dynamics is negligible. Reference is made to natural and anthropogenic influence in sections 4.2 and 4.3.

Page 16, section 4.6 “Exposed boulder areas along the shoreline to the north of the proposed development may be subject to burial by silt. These features appear to be manmade and if necessary could be reconstructed elsewhere along the shore.” A more detailed description of these features is required – what are they used for/by, will a loss of these be significant? More information on these is required.

These features have been illustrated by means of a new Figure 10.

Page 16, section 4.7 “As such the North Killingholme Pits foreshore will not be subject to enhanced sedimentation except potentially at the southern end of the reserve.” This potential issue needs further discussion.

Improved modelling results have revealed a recirculation zone in the area which will raise shear stresses locally significantly reducing the likelihood of sedimentation. This is reported in section 4.8.

Page 20, section 5.1 “The present restrictions on lateral development are imposing significant pressure on intertidal saltmarsh with mudflat development currently dominant. Managed realignment sites should help to mitigate against saltmarsh loss.” Whilst new developments increase the pressure, both sides of this issue should be highlighted, this report clearly recognised the problem development causes, managed realignment is not the ideal situation; particularly as they will be created outside the designated site and therefore cannot mitigate any impacts within the site boundary. This report needs to recognise that this development will add to this issue.

This issue is stressed further in section 5.1 which describes the need for additional mitigation.

Best wishes

Emma

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References

Allen, J., Boyes, S., Burdon, D., Cutts, N., Hemingway, K., Jarvis, S., Jennings, K., Mander, L., Murby, P., Proctor, N., Thomson, S. & R. Warren, (2003). The Humber Estuary: A comprehensive review of its nature conservation interest. English Nature Research Reports, Number 547. ISSN 0967-876X.

ABP Marine Environmental Research Ltd (2004). Historical Analysis of Humber Estuary Morphology. Report R.1005. Environment Agency North East Region.

ABP Marine Environmental Research Ltd (2009). Immingham Oil Terminal Approach Channel Dredging Environmental Statement. Associated British Ports & Total Lindsey Oil Refinery. Report R. 1416.

ABPmer (2009). Humber CHaMP Monitoring Study. Report No. R.1467, July 2009.

ABPmer (2004). Humber Estuary Shoreline Management Plan – Stage 2. Humber Estuary Data Report. Report R932. Environment Agency North East Region.

ABP Research, (1996), Humber Estuary form analysis, Report No: RN.690, 1-19.

ABP Research (2000). Improving Navigation – Immingham Waterfront. ABP Grimsby and

Immingham, Report R. 883.

Balson P. S. & Philpott, S. L. (2004). Sediment sources, sinks and pathways at the mouth of the Humber Estuary. British Geological Survey Report CR/04/159. 16pp.

Black. K. S. (1998). Suspended sediment dynamics and bed erosion in the high shore mudflat region of the Humber Estuary, UK. Marine Pollution Bulletin, 37, 122-133.

Black and Veatch (2004). Humber Estuary Shoreline Management Plan Phase 2. Short term water level and geomorphology impacts of managed realignment in the Humber. Environment Agency, Leeds.

Black & Veatch Consulting Ltd and Environment Agency, (2005). Humber Coastal Habitat Management Plan, May 2005.

Black and Veatch (2011). Cherry Cobb Sands Compensation Site Evolution of the existing foreshore. 21pp.

Boyes, S. & M. Elliott, (2006). Organic matter and nutrient inputs to the Humber Estuary, England. Marine Pollution Bulletin, 53 (1-4), pp. 136–143.

British Transport Docks Board. (1970). Silt movement in the Humber Estuary. British Transport Docks Board (BTDB), Research Station Report No. R.221.

Brown, E. A. Colling, D. Park, J. Phillips, D. Rothery, J. Wright (2005) Waves, Tides and Shallow Water Processes. Open University.

Cutts, N.D., Murby, P. And Hemingway, K.L., (2008). Habitat Loss in the Humber Estuary. Institute of Estuarine & Coastal Studies (IECS), University of Hull, UK. Report produced as part of the European Interreg IIIB HARBASINS project.

Davidson, N.C., (1995). Chapter 4.1 Estuaries. In coasts and seas of the United Kingdom. Region 6 Eastern England: Flamborough Head to Great Yarmouth, ed by J.H.Barne, C.F Robson, S.S. Kaznowska, J.P. Doody and N C Davidson, 63-66, Peterborough, Joint Nature Conservation Committee.

Environment Agency (2004). Humber Estuary Shoreline Management Plan Phase 2: Summary of Geomorphology studies 45pp

ESTPROC/rapport (2004). The transport of fine sediment in the Humber estuary (ESTPROC/rapport 04 Z3040-30/hw/22-05-1 03)

Gameson, A.H.L. (Ed.), 1982. The Quality of the Humber Estuary 1961– 1981. Yorkshire Water Authority, Leeds, p. 88.

GeoSea Consulting (1990). The Anglian Sea Defence Management Study - Phase III. Field Survey Report. Volume 3. Estuary Sediment Trends. GeoSea Consulting, Cambridge.

Hemingway, K.L., Cutts, N.D., Allen, J.H. & S. Thomson, (2008). Habitat Status of the Humber Estuary, UK. Institute of Estuarine & Coastal Studies (IECS), University of Hull, UK. Report produced as part of the European Interreg IIIB HARBASINS project.

Le Hir, P., Roberts, W., Cazaillet, O., Christie, M., Bassoullet, P. and Bacher, C., (2000), Characterization of intertidal flat hydrodynamics. Continental Shelf Research, 20, 1433-1459.

Mazik, K., Smith, J. E., Leighton, A. & Elliott, M. (2007). Physical and biological development of a newly breached managed realignment site, Humber Estuary, UK. Marine Pollution Bulletin, 55, 564-578

Metcalfe, S. Ellis, S., Horton, B., Innes, J., MacArthur, J., Mitlehner, I., Parkes, A., Pethick, J., Rees, J., Ridgeway, G., Rutherford, L., Shennan, I., and Tooley, M., (2000), Holocene evolution of the Humber Estuary. Geol Soc London Spec. Publ.. 166, 97-118.

Mitchell, S. B., Couperthwaite, J. S., West, J. R. & Lawler, D. M. (2003). Measuring sediment exchange rates on an intertidal bank at Blacktoft, Humber Estuary, UK. The Science of the Total Environment. 314-316, 535-549.

Ormondt, M. van and D. Roelvink (2004) Short-term morphologic modelling of the Humber Estuary with Delft3D, WL|Delft Hydraulics, Delft, Netherlands

Pethick, 1990. The Humber estuary. In: (Ellis, S. and D.R. Crowther, Eds.) Humber perspectives: A region through the Ages. Hull University Press, Hull

Rees, J. G. (2006). Sea-level topographical and sediment supply controls on Holocene sediment composition in the Humber Estuary, UK. Philosophical Transactions of the Royal Society A. 364, 993-1008.

Townend, I., Pethick, J., Balson, P., Roberts, W. & Young, R., (2000), The Geomorphology of the Humber Estuary. In: Proceedings of the 35th MAFF Conference of River and Coastal Engineers, Keele, 2000.

Townend. I. & Whitehead, P. (2003). A preliminary net sediment budget for the Humber Estuary. The Science of the Total Environment, 314-316, 755-767.

Townend, I, Wang, Z. B. and Rees, J. G. (2007) Millennial to annual volume changes in the Humber Estuary. Proc. R. Soc. A, 463, 837-854.

Uncles, R. J., Easton, A. E., Griffiths, M. L., Harris, C., Howland, R. J. M., King, R. S., Morris, A. W. and Plummer, D. H. (1998). Seasonality of the Turbidity Maximum in the Humber – Ouse Estuary, UK. Marine Pollution Bulletin, 37, 206-215.

Uncles, R. J. Stephens, J. A. & Law, D. J. (2006). Turbidity maximum in the macrotidal, highly turbid Humber Estuary, UK: Flocs, fluid mud, stationary suspensions and tidal bores. Estuarine, Coastal and Shelf Science. 67, 30-52.

Van Ormondt, M. & Roelvink, D. (2004). Short-term morphologic modelling of the Humber Estuary with Delft3D.

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