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COASTAL AND MARINE ENGINEERING AND MANAGEMENT
COMEM

A STUDY OF MORPHOLOGICAL CHANGES WITHIN MANAGED REALIGNMENT SITES ALONG THE HUMBER ESTUARY (UK)

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A study of morphological changes within managed realignment sites along the Humber Estuary (UK)

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A dissertation submitted in partial fulfilment of the degree of MSc in Engineering in the Coastal Environment by instructional course.

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Abstract

Managed realignment involves the deliberate breaching of engineered defences to allow landward coastal migration whilst at the same time creating intertidal marshes and mudflats. Over the last two decades, this practice has become more common; however, the monitoring of realignment schemes is relatively limited and morphological changes are generally not monitored in great detail. The monitoring programmes of the sites in the Humber Estuary are a clear example of this issue; here the morphological changes of the four realigned sites are mostly represented by generalised rates of accretion or erosion. The aim of the this study was to analyse in detail the morphological changes that have taken place at the four managed realignment sites in the Humber Estuary, using LiDAR in order to obtain elevation change plots, cross section profiles, hypsometric curves and sediment volumes in an ArcGIS environment. In addition the physical processes driving these morphological changes were also identified and the future evolution trend of the sites was proposed.

The four managed realignment sites in the Humber Estuary presented an accretionary trend over the period of analysis, driven by tides and characterised by high deposition rates during the first years after breaching. However, clear differences in the evolution of the sites were observed, mainly related to the sites location along the Humber Estuary and their configuration. Furthermore, it is thought that, due to the high concentration of suspended sediments in the estuary, the long term sustainability of mudflat habitats (i.e. beyond 10 years) will be difficult with rapid accretion rates within the sites mostly leading to saltmarsh development.

The use of LiDAR data in order to monitor morphological changes in managed realignment sites has several advantages; most importantly, the method covers large areas in a relatively small period of time providing detailed data. However, inaccuracies are observed in relation to the presence of water or vegetation, as well as reflective mud surfaces.

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List of Abbreviations

AA	-	Appropriate Assessment
ABP	-	Associated British Ports
ABPmer	-	Associated British Ports Marine Environmental Research
ArcGIS	-	a Geographic Information System
BAP	-	Biodiversity Action Plans
CD	-	Chart Datum
CEH	-	Centre of Ecology and Hydrology
CHaMP	-	Coastal Habitat Management Plan
Defra	-	Department of Food and Rural Affairs
DEM	-	Digital Elevation Model
DTM	-	Digital Terrain Model
EIA	-	Environmental Impact Assessment
ESMP	-	Estuary Shoreline Management Plans
EU	-	European Union
GPS	-	Global Positioning System
HAT	-	High Astronomical Tide
HW	-	High Water
IECS	-	Institute of Estuarine and Coastal Studies
JNCC	-	Joint Nature Conservation Committee
LAT	-	Low Astronomical Tide
LiDAR	-	Light detection and ranging
LW	-	Low water
MHW	-	Mean High Water
MHWN	-	Mean High Water Neap
MHWS	-	Mean High Water Spring
ODN	-	Ordnance Datum Newlyn
OMReG	-	Online Managed Realignment Guide
OS	-	Ordnance Survey
RAMSAR	-	Convention on Wetlands
RMSE	-	Root Mean Square Error

RSPB	-	Royal Society for the Protection of Birds
SAC	-	Special Area of Conservation
SLR	-	Sea Level Rise
SMP	-	Shoreline Management Plans
SPA	-	Special Protection Area
SSC	-	Suspended Sediment Concentration
SSSI	-	Special Site of Scientific Interest
UK	-	United Kingdom
UKHO	-	United Kingdom Hydrographic Office
WFD	-	Water Framework Directive

Chapter I: Introduction

1.1. Introduction

Managed realignment involves the deliberate breaching of engineered defences to allow landward coastal migration with the creation of extended intertidal marshes and mudflats. Over the last two decades, this practice has become more common, and the strategy to keep the coastline in a fixed position has begun to be reconsidered. At present, there are 51 managed realignment schemes in the UK (102 in northwest Europe) with 23 of these sites being in eastern England between the Humber and Thames estuaries (OMReG, 2013).

Drivers for managed realignment are varied. They are often related to the present sea level rise scenario and the consequent squeeze of the coastal zone, caused by its inability to adapt to the new conditions migrating landward, resulting in valuable intertidal habitats eventually being lost through inundation and erosion.

There are two main consequences of this 'squeeze' effect. It can be argued that the ability of the intertidal zone to absorb energy and water, thereby contributing to sea defence, will be diminished. The loss of a 'first line' of defence against waves and tides, especially during storm conditions, can result in increased capital and maintenance costs for engineered defences. Secondly, coastal squeeze results in the degradation or destruction of mudflats, sandflats and saltmarsh habitats. These habitats provide a number of ecosystem services, they are significant reservoirs of biodiversity, and have attracted a range of conservation designations. Managed realignment, therefore, offers a way of mitigating for coastal squeeze losses, and in addition, allowing for compensation of habitat loss due to development.

In the UK, managed realignment is now considered as one of the four strategies of the 2nd phase of Shoreline Management Plans, highlighting its potential in the medium long-term scale. However, managed realignment strategies are still a minority in comparison to the 'hold the line' and 'no active intervention' approaches, covering only a small percentage of UK coast. Nevertheless, the number of realignment schemes has increased in the last 20 years.

The Humber Estuary, one of the principal estuaries of the North Sea, is the site of four realignment schemes. The estuary is of international importance for its biodiversity, and is of national importance for the United Kingdom's (UK's) economy and historic environment. It is estimated that approximately 90,000 ha of land surrounding the Humber Estuary is below high spring tide level and is currently protected by 235 km of flood and coastal defences (Turner *et al.*, 2007).

The estuary has not only experienced extensive intertidal habitat loss due to reclamation and coastal squeeze, but also, many of its defences are now reaching the end of their design life and are currently unsatisfactory and in need of repair or replacing. With the reduction of intertidal habitats and increasing costs of maintaining defences, the flood defence strategies for the

Humber Estuary are being reassessed and managed realignment schemes are now being considered and implemented where appropriate.

Whilst managed realignment is becoming a more common approach, particularly in the last two decades, the monitoring of post-realignment schemes is relatively limited. Monitoring programmes of the existing realigned sites provide the opportunity to study the evolution of the scheme, thus supporting future policy and decision makers as well as verifying impacts and habitat predictions. However, these monitoring studies tend to focus on the ecological development of the sites. Morphological changes are generally not monitored in detail, and therefore, the spatial changes occurring within the sites, the processes that drive them and the subsequent future predictions are often not considered (in detail). The monitoring programmes of the Humber Estuary realignment sites are a clear example of this issue, where the morphological changes of the four sites are mostly, with some exception, represented by generalised rates of accretion or erosion.

1.2. Aims and objectives of the project

Whilst managed realignment has become a fairly commonly applied technique over the past two decades, very few detailed morphological studies have been undertaken to date.

The aim of this study is to analyse in detail the morphological changes that have taken place at the four managed realignment sites in the Humber Estuary, using LiDAR data and to identify the physical processes which may have driven these changes

The main objectives of the project are detailed following:

- To describe in detail the morphological changes that had occurred in the realigned sites since breaching in terms of spatial changes through the analysis of cross-sectional profiles, accretion and erosion difference plots and volume calculations;
- To relate the observed morphological changes in the realigned sites to the physical processes of the estuary;
- To predict the site evolution over the next 5 to 10 years in order to improve their future management and monitoring (at existing and yet to be implemented sites); and
- To assess the actual site monitoring techniques and to suggest improvement in order to achieve a more comprehensive future monitoring of site evolution.

1.3. Thesis structure

This thesis is structured as follows. Chapter II compromises a brief literature review of managed realignment including approaches, elements, drivers and the policy context. In Chapter III, the Humber Estuary and its managed realignment sites are described in detail. This is followed by Chapter IV in which the methodology used during the research is addressed. Chapter V presents the outcomes of the morphological analysis undertaken on the four realigned sites. Finally, Chapter VI presents the discussion, conclusions and recommendations are presented in Chapter VII.

Chapter II:
Literature Review

The aim of this study is to investigate in detail the morphological changes at the four Humber managed realignment schemes and to relate them to physical drivers. In order to achieve this, firstly, it is essential to understand the background to managed realignment. A literature review is now provided to facilitate this process. In addition a review of the selected estuary was addressed in order to describe its characteristics (morphology, hydrodynamic regime, sediment transport, erosion and accretion) and can be found in the Appendix 1.

2.1. Managed realignment

2.1.1. Introduction

Managed realignment is the process of deliberately removing or breaching flood defences and reintroducing tidal regimes to previously reclaimed land. The approach involves relocating the line of defence landwards of its existing position and is also known as ‘set back’, ‘managed retreat’, or de-poldering in the Netherlands (French, 2006), however, the term managed realignment reflects a more positive approach, and is thus commonly used in the UK (Blott and Pye, 2004).

Policies of managed realignment can also allow the landward transgression of natural flood defences, such as shingle banks or dune barriers.

Over the two decades the approach has become more common, but has largely progressed in a scientific arena containing little knowledge of its implications (French, 2006). Across northern Europe some 102 realignment schemes have been completed over the last 20 years, 51 of them in the UK (OMReG, 2013), however the concept is not new, it has been historically used in fluvial applications to compensate for extreme run-off events, either due to direct rainfall, or from melt-waters.

Depending on the objectives to be achieved, realignment can be undertaken with varying degrees of management from partial managed abandonment to the fully managed decommissioning of seawalls (Pontee, 2007).

Unmanaged realignment relates to accidental breaching during storm surges, and is not considered to fall under the managed realignment umbrella. The different approaches to managed realignment are further considered in Section 2.1.2.

The technique in the estuarine context involves to return land to the sea, so as to allow salt marsh and intertidal mudflats to develop landward of those already in existence. The perceived benefits of this are manifold, and include cost efficiencies, flood risk management benefits and biodiversity gains (see, for example French, 2006; Pontee, 2007). The need of the estuarine areas with substantial assimilative capacity (especially saltmarshes and mudflats) has increased, as a result of sea-level rise (including isostatic readjustment in some areas) and the increased risk of storm events, leading to tidal surges as well as rapid and extreme fluvial run-off. In addition, the historical need for flood protection and land claim has exacerbated the rate of habitat loss due to coastal squeeze, whilst at the same time, the importance of intertidal mud and sandflats, saltmarsh, grazing marsh, reedbed and wet grassland for their intrinsic natural value and biodiversity value has increased. These conflicting components have meant that the maintenance of quality and increases in provision of such habitats is now an important consideration in coastal management decisions (IECS, 2008). Section 2.1.4 describes in detail the drivers behind managed realignment. Prior to this, approaches to, and key elements of, realignment, are outlined in the next two sections.

2.1.2. Approaches

Managed realignment may take many forms depending on the reasons for undertaking it and the techniques, or combination of techniques, applied.

As was previously briefly mentioned, the process can be undertaken with varying degrees of management from ranging from:

- catastrophic realignment that involves the unplanned-for failure of sea defences leading to the inundation of unquantified areas ('unmanaged realignment'); via
- natural realignment, a partially managed process that involves the identification of areas were realignment is an option, the quantification of the likely consequences and the cessation of defence maintenance, also termed 'no active intervention', 'do nothing' or 'walk-away' policies; to
- engineered realignment, a fully managed technique that involves the breaching or removal of an existing flood defence corresponding to 'retreat the line' policies (Pontee, 2007).

Furthermore, the approaches can involve the use of different breaching techniques. In general terms these can include

- the regulation of tidal exchange using tidal flaps, valves and weirs/spillways,
- the removal of a section of defence to create a breach (breached realignment), or
- the removal of the entire defence (banked realignment).

By frontage length, breached realignment schemes have been the most popular approach to realignment in the UK. The main reasons for the adoption of breached realignment appear to have been the requirements to promote high accretion rates, recreate saltmarsh habitats and minimise earth works. Breach realignment provides excavated openings in the defence line that allow tidal exchange whilst at the same time retaining sections of defence to create internal site sheltering and encourage sedimentation and vegetation establishment (Pontee 2007). This approach has been widely adopted in the UK and it attempts to achieve a situation, in the context of a particular number and spacing of breaches, in which the geometry of each individual breach is in hydraulic equilibrium with the local tidal prism (Spencer *et al.*, 2012).

2.1.3. Key elements

Several processes have a major influence in managed realignment schemes: morphological, hydrodynamic and sediment characteristics and availability are considered the main (Leggett *et al*., 2004).

Morphological elements such as the topography of the site are related to the soil character of the reclaimed land. The use of previously reclaimed land is often argued as a pre-requisite for realignment. Partly this is because if the land had originally been saltmarsh, then it has a proven ability to support such an environment. However, the post-reclamation history is equally important as it will control the extent to which the original soil structure has been preserved. Also of importance would be the duration of land claim, as over time, claimed areas will drop in elevation relative to the contemporary marsh due to dewatering and compaction. Elevation is key to the planning of a managed realignment scheme; one of the main criterion for suitable site selection is the frequency and duration of tidal inundation after breaching (French, 2006). In some instances, former agricultural surfaces within managed realignment sites may lie as much as 1.0–1.5 m below natural marsh surfaces outside such a site (Spencer *et al.,* 2012).

Sediment supply is another key element which relates to sediment accretion within realignment sites, as many sites need to increase in elevation to compensate for years of dewatering and compaction. Sedimentation rates influence habitat formation and hence the degree of wave energy attenuation (ABPmer, 2008). In addition, once established, marshes also need to continue accreting vertically to keep pace with accelerating sea level rise (Spencer *et al.,* 2012). However, excessive sedimentation might negatively affect fisheries and invertebrates (ABPmer, 2008).

Hydrodynamics elements are also critically important; these relate to the tides, waves and current velocities.

The tidal range and levels determine inundation frequency and thus the location of development of specific intertidal habitat (ABPmer, 2008). On an estuary-wide scale the tidal prism needs to be understood in terms of rates of tidal flow, and its associated currents. Major realignment schemes can represent major local changes in tidal volume, which may be manifest as increased tidal scour and impact tidal exchange and symmetry (French, 2006).

One of the main concerns in realignment sites is that the morphology of the breach, its positioning, and the increased tidal prism of the estuary can modify tidal flow both within the site, and in the estuary as a whole. Some basic considerations should include the existing marsh outside of the breach (French, 2006) since the internal dynamics of realignment sites may impact the response of the external mudflat/saltmarsh system to modified tidal exchange (Spencer *et al.,* 2012).

Currents need to slacken enough inside realignment sites to allow deposition. Hence, the reduction of wind generated waves within the realignment site is important in controlling the rate and type of sediment accreted. Once the deposition threshold is reached, local topography and currents will govern where, and to what extent, sediments will settle (Spencer *et al.,* 2012).

2.1.4. Drivers

In general terms, the primary motives for carrying out managed realignment are to adapt to sea level rise, to enhance coastal protection levels, to create a more cost-effective defence alignment and/or to create new coastal habitats. The habitat creation objectives are, in turn, driven by the need to compensate for losses following coastal developments or to restore and conserve habitats that have been, and are, subject to more general deterioration (Townend *et al*., 2010). Furthermore, there are many socioeconomic benefits that are considered during decision making processes. In the next sections, the main managed realignment drivers are discussed.

2.1.4.1.1. Coastal and flood management drivers

Managed realignment can be effectively used to provide flood risk management. The technique can potentially alleviate flooding in terms of changing the hydrodynamics of an estuary or coast, such that the risk of flooding at another location is reduced or the hydrodynamic and sedimentary system is improved in its functioning. This can ensure long-term sustainability of defences and reduce costs, particularly where it is no longer economic to defend land; taking advantage of the intertidal area to reduce waves and thus reduce the capital and maintenance costs of realigned flood defences. Furthermore, the effects of sea level rise can also be managed by moving defences landward to less exposed positions and providing capacity for estuaries to adapt to higher sea levels (Leggett *et al*., 2004).

According to Environment Agency (2012), with no saltmarsh as a buffer zone, there is an exponential rise in the cost of maintenance and construction requirements of the flood defences due to the increase of the risk of overtopping and breach of the current seawalls. Saltmarshes recession could ultimately affect the backshore boundary, which has implications in terms of the future management of coastal areas. Continued habitat depletion will also release significant quantities of fine sediment that may be deposited in navigation channels requiring periodic removal by dredging (Baily and Pearson, 2007).

From the 51 managed realignment scheme in the UK, the primary motive of 42% have been flood defence improvement or cost reduction (Environment Agency, 2012).

2.1.4.2. Environmental benefit drivers

Habitat creation, conservation or restoration is the most common reason for managed realignment in the UK. From the 51 realignment scheme reported, 44% of the schemes were related to conservation/habitat creation (Environment Agency, 2012).

There are several environmental benefits related to managed realignment. The main habitats created through managed realignment are saltmarshes and mudflats; these habitats have often been undervalued, which has typically led to urban encroachment and agricultural land claim. However, their conservation importance has nowadays been recognized. The greatest significance for nature conservation is their position at the base of the estuarine food web (Baily and Pearson, 2007). Furthermore, they increase the coastal stability, and they provide a first line defence dissipating tides and waves energy particularly during storm conditions. Saltmarshes have the ability to act as pollution sinks for both heavy metals and organic pollutants, thereby improving water quality. In addition the saltmarshes acts as a spawning and nursery habitat for several fish communities, as feeding, roosting and nesting sites for birds and the habitat has a role in carbon sequestration. Anthropogenic uses include sailing, walking, bird watching, commercial fishing, tourism and associated leisure activities (Dixon *et al*., 1998).

Mudflats and saltmarsh loss has has been significant over the centuries mainly due to land claim for agriculture and development. Furthermore, coastal squeeze has also contributed to losses, and is anticipated to increasingly do so in the future due to accelerated sea level rise. The natural response of a coastline to rising sea levels is to slowly retreat landwards, unless is impeded by steep cliffs, coastal structures or the local supply of sediment is sufficient to maintain seaward progradation. Where landward movement is prevented by rock cliffs or artificial ‘hard’ sea defences, erosion and narrowing of the intertidal zone occurs, causing ‘squeeze’ of intertidal environments and the loss of the habitat (Blott and Pye, 2004).

Due to the environmental services provided by intertidal habitats, such losses have a number of consequences in terms of conservation, recreation, and flood protection. One of the principal impacts of saltmarsh loss would be upon wildlife. (Baily and Pearson, 2007).

2.1.4.3. Legislation-Policy drivers

The need for managed realignment schemes is often driven by, or at least supported by, a range of national and international legislative and policy drivers. The European Union Habitats Directive (Council Directive 92/43/EC on the conservation of natural habitats and of wild flora and fauna) was incorporated into UK Law through the Conservation Regulations 1994. The Habitats Regulations require that a plan or project that might adversely affect the integrity of a classified Special Area of Conservation (SAC), Special Protection Area (SPA), a Natura 2000 sites or Ramsar wetlands, may only go ahead if there are no alternatives, the scheme is in the over-riding public interest, and compensatory habitat is provided to replace what will be lost (Leggett *et al*., 2004). In the UK, 14% of the schemes have been undertaken for this reason (Environment Agency, 2012). It should be noted that, where an existing coastal defence prevents saline inundation or erosion of an internationally designated freshwater or terrestrial habitat, the Regulations might then act as a constraint to managed realignment (Leggett *et al*., 2004).

Another international policy driver for the offsetting of historic and on-going coastal habitat losses is Biodiversity Action Planning (BAP), for which objectives for the restoration of saltmarsh, mudflat and saline lagoon habitats have been identified in response to the 1992 Rio Convention on Biological Diversity. For example, the UK government has BAP targets for saltmarsh and mudflat creation that add up to 600 ha per year combined, with an additional target to create a further 3600 ha by 2015 to offset historic losses (Townend *et al*., 2010).

Management realignment is also used to meet the UK obligations under the EU Water Framework Directive (WFD), including the requirement to restore water bodies to good ecological status by 2015 maintaining the condition of water quality, the functioning of morphology within a coastal or estuarine system and re-establishing the ecological integrity of intertidal habitats (Leggett *et al*., 2004).

The Wildlife and Countryside Act, as amended, creates a duty for public authorities to conserve and enhance Sites of Special Scientific Interest (SSSIs) and protect certain species, when exercising their functions. Although less stringent than the requirements of the Habitat Regulations, this duty applies to a wider variety of sites and to a wider variety of classified interests within them. It may act as a driver for Managed Realignment where the conservation of SSSI interest features would benefit from such an approach (Leggett *et al*., 2004).

2.1.5. Policy context

Some policies have been already defined as drivers or constrains of managed realignment, however, in this section a complete description of the policy context that surround the process will be provided.

In England and Wales, Shoreline Management Plans (SMPs), Coastal Defence Strategies, Biodiversity Action Plans (BAPs) and Coastal Habitat Management Plans (CHaMPs) are the principal tools for strategic shoreline planning ("top-down" approach) and provide the means to identify opportunities for managed realignment and the required extent of them (Leggett *et al*., 2004).

- **Shoreline Management Plans**

  Around all of England and Wales, and in parts of Scotland, Shoreline Management Plans (SMPs) are now in existence. These documents focus principally on the open coastline and where necessary also consider estuary-coast process interactions. SMPs are non-statutory but set coastal defence policies for the coast. The second generation of SMPs considers changes up to 100 years in the future and nationally there are 22 of them. The options defined in new draft procedural guidance are 'hold the line', 'advance the line', 'no active intervention' and 'managed realignment'. The dominant strategy by length is 'hold the line', which includes beach management, followed by limited intervention. Managed realignment is proposed on less than 5 % of the national frontage (Nicholls *et al.* 2013).

- **Coastal Defence Strategies**

  Coastal defence strategies cover a smaller section of coast in more detail than SMPs and they describe how to achieve the adopted SMP policies (Leggett *et al*., 2004).

- **Coastal Habitat Management Plans (CHaMPs)**

  CHaMPs are non-statutory plans aiming to assist in identifying the best strategic approach for coastal and estuarine habitats and their associated ecological interests where there is a conflict between coastal evolution, coastal defence measures and the needs of Natura 2000 sites. They provide a strategic overview quantifying habitat change (loss and gain) over a 30-100 year period (Leggett *et al.*, 2004).

- **River Basin Management Plans**

  The River Basin Management Plans are produced in relation to the WFD and describe a river basin district, and the pressures that the water environment faces. They set out what improvements are possible by 2015 and how the actions will make a difference to the local environment - the catchments, estuaries, the coast (up to one nautical mile) and groundwater. A River Basin Management Plan will be produced for each river basin district, every six years (Environment Agency, 2013).

- **Biodiversity Action Plans**

  The UK BAP was prepared in 1994 and forms a blueprint for conserving the range of species and habitats in Britain. The national and local BAPs set specific targets for habitat creation to offset previous and predicted losses and provide ecological enhancements. Habitats, for which targets have been set, that are important in the coastal context include saltmarsh, sand dunes, vegetated shingle, mudflats, maritime cliff, grazing marsh and reed beds. BAP targets for saltmarsh, mudflat and other intertidal habitat creation are becoming an increasingly important driver for managed realignment in estuaries (JNCC, 2013a).

2.2. Morphological response of managed realignment sites

As previously mentioned, in the last two decades there has been an increase in managed realignment schemes despite the deficient comprehensive understanding of the morphological response of these sites and the degree of their successful in meeting the design objectives. Several studies have been undertaken in order to try to describe and understand the evolution of managed realignment sites and the morphological processes that control them.

Nikolaou (2012) conducted a research study aimed at assessing the evolution of managed realignment sites by interrogating changes in site tidal prism and breach cross-sectional area and by investigating the validity of commonly used empirical breach design formulae. The study analysed 19 sites located around the UK, using LiDAR data. It found that all the study sites had accreted and that there is a strong correlation between the tidal prism of a site and the dimensions of a breach.

Furthermore, Hampshire (2011) studied creek evolution within the Freiston Shore managed realignment (on The Wash) using aerial photography and LiDAR data. According to the research, slow growth rates in total creek lengths and drainage densities were experienced after breaching; once creek mouths expanded to accommodate the tidal prism, growth rates increased. Exponential decreases in creek width landwards were observed. The results indicate that creek evolution is not a simple progression from one stage to another, but that areas evolve at different rates.

Morris (2013) concluded that the position of most UK realignment sites within the tidal frame means that the schemes will almost invariably form saltmarsh in estuaries with high levels of suspended sediment. The same outcome can be expected elsewhere (in estuary with lower levels of sediment) elsewhere but the time involved is much longer. According to the study, the creation of mudflats in terms of compensation habitat is extremely limited to the short to medium-term, suggesting that for sites smaller than 100 ha, saltmarshes habitat will dominate after a relatively short period of time. The research also provides important evidence of how the shape of the site and the nature of breach design can influence the evolution of inter-tidal habitat. Where managed realignment sites are small or are orientated so that the shortest fetch coincides with prevailing winds, saltmarsh development will be faster than in those sites that are bigger or where their orientation allows the generation of bigger wind-driven waves. Furthermore, sedimentation processes occur in intertidal habitat due to their exposure for longer periods to tides, allowing increased dewatering through drainage and evaporation.

Further details related to the evolution of managed realignment site can be found in Symonds (2006) PhD research related to the impacts of management realignment on intertidal sediment dynamics in Freiston Shore, UK. The study observed that the managed realignment had improved the coastal defence of the area; however, the channels within the breaches in the embankment were eroded, and a creek system over the adjacent intertidal flats experienced an enhancement in its development.

Finally, many other managed realignment sites have been studied individually, e.g. Tollesbury, however, very limited cross-site comparisons are available, highlighting the importance of this research.

Chapter III:
Study Area

Previous chapters presented a description of the main objectives of this study and literature review. The following chapter will provide a brief description of the existing managed realignment sites in the Humber Estuary, as well as the estuary itself.

3.1. The Humber Estuary

The Humber Estuary, one of the largest estuaries in the UK, is located on the northeast coast of England and drains a catchment area of some 23690 km^2 (Law *et al.*, 1997). It is approximately 6.5 km wide at its entrance and 2.5 km along its upper reaches (some 48 km upriver) (ABPmer, 2010). Fresh water run-off flows to the estuary through many rivers and tributaries, draining more than one fifth of the area of England (Townend and Whitehead, 2003).

The Humber Estuary is of high economic and social value, with major ports, chemical industries, oil refineries and power generation plants, together with a population of over 300,000, being located on its banks and 12 million inhabitants within the whole catchment (Mazik *et al.*, 2007). Furthermore, the estuary is of great ecological importance, being a designated European Marine site, SPA, SAC (JNCC, 2013), Site of Special Scientific Interest (SSSI) and Ramsar site (Mazik *et al.*, 2010).

Therefore, whilst economic development and flood defence are a priority, these activities must be carried out in compliance with the requirements of the European Habitats Directives and the UK Habitats Regulations 1994 (Edwards and Winn, 2006). As a result of these designations, the Environment Agency has a policy of a 1:3 ratio of replacement for habitat loss due to flood defence and a 1:1 ratio for habitat likely to be lost as a result of coastal squeeze. Port development affecting the intertidal also have to undertake compensatory habitat creation. (Mazik *et al.*, 2010). The estuary is shown in Figure 1. A more detailed description of the area is presented in Appendix 1, including morphology, hydrology and sediment transport within the Humber Estuary. It is noteworthy that the estuary's intertidal area has been greatly reduced since the 17th century when large-scale reclamation commenced; the drained floodplain now amounts to some 90,000 ha (Edwards and Winn, 2006).

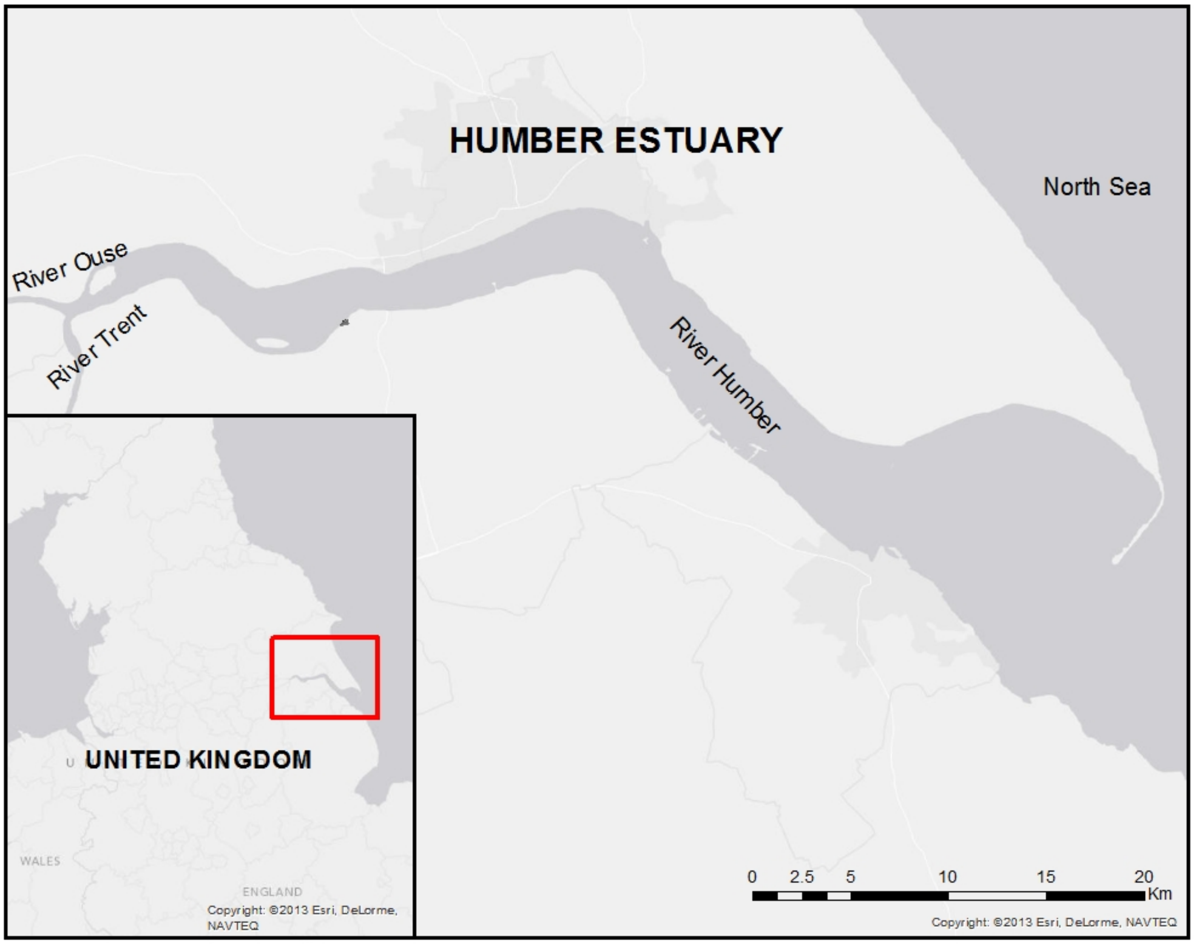

Figure 1. Humber Estuary, United Kingdom

3.2. Managed realignment sites in the Humber Estuary

In eastern England, recent realignments have benefited from the work of the Environment Agency on estuary shoreline management plans and related flood defence strategies. This is particularly noteworthy on the Humber where the highest concentration of realignments has occurred in recent years (Dixon *et al*., 2008). Here, the Environment Agency's planning for the rising tides flood risk management strategy has to date led to the implementation of two managed realignments schemes, Paull Holme Strays and Alkborough. Further schemes are also planned for the short to medium term (Donna Nook, Skeffling, Welwick, Keyingham and Goxhill). These schemes primarily address (designed) intertidal habitat loss due to coastal squeeze, but also the direct loss of intertidal habitat resulting from ongoing flood defence works on the estuary (IECS, 2008).

In addition to the Environment Agency's managed realignment projects, two sites have also been implemented by Associated British Ports (ABP) for compensatory purposes; these are located at Welwick and Chowder (IECS, 2008a).

Table II and Figure 2 detail both existing and proposed managed realignment schemes for the Humber Estuary. Thereafter, the four existing sites are briefly described based on existing information; Appendix 2 offers a meticulous review of the schemes. The site order indicates their position in the estuary, starting from the outer part of it.

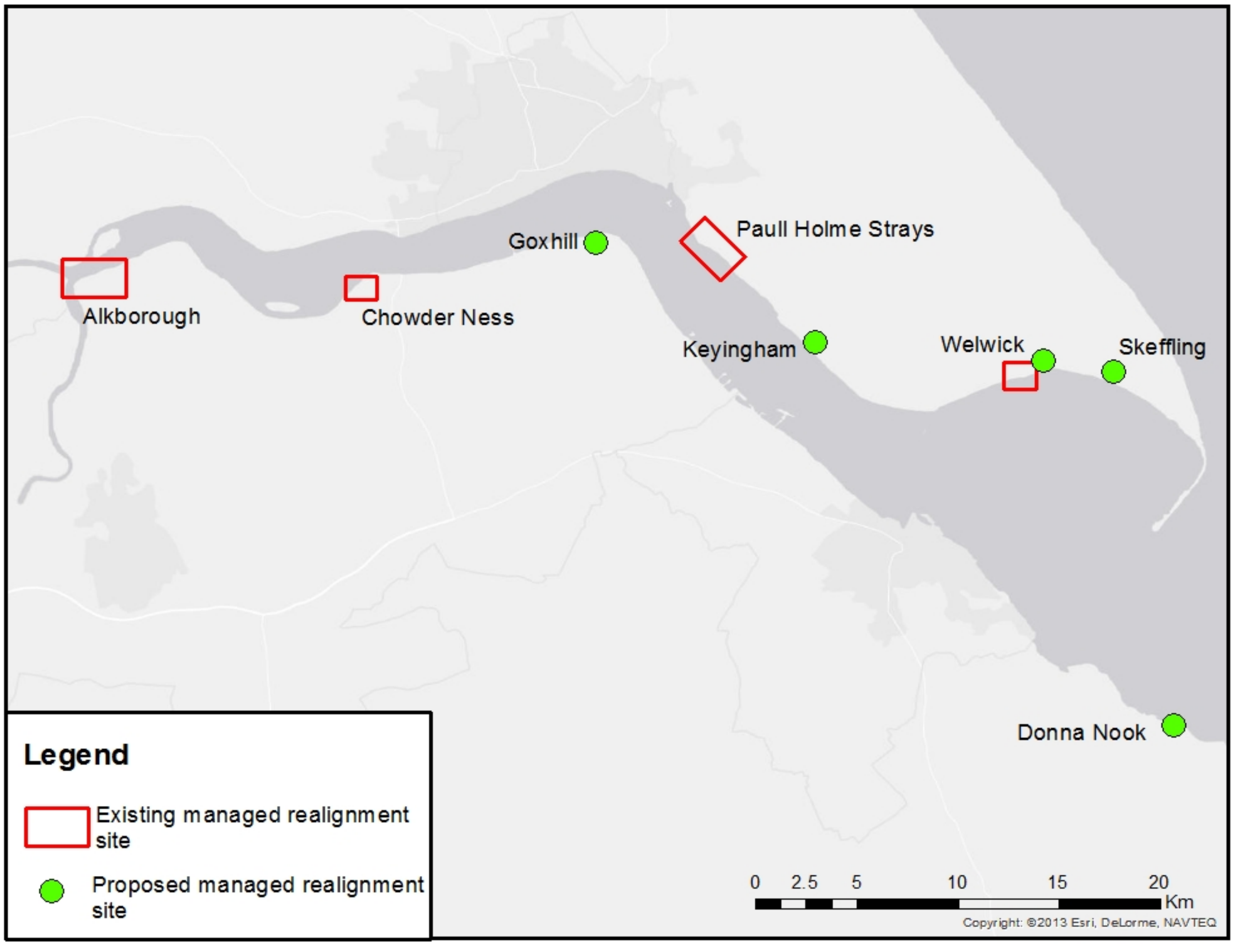

Figure 2. Existing and proposed managed realignment in the Humber Estuary

Table I. Existing and proposed managed realignment schemes in the Humber Estuary, UK (adapted from IECS, 2008a).

Site	Authority	Date	Size	Main drivers
COMPLETED				
Paull Holme Strays (North bank)	Environment Agency	2003	80 ha	Provide cost effective flood risk management for the area, in addition to the creation of intertidal habitat for compensation
Alkborough (South bank)	Environment Agency	2006	440 ha	Provide a flood storage area and creation of new wetland habitat
Welwick (North bank)	Associated British Ports	2006	54 ha	Create intertidal habitat to compensate for the lost through ABP port development.
Chowder Ness (South bank)	Associated British Ports	2006	15 ha	
PROPOSED				
Donna Nook (South bank)	Environment Agency	After 2013		
Skeffling (North bank)	Environment Agency	2010-2020		
Welwick (North bank)	Environment Agency	After 2020		
Keyingham (North bank)	Environment Agency	After 2030		
Goxhill (South bank)	Environment Agency	Medium long term		

3.2.1. Welwick

The managed realignment at Welwick forms part of the compensation package for port developments at Immingham and Hull. These developments resulted in the direct loss of 22 ha of intertidal mudflat and potentially up to 5 ha of indirect losses in the recently designated Humber Estuary SPA and candidate SAC (ABPmer, 2011). The scheme design was based on habitat compensation requirements, technical issues and the concerns of Natural England, the Royal Society for the Protection of Birds (RSPB) and the Environment Agency (Pontee, 2007).

The primary objectives at Welwick were to create between 15 and 38 ha of intertidal mudflat, together with 12-28 ha of saltmarsh and 4-10 ha of grassland (ABPmer, 2011). The site was completed in 2006 following the construction of new flood defences, re-profiling and creation of temporary borrow pits, the removal of the existing seawall and the breach of the frontal saltmarshes.

Table II presents a summary of the main characteristics of the site. Figure 3 presents its actual configuration and Appendix 2 contains a detailed description of the site background, objectives, realignment approach, construction, and the previous assessment of site evolution.

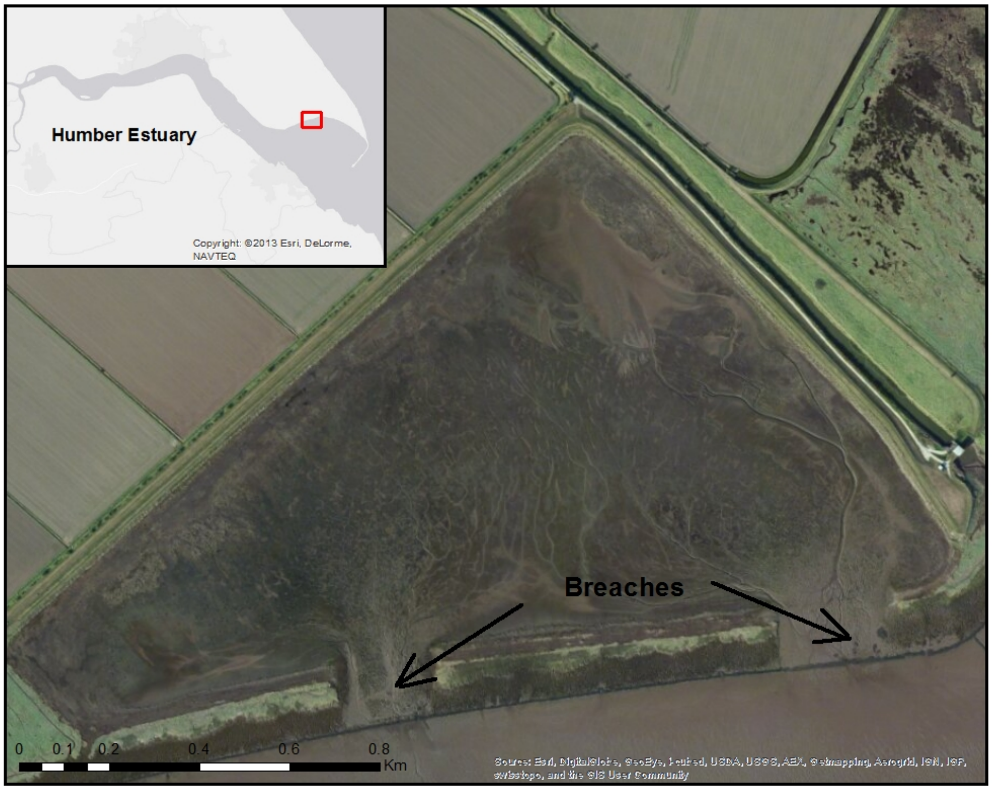

Figure 3. Welwick managed realignment site

Table II. Welwick site parameters and characteristics

Site Name	**Welwick**
Location	Outer estuary, north bank
Total area • **Saltmarsh** • **Mudflats** • **Other**	54 ha 12-28 ha 15-38 ha 4-10 ha
Year	2006
Type of breach	1,400 m of flood bank removed; two 130 m breaches cut through fronting saltmarsh (Environment Agency, 2012).
Previous land	Arable (ABPmer, 2008)
Land preparation	Re-profiling, two breaches through fronting saltmarshes (ABPmer, 2008)
Foreshore in front of realignment	Fronted by saltmarsh (Morris, 2013)
Elevation (OD)	1.75-4 m (Morris, 2013)
Tidal range	6 m (ABPmer, 2008)
Fetch and direction	>10 km fetch (S/SE). (Environment Agency, 2012).
Significant wave height	0.3-1.5 m (McBain, 2007)

3.2.2. Paull Holme Strays

Paull Holme Strays is the site of the first major managed realignment scheme on the Humber. Created by the Environment Agency in 2003 as part of the Humber flood risk management scheme, the site provides approximately 80 ha of new intertidal habitat (Environment Agency, 2012) having the dual role of coastal protection and habitat restoration (Mazik *et al.*, 2007).

The site existing sea wall was breached in two locations 1.5 km apart: the eastern breach is 50 m wide; the western breach has a width of 150 m.

Table III presents a summary of the main characteristics of the site. Figure 4 presents its actual configuration and Appendix 2 contains detailed a description of the site background, objectives, realignment approach, construction, and the previous assessment of site evolution.

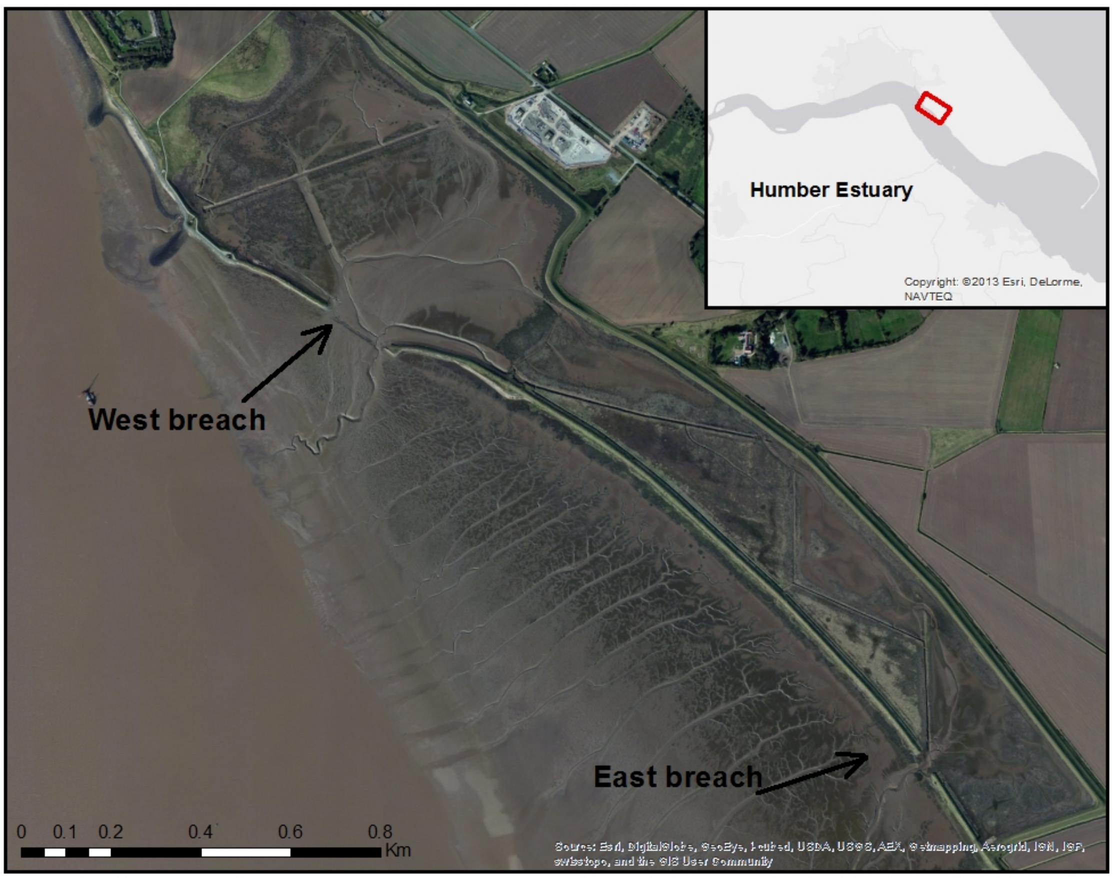

Figure 4. Paull Holme Strays managed realignment site

Table III. Paull Holme Strays site parameters and characteristics

Site Name	Paull Holme Strays
Location	Middle estuary, north bank
Total area (Ha) • **Saltmarsh** • **Mudflats** • **Other**	80 35 45 0
Year	2003
Type of breach	Two breaches: 150 m and 50 m wide; approx. 2,300 m of embankment remains along frontage (Environment Agency, 2012).
Previous land	Arable, pasture (ABPmer, 2008)
Land preparation	Artificial creek dug (ABPmer, 2008)
Foreshore in front of realignment	Eroding, and toe exposed, wall unsuitable (Morris, 2013)
Elevation	5.1-6.7 OD (OMReG, 2013)
Tidal range	6.4 m (ABPmer, 2008)
Fetch and direction	3.5 km fetch (SW). (Environment Agency, 2012).
Significant wave height	0.2-0.6 m (McBain, 2007)

3.2.3. Chowder Ness

Chowder Ness was undertaken for the same purpose as another realignment on the Humber, Welwick, which was presented in Section 3.1.1. Both schemes were designed and implemented by the same organisations (Associated British Ports (ABP) and ABPmer), with very similar timescales and principles (ABPmer. 2011b).

The initial objective of Chowder Ness was to create 10.5 ha of mud and 0.8 ha of saltmarsh to support a variety of invertebrate and bird species (ABPmer, 2011b).

These works included the creation of a gentle slope from the fronting mudflats to the rear of the sites to assist drainage, new flood defences construction, re-profiling and creation of temporary borrow pits. The existing seawall was removed over a length of 570 m (ABPmer, 2011b).

Table IV presents a summary of the main characteristics of the site. Figure 5 presents its actual configuration and Appendix 2 contains a detailed description of the site background, objectives, realignment approach, construction, and the previous assessment of site evolution.

Figure 5. Chowder Ness managed realignment site

Table IV. Chowder Ness site parameters and characteristics

Site Name	**Chowder Ness**
Location	Inner estuary, south bank
Total area (Ha) • **Saltmarsh** • **Mudflats** • **Other**	15 0.8 10.5 3.7
Year	2006
Type of breach	Most of embankment removed (over 570 m); 200 m remains. (Environment Agency, 2012).
Previous land	Arable (ABPmer, 2008)
Land preparation	Re-profiling (ABPmer, 2008)
Foreshore infront of realignment	Small area of green foreshore, most of sea wall exposed (Morris, 2013)
Elevation	1.6-4.5 m (Morris, 2013)
Tidal range	6.9 m (ABPmer, 2008)
Fetch and direction	6-10 km fetch (W/NW). (Environment Agency, 2012).
Significant wave height	--

3.2.4. Alkborough

The Alkborough site, is the largest managed realignment site on the Humber with 440 ha, was breached in September 2006 and is the fourth managed realignment site to be created as part of the Humber flood defence upgrade (Urgent Works) undertaken by the Environment Agency (IECS, 2011).

The scheme's main objective was to act as a flood storage area in the event of an extreme flood event. The main works included a breach 20 m wide with boulder sill, 1.5 km of lowered defences, modification to the creek network inside site and a 1.6 km 'distributor' channel.

Table V presents a summary of the main characteristics of the site. Figure 6 presents its actual configuration and Appendix 2 contains a detailed description of the site background, objectives, realignment approach, construction, and the previous assessment of site evolution.

Figure 6. Alkborough managed realignment site

Table V. Alkborough site parameters and characteristics

Site Name	Alkborough
Location	Inner estuary, south bank
Total area (Ha) **Saltmarsh** **Mudflats** **Other**	440 170 (intertidal) 270 (grassland)
Year	2006
Type of breach	20 m breach with sill set at 2.8 mODN. Approx. 5,000 m of embankment remains (including lowered 1,500 m section, which is at HAT levels). (Environment Agency, 2012).
Previous land	
Land preparation	
Foreshore in front of realignment	Steep mudflats and limited saltmarsh. Sea walls very poor condition. (Morris, 2013)
Elevation	
Tidal range	5.9 m (OMReG, 2013)
Fetch and direction	Fetch very limited (max. 800 m, from NW only). (Environment Agency, 2012).
Significant wave height	

3.3. Summary

In previous sections the four managed realignment sites of the Humber Estuary have been described in term of their main characteristics. According to the detailed information obtained and presented in Appendix 2, the sites had a monitoring programme since the first year after breaching based on fixed site measurements resulting in general accretion/erosion trends.

The lack of a detailed morphological analysis, however is evident and, therefore, the need for this research. The morphological changes of the sites and the processes that divine them will be investigated using LiDAR datasets in order to provide a complete description of the site behaviour and evolution after breaching. From the information obtained along this study, the future evolution (up to 10 years) of the managed realignment sites of the Humber will be analysed.

Chapter IV: Methodology

In this chapter, a detailed description of the methodology employed in order to achieve the aim and objectives of this study is provided. This study involved the analysis of LiDAR data and thus it is important to understand the limitations and advantages of this technique. In the first section an explanation of the LiDAR data is provided in terms of its accuracy, limitation and outputs. The subsequent sections focus on data processing, the analysis and the methods used in order to obtain the main results of this research.

4.1. LiDAR data: accuracy, outputs and limitations

LiDAR (Light Detection and Ranging), also known as scanning laser altimetry, is an airborne terrain mapping system which is analogous to radar (radio detection and ranging) and sonar (sound navigation and ranging) in its principle of operation. The system is usually fitted to a helicopter or fixed-wing aircraft, and by measuring the time taken for laser pulses to hit the ground and return, the distance to the ground under the flight path can be calculated. The altitude and position of the aircraft are determined by differential Global Positioning System (GPS), which is corrected using known ground reference points, and an inertial navigation unit allows measurements to be corrected for the pitch, roll and yaw of the aircraft (Jones *et al.*, 2007). By scanning the laser perpendicular to the line of flight, the system can survey a swathe some 250–700 m wide beneath the flight path. The compilation of multiple swaths allows the generation of a digital terrain model (DTM). The technique has been used throughout the world for a number of years for a variety of applications including measurements of ice sheets, shoreline morphology and bathymetric surveys for sediment transport studies and navigation purposes. The vertical accuracy of LiDAR data is generally claimed to be in the range of 5 cm to 15 cm (Geomatics Group, 2013).

In the UK, LiDAR campaigns undertaken by the Environment Agency now cover 68% of England and Wales, including many major urban areas and rural flood plains (Geomatics Group, 2013). UK LiDAR data normally cannot be obtained below the level of the Lowest Astronomical Tide (LAT) due to the high turbidity of the coastal waters and because of the type of LiDAR (wavelength) used (Saye *et al.*, 2005).

This method has the advantage to generate a spatially dense data set over short periods of time, which can be used to provide comprehensive and accurate spatial representation (Woolard and Colby, 2002). Furthermore, airborne remote sensing can successfully map dynamic coastal change in areas sensitive to disturbance during ground monitoring (Friess *et al.*, 2012).

It is however accepted that LiDAR data has some accuracy issues. These are related to the technology used to obtain the data and to interpreting the surface from which the laser signal is reflected. Technology issues involve the accuracy of the horizontal and vertical data values (Gares *et al.*, 2006). Inaccurate positioning of the aircraft by GPS can lead to errors in geo-referencing and data collection can be affected by various interferences. The reported horizontal (positioning) error is often c. 1 m and most processed data are provided at 2 m grid resolution, although occasionally at 0.25 m resolution (Saye *et al.*, 2005).

The nature of the surface is in itself a potential source of error. There is little problem where bare sand surfaces are involved, but the presence of dense or tall vegetation cover or of human artefacts may give a false elevation (Gares *et al.*, 2006). Further inaccuracies are related to the presence of water and reflective mud surfaces (ABPmer, personal communication).

The Environment Agency have developed a processes that allows surface objects such as vehicles, buildings and vegetation to be identified and removed, producing filtered LiDAR data, or in other words, 'bare earth' DTMs.

4.2. Data acquisition and processing

Filtered LiDAR data was obtained from the UK Environmental Agency covering part of the Humber Estuary from 2003 to 2012 in order to monitor the geomorphological changes of the four study sites described in Chapter III. The vertical accuracy of the dataset was ±15 cm, with a resolution that ranged from 0.5-2 m depending on the year flown. Table VI presents the details of the LiDAR dataset that was used in the analysis. As can be seen, different year resolutions were available for each site and no constant annual coverage for any of the site was obtained. Furthermore, 2006 Chowder Ness and Welwick DTMs were obtained from ABP; they were produced with a ground based LiDAR technique. Its resolution and accuracy are also specified in Table VI.

The LiDAR data were used to produce Digital Elevation Models (DEMs) which were processed in ArcGIS 10.1 environment in order to analyse the morphological changes of the four realignment sites (the method is described in the next section).

Finally, LiDAR datasets that included no data pixels were replaced using an average value of their nearest neighbours using a generalisation tool in ArcGIS 10.1. It is important to mention that this procedure was applied only to datasets with small areas of no data. LiDAR images with larger areas of missing values were not treated in order to maintain the accuracy of the analysis.

Table VI. LiDAR dataset characteristics used in the study

Site	Years	Resolution	Accuracy	Source	Date Flown
Paull Holme Strays	2003	2	± 0.15 m	Environment Agency	12 - 15 July
	2004	2			18 - Aug
	2005	2			16 - 22 Sep
	2007	1			10 - 29 Sep
	2010	1			31 Jan - 2 Mar
Welwick	2006	2	± 0.5 m	ABP	-
	2007	1	± 0.15 m	Environment Agency	10 - 29 Sep
	2009	1			17 - Apr
	2010	0.5			31 Jan - 2 Mar
	2011	1			13-May
Chowder Ness	2006	2	± 0.5 m	ABP	-
	2007	1	± 0.15 m	Environment Agency	10 - 11 Sep
	2009	1			17 - Apr
	2010	0.5			31 Jan 2 Mar
	2011	1			13 - May
Alkborough	2007	1	± 0.15 m	Environment Agency	10-11 Sep
	2010	0.5			31 Jan - 2 Mar
	2012	0.5			Dec 11 - Mar 12

4.3. Morphological changes analysis

For each one of the realignment sites, a detailed analysis of morphological changes over time was undertaken by interpreting LiDAR data. In the next sections, a description of the different procedures is presented.

4.3.1. Elevation changes

An analysis of the accretion/erosion of each site was undertaken by comparing the elevation changes. Using the spatial analyst tool of ArcGIS 10.1, the DEMs of consecutive years were compared mapping the differences in elevation.

4.3.2. Cross Section profiles

In order to observe the morphological evolution of the sites, several profiles lines were produced and analysed for each site. The locations of these profiles lines were selected in order to include relevant features (e.g. main channels) in the analysis. Using the spatial analyst tool of ArcGIS 10.1, the elevations along the profiles lines were extracted according to the image resolution, in order to obtain cross section for each year. Figure 7 presents the location of the profiles lines for each site.

Figure 7. Location of the cross section profiles for the four managed realignment sites

4.3.3. Neap tide profiles

In order to document in detail the morphological changes occurring in each of the realignment schemes, a cross section profile over the MHWN elevation tide line in the first year after breaching was drawn. MHWN was chosen as this is typically understood to represent the tide level where saltmarsh starts to become established. According to Nottage and Robertson (2005), tidal flats typically develop in areas up to approximately MHWN, whilst pioneer marsh becomes established around the MHWN mark. Low marsh tends to be found around the MHW mark, upper marsh develops between MHW and MHWS levels, and finally high (or transitional) marsh is located above the MHWS mark.

The evolution of the sites according this MHWN tide line profile was then studied, using the spatial analysis tool. Table VII presents the MHWN level used for each site.

In the case of the Alkborough realignment site, the MHWN tide level is lower than the elevation of the breach (2.8 mODN), therefore, MHWN tide level inundation was impossible to identify and study.

Table VII. Tidal data used for volume calculation for each site ((UKHO Admiralty Tide Tables from Environment Agency (2012)).

Realignment site	Tidal record	HAT (mODN)	MHWS (mODN)	MHWN (mODN)
Welwick	Immingham	4.1	3.4	1.9
Paull Holme Strays	Hull	4.5	3.7	2.1
Chowder Ness	Humber Bridge	4.7	3.9	2.1
Alkborough	Blacktoft	5.0	4.2	2.5

4.3.4. Hypsometric curves

Hypsometry is a concise and quantitative method to characterise and understand the morphological characteristics of the Earth's surface. By analogy, hypsometry is a sensitive morphological parameter of the tidal basin and tidal flats, being not only related to hydrodynamics and morphodynamics, but having also been shown to be useful in an ecological and environmental context (Yu *et al.*, 2012).

With the purpose to observe how the area of a site varies with its elevation, hypsometric curves for each of the realignment schemes were calculated for the first year after breaching and the most recent dataset.

In order to ensure an accurate comparison of the areas, the LiDAR data for each year was extracted by the same mask, assuring the same coverage for each one of the years analysed. The area lying between successive pairs of contours defined every 20 cm was measured. The percentages of the total that each of these areas constitute were then computed, and the percentage of the total area lying below each different contour was then obtained by summation.

Hypsometric curves were finally made plotting the percentage of the surface against the elevation for the first and last year of data of each site.

4.3.5. Volumes

An analysis of the change in the volume of sediment over time for each site was conducted. Firstly, the LiDAR data was again extracted by the same mask in order to ensure the same comparison area. Secondly, the volume of water below a reference level was calculated using a 3D analysis tool of ArcGIS 10.1. Three references levels were considered: HAT, MHWS and MHWN. Table VII presents the tide levels for each site and Figure 8 illustrates the volume calculation.

Assuming that a reduction or increase of the volume of water in the site was directly related to the respective accretion or erosion of the surface of it, the differences between the volumes of water over time were used to obtain the change in the volumes of sediment of each site.

Both the changes of the water volumes and the sentiment volumes according to the different tidal levels were plotted and analysed.

The same procedure was conducted for each one of the four realignment sites, however special data treatment was completed in the case of Paull Holme Strays scheme due to large areas of non-data.

Paull Holme Strays 2005 and 2007 LiDAR data contained large areas of non-data that were not interpolated in order to avoid an introduction of inaccuracies. This is because, during volume calculation, this lack of data would be translated into an underestimation of the total site volume. In order to avoid this effect, the areas of non-data were filled with the values of the previous year to 2005, in this case, 2004. The choice to use previous values elevation was made with the purpose to avoid an inaccurate interpolation obtaining a more truthful result.

In the case of Alkborough site, the LiDAR data for which also had large areas of non-data, this approach was not feasible due to a lack of data in the first year of survey (2007).

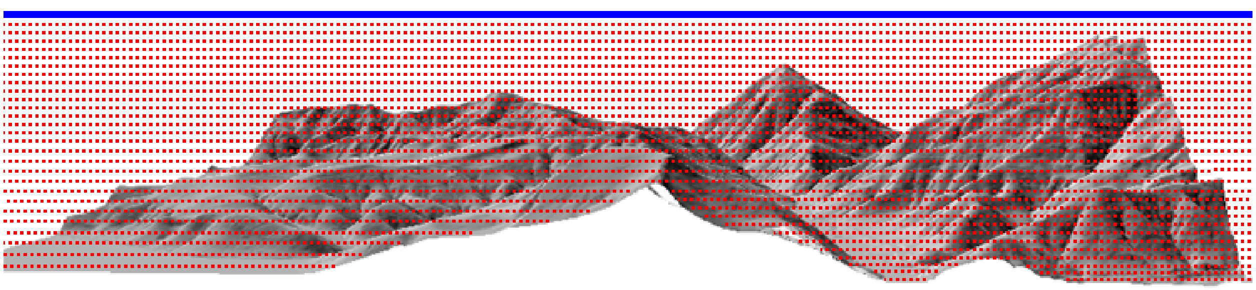

Figure 8. Schematisation of volume of water calculation. The blue line represents the reference plane or level (Esri, 2012).

Chapter V: Results

In this chapter, a detailed description of the results of the processing/analysing the LiDAR data is presented for each managed realignment site in turn, according to the elements of morphological changes analysis described in the previous chapter. The sites are discussed relative to their position within the Humber Estuary, from the outer estuary and heading upstream (i.e. in a westward direction). This chapter contains the most pertinent results from the analysis; however, the complete datasets for each site (and subsequent analysis) obtained through this study are presented as additional support material in Appendix 3.

5.1. Welwick

As detailed in Chapter III and Appendix 2, the 54 ha Welwick managed realignment site is located on the north bank of the Humber Estuary approximately 9 km from the estuary mouth.

The scheme was completed in 2006 following the breaching of the existing seawall, the re-profiling of the land from an original relatively flat elevation averaging around 2.8 mODN and the construction of the new embankments. In the next sections, the evolution of the site since breaching is analysed in detail.

5.1.1. Elevation changes

The evolution of the entire site was firstly studied in terms of the changes in its elevation and its arrangement (e.g. position of main channels). Figure 9 presents the evolution of the Welwick DEM over the years.

In 2006, the elevation of the front (and lower) part of the site ranged between of 1 to 1.5 mODN (note the lower accuracy associated with the 2006 data, with an error margin of +/- 50 cm). In 2007 a clear accretion of this lower part of the site is observed, particularly in the areas away from the breaches. According to Figure 9, the increase in elevation was larger in the western section of the realignment scheme, while in the eastern section the presence of a deeper channel can be observed. After 2009, 80% of the site lies at an elevation higher than 2.25 mODN (which is 35 cm above the MHWN level), with the exception of 2010 data in which a lower area is observed in the rear of the site. This lower area is related to a small lagoon feature, which was initially present and has recently (post 2010) mostly filled in (ABPmer, personal communication). This lagoon was likely drained during the 2010 survey, possibly due to the development of a creek during the year in consideration or a prolonged period without inundation. However, for the 2011 survey, the lagoon appears to have filled with water again.

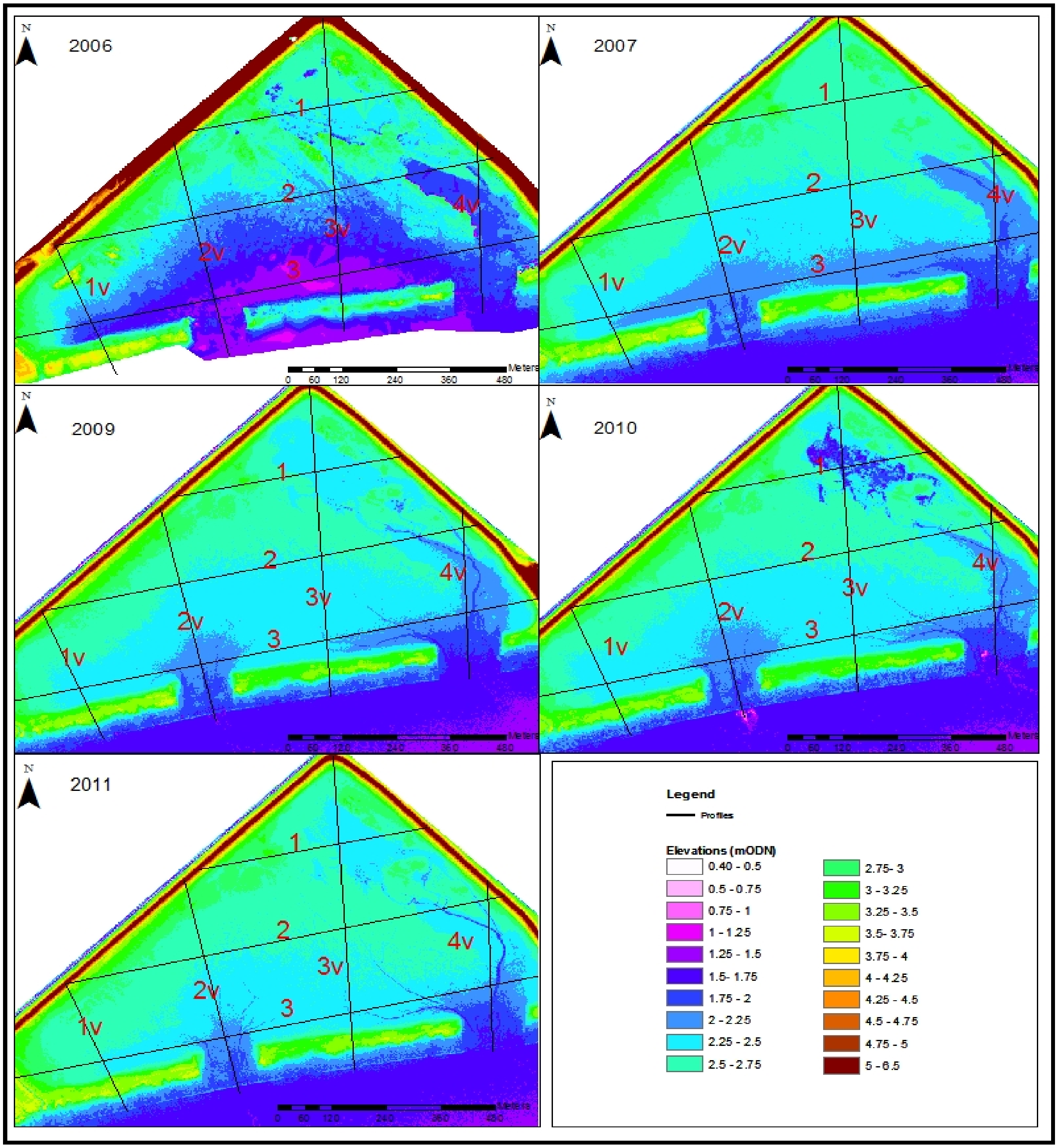

Figure 9. Elevation of Welwick obtained from LiDAR data (profiles lines used as a reference

Figure 10 shows the differences in elevation between the different surveys. Again, a larger positive difference in terms of elevation (accretion) can be observed in the lower and sheltered parts of the site, between 2006 and 2007, this was in the order of 0.5-1 metre (again, the lower accuracy of 2006 data should be noted). After the rapid initial accretion during the first year, smaller positive changes are generally recorded, in the order of 0-0.25 metres across the whole site. The figure clearly indicates a large accretion in the front part of the realignment during the first year after breaching and a more stable situation in the following years.

In terms of negative elevation changes (erosion), between 2006 and 2007 the only significant reductions in elevation are observed outwith the realignment site and along the new embankment line. With regards to the latter, this is likely related to settlement of the newly constructed embankment, whereas vegetation filtering errors are the most likely the cause of the elevation decreases evident in the mature saltmarsh south-west of the site boundary. Smaller areas of elevation decrease (0.25 m) are observed along the back of the site, close to the embankments. This was especially recorded during the first year of survey, but the trend also continued over the analysis period. This could represent settling or slumping of re-profiled material as well as weathering, and possibly some erosion.

A decrease in the elevation of the order of 0.5 to 0.75 m is observed between 2009 and 2010 in the rear part, corresponding to the area previously identified as a small lagoon. These negative changes in the elevation are likely the result of water remaining within the lagoon during the 2009 LiDAR survey, thus providing an inaccurate reading of bed elevation; the erosion of sediments from the area is considered unlikely. During survey following the 2010 (when low values were returned), i.e. in 2011, this region presents an increase on the elevation of approximately the same order, suggesting the filling of the lagoon with water. According to the latest 2012 ABPmer field survey the lagoon feature has now largely filled in with sediment and does not hold much water at high tide (ABPmer, personal communication).

Figure 11 shows the overall changes at the site over the analysis period (i.e. the difference between 2006 and -2011). The same elevation increase/decrease patterns are observed, indicating that the general trend of the site was the increase of its elevation, with larger rates in the front of it, approximately 1 metre over the 5 years of analysis. The back of the site behaved completely differently. Reasons for this are thought to mainly relate to the higher elevation of the area (and thus less frequent inundation), settlement of the embankment and re-profiled areas, and also the probable presence of water in the lagoon during the first three survey years, affecting LiDAR measurements. The eastern section of the site presents a smaller increase in the elevation compared to the western section, suggesting a more exposed environment.

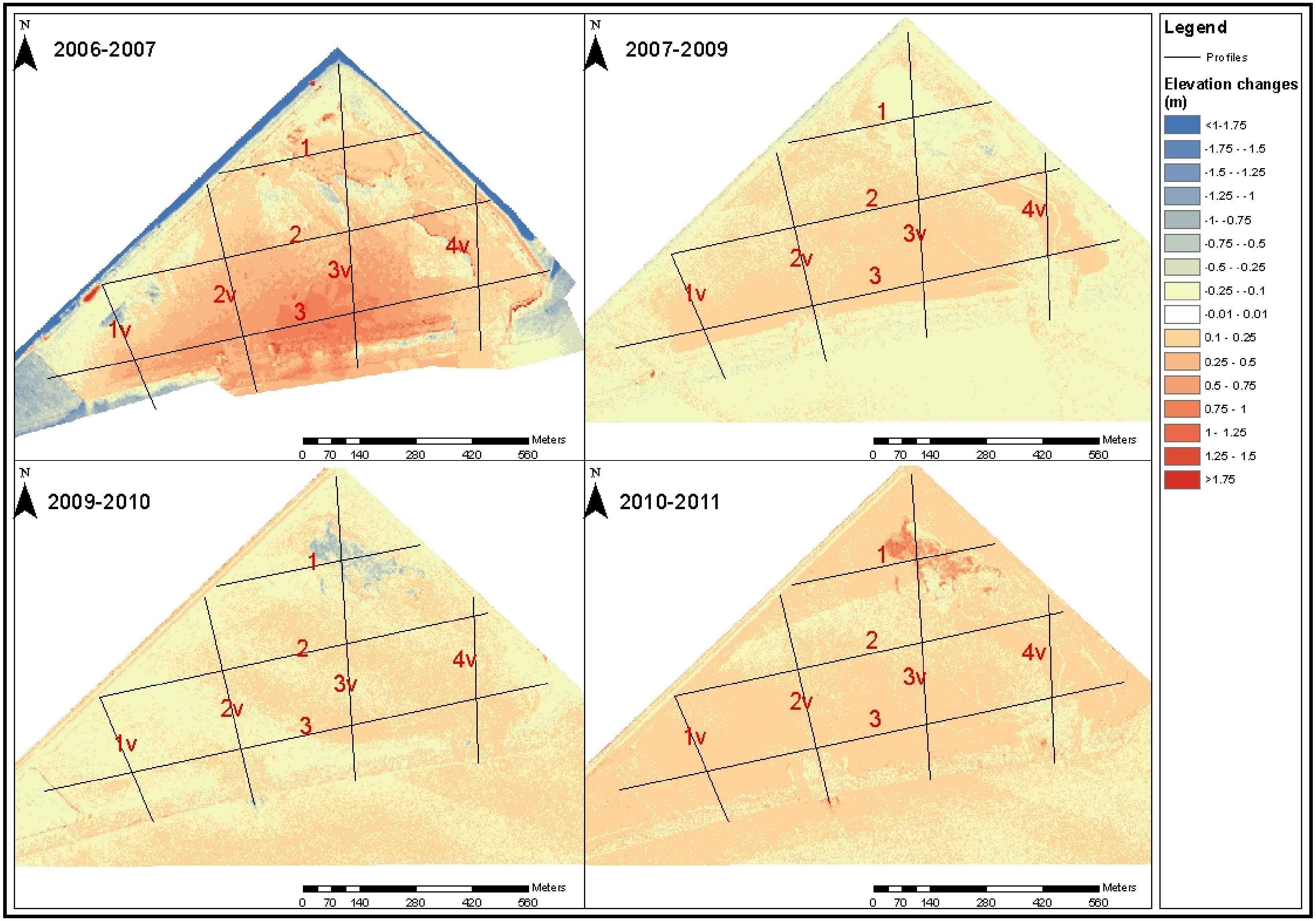

Figure 10. Elevation changes between survey years at Welwick obtained from LiDAR data

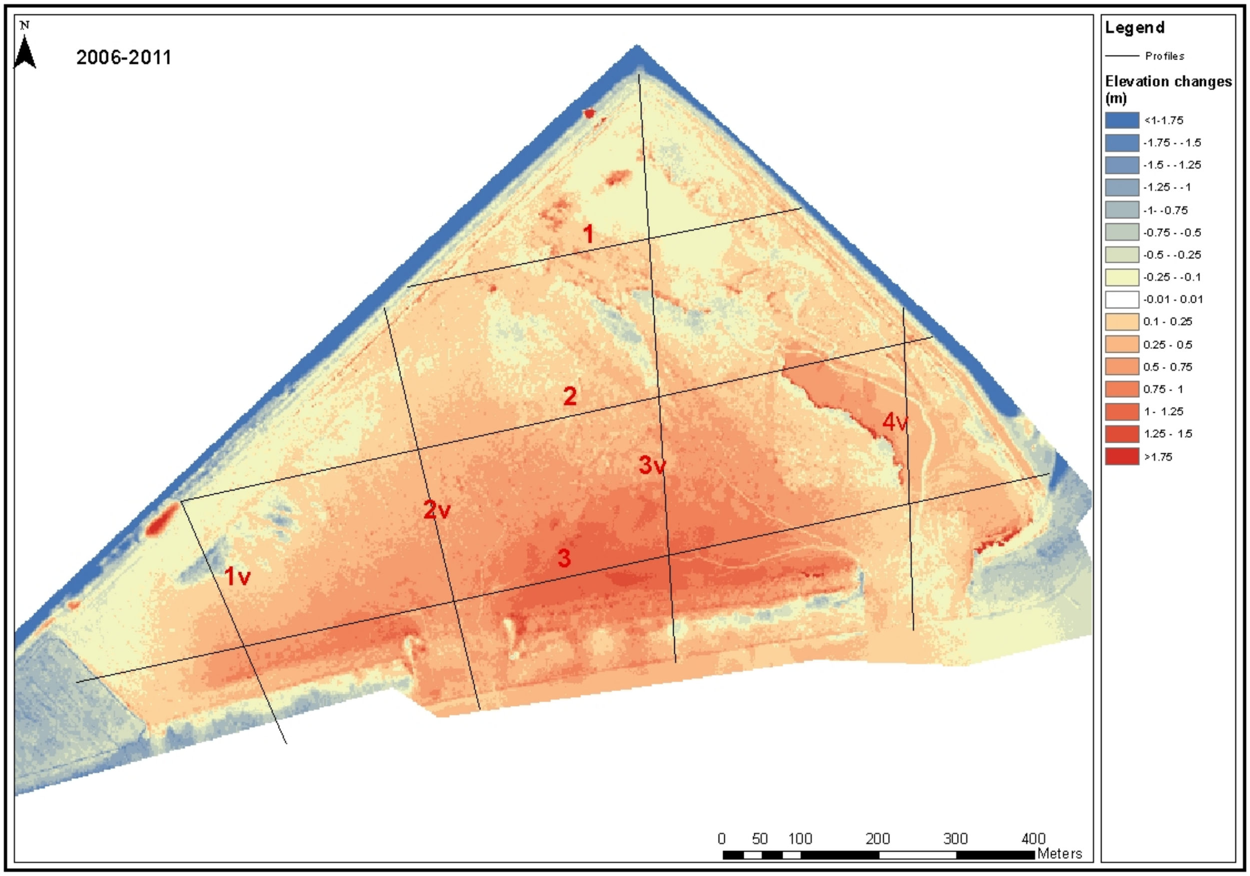

Figure 11. Welwick overall changes in elevation between 2006 and 2011

5.1.2. Cross section profiles

Cross section profiles along the entire site constituted the second stage of the analysis. Figures 9 to 11 above presented the locations of the horizontal (W-E) and vertical (S-N) profiles. Horizontal profiles are shown in Figure 12 and three of the vertical ones in Figure 13 (for all profiles, please refer to Appendix 3).

Figure 12 demonstrates that in 2006, immediately following the breaching of the site, approximately 59% of the front area of the site was below the MHWN tide level (1.9 mODN), as can be observed in Profile 3. This large percentage of low lying areas was the result of excavation to increase the potential for mudflat creation. The greatest proportion of this was found at the front of the site, as shown in Profile 3, due to the excavation of the breaches and subsequent internal channels designed to assist in the inundation of the site. In contrast, the second year survey (undertaken in 2007) identifies that the same profile lay mostly above the MHWN tide level one year on, with significant accretion evident in the central part of the site between the breaches, i.e. in the shelter of the remaining sea defence bases and fronting saltmarshes.

The same high initial accretion of the front part of the site is also observed in the first 250 m of vertical profiles 1, 2, and 3, which were lying below the MHWN tide level in 2006; by 2007 these low lying frontal areas were mostly infilled.

The central portion the site, described by Profile 2, had an original (2006) elevation above the MHWN tide level, with the exception of a channel located in the eastern part; nevertheless, this portion of the site experienced a significant initial accretion after breaching. Higher accretion was observed in the middle part of the profile, representing a sheltered area subject to flooding, though on a smaller scale compared to the font of the realignment site, probably due to lower tidal volume flooding this higher elevation.

The back of the realignment scheme, described by Profile 1, accreted less due to its initial higher elevation, lesser tidal volume exchange and consequent lower sediment availability. This is excluding the creeks which can be seen within the first 250 metres of the profile, which filled in rapidly, indicating that the flows were not sufficiently fast enough to re-erode the deposited sediments following HW and LW slacks periods.

At a distance of 300 metres along Profile 1, a reduction in elevation is observed in 2010. This trend is also visible in the vertical Profile 3 at a distance of 500 m. This is thought to represent the bottom of the previously mentioned lagoon, which would generally have been filled with water. The LiDAR surveys may have measured the water surface of the lagoon with the exception of the 2010 one, which could represents the actual surface elevation of this area.

Over time, the accretion rate across the site clearly decreases after 2007. The front profile (Profile 3) presents an average increase of elevation of 0.15 m between 2007 and 2011, compared to the average accretion rate of 0.59 m (along Profile 3) during the first year of survey data. The average accretion rate between the 2010 and 2011 was 0.09 m. The same pattern is observed toward the back of the site, reducing the average rate of accretion along Profile 2, from 0.17 m during the first year to 0.07 m between 2007 and 2011. This reduction of the accretion rate over time suggests that the major site changes occurred during the first year after breaching in the lower part of the site, as a consequence of the more frequent tidal flooding, the reduction of current velocities and the deposition of sediment from the water column.

The main channels through/from the breaches present an exception to the general trends described so far. The accretion rates in the areas of the main channels are reduced likely due to their more exposed position and higher flow rates generally experienced within such channels. This can be observed at a distance of 450 m and 1100 m along Profile 3, as well as the initial ca. 150 metres of vertical profiles 2 and 4. The accretion in the channel through the eastern breach into the site is almost negligible, compared to the one through the western breach. This indicates that the eastern breach is probably more exposed to higher flow velocities (possibly due to a larger percentage of the site draining through it) and, possibly waves; decreasing its ability to accrete. This larger exposure along the eastern side of the site is also clearly visible in the first 150 metres of vertical Profile 4, which indicates very limited changes in the channel’s elevation during the whole period of the analysis After this distance, an accretionary trend is observed over

time; however at a lower rate than in the channel through/from the western breach, confirming the assumption previously stated, of the higher exposure of this side of the site.
The high rates of initial accretion at the front of the site are also illustrated in Figure 14, which shows the evolution of the MHWN tide line (i.e. 1.9mODN). According to the figure, only during the first year after breaching did the MHWN tide line extended well into the site; during the following years the site elevation was largely too high, significantly reducing the tidal exchange. Only around the easterly breach does the line extend into the site until 2011.
Figure 15 presents a cross section showing the changes in elevation along the initial (2006) MHWN tide line. The variations of the entire profile again indicate an initial high accretion, which average around 0.40 m during the first year, similar to the one described for the middle portion of the site (Profile 2). After 2007 the accretion rate decreases, high water would not extend far into the site during neap tides, and thus less sediment would have been imported into the site due to decreased inundation frequencies. The eastern part of the cross section profiles of Figure 15, corresponding to the area immediately at the back of the eastern breach, indicates relatively small changes in its elevation, representing the main channel that has been preserved over the period of analysis due to the likely higher flows and its more exposed location, as was earlier described.
Furthermore, large accretion in the order of up to 1 metre is observed at the eastern and western extremes of the cross sectional profiles (see Figure 15). These ‘spikes’ are thought to most likely be related to slumping of the old seawall base, as the cross section line would have been drawn immediately along its base. The spikes could also relate to inaccuracies introduced by data interpolation in relation to the ground based radar survey the 2006 data was derived from (taken from various locations along the new and old seawalls).
Finally, Figure 15 clearly shows the site approaching an equilibrium state with reducing rates of change over time. The higher initial accretion observed in the year after breaching decreases during the following years.
In summary, all the cross section profiles indicate that there was a considerable accretion in the front of the site during the first year, as show in Figures 10 and 15 and in the previous section. However, accretion rates are not uniform across the front section of the site, but vary depending largely on the initial depth of the site and the flow velocities in any particular area, i.e. deep sections of the site with relatively low flows accreted the fastest. Furthermore, the accretion rates toward the back of the site appear to have been lower, likely due to the higher elevation, smaller tidal exchange/lower inundation frequency and the consequent lower sediment availability.

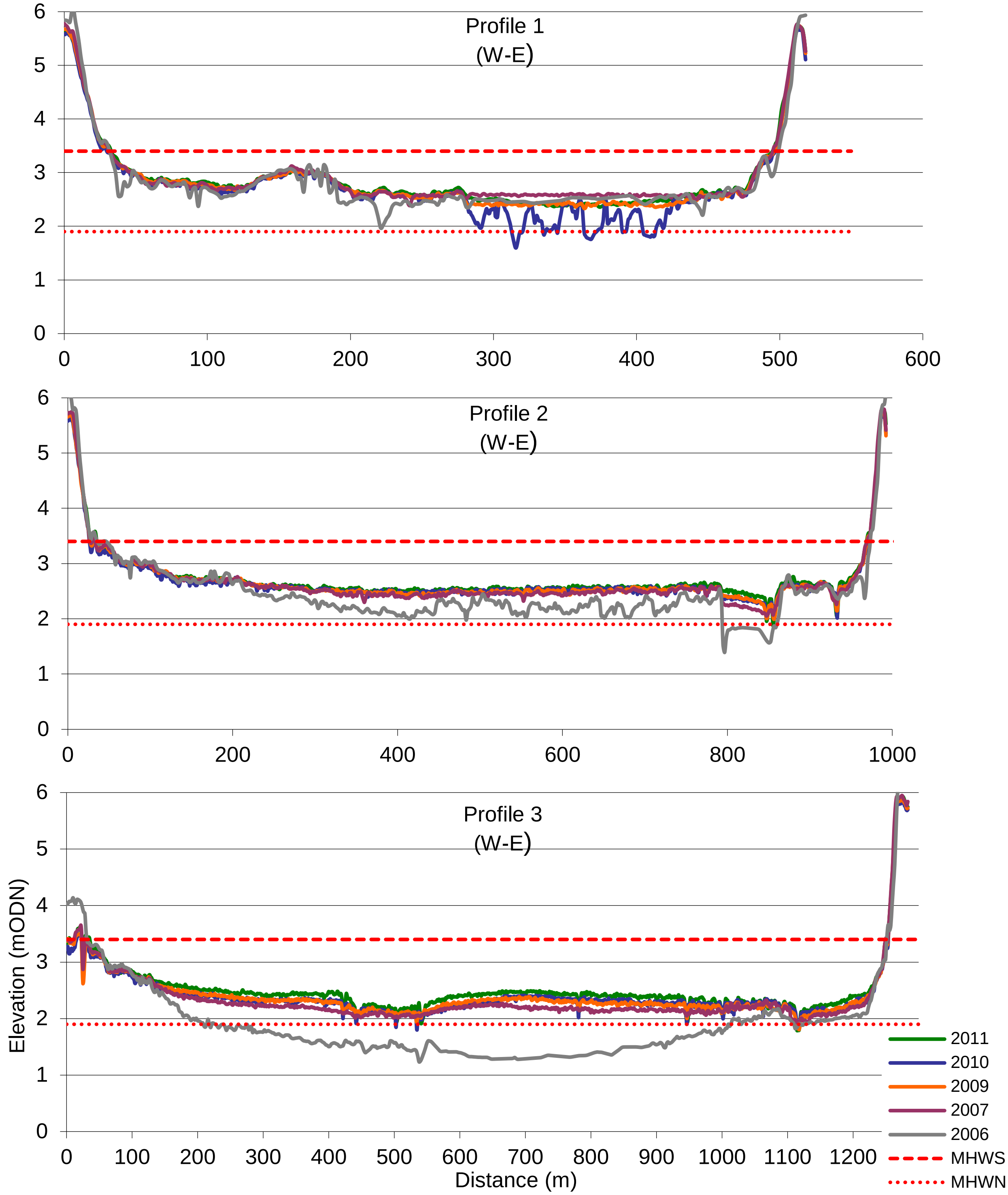

Figure 12. Horizontal (W-E) Welwick cross section profiles (vertical accuracy ±15 cm, with the exception of 2006 data (vertical accuracy ±50 cm))

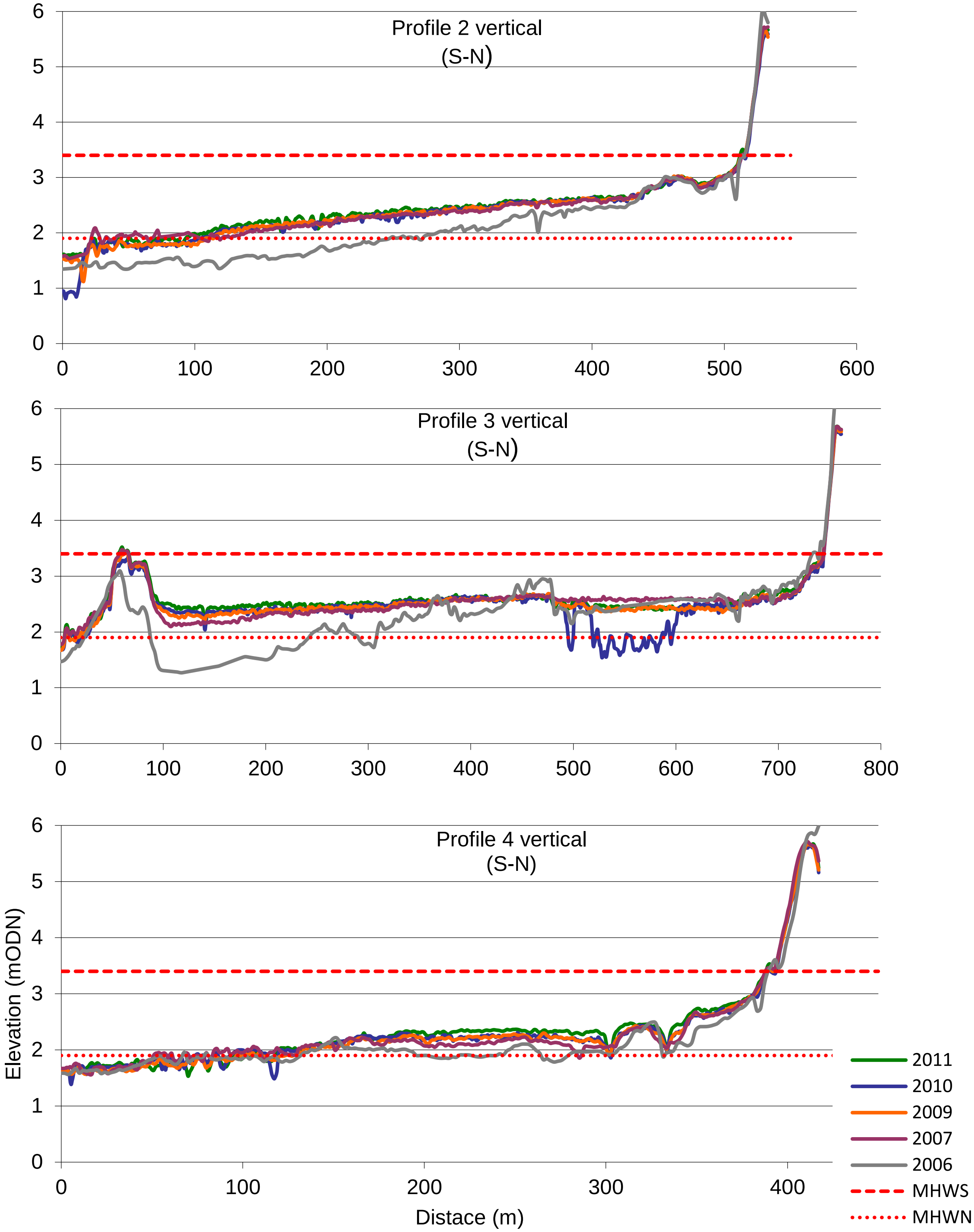

Figure 13. Vertical (S-N) Welwick cross section profiles (vertical accuracy ±15 cm, with the exception of 2006 data (vertical accuracy ±50 cm))

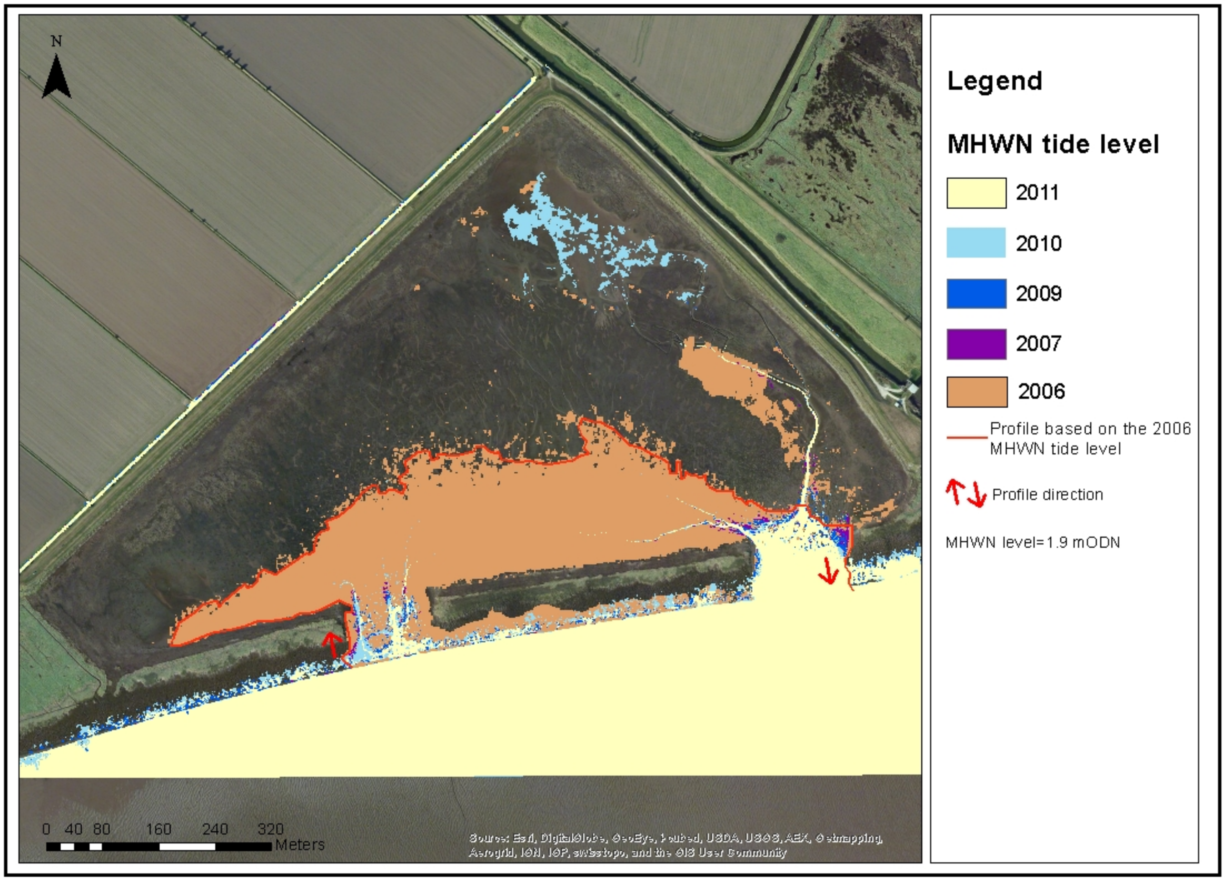

Figure 14. Mean high water neap tide inundation extent

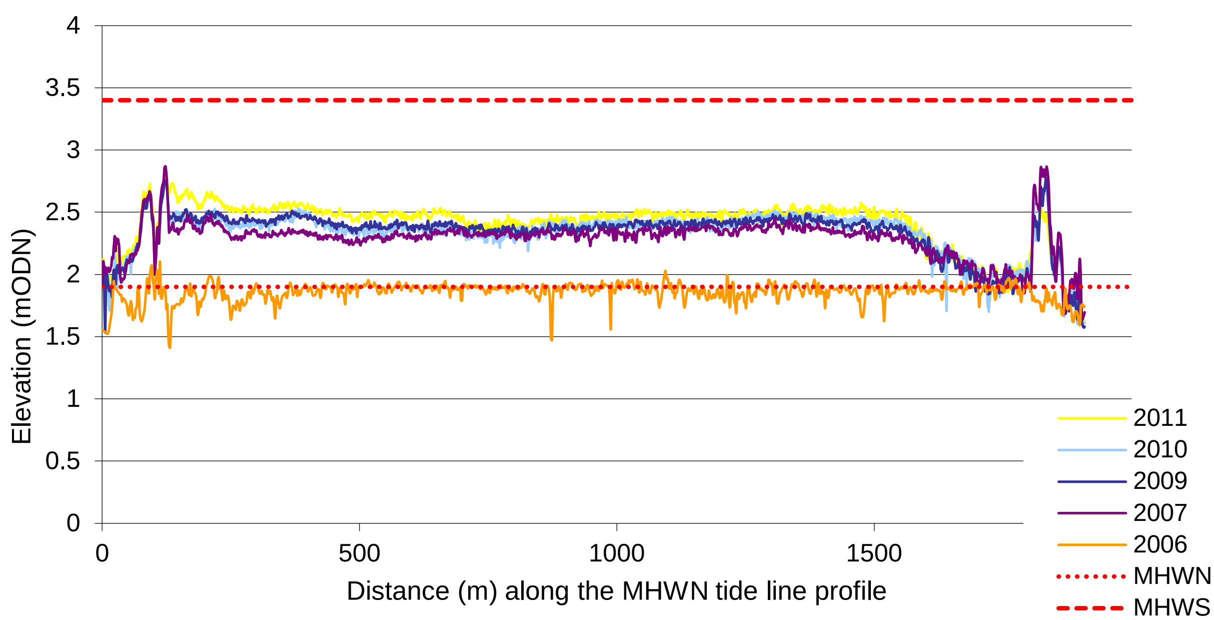

Figure 15. Welwick cross section profiles along the MHWN tide line of 2006 (noting the higher margin of error in the 2006 vertical accuracy (±50 cm))

5.1.3. Hypsometric curve

Hypsometric curves were obtained for the first and last year of analysis (Figure 16). In 2006, 30 % of the site was lying below the MHWN tide level, 50% between the MHWN and MHWS tide levels and only 20% of the site surface was higher than 3.4 mODN (MHWS tide level).

In 2011 only 9.5% of the realignment area was below the MHWN tide level, 83.1% of it was lying between the neap and spring high water tide level, and only the 7.4% of it was above MHWS tide level.

The curves of Figure 16 clearly indicate how a significantly larger percentage of the site (90.5%) lies above MHWN tide level in 2011 (compared to the 70% in 2006); however, the behaviour of the elevation related to the site area changes at 2.4 mODN. An increase in the surface elevation up to the 2.4 mODN level is observed between 2006 and 2011, coinciding with the accretion of the lower part of the site that was described in the previous sections. On the other hand, a decrease in the elevation above the 2.4 mODN level between 2006 and 2011 is seen, as previously discussed likely corresponding to setline, slumping and localised small scale erosion around the back of the site.

The curve indicates a larger area lying between the two tidal reference levels by 2011. The slope of the site has clearly decreased during the period of analysis, and the site has become more flat.

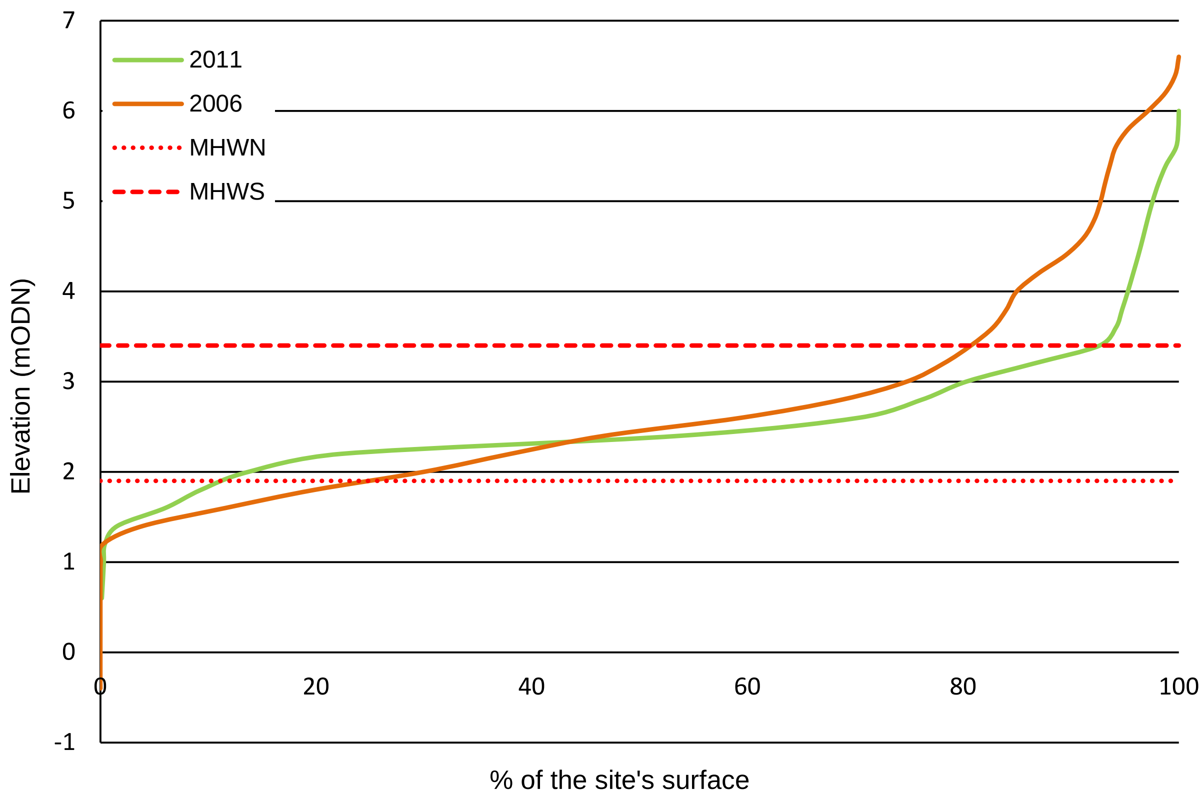

Figure 16. Welwick hypsometric curve for 2006 and 2011

5.1.4. Volume

According to the volume of water flooding the site based on tide reference levels (HAT, MHWS and MHWN tides) the changes in the volume of sediments of the realignment were calculated as described in the methodology chapter. Figure 17 indicates the changes of the volume of water over time. The data is presented in Table VIII.

Due to the accretion processes, the volume of water flooding the site, according to a tide reference level, has decreased over time. According to the data presented in Table VIII, between 2006 and 2011, the volume of water at HAT tide level reduced by 8.05%, at MHWS by 19.83% and at MHWN by 75.94%. The larger reduction at the neap high tide level indicates a higher accretion in the lower parts of the site, as was observed in the previous sections.

Table VIII. Welwick volume of water (m^3) over the site according to different reference levels

Years	HAT	MHWS	MHWN
2006	1116443.94	689019.63	51729.4764
2007	1055707.6	582385.211	10344.7656
2009	1062606.39	585820.279	15151.7793
2010	1080221.1	600180.904	15757.5029
2011	1026569.1	552322.133	12446.0624

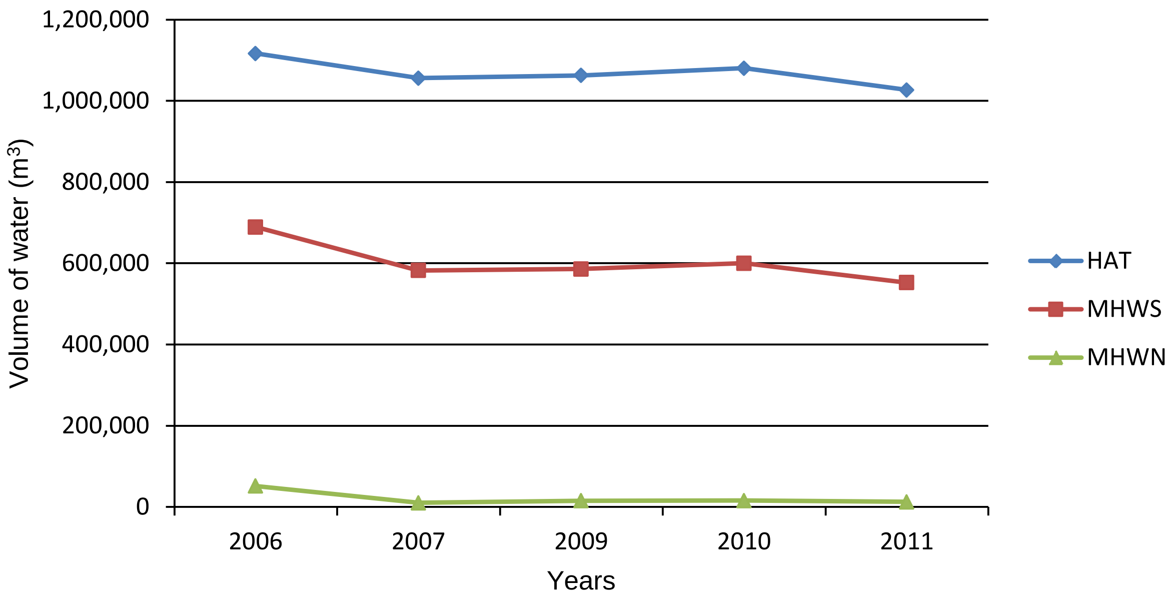

Figure 17. Welwick volume of water (m3) over the site according to different reference levels

From the water volume reduction, the changes of volume of sediment were obtained. Table IX and Figure 18 present the results. Firstly is important to notice, that during the first year, the site presented large accretionary trends, however, during the two following surveys (covering a period of three years) overall increase in water volume was seen within the site, which could indicate erosion. During the last year of analysis (2010-2011), the apparent accretionary tend return. The overall volume change (2006-2011) is negative, indicating overall accretion of the site meeting the expectations based on previous sections. However according to the data, during the first year after breaching 67.5% of the total overall accretion at HAT tide level occurred, indicating a high initial volumetric change. In the case of the volume at MHWN tide level, the initial accretion (2006-2007) is larger than the overall one, representing the increased of elevation of the front of the site during the first years after breaching and its later stabilisation/dramatic decreases in accretion rates.

Table IX. Welwick sediment volume changes at different reference levels based on the change of the water volume. Negative values indicate accretion of the surface.

Years	**Volume change (m^3)**		
	HAT	**MHWS**	**MHWN**
2006-2007	-60736.3406	-106634.419	-41384.7109
2007-2009	6898.7885	3435.06762	4807.01374
2009-2010	17614.7088	14360.6253	605.723588
2010-2011	-53651.9943	-47858.7707	-3311.44047
2006-2011	-89874.8376	-136697.497	-39283.414

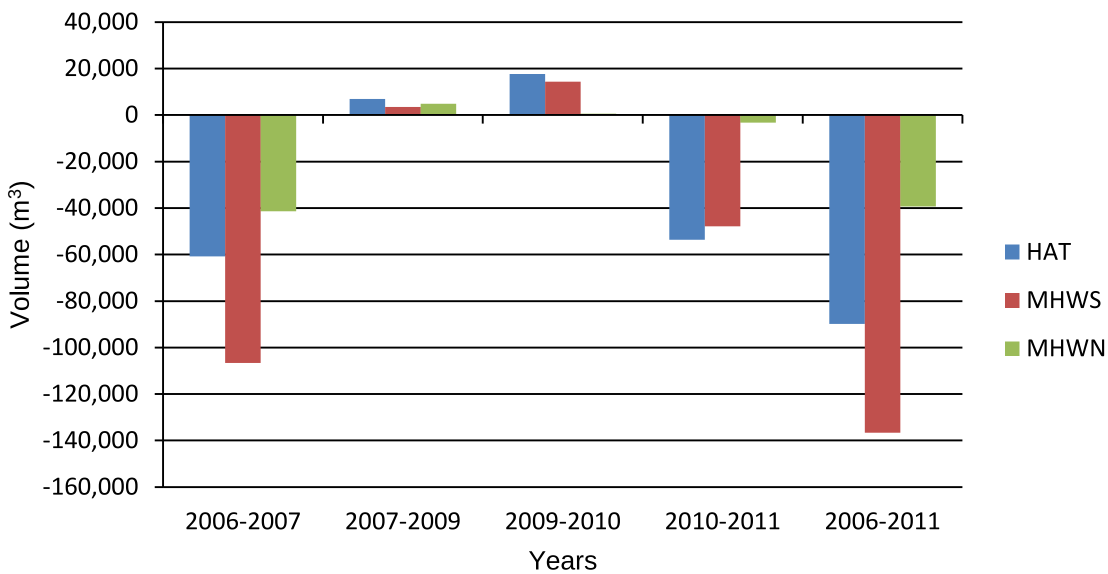

Figure 18. Welwick sediment volume changes at different reference levels based on the change of the water volume. Negative values indicate accretion of the surface

By undertaking a detailed analysis of Table IX and Figure 18, several important observations can be made/confirmed. The overall change indicates a larger volume change at the MHWS tide level than at HAT level. An even accretion over the entire site would result in the larger sediment volume at HAT level reference; however, the volume of sediments at HAT level is lower than at the MHWS tide level, indicating some erosion/compaction/settlement of the higher areas of the site. This erosion or settlement of the site at higher elevations was already observed in the previous sections. According to the volume data, 46,822 m^3 of sediments have been "lost" between 2006 and 2011 above the MHWS tide level (i.e. in the area associated with higher saltmarsh). The same situation, reduction of the site volume above MHWS, is observed between 2006 and 2007, however, during the rest of the years, the volume changes indicates the same trends over the entire site, that is, an accretion or erosion at all elevation.

Furthermore, according to the volume calculations, from 2007 to 2010, one could assume that the site experienced an erosion trend. However, it is more likely that settlement of the higher areas, as well as autocompaction of the layers of deposited sediments as well as the presence of water in the site during 2006 to 2009 surveys account for the majority of the positive volume change. With regards to the water on site, as previously mentioned, it is assumed that water was present in the lagoon during the 2006 to 2009 surveys, and likely again in 2011, but not in 2010. Under this hypothesis, the draining of the lagoon in 2010 could be interpreted as a decrease of the site volume or "artificial erosion".

In summary, it is important to notice that the volume calculations are affected by the presence of water in the site. The presence of water in specific areas, as the small lagoon in the rear side, can generate "artificial accretion" or "artificial erosion" of the site.

5.2. Paull Holme Strays

The 80 ha Paull Holme Strays managed realignment site was the first to be implemented in the Humber Estuary; it is located on the north bank of the middle estuary and was breached in 2003. The site was breached at two points 1.5 km apart; the west breach is the wider one (150 m), while the east one is 50 m. The eastern part of the site is located at higher elevations than the western part. During construction, large pits were dug in order to obtain material for the new defences; Chapter III and Appendix 2 describe in more details the characteristics of the site and the construction process; in the next sections, the evolution of the site after these initial processes has been studied.

5.2.1. Elevation changes

The evolution of Paull Holme Strays is presented in Figure 19. Firstly, significant elevation differences between the eastern and western sections of the realignment site are observed since the first year of survey. The western part represents a lower area, with elevations lesser than 2 mODN in 2004. This region accreted over the time, from 2004 to 2010 an increase in elevation is observed in the figure, reaching 2.25-2.5 mODN with the exception of the channels and creeks.

The eastern section of the site, on the other hand, lies over a higher original surface, with elevation ranting between 2.75 and 3.5 mODN in 2004. The elevation changes over this side of the site are smaller; the figure presents a decrease in height between 2004 and 2010 especially in the back part of the area and in front of the east breach.

Furthermore, Figure 20 presents the elevation changes during the whole period of data. The changes between 2003 and 2004 are related to the breaching and construction works of the site; 2003 LiDAR data represents the site before breaching. As it is unclear how much the site changed after the 2003 data was taken, this data set has not been analysed in details. Thus, after the first year of survey (2004-2005), increases in the site elevation were observed in the lower western area between 0.25 and 0.5 metres. The accretion of this area continued between 2005 and 2007; however, in the last 3 years of data, the rates of elevation change were lower (0-0.25 m). In addition, erosion rates of 0.25-0.5 m were observed in front of the west breach during the first year, probably as a result of channel development. This erosion decreased in the following years such that between 2007 and 2010 the changes in front of the west breach were positive, indicating a depositional rate of maximum 0.25 m.

The central and eastern section of the site presented small positive changes (maximum of 0.25 m) during 2004 and 2005, however, this accretion trend progressively changed to an erosional one between 2005 and 2010. Due to the lack of data, no information is available for the rear side of the site during 2005; however, Figure 20 indicates that between 2007 and 2010 the back west and central parts of the site experienced a decrease in their elevations of 0.25-0.5 metres, similar to the one recorded in front of the east breach in the same period.

Finally, Figure 21 presents the total elevation changes across the site over the analysis period (2004-2010). The same accretion/erosion patterns are observed, indicating the accretion of the western part of the site and the more erosional trend of the eastern section. Accretion of almost 1 metre is observed in the lower western part of the site, with the clear development of a channel and tidal creeks. In the eastern breach the development of a tidal channel is detected indicating the erosion and deepening of it, probably related to high velocity currents during the ebb period. At high water, due to the position of the breach in the estuary (and its drainage patterns – i.e. west to east), relatively high volumes of water would be expected to force their way through the eastern breach, probably causing this erosion of the channel.

The rear side of the site and the low lying region in front of the eastern breach experienced a decrease in elevation between 0.25 m to a maximum of 0.5 m. The surrounding areas and the embankments are also presenting a negative elevation change of the order of 0-0.5 metres, probably resulting from settlement of the defences in addition to weathering of the surface.

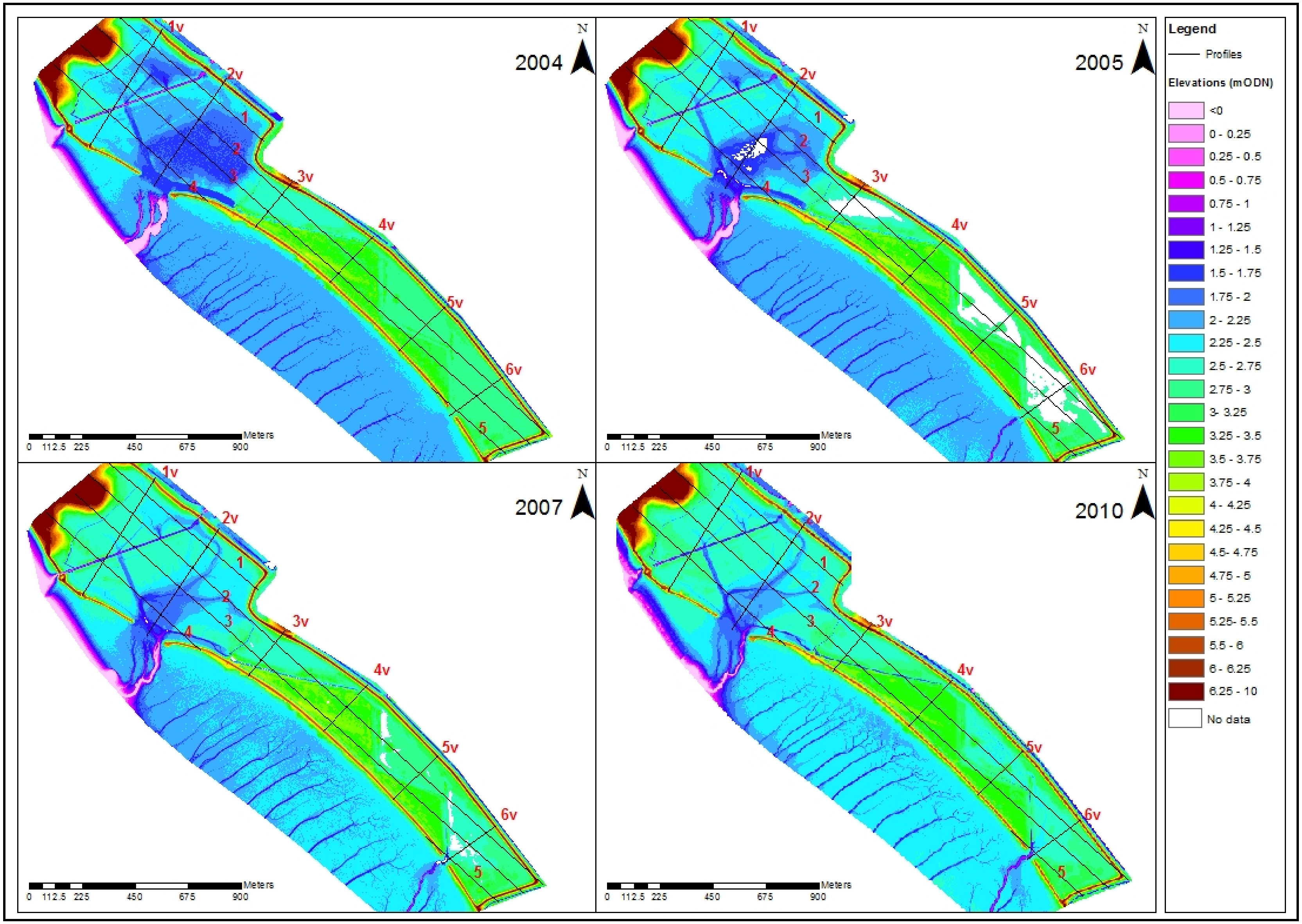

Figure 19. Elevation of Paull Holme Strays obtained from LiDAR data (profiles lines used as a reference)

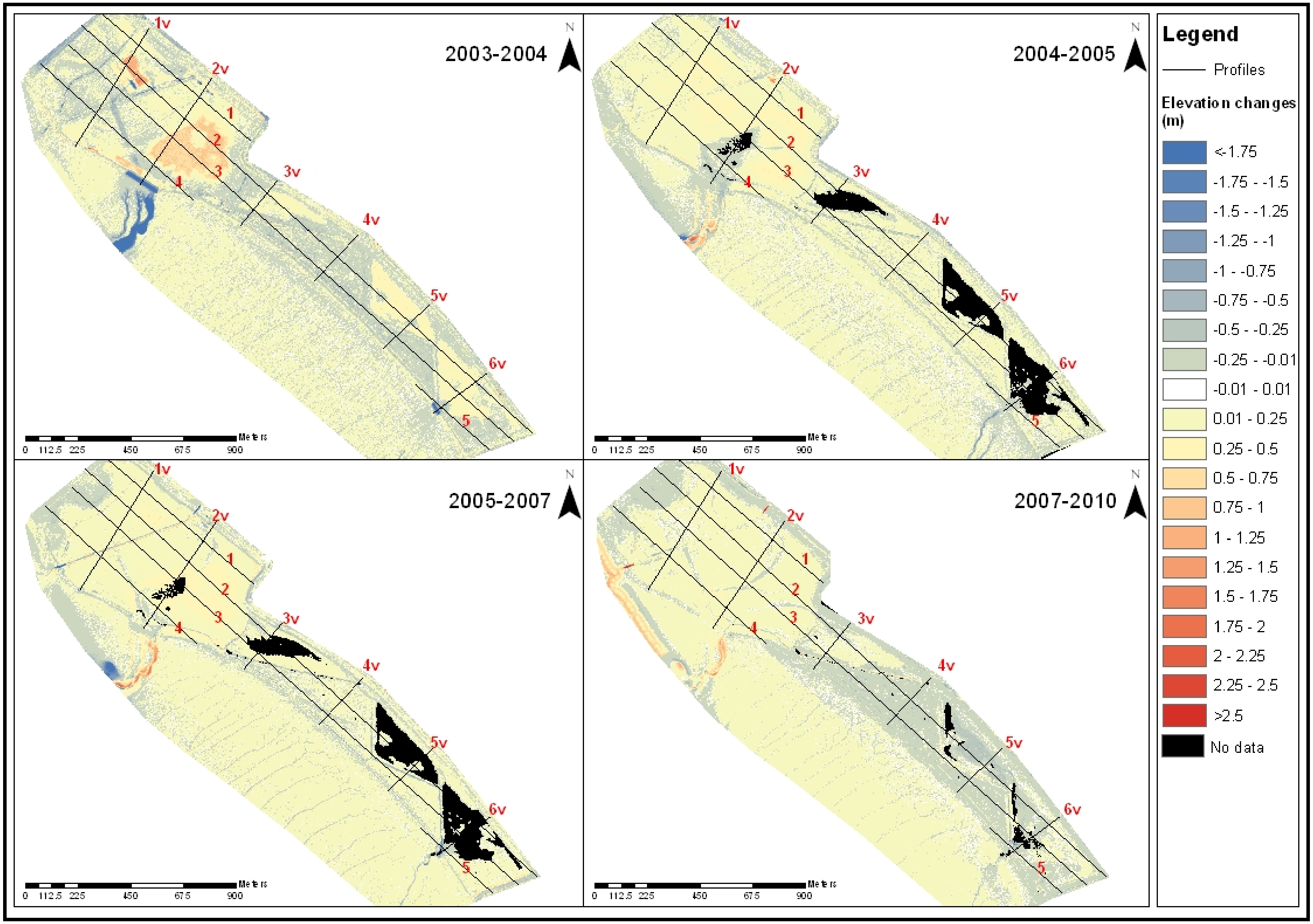

Figure 20. Elevation changes between survey years at Paull Holme Strays obtained from LiDAR data

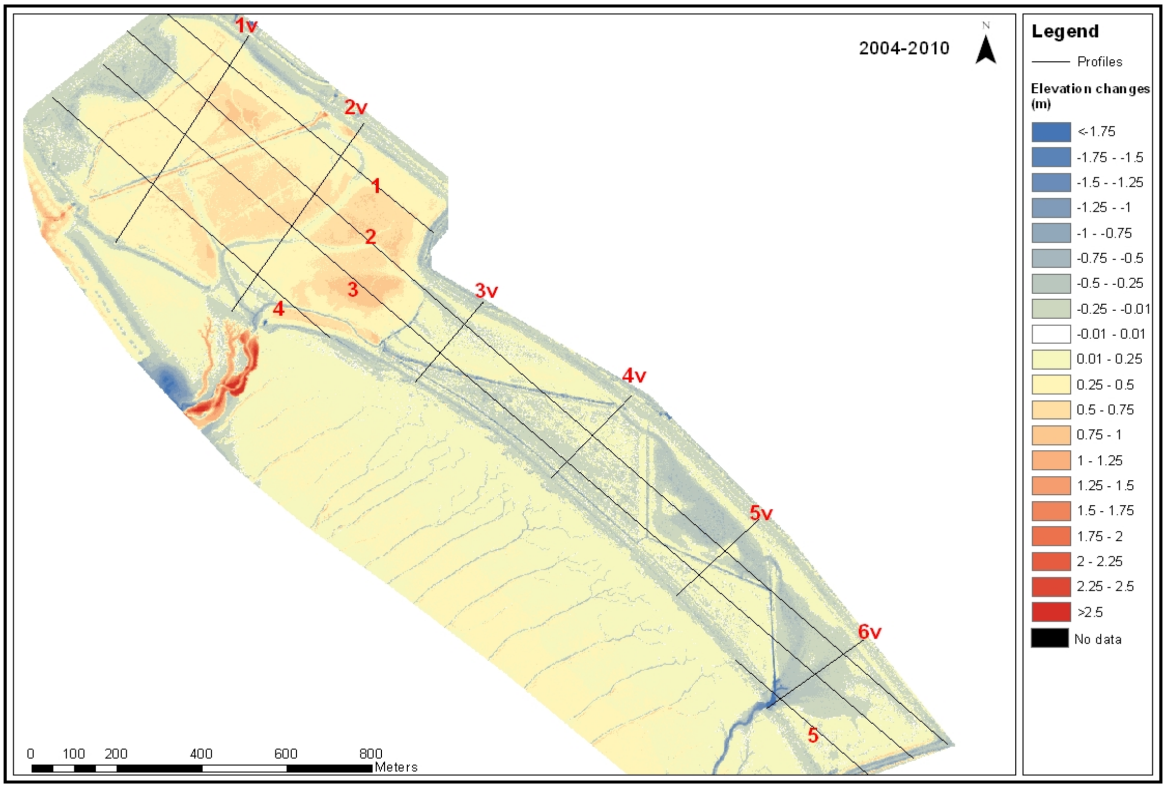

Figure 21. Paull Holme Strays overall changes in elevation between 2004 and 2010

5.2.2. Cross section profiles

The complete dataset of cross section profiles of the Paull Holme Strays managed realignment site is presented in Appendix 3. The location of the profiles is obtainable from Figures 19 and 20. Three of the five horizontal profiles that cross the site in a NW-SE direction were selected as representative and they are shown in Figure 22. Figure 23 presents three of the six vertical profiles, also selected as representative.

Firstly, one of the main characteristics of this site is the difference in elevation between the eastern and western sections of it. Profile 3, which crosses the entire site, presents these two sections of the realignment site, defining the western part in the first 1000 metres along the profile and the eastern from 1000 metres toward the end of the profile. In the western section, the elevation of the site is between 2 and 3 mODN, with the exception of the channel area. On the other hand, the eastern part has an elevation higher than 3 mODN.

These two sections presented distinctly different topographic changes. From the original elevation before breaching (2003 data) accretion can be observed in the western part of the site. Along the first 500 m of Profile 3, representing the central part of the site, the elevation increases from the MHWN tide level (2.1 mODN) to an average of 2.6 mODN in 2010. From 500 m to 1000 m along this profile, the site has a lower region, an area directly exposed and flooded behind the westerly breach. This lower zone was almost flat in 2004 with an elevation of

1.6 mODN. However, over time, its elevation has increased, and a channel has formed around the MHWN tide level.
In summary, the first 1000 metres of the Profile 3, representing the western part of the site, shows an accretion pattern over the 6 years of data. Horizontal Profiles 1 and 2 (Appendix 3) presents the same type of accretion that led elevations form MHWN tide level to 2.25-2.75 mODN over a period of 6 years.
The eastern section of the site presents a distinctly different behaviour than the described above. According to Profile 3, after a distance of 1000 metres until 2000 metres along the cross section, the elevation of the site is higher than 3 mODN, almost reaching the MHWS tide level of 3.7 mODN. In this higher section, the changes are smaller and negative, indicating a decrease in elevation between 2004 and 2010. At a distance of 2000 m along the profile, another flat and exposed area is observed in 2004; however, after the first year, a tidal channel developed and the decreasing in elevation is recorded behind the easterly breach.
The areas immediately behind the two breaches are shown in horizontal profiles 4 and 5 (west and east respectively) of Figure 22. The first 500 metres of Profile 4 consistently lie above the MHWN tide level, with the exception of a deep creek at a distance of 300 metres along the profiles (which is present as a major field drain prior to breaching, as it is shown in the 2003 data set). This creek has accreted at fairly low rates at the intersection with cross section 4. The surface after the creek presented a general accretion trend, probably due to the more frequent inundation and the sheltering effect of the sea defences (which were not lowered, unlike at Welwick). The second half of the profile lies in a lower area, directly exposed to the breach; lower rates of accretion are observed here, likely due to the higher flow velocities experienced and possibly wave exposure. Here the elevation has yet to reach the MHWN tide level after 6 years of surveys.
The evolution of the site, from the western breach towards the back is represented by vertical Profile 2 (Figure 23). In 2004 (one year post breach), 67% of this profile was below the MHWN tide level; another year later, this was 54% of it, and a further two years thereafter it was 45%; by 2010 only 39% of the cross section was below the neap tide level, indicating a larger accretion of the site in the front and lower part of it, however, the presence of the breach, the tidal exchange and the higher tidal currents have not allowed the accretion rate to reach elevation above the MHWN tide level in this area, as was also notice in Profile 4. In summary, accretion is observed along the whole western part, especially between 2004 and 2007, however, the rate decreases considerably during the last 3 years of surveys (2007-2010), due to the higher level of the surface and the consequence reduction on the flooding period and sediment availability.

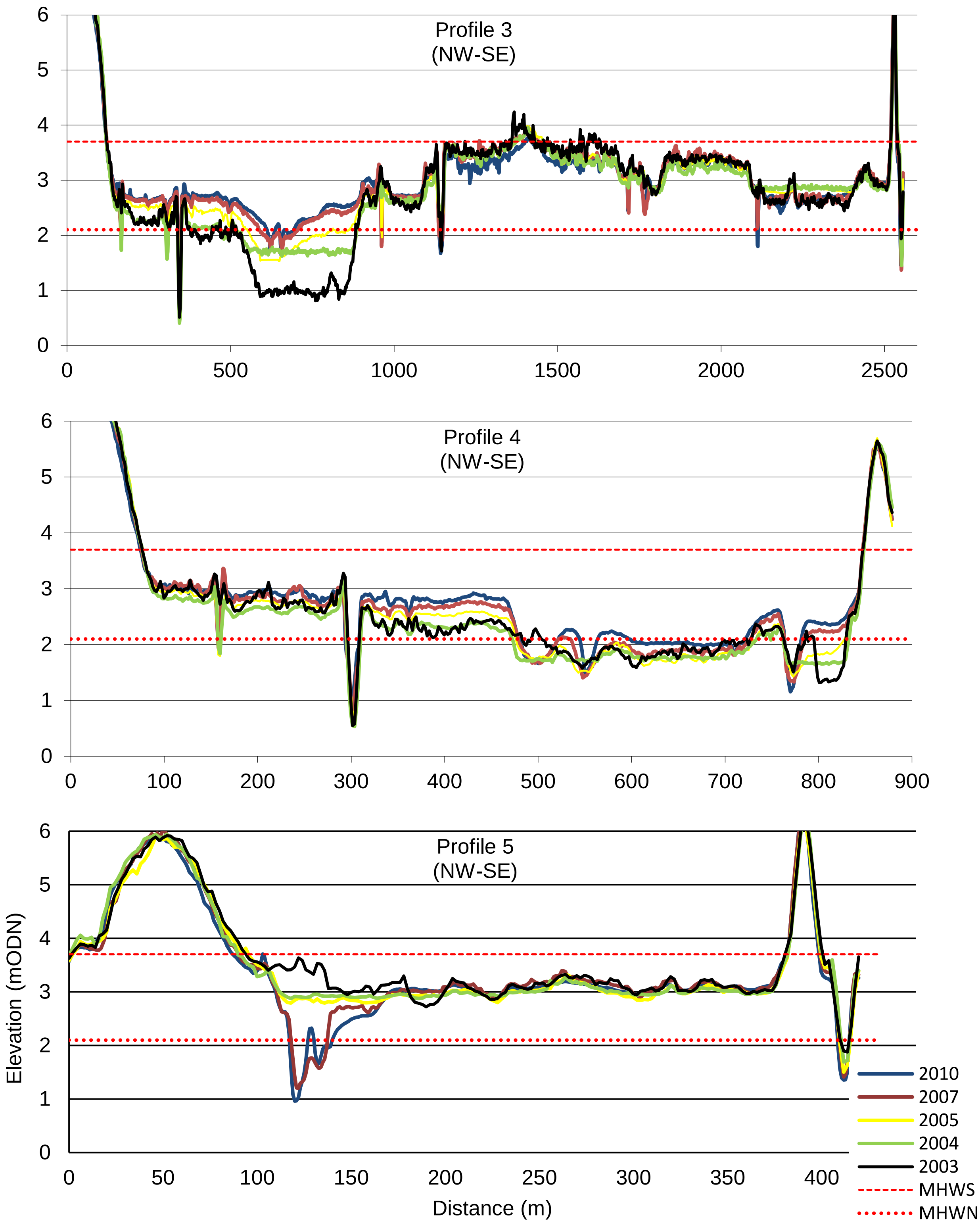

Figure 22. Horizontal (NW-SE) Paull Holme Strays cross section profiles. The black line (2003) represents the site before breaching (vertical accuracy ±15 cm)

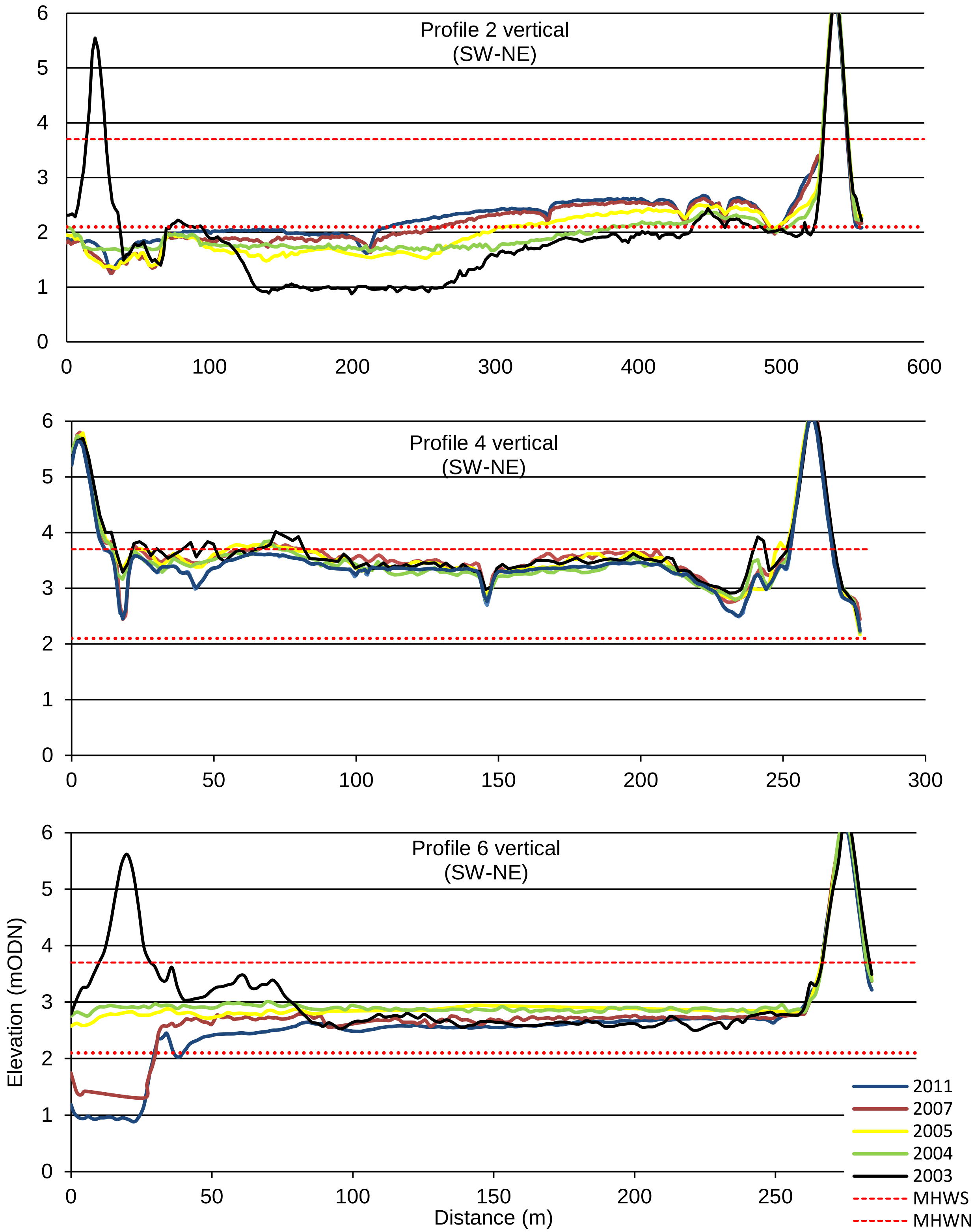

Figure 23. Vertical (SW-NE) Paull Holme Strays cross section profiles. The black line (2003) represents the site before breaching (vertical accuracy ±15 cm)

In the case of the eastern breach, crossed by Profile 5 (Figure 25), the clear development of a tidal channel can be observed between 2004 and 2010; however, the rest of the profile presents smaller variations in its elevation, indicating a lower tidal exchange for this part of the site. The channel did not develop immediately after breaching; according to the data the channel excavation occurred between 2005 and 2007 (the loss of 2 metres of material is observed) continuing in the following year producing a deeper and wider channel. Furthermore, it is important to notice, that the area behind the eastern breach (Profile 5 and vertical Profile 6), with the exception of the channel, lies above MNWN tide level at an elevation of 3 mODN, which explain the smaller influence of the tide.

The central area of the realignment site is completely sheltered by the all seawall and it behaves in a complete different way. The elevation of the area is of the order of 3-3.5 mODN, with some places higher than the MHWS tide level (Profile 4 vertical). The entire section presented a decrease in its elevation over the period of the analysis, the same decrease described in the second half of the horizontal Profile 3.

In addition, a cross section profile along the MHWN tide line of the first year after breaching was used as a reference point to study the site evolution. Figure 24 indicates extent of the MHWN tide line one year after breaching (2004) and its change over the time as a consequence of the accretion of the realignment scheme. The figure only indicates the evolution of the MHWN tide elevation for the west breach because the eastern breach had an original elevation higher than the MHWN tide level of 2.1 mODN.

Figure 25 presents the changes in elevation along a MHWN tide line in the western part of the site. The variations of the entire profile indicates an initial accretion of 0.20 m along the whole profile; the same increase in elevation (0.20 m) is also observed in the following two years between 2005 and 2007, decreasing by half the yearly accretion rate. During the last three years of survey (2007-2010), the accretion of the site continued, however, the accretion rate decreases even more, showing an increase of elevation of 0.10 m in a period of three years, due to the shorter and less common tidal exchange and the consequent reduction of sediment availability.

As in the case of the previous realignment site analysed (Welwick), a “near” equilibrium in the accretion/erosion rates is reached. The higher initial accretion observed after breaching decreases during the following years and accretion/erosion rates does not experience abrupt changes.

Furthermore, the profile of Figure 25 clearly indicates the presence of four main tidal channels that have not experienced significant accretion over the six years of analysis. The channel bottom elevation has largely been constant over the site evolution, probably due to high tidal current velocities; however the surface surrounding the channels increased creating deeper channels between 2004 and 2010.

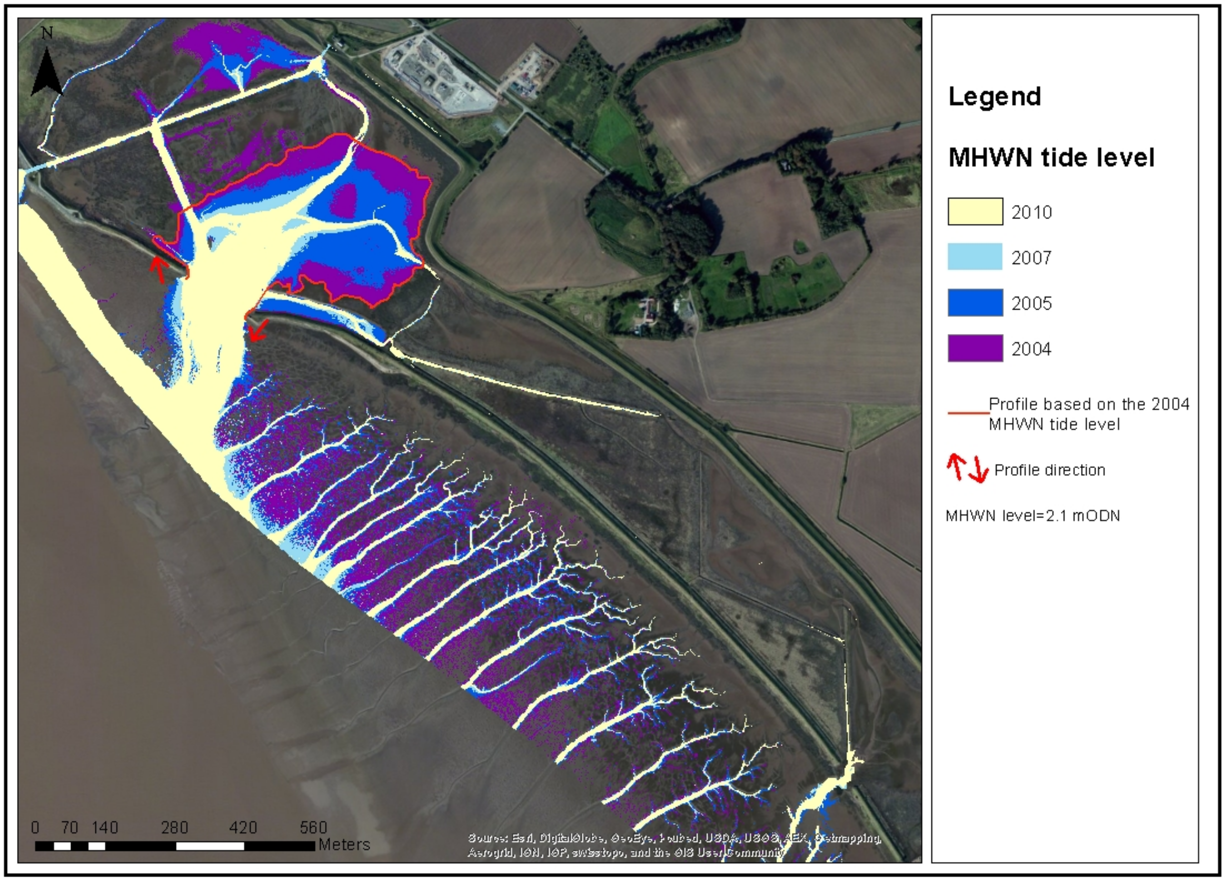

Figure 24. Mean high water neap tide inundation extent

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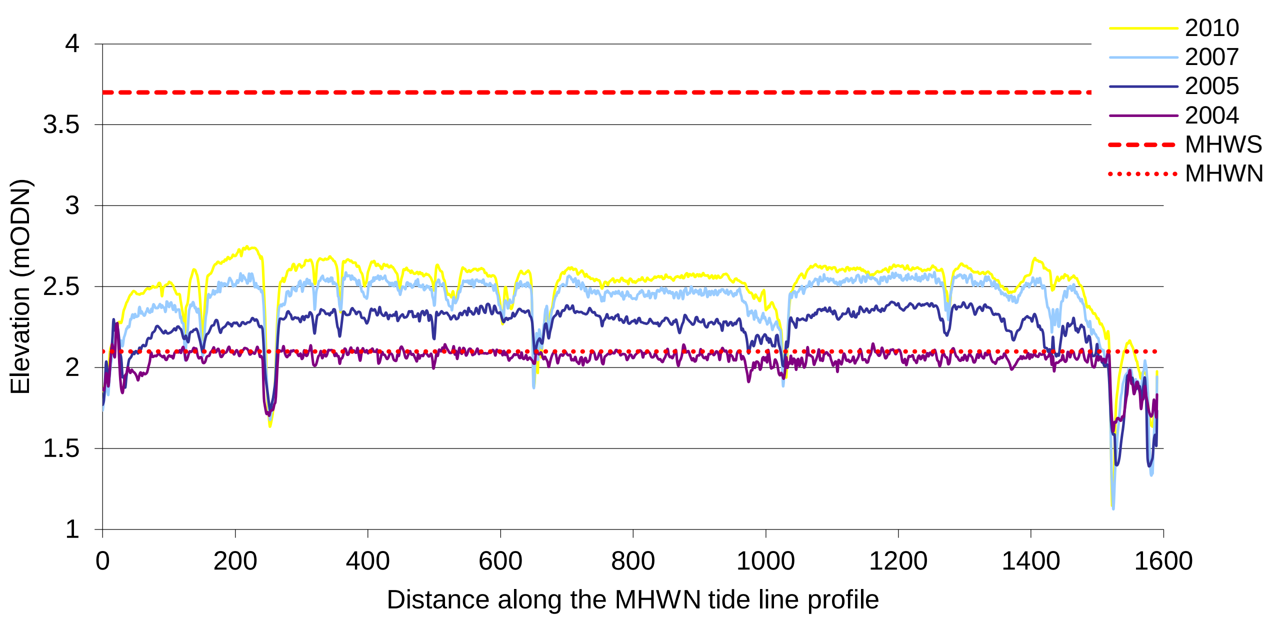

Figure 25. Paull Holme Strays cross section profiles along the MHWN tide line of 2004

5.2.3. Hypsometric curve

Hypsometric curves were obtained for the first and last year of analysis (Figure 26). In 2004, 20% of the site was lying below the MHWN tide, 66% between the MHWN and MHWS tide level and only 14% of the site surface was higher than 3.7 mODN (MHWS tide level).

In 2010 only 4% of the realignment area was lower than the MHWN tide level, 82% of it was lying between the neap and spring high water tide level, and the same 14% of it was above the MHWS tide level.

The curve of Figure 26 clearly indicates how a larger percentage of the site (96% compared to 80%) lies above the MHWN tide level in 2010; however an interesting point can be noted in the curve in relation to the distribution of the surface and its elevation.

The increase in elevation between 2004 and 2010 is observed only up to 2.8 mODN, indicating the accretion of the lower areas of the site. After a height of 2.8 mODN, no significant changes in the elevation of the realignment site have occurred.

These observations are consistent with the elevation analysis of the previous section, in which the main accretion was recorded for the lower laying western section of the site. On the other hand, previous analyses have shown negative changes in the rest of the site, especially above 2.5 mODN, however, this loss of elevation is not immediately apparent in the hypsometric curve.

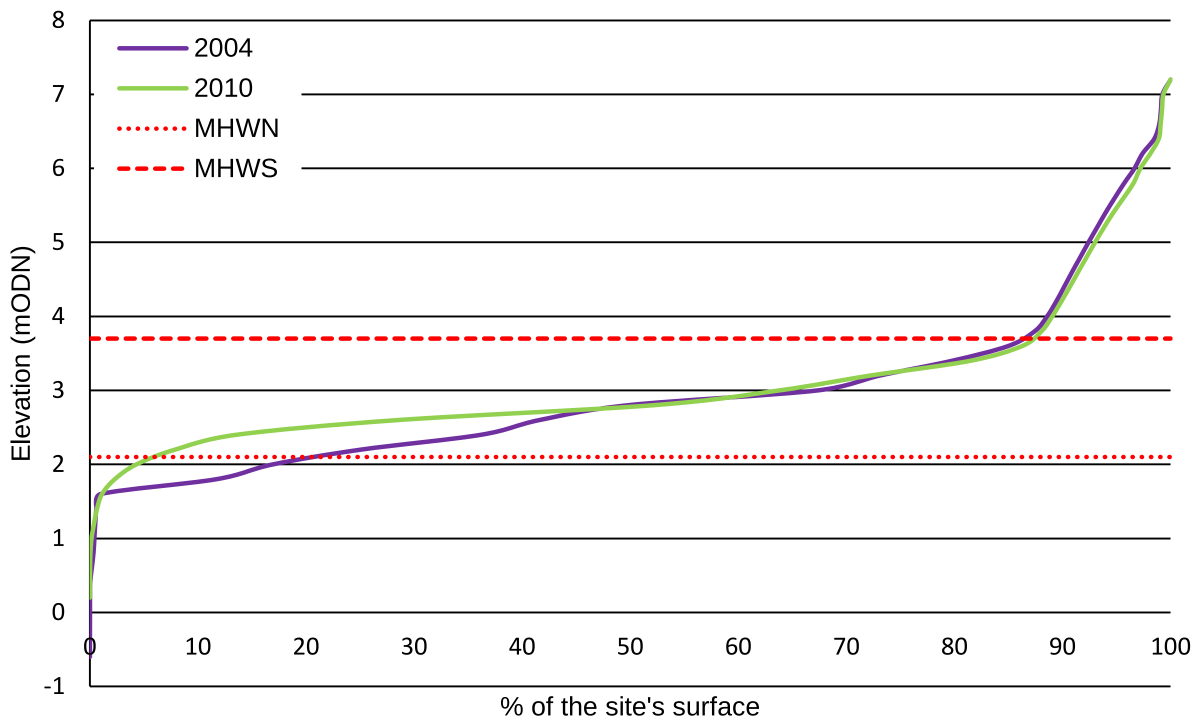

Figure 26. Paull Holme Strays hypsometric curve for the first year of analysis (2004) and the last one (2010) (vertical accuracy ±15 cm)

5.2.4. Volume

Figure 27 indicates the changes in the volume of water over the time based on tide reference level (HAT, MHWS, MHWS); the data is presented in Table X and was used in order to calculate the volume of sediment of the realignment as described in Chapter IV. The data of 2003 represents the original surface of the site before breaching and it is included as a reference. As was expected, the volume of water flooding the site deceased over the time of the analysis as a result of the increased of the surface. According to the data presented in Table X, between 2004 and 2010 the volume of water at HAT tide level reduced by 8.4%, at MHWS by 15.19% and at MHWN by 70.62%. The larger reduction at the neap tide level indicates a higher accretion in the lower parts of the site, as was observed in the hypsometric curve and the cross section profiles analysis. The very small reduction above the MHWN tide level is also consistent with the hypsometric curve (Figure 26) which indicates elevation changes until 2.8 mODN. It is important to notice, that a small increase in the volume of water at the MHWS tide level is observed between 2007 and 2010. This could indicate a small erosion/compaction of the site between 2.1 and 3.7 mODN, perhaps representing the decrease in elevation observed in the eastern and back part of the site during the cross section profile and the elevation analyses.

Table X. Paull Holme Strays volume of water (m^3) over the site according to different reference levels

Years	HAT	MHWN	MHWS
2003	1567195.41	111419.353	930252.245
2004	1531338.24	56416.0157	888837.268
2005	1455800.84	35430.235	814639.385
2007	1398396.66	21151.3596	752743.087
2010	1402245.73	16573.5658	753739.484

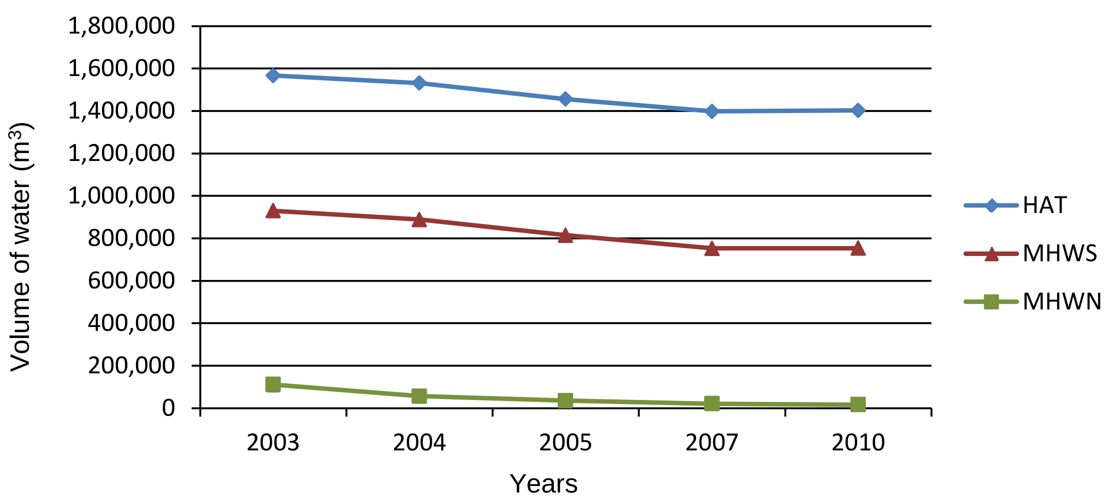

Figure 27. Paull Holme volume of water (m^3) over the site according to different reference levels

From the water volume reduction, the changes of volume of sediment were obtained. Table XI and Figure 28 present the results. Firstly is important to notice that during the first three years, the site largely accreted, however, during the following survey, covering a period of two years, a decrease of it was recorded above MHWN tide level. Below MHWN tide level, the accretion trend was constant over the entire period of analysis. The overall volume change between 2004 and 2010 is negative at all tide reference levels, indicating accretion of the site according to the expectations.

During the first year after breaching, 58.5% of the total accretion is observed at HAT tide level, indicating an initial large volume change in the site and a lower rate in the following years; however, after three years the total volume change at this reference level was reached.

Table XI. Paull Holme Strays sediment volume changes at different reference levels based on the change of the water volume. Negative values indicate accretion of the surface

Years	**Volume change (m^3)**		
	HAT	**MHWN**	**MHWS**
2004-2005	-75537.4076	-20985.7807	-74197.8829
2005-2007	-57404.1798	-14278.8754	-61896.2985
2007-2010	3849.07175	-4577.79384	996.397146
2004-2010	-129092.516	-39842.45	-135097.784

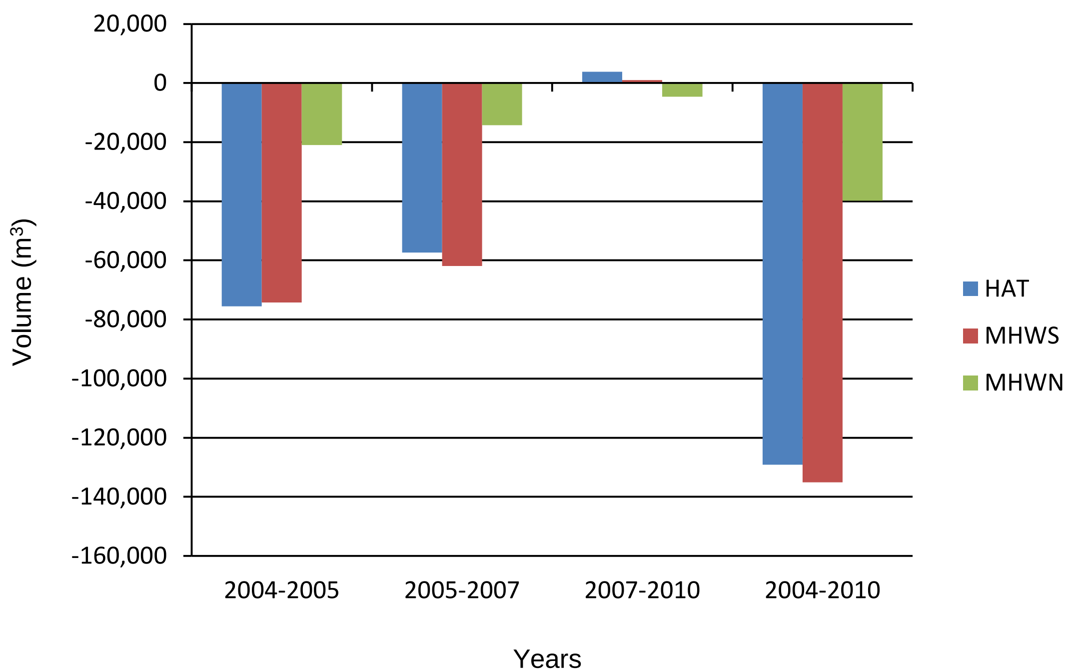

Figure 28. Paull Holme Strays sediment volume changes at different reference levels based on the change of the water volume. Negative values indicate accretion of the surface

Table XI and Figure 28 enable several important insights. As in the case of the Welwick realignment site, the overall change indicates a larger volume change to the MHWS tide level than at HAT level. As previously discussed, an accretion over the entire site would results in the larger sediment volume at HAT reference level, however, the results indicates a smaller volume at HAT than at the MHWS tide level. This observation points to the erosion/compaction/settlement of the higher surfaces of the areas (higher than MHWS tide level). This erosion or settlement of the site at higher elevations was already observed in the previous sections (Figure 21) in the eastern and higher part of the site. According to the volume data this sediment “loss” or compaction at higher elevation, corresponds to 6005 m^3 between 2004 and 2010. It is important to remember, that the potential presence of standing water in the site would have affected this volume calculations. The same situation, reduction of the site volume above the MHWS, is observed between 2005 and 2007 (three years after breaching).

Furthermore, according to the volume calculations, from 2007 to 2010, the site experienced a decrease in its volume only above the MHWN tide level. The positive values of sediment volume are, once again, consistent with the elevation analysis of Section 5.2.1.

Finally, it is important to mention, that the volumes of sediment between 2005 and 2007 are affected by the “filling” of 2005 the non-data areas with the elevation of 2004 data (for more details see Chapter IV), with the purpose of avoiding an overestimation of the volumes. All these non-data areas represent a non-change in the elevation of the site between 2004 and 2007, not contributing to the volume increase/decrease calculations.

5.3. Chowder Ness

As mentioned in Chapter III and Appendix 2, the 15 ha Chowder Ness managed realignment site is located on the south bank of the Inner Humber Estuary. The scheme was completed in 2006 following the breaching of the original defences over a distance of 570 m, the re-profiling of the land from an original average elevation of 2.8 mODN, the creation of a gentle slope from the fronting intertidal and the construction of the new defences. In the next sections, the evolution of the site post breach is analysed in details.

5.3.1. Elevation changes

The evolution of the realignment site is presented in Figure 29. The two low lying regions are observed in 2006 (note the lower accuracy associated with the 2006 data, with an error margin of +/- 50 cm), one in the front part of the site and the other in the northern-eastern region, with elevation below MHWN tide level (2.1 mODN). The rapid accretion of the site is observed; by 2007 the low lying areas had an elevation similar to the rest of the site (higher than 2.5 mODN).

Figure 30, presents the changes in elevation over the period of the analysis. A rapid accretion (again, the lower accuracy of 2006 data should be noted) (0.75 to 1 m) was recorded during the first year after breaching (2006-2007), in the front and north-eastern section of the site, probably as a result of the extensive flooding periods, the decrease of tidal velocity and the deposition of the sediment from the water column. Furthermore, during this first year, erosion between 0.25-

0.75 m, was observed in the area along the original embankments. This loss of material can likely be related to changes of the remaining sea defences due to tidal and waves actions. In addition, decrease in elevation of the rear side of the site, close to the new seawall, is identified during the first year of survey, with maximum rates of 0.25 m. Some decrease in elevation, most likely due to settlement, was also observed in the new sea defences.

During 2007-2009, the accretion of the frontal and northern-eastern region of the site continued at a lower rate, 0.25 to 0.5 m in two years; the decrease in elevation rates previously reported close to the new sea walls disappeared and maximum positive changes of 0.25 m are recorded instead. On the other hand, the erosion observed in the old embankment continued between 2007 and 2009 with smaller rates (0 to 0.25 m), similar to the one observed in the new defences during this period of time.

After 2009, the changes were smaller; the accretion rates decreases to maximum values of 0.25 m over the entire site, the decrease in the elevations in the outer part and in the new embankments also were reduced to minimal changes. This reduction in the increase/decrease in elevation changes indicates that the major changes of the realignment site occurred during the first three years after breaching; after this period, the combination of site elevation, water depth and inundation periods generates a more stable situation.

Finally, Figure 31 indicates the overall changes of the site between 2006 and the last year of survey (2011). The same accretion/erosion patterns are observed, indicating that the general trend of the site was the increase of its elevation, with larger rates in the front and in the northern-eastern region of it, between 0.25 and 1.25 over the 5 years of analysis. The decrease in elevation of the previous sea defences is observed, with rates between 0.25 to 0.75 m, probably due to the interaction between the remaining embankment and the physical processes (waves/tidal current action), as well as the proximity to the main navigational channel. In addition, the decrease of the elevation of the embankments and their slopes, as a result of settlement and weathering was identified, with values between 0.25-0.75 m.

5.3.2. Cross section profiles

Cross section profiles along the entire site were the second stage of the analysis. Figures 29 and 30 present the location of the horizontal (SW-NE) and vertical (NW-SE) profiles. Three of the four horizontal profiles are introduced in Figure 32; two of the three vertical ones are presented in Figure 33. The complete Chowder Ness dataset of profiles can be found in Appendix 3.

The front of the site is described by Profile 3 and 4 and it represents a low lying area in the south-western section of the site with an initial elevation below the MHWN tide level. During the first year after breaching a very high rate of deposition is observed in this area, especially in the region originally below the neap tide level.

A maximum accretion of 0.60 m was recorded during the first year, decreasing to a maximum of 0.40 m between 2007 and 2009 along the front of the site (Profile 4). On the other hand, Profile 3, located just behind Profile 4, presented a maximum accretion of 1 m, with an annual average of 0.30 m. Between 2009 and 2007 the accretion of the site continued at a lower rate (an average of 0.27 m in the two years period). After 2009 the rate of deposition of sediment decreases as a result of the higher surface and the smaller tidal exchange and sediment availability.

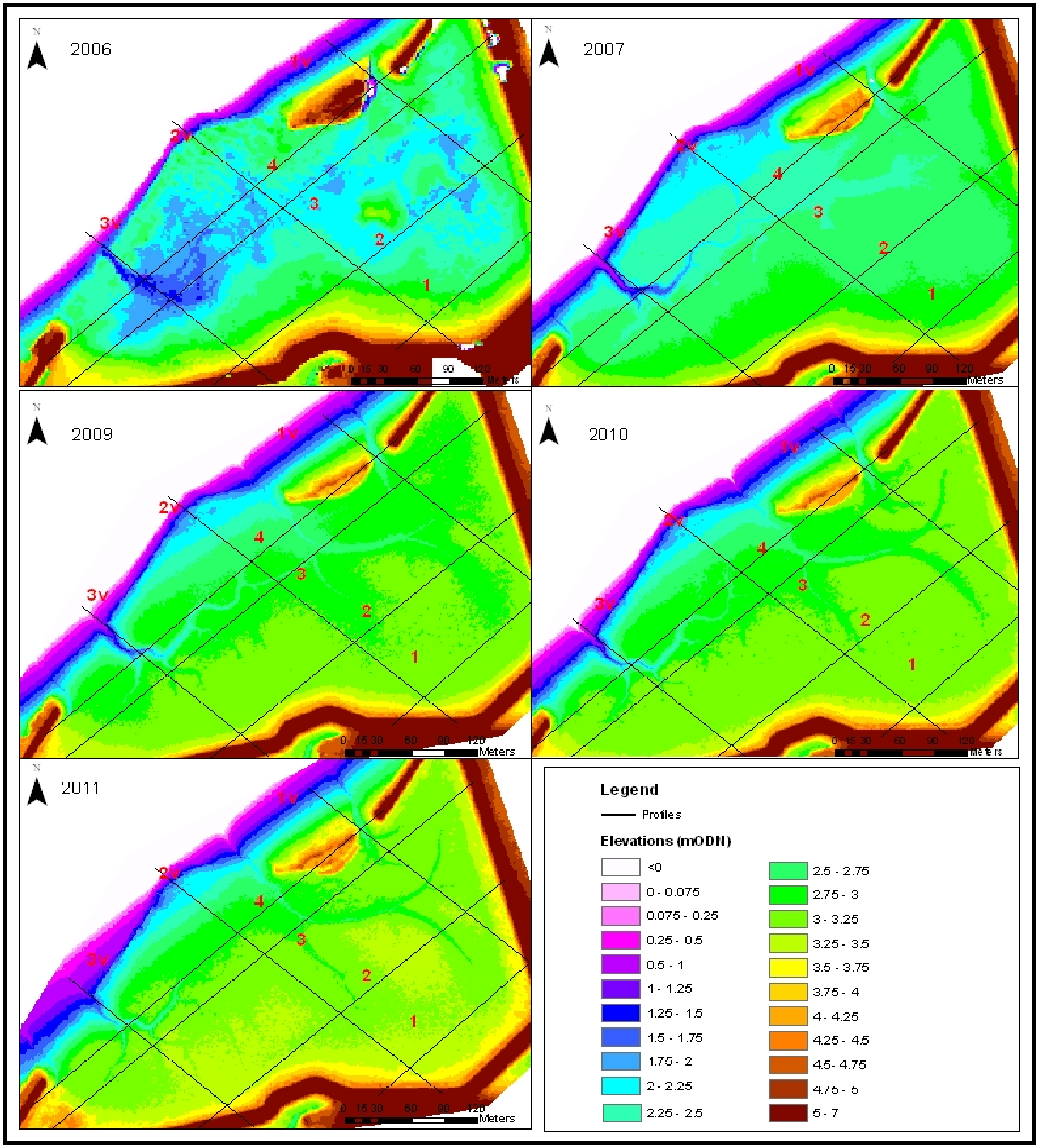

Figure 29. Elevation of Chowder Ness obtained from LiDAR data (profiles lines used as a reference)

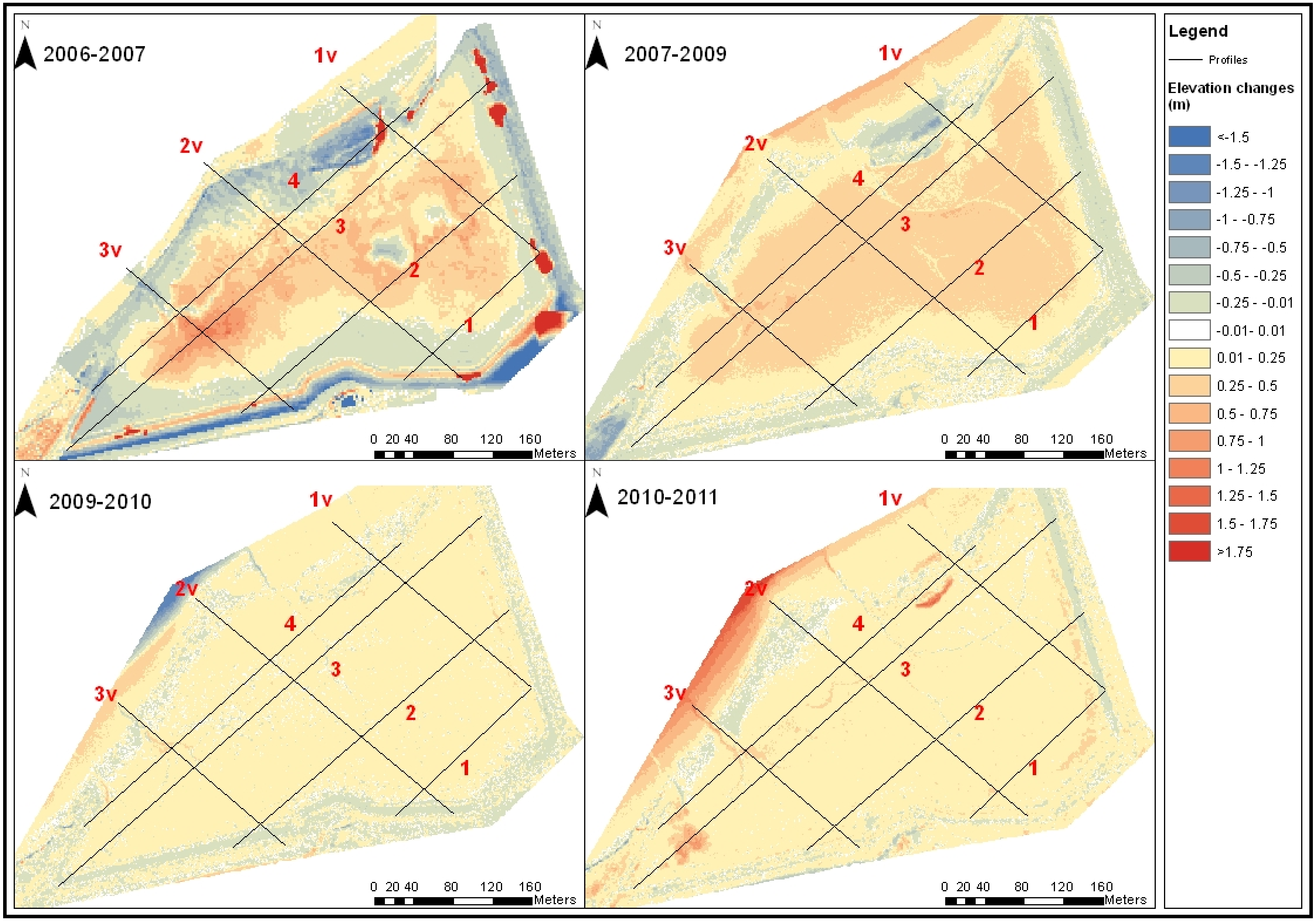

Figure 30. Elevation changes between survey years at Chowder Ness obtained from LiDAR data

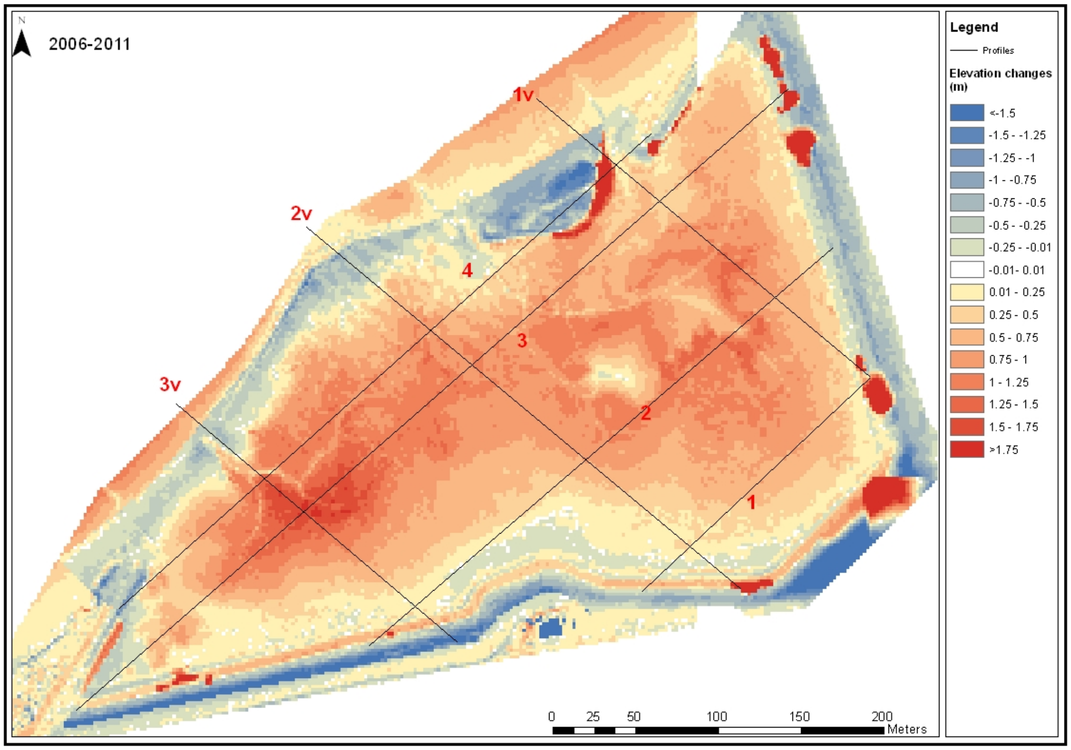

Figure 31. Chowder Ness overall changes in elevation between 2006 and 2011

In the front part of the site, the main tidal channel can be noticed from the first year of the surveys (Profile 4 and vertical Profile 3). The evolution of the site led to the narrowing and siltation of this main channel, located between 100 and 130 metres along the Profile 4. Furthermore, the development of a smaller creek was recorded at 300 metres along the cross section after 2009.

In the north-eastern front part of the site, located behind the small section of old embankment left in place accretion rates were lower, as can be observed in vertical Profile 1, probably due to higher current velocity and re-suspension of sediment as an effect of the remaining sea defence. Furthermore, the profile indicates a decrease in the elevation of the remnants of the old embankment, becoming wider. This change can be related to a sliding or modification of the lowered wall after 2006.

Site inwards, the development of several creeks is observed after 2007 in Profile 3. As part of their evolutions, the creeks became narrower and fairly limited increases were observed in their bottom elevation indicating high flow velocities. In the first 100 metres of this profile, during 2011, significant increase of the elevation is observed close to the embankment, probably representing a partial sliding of it or an error in the data processing in terms of vegetation not properly filtered.

The eastern back part of the site, according to the profiles, was also an originally (2006) low lying area. Figure 32 presents Profile 2 (Profile 1 can be observed in Appendix 3), in which a lower eastern area was recorded in 2006 at an elevation close to MHWN tide level (2.1 mODN).

This low lying zone accreted almost 0.60 m during the first year after breaching; however, the rest of the site described by this cross section did not present with the same depositional rate, but rather an decrease in elevation was observed along the first 150 m of the profile, probably caused by the compaction of the re-profiled areas during the first year.

In the following two years, the accretion over the same original low lying area continued, at a smaller rate, observing changes of 0.30-0.40 m between 2007 and 2009. The decrease in elevation previously found in the first 150 m of Profile 2 was not detected during the next years, probably indicating a process related to the first stages of the evolution of the recent breached site.

By 2009 the original low lying eastern area had reached an elevation of 3 mODN, creating a more flat and uniform site surface. On the other hand, the beginning of the development of a tidal creek around the 300 metres along Profile 2 is observed. In the following years (2010 and 2011), the creek became more defined (deeper and narrower, i.e. reduced cross-sectional area indicting a reduction in the prism it was serving) and very small rates of accretion are observed within it. After 2009, the deposition over the central part of the site is lower, as a result of the increase of its elevation and the consequently less frequent period of inundation. By 2011, the whole cross section of Profile 2 has almost the same elevation, and a second (and smaller) creek has developed at 190 m along the cross section.

Figure 34 presents the MHWN tide level evolution of the site. The figure clearly indicates the two low lying areas described by the profiles, one in the front of the site and the other in the northern-eastern region. Following breaching these two areas flooded during neap high waters; however, the rapid accretion of the site during the first year indicates the reduction of the tidal inundations, by 2007, the neap high waters no longer flooded large sections of the site and were mainly limited to the main channel. In the subsequent years, a further reduction of the neap tide inundation extend is observed, by 2011 only a small fraction of the main tidal channel is flooded by this tidal level, indicating the accretion of the frontal section of the site.

Figure 35 presents the evolution of the frontal low lying area along the MHWN tide line immediately after breaching (2006). A maximum initial accretion of 0.60 m was recorded during the first year after breaching in the low deeper region at the NE of the main channel. This high accretion, related to the decrease in the flow velocities due to the depth and the consequent deposition of sediments, was reduced to a maximum of 0.40 m between 2007 and 2009, and 0.20 m between 2009 and 2011. Furthermore, the profile experienced varying accretion rates along it. The site surface in 2006, according to the cross section, had the same elevation, however, after the initial accretion, the elevations increased faster in the northern part of the site than the southern low lying region, possibly due to the presence of the main channel proximity to the estuary, and therefore, higher flow velocities.

In summary, the site presented an accretion trend over the period of analysis, with major changes in the front section during the first years after breaching. Accretion rates were not uniform across the site, but varied depending largely on the location within the site, and exposure to high flows (and possibly waves).

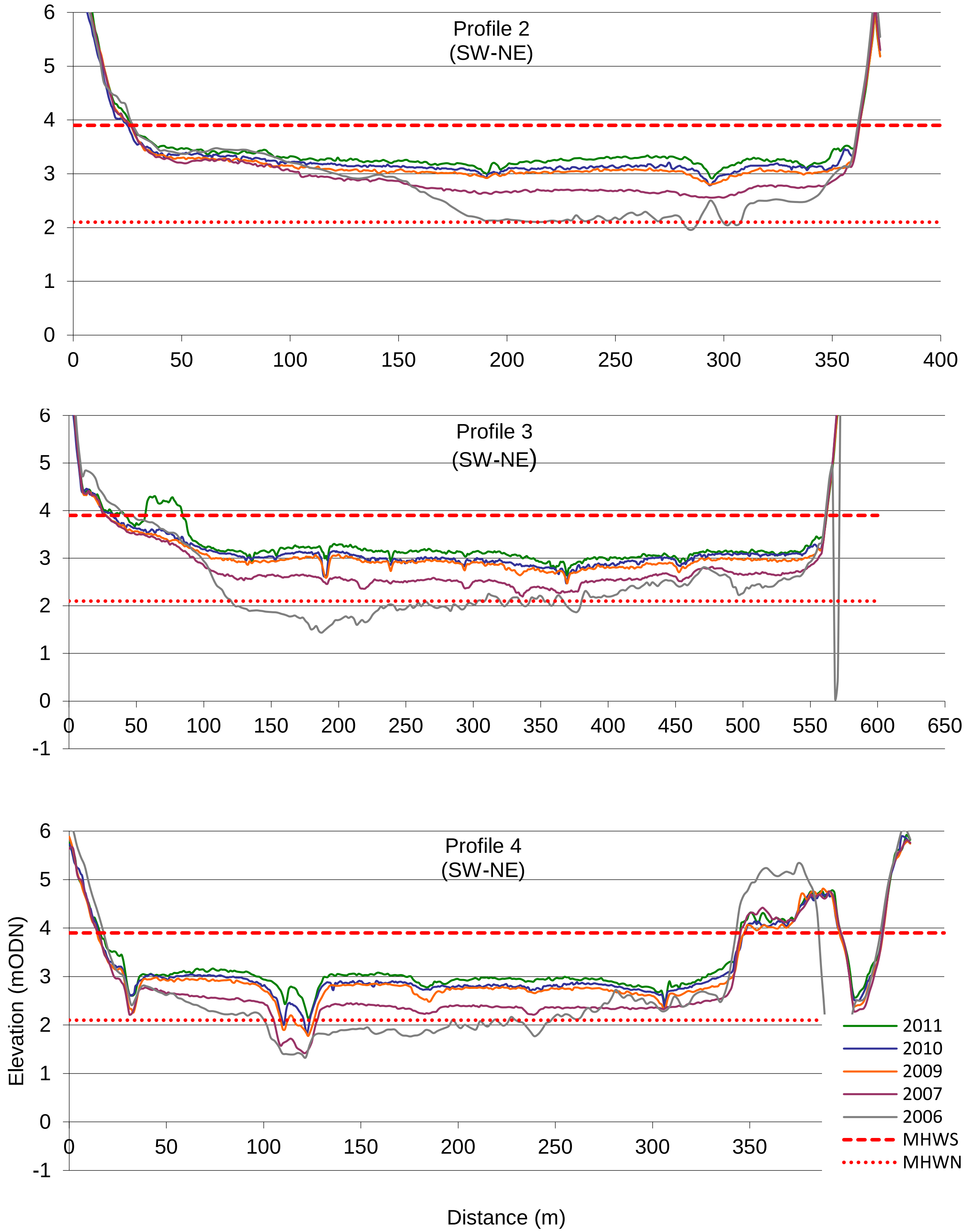

Figure 32. Horizontal (SW-NE) Chowder Ness cross section profiles (vertical accuracy ±15 cm, with the exception of 2006 data (vertical accuracy ±50 cm))

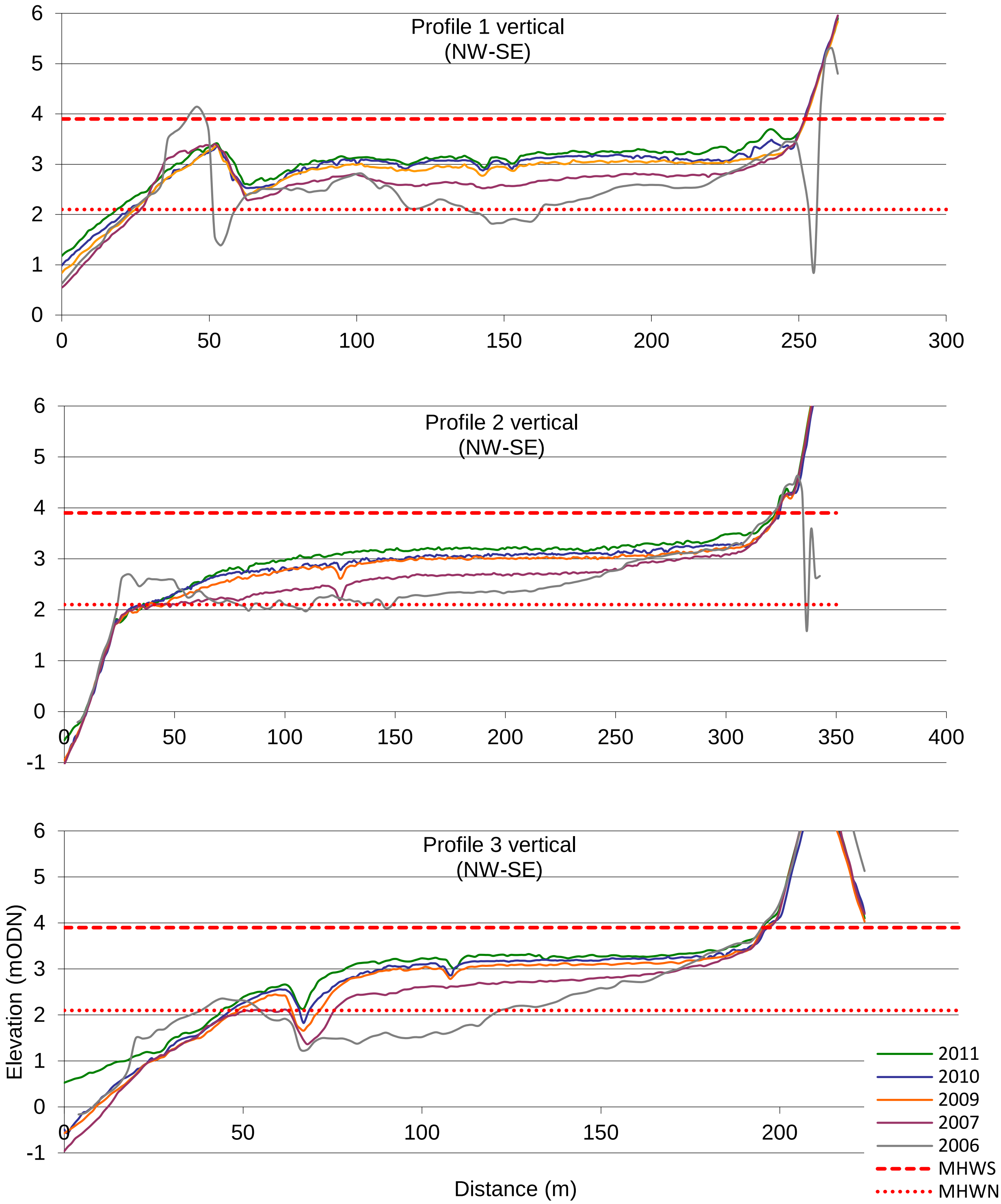

Figure 33. Vertical (NW-SE) Chowder Ness cross section profiles (vertical accuracy ±15 cm, with the exception of 2006 data (vertical accuracy ±50 cm))

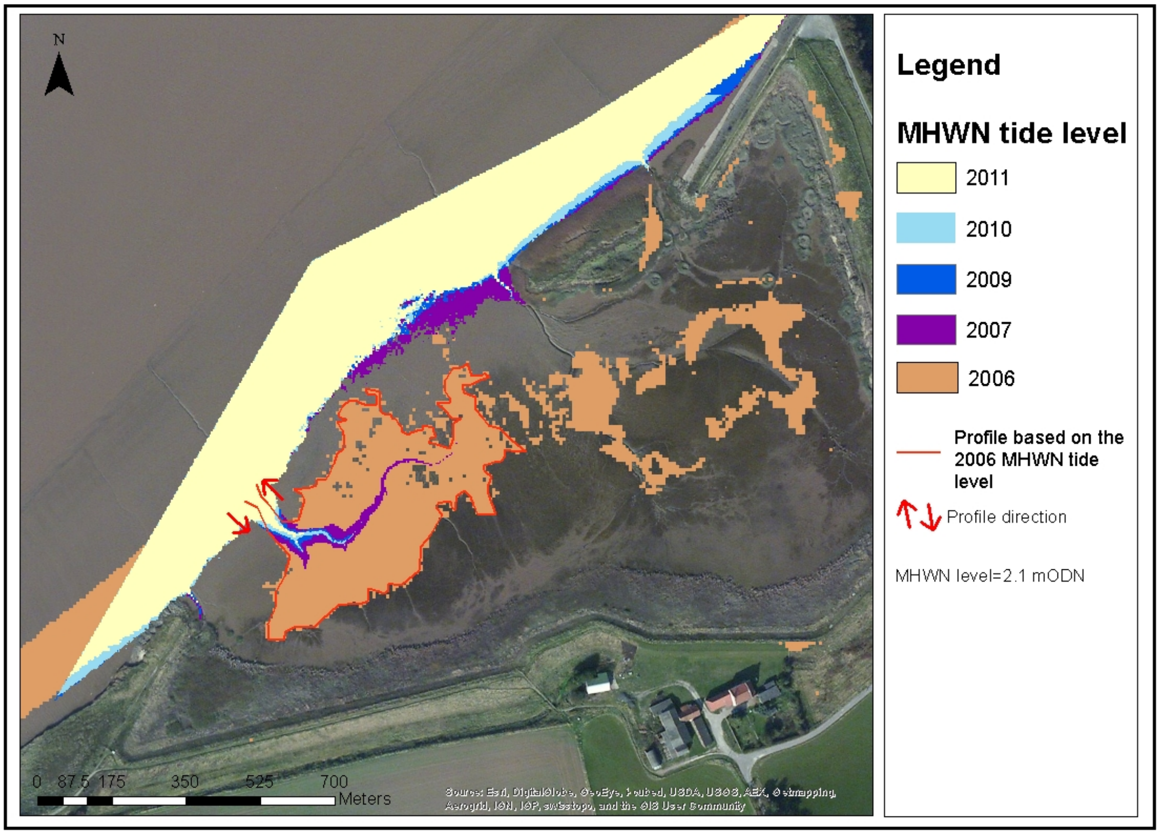

Figure 34. Chowder Ness MHWN inundation extend

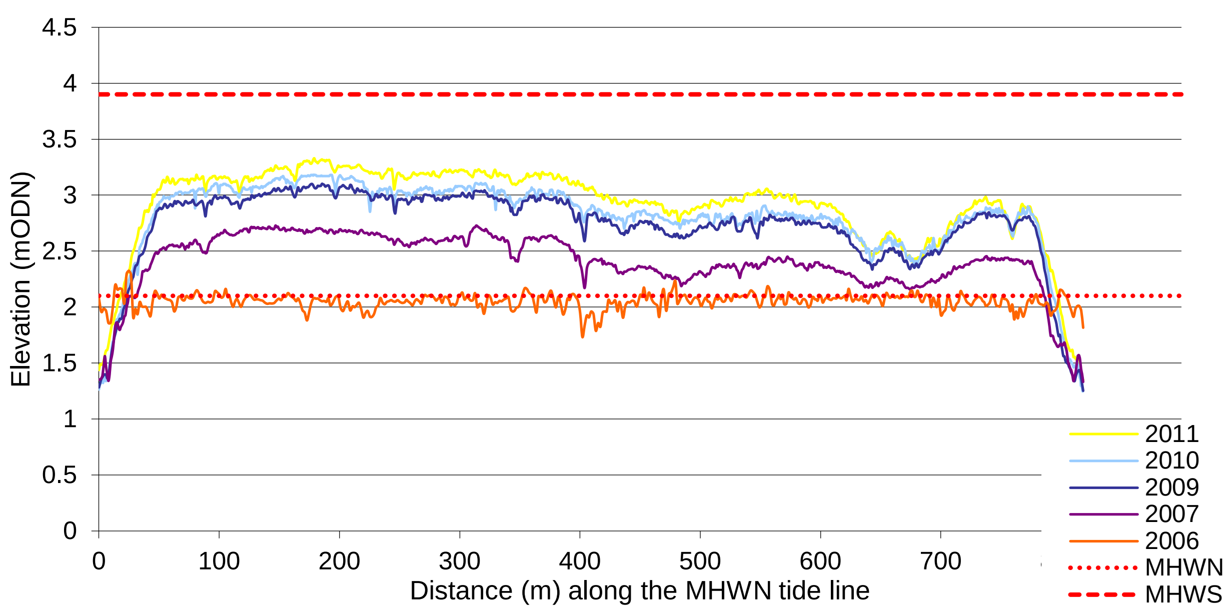

Figure 35. Chowder Ness cross section profiles along the MHWN tide line of 2006 (noting the higher margin of error in the 2006 vertical accuracy (±50 cm))

5.3.3. Hypsometric curve

Hypsometric curves were obtained for the first and last year of analysis (Figure 36). In 2006, 20 % of the site was below the MHWN tide, 63% between the MHWN and the MWNS tide level and only 17% of the site surface was higher than 3.9 mODN (MHWS tide level).

In 2011 only 8% of the realignment area was lower than the MHWN tide level, 75% of it was lying between the neap and spring high water tide level, and the same 17% of it was above the MHWS tide level.

The curve shown in Figure 36 clearly indicates how a larger percentage of the site (92% compared to 80%) lies above MHWN tide level in 2010; according to this, the surface between the MHWN and the MHWS tide presented a clear increase in elevation. Following breaching, the curve has a steeper slope between the two tide reference levels; in 2011 approximately 50% of the site is lying between 3-3.5 mODN, indicating an increase in elevation of almost 1 metre in half of the site.

On the other hand, very limited changes in the site were recorded above the MHWS tide level, the same percentage of the area lies above the MHWS tide level in 2011, however, the maximum elevation of the site is lower (6.6 m in 2011 compared to 7 m in 2011) indicating some settlement of the embankments and/or weathering processes.

These observations are consistent with the elevation analysis of the previous section, in which the main accretion was recorded for the lower laying areas of the site.

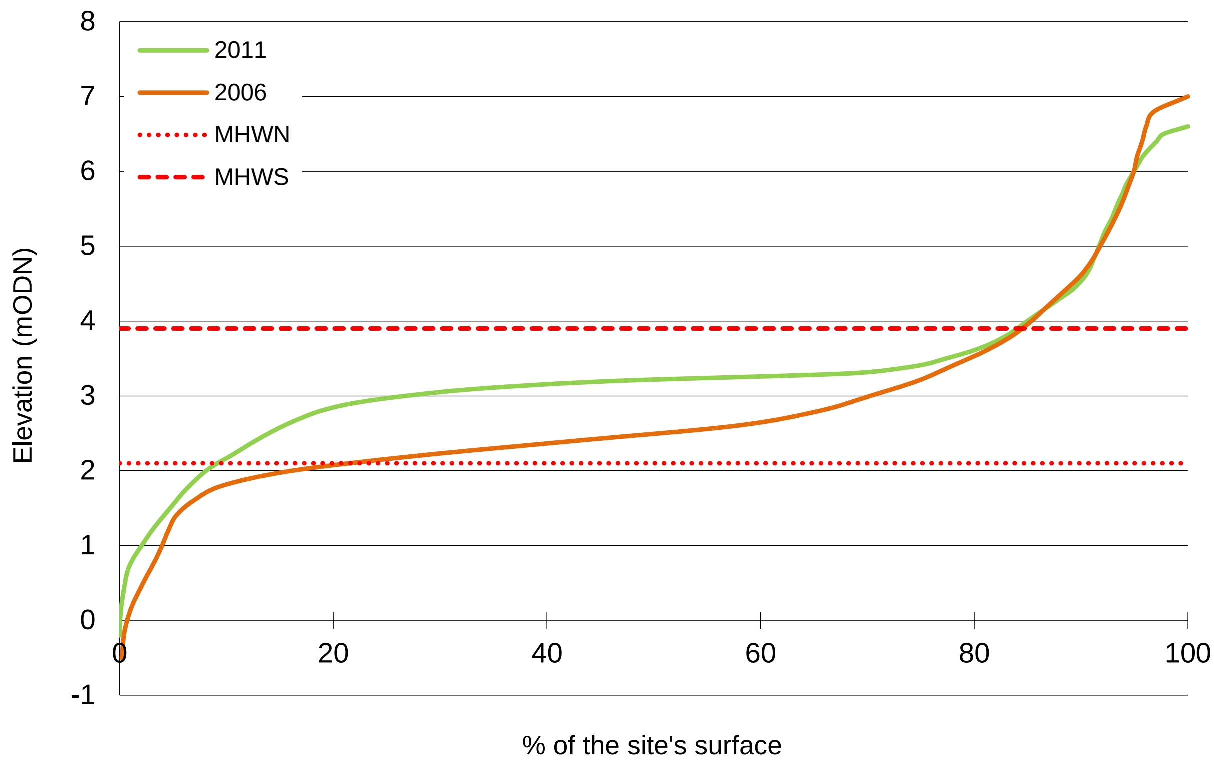

Figure 36. Chowder Ness hypsometric curve for 2006 and 2011

5.3.4. Volume

According to the volume of water flooding the site based on tide reference levels (HAT, MHWS and MHWN tides); the changes in the volume of sediments of the realignment were calculated as described in the methodology chapter. Figure 37 indicates the changes of the volume of water over the time. The data is presented in Table XII.

As was expected, the volume of water flooding the site deceased over the time of the analysis as a result of the increase of the surface. According to the data presented in Table XII, between 2006 and 2011 the volume of water at HAT tide level reduced by 22.8%, at MHWS by 36% and at MHWN by 40.4%. The larger reduction occurred at the neap tide level, indicating a higher accretion of the lower part of the site; however, a very similar decrease of the volume of water at the MHWS tide level indicates that the accretion of the site continued above the MHWN tide level. These results are consistent with the hypsometric curve (Figure 36) which indicates an elevation change of the site surface up to MHWS tide level (3.9 mODN).

Table XII. Chowder Ness volume of water (m^3) over the site according to different reference levels

Years	HAT	MHWS	MHWN
2006	249835.4	160510.7	12978.32
2007	238371.7	147842.4	11779.09
2009	215371.8	124427	10604.64
2010	208083.9	116851	10062.71
2011	192713.4	102618.6	7734.877

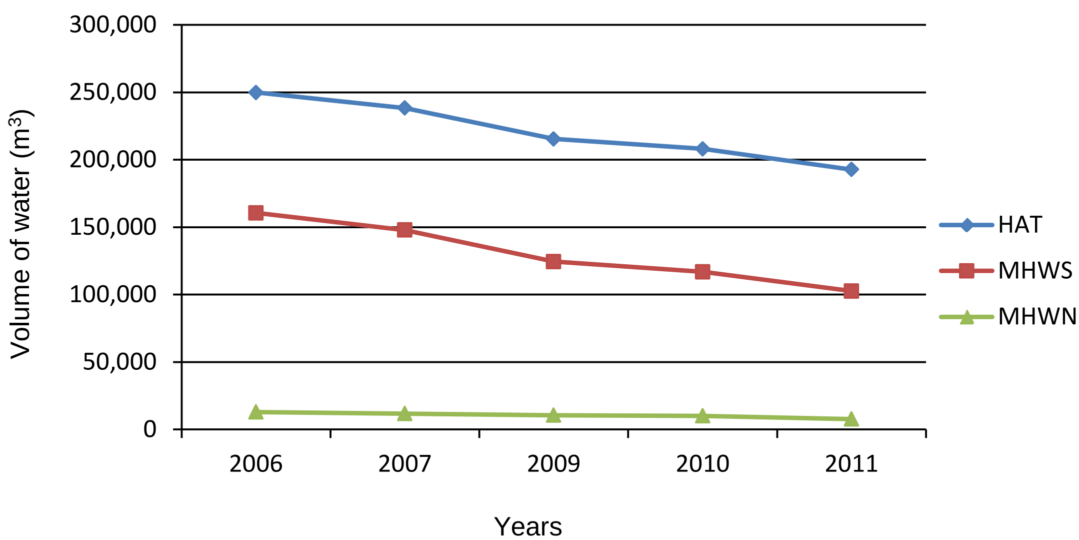

Figure 37. Chowder Ness volume of water (m^3) over the site according to different reference levels

From the water volume reduction, the changes of volume of sediment were obtained. Table XIII and Figure 38 present the results. Firstly is important to notice, that the site experienced an accretion trend during the entire period of analysis. The volume of overall change between 2006 and 2011 is negative at all tide reference levels, indicating accretion of the site according to the expectations.

During the first 3 years after breaching (2006-2009), 60% of the total accretion is observed at HAT level, indicating an initial large volume change in the site. However, according to the data of Figure 38, the Chowder Ness realignment site experienced a more constant accretion after breaching, compared to the initial large change of the previous site during the first year.

In 2009, the accretion rates decrease; however, between 2010 and 2011, the rate of deposition is very similar to the one recorded for the first year of analysis. This data indicates that the infilling of the site has continued over the period of analysis at all tide reference level.

Table XIII. Chowder Ness sediment volume changes at different reference levels based on the change of the water volume. Negative values indicate accretion of the surface

Years	**Volume Change (m^3)**		
	HAT	**MHWS**	**MHWN**
2006-2007	-11463.7	-12668.3	-1199.23
2007-2009	-22999.9	-23415.4	-1174.45
2009-2010	-7287.88	-7575.99	-541.93
2010-2011	-15370.5	-14232.3	-2327.83
2006-2011	-57122	-57892	-5243.44

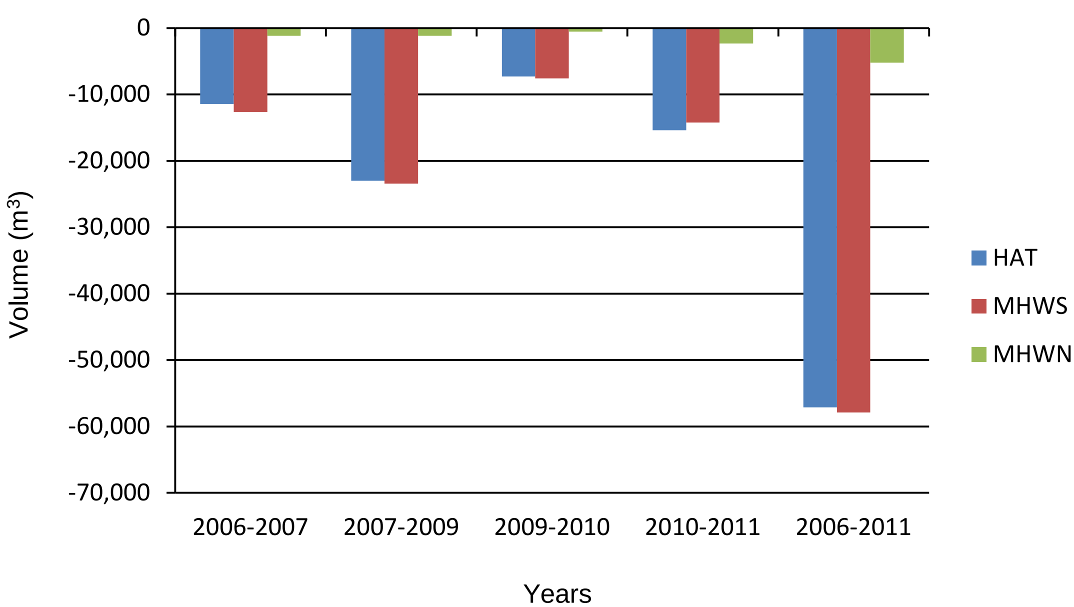

Figure 38. Chowder Ness sediment volume changes at different reference levels based on the change of the water volume. Negative values indicate accretion of the surface

Analysing in detail Table XIII and Figure 38, several important observations can be made/confirmed. As in the case of the previously analysed realignment sites, the overall changes indicate a slightly larger volume change at the MHWS tide level than at HAT level. As previously discussed, an accretion over the entire site would result in a larger sediment volume at HAT level reference, however, the lower volume at HAT than at the MHWS tide level indicates, some decrease in elevation of the higher areas of the site. This erosion/settlement/compaction of the site at higher elevations was observed in the previous analyses (Figure 31), in which the rear side of the site presented some decrease in surface elevation corresponding to the new embankments and their slopes. On the other hand, according to the data, this sediment "loss" at higher elevation corresponds to a very small volume, 770 m^3 over a period of 5 years, and could be related to LiDAR inaccuracies. The same situation, reduction of the site volume above MHWS, is observed during the whole period of analysis with the exception of the 2010-2011 volume changes; this is because the consolidation of the embankments and its slopes could have stopped by 2010.

5.4. Alkborough

The 440 ha Alkborough managed realignment site is the largest on the Humber Estuary; it is located on the south bank of the inner estuary and was breached in 2006. The site has a narrow armoured breach of 20 m with a bottom/invert level which is fixed at an elevation of 2.8 mODN. This is 0.30 m above the level of MHWN, hence, the site is not flooded during every tide and does also not fully drain, as it contains significant areas below this elevation. Within the site, the main earth works related to the creation of a 1.6 km long distributor channel extending from the breach. Chapter III and Appendix 2 describe in more details the characteristic of the site and the construction process; in the next sections, the evolution of the site after these initial processes has been studied.

5.4.1. Elevation changes

The evolution of the entire site was studied in terms of the changes in its elevation and its arrangement. Figure 39 presents the evolution of Alkborough over 5 years of LiDAR surveys.

In 2007, one year after breaching, the elevation of the site was between 2.8-3.25 mODN, with the exception of the main channel, some lower lying areas in the SE and SW of the site and the higher embankments that are surrounding the realignment scheme.

By 2010, four years after breaching, an increase in elevation of the central part of the site was recorded; however, the data of Figure 39 also presents low lying areas of 2.5-2.8 mODN. The erosion of these areas in unlikely, due to the constrained configuration of the site's breach and its sill level of 2.8 mODN. Therefore, the presence of water over much of the site in the previous survey must be considered. Due to the higher level of the sill, the flooding and drainage of the site is restricted, therefore, the presence of standing water or water which has yet to drain from the site could have interfered with the LiDAR, measuring water instead of surface elevation. The low lying areas of 2010 data could represent the actual elevation of the site during a relatively drained configuration (the same effect was also observed at Welwick; this could be due to the survey having been undertaken during neap tides). Unfortunately, due to the dates given for the survey (ranging over more than 1 month), it was not possible to pinpoint the likely tides it was flown at.

According to the last survey (2012), the central part of the site has reached elevations higher than 3.5 mODN (some 70cm below the MHWS level), the low lying areas identified in 2010 now present elevations above 2.8 mODN, not necessarily indicating accretion but possibly standing water. Furthermore the development of some creeks from the main channel can be noticed in the figure.

Figure 40 presents the elevation changes at the site. Between 2007 and 2010, the accretion of the central part of the site is observed, with increases in elevation of a maximum of 0.25 m in the eastern part of the main tidal channel. In addition, there appear to have been erosion of large areas in the west of the distributor channel, between 0.25-0.5 m. It is important to notice, however, that 2010 survey recorded a lower surface than the 2007 one, as was mentioned previously, therefore, the erosion observed between these years could represent the absence of standing water during the 2010 survey (as the site may have drained during neap tides, even below the breach sill level due to seepage/evaporation).

Between 2010 and 2012, the accretion of the central and eastern part of the site continued at rates similar to the previously reported. A clear accretion of 0.5 m of the areas previously “eroded” (2007-2010) is observed, again indicating the probable presence of water on the site during 2012.

Finally, Figure 41 presents the overall changes of the site during the 5 years of survey. According to this figure, the eastern part of the site presented larger accretion rates, between 0.5-0.75 m; at the west side of the main channel the accretion was slightly lower (0.25-0.5 m). The northern side of the site, also experienced accretion rates of 0.25-0.5 m, while, a decrease in elevation of the main tidal channel is observed during the 7 years of survey, probably related to lower water levels in the channel during the surveys, the actual erosion of material is unlikely.

5.4.2. Cross section profiles

Cross section profile over the site was the second stage of the analysis. Figures 39 and 40 present the location of the profiles. Three of the five horizontal profiles that cross the site in a W-E direction were selected as representative and they are shown in Figure 42. Figure 43 presents three of the six vertical profiles (N-S), also selected as representative. The complete dataset of cross section profiles is presented in Appendix 3.

Firstly, it is important to notice that one of the main characteristics of the site it is its constrained and higher than the MHWN tide level breach, which restricts the tidal exchange. Because of it, the site not always drained and water may be present in the lower areas even during low tides. LiDAR data could have measured water instead of site surface elevation, as was previously discussed, causing errors in the elevation changes calculations and in the site evolution analysis.

The front of the site and the main channel are presented in the vertical Profile 2 of Figure 43. The fix position of the breach at 2.8 mODN can be observed in the figure and the first 300 metres of the channel presents and erosional trend between 2010 and 2012.

The northern-eastern part of the site is described in Profile 1 between 1400-2200 m. According to this cross section, this area has accreted during the 5 years of survey between 0.20 and 0.40 m; however, at a distance of 1800 metres along the profile, 2010 elevation were lower than 2007, likely identifying the real elevation of the area.

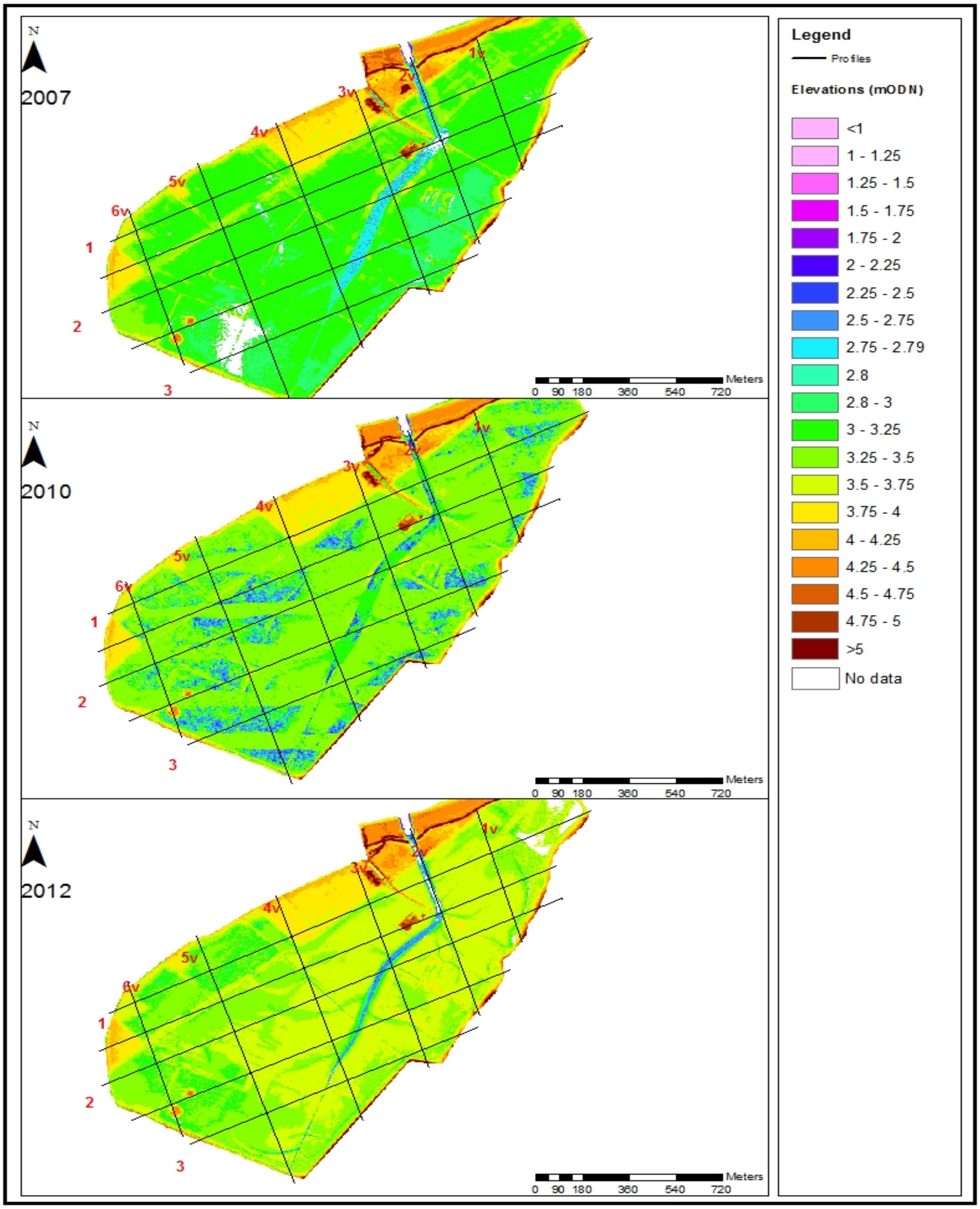

Figure 39. Elevation of Alkborough obtained from LiDAR data

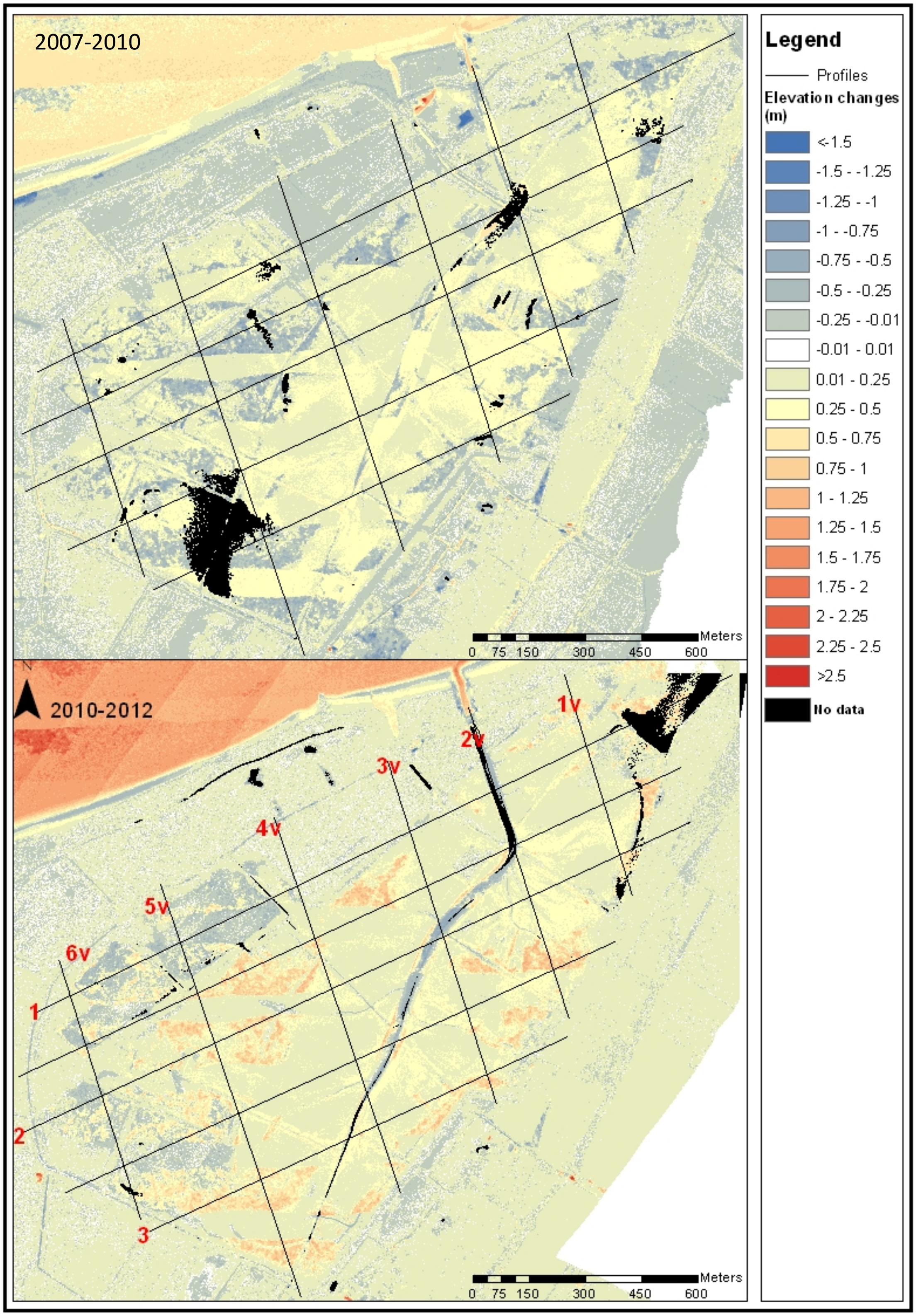

Figure 40. Elevation changes between survey years at Alkborough obtained from LiDAR data

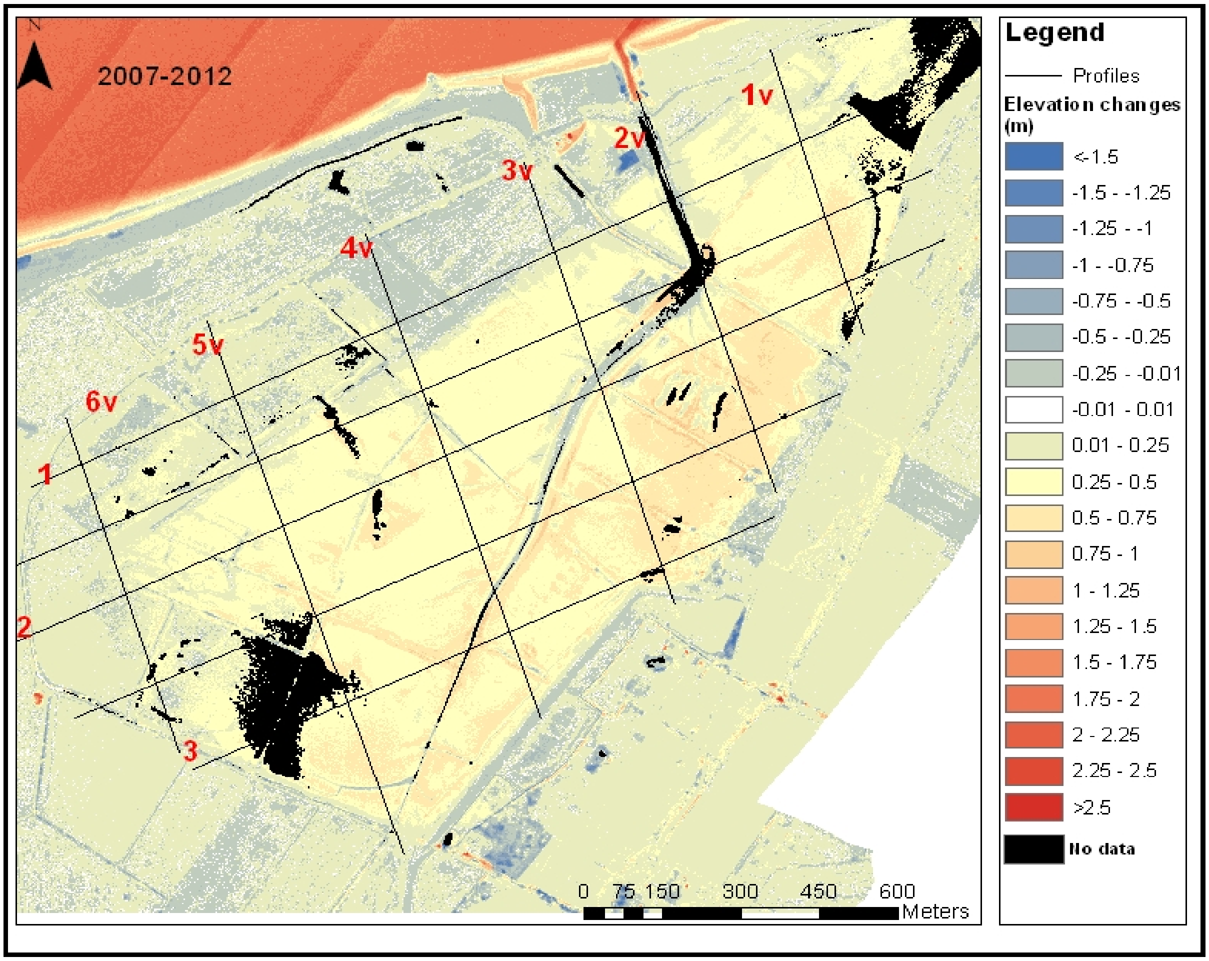

Figure 41. Alkborough overall changes in elevation between 2007 and 2012

The region at the SE of the main channel presented a maximum accretion of 0.60 m between 2007 and 2012, observed in Profile 2 (Figure 42) and Profile 2a (Appendix 3); some low lying area in 2010 are also detected in this region of the site as can be observed in vertical Profile 2 and 3 after the main channel.

On the other hand, the region NW of the tidal channel, presented an accretionary trend between 0.20 and 0.35 m during the whole period of analysis (Profiles 2 and 1a); however there is a large presence of low lying areas in 2010, as was observed in the previously section. According to the data, large areas in 2010 lies below 2007 measurements, and by 2012, the surface presents elevation similar to the one described in the first year after breaching. As was already discussed, the erosion of material in unlikely, the presence of non-drained water could explain this "artificial" increase on elevation. Vertical profiles 3, 4 and especially vertical Profile 5 also detected low lying areas and creeks in the region in 2010 (Figure 43).

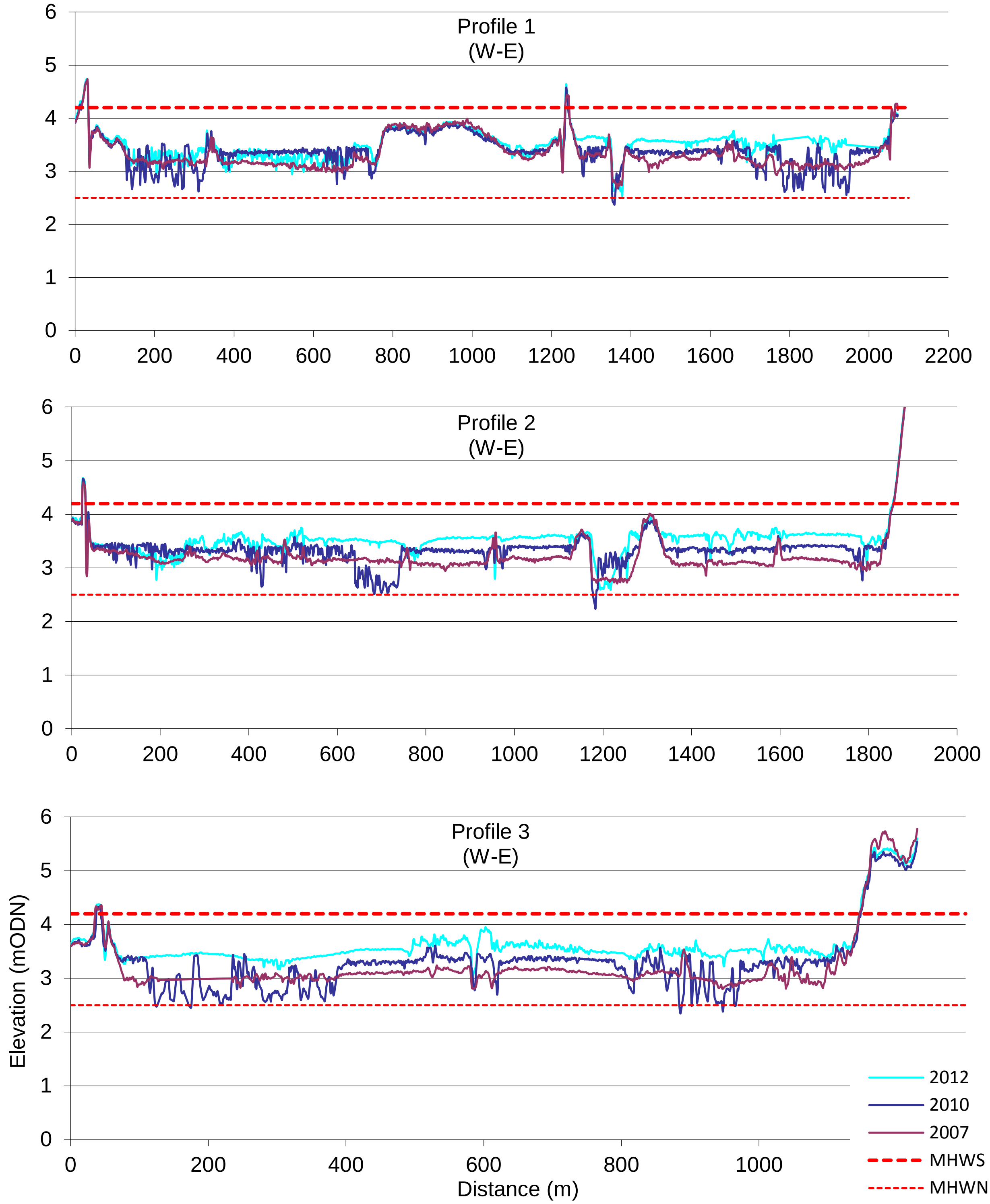

Figure 42. Horizontal (W-E) Alkborough cross section profile (vertical accuracy ±15 cm)

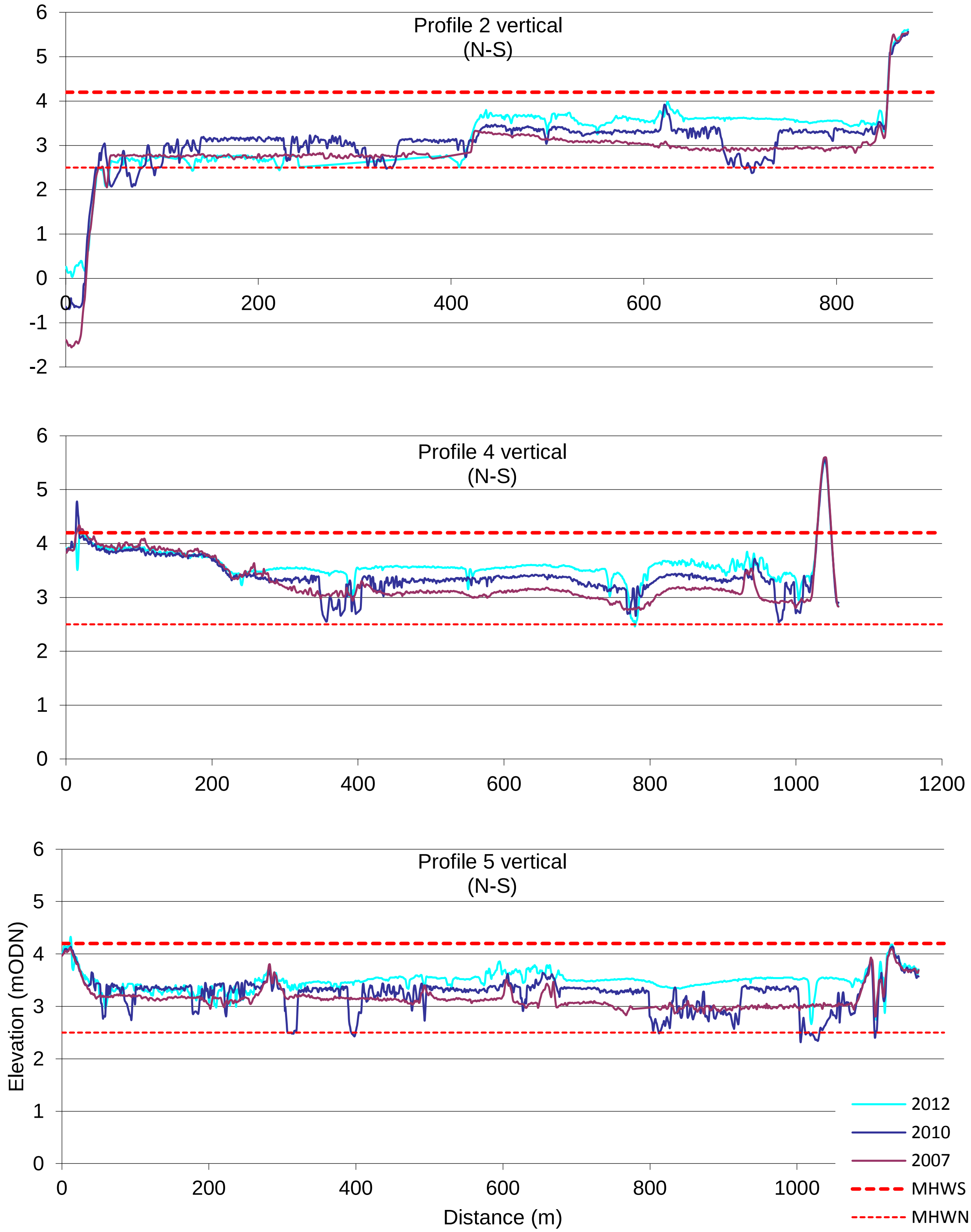

Figure 43. Vertical (N-S) Alkborough cross section profiles (vertical accuracy ±15 cm)

The back section of the site, represented by Profiles 2a and 3, presented the same behaviour as the previous section, with accretion rates of 0.50-0.60 m between 2007 and 2010, together with areas showing "accretion" in 2010, one more time, probably due to the drain of the site surface.

In summary, then site has experienced positive elevation changes, however, the realistic quantification of these are difficult due to the constant presence of water on site. The restricted and high breach causes a more controlled tidal exchange. The flow velocities on the site decrease due to the depth thus likely allowing sediment to deposit more easily from the water column, and because water does not always drain during ebb period, the re-suspension rate of sediments is limited. In addition, the wave action in the site is likely almost insignificant, causing an even more depositional environment. The site is therefore accreting, the rates observed in most of it are probably close to reality; however, caution needs to be applied to interpreting data over the lower lying areas, where significant erosion/accretion is indicated, but the presence of varying water levels is likely. Whilst the LiDAR would have been flown at low tide, the site could possibly not have drained completely yet. Also, the timing of the surveys in relation to spring tides would be pertinent, as immediately following a high spring tide, a large amount of standing water would likely still remain on site as low tide approaches; whereas this would not be expected to be the case on lower neap tides, when the site does not flood and seepage/evaporation may lead to water draining to below the sill level.

5.4.3. Hypsometric curve

Hypsometric curves were obtained for the first and last year of analysis (Figure 44). Due to the high elevation of the breach, the site does not flood during neap tides; therefore this tidal level has not been used as a reference of accretion/erosion of the realignment site.

On the other hand, the level of the sill was used as a reference of the changes of the site. Figure 44 indicates that the site elevation was higher than the breach sill level (2.8 mODN) during the first year after breaching (2007). According to the figure, after 5 years, the surface of the site has increased approximately 0.40 m up to an elevation of 3.8 mODN. At higher elevation there were no changes in the site configuration.

Finally, it is important to notice that the presence of water has affected the results of the analysis, therefore, a carefully consideration is required.

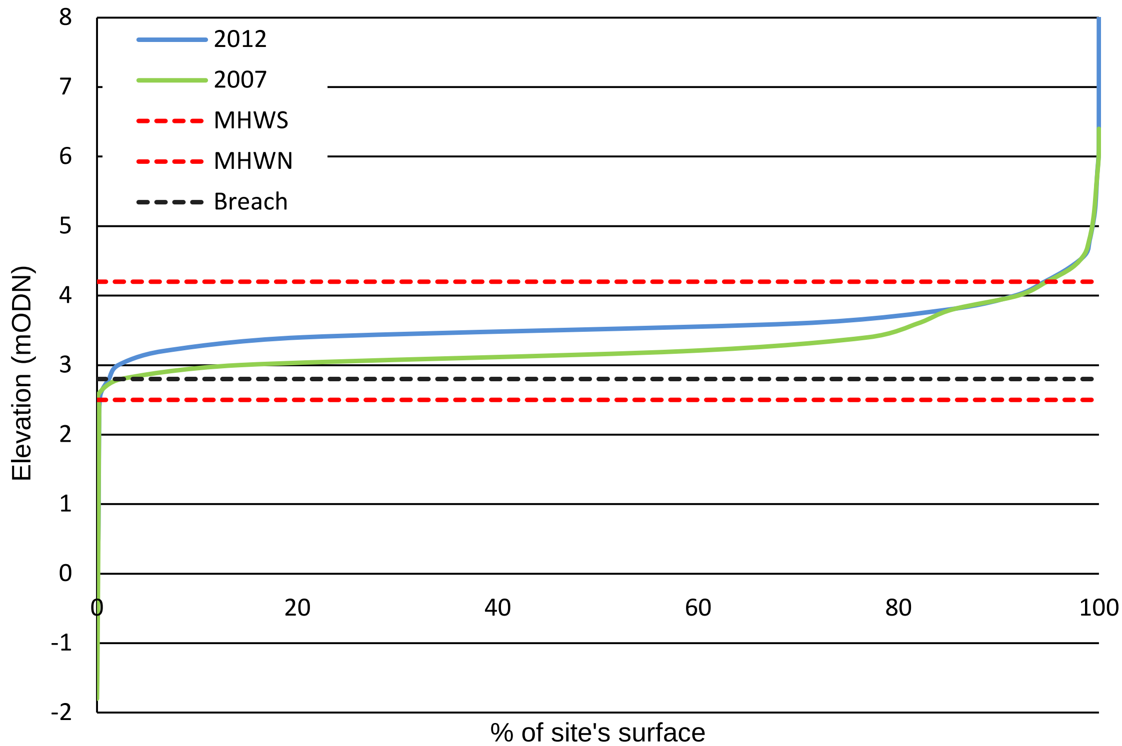

Figure 44. Alkborough hypsometric curve for 2007 and 2012

5.4.4. Volume

Figure 45 indicates the changes of the volume of water over the time based on tide reference level (HAT, MHWS, MHWN); the data is presented in Table XIII and was used in order to calculate the volume of sediment of the realignment as described in Chapter IV.

As was expected, the volume of water flooding the site deceased over the time of the analysis as a result of the increased of the surface. According to the data presented in Table XIII, between 2007 and 2012 the volume of water at HAT tide level reduced by 15.6%, at MHWS by 29.5% and at MHWN by 24%.

The larger decrease in the water volume flooding the site was below MHWS tide level (4.2 mODN) indicating the main accretion of it up to this elevation. It is important to notice than the MHWN tide level (2.5 mODN) does not flood the site due to the higher breach (2.8 mODN); however, accretion in observed in the site until this elevation, probably in the lower areas.

Furthermore, a small increase in the water volume until MHWN tide level is observed during 2010. This could be related to the low lying areas detected in previous sections during this year; if the site was (almost) drained in 2010, the tidal prism would be larger than the previous survey undertaken in 2007, in which the water trapped in the site would have reduced the tidal prism calculations.

Table XIV. Alkborough volume of water (m^3) over the site according to different reference levels

Years	HAT	MHWS	MHWN
2007	2811831.23	1517282.24	8573.98197
2010	2784531.53	1437605.27	9141.01018
2012	2372947.99	1069920.53	6523.7382

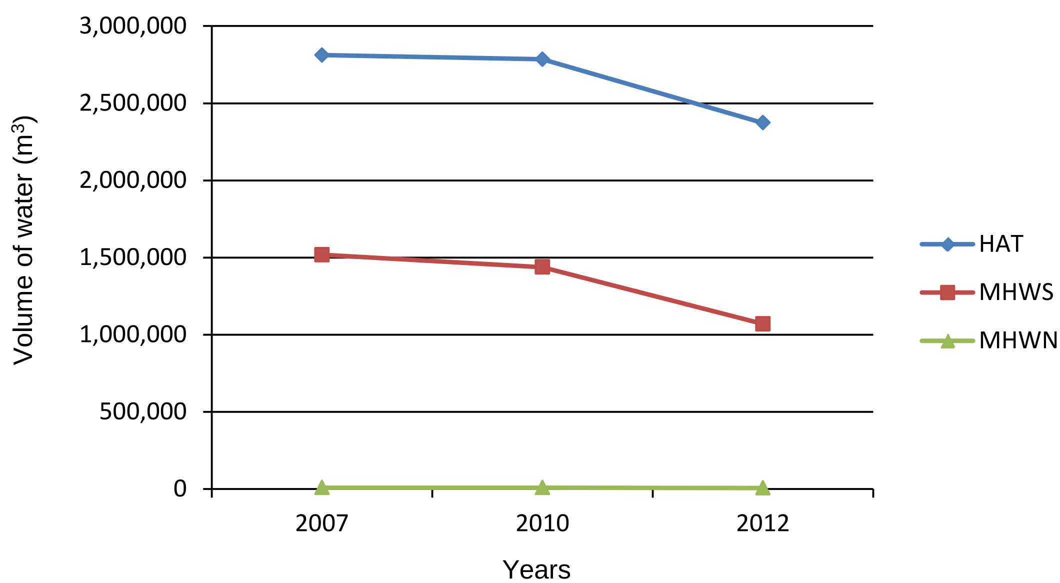

Figure 45. Alkborough volume of water (m^3) over the site according to different reference levels

From the water volume reduction, the changes of volume of sediment were obtained. Table XIV and Figure 46 present the results. Firstly is important to notice that the site has experienced accretionary trend over the years, with the exception of the first three years, during which a decrease of elevation below MHWN tide levels was recorded ("artificial" erosion), most likely related to the drainage of the site during 2010 previously discussed.

Furthermore, the overall volume change between 2007 and 2012 is negative at all tide reference levels, indicating accretion of the site according to the expectations; however, the change between 2010 and 2012 is exponentially larger than the one recorded during the first years of survey. The accretion of the site is evident; nevertheless, these large volume changes are very likely related to the near absence of water in the realignment site during 2010 survey and its later presence in 2012.

Table XV. Alkborough sediment volume changes at different reference levels based on the change of the water volume. Negative values indicate accretion of the surface

Years	**Volume change (m^3)**		
	HAT	**MHWS**	**MHWN**
2007-2010	-27299.7045	-79676.9744	567.028205
2010-2012	-411583.535	-367684.736	-2617.27197
2007-2012	-438883.239	-447361.711	-2050.24377

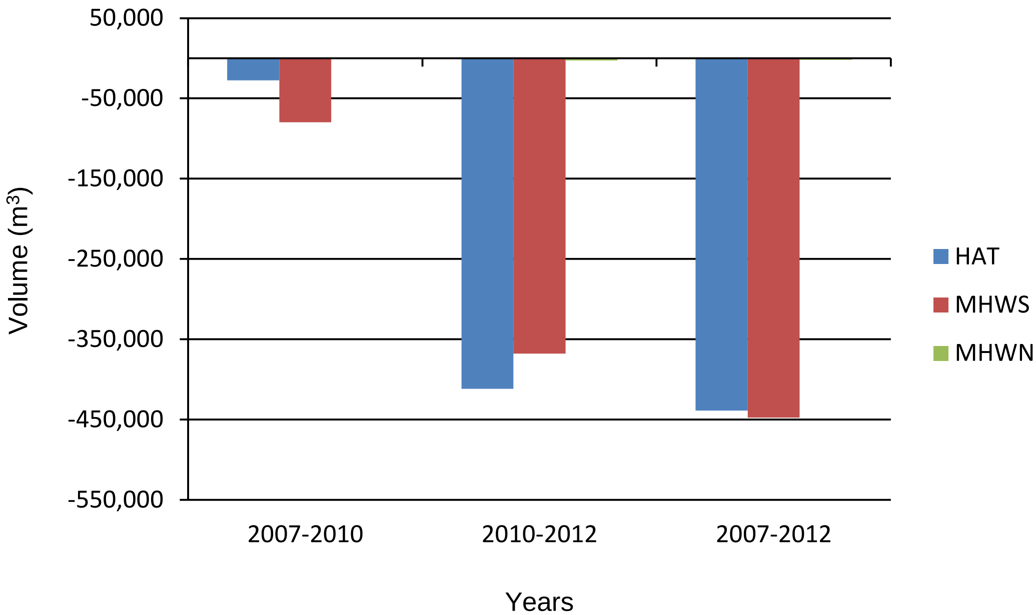

Figure 46. Alkborough sediment volume changes at different reference levels based on the change of the water volume. Negative values indicate accretion of the surface

Chapter VI: Discussions

In this chapter, a discussion of the main processes which appear to have influenced the managed realignment sites on the Humber is presented. The sites are again presented relative to their position within the Humber Estuary. The chapter will conclude with a comparison between sites, the future expectations, followed by a discussion of LiDAR accuracy and monitoring issues.

6.1. Welwick morphological changes and processes

The Welwick site showed an overall accretionary trend over the 5 years of the survey period. The depth of accretion decreased towards the back of the site, and was thus non-uniform.

The frontal section experienced high accretion rates, especially during the first year after breaching. Elevations which were initially below the MHWN tide level along the front of the site accreted by 0.5-1 metres during the first year (noting however the fairly large margin of error associated with the 2006 data (+/- 50cm)). The low initial elevation of the front of the site was the result of the re-profiling of it, large excavations were undertaken in order to lower the surface and favoured mudflat habitat creation. One of the key issues with realignment sites, linked to the sediment they receive, is their elevation relative to the tidal frame, as this dictates both the number of tidal inundations the area will receive, and the type of habitat which will ultimately result. Whilst the elevation of the land surface controls the number of tidal inundations, so it will govern, to some extent, the amount of sediment it will receive, the general rule being that the lower the elevation, the more frequent the sediment supply and the more rapid its accretion. However, the other important factor is the ability of the sediment to settle out, and the land surface to retain it. Currents need to slacken enough inside realignment sites to allow deposition and a small re-suspension of sediment by wind- induced wave need to be achieved. Once the deposition threshold is reached, local topography and currents will govern where, and to what extent, sediments will settle (French, 2006). The Welwick site is partially sheltered by the base of the old sea wall, and the fronting saltmarshes. Particularly deep areas were excavated in the sections protected by the remainder of the base of the seawall. This sheltering effect is thought to reduce the tidal flow velocity, thus increasing the opportunity for sediment deposition from the water column. Due to the relatively frequent inundation (on every high tide, as it was below MHWN), the front of the site accreted relatively quickly, especially as the Humber is known to have high SSC (Appendix 1).

In addition, the managed realignment site is located in the Outer estuary; therefore it is affected by waves, especially during storm conditions. According to Roman *et al.* (1997), storm could be important in delivering pulses of sediment into the site. Wave action could cause the movement of sediment from the fronting mudflats into the site, trapping it in the sheltered low area behind the remaining embankment.

Toward the back of the site, the accretion rates were clearly smaller. Deposition of sediment from the water column can only occur when the site is flooded; an accretion limit is reached when elevation would cause inundation frequencies to level off, eventually leading to a reduced accretion rate (Goodman *et al.,* 2007), as was observed at Welwick

Furthermore, negative elevation changes were observed especially during the first year on the new embankments and fronting land which was piled up to create saltmarsh elevation. These losses in elevation are probably related to the compaction of the new defences and re-profiling areas due to the settlement of the earth material and weathering processes. It is not thought represent the actual loss of material (erosion), but rather a change in the characteristic of the soil (i.e. density).

The presence of a saline lagoon toward the back of the site caused some unusual changes in the site behaviour and made data interpretation difficult. Based on volume calculations, a comparison of the site data between 2007 and 2010 appears to show 'erosion' in the lagoon area, however, it is thought that, the real loss of material was unlikely (especially as the same anomalies in the 2010 data are also seen at Alkborough). Instead the drainage of the lagoon could explain the recorded process in terms of volume change. Furthermore, the infilling of the creeks of the rear part of the site suggests that the flow velocities in this region were not high enough to re-erode the deposited material, supporting the idea that the real erosion of the saline lagoon is improbable.

Moreover, the changes along the site were also not uniform in a west-east direction. The presence of deeper areas and the position of the breaches appear to have caused a higher accretion rate in the western section of the site and smaller changes in the east. This is particularly apparent when comparing the breach channels – the easterly channel has not accreted much, including a distance of some 200 m into the site, whereas the westerly channel as experienced accretion, though not at levels observed around the channel. It is thought that the easterly breach experiences higher flow velocities that have caused a smaller capacity for deposition. This higher flow velocity in the eastern breach is probably related to the position and orientation of the site in the estuary; i.e. the estuary draining in an easterly direction. This appears to have led to the easterly breaching accommodating larger tidal exchange. The presence of the saline lagoon in the back-eastern part of the site suggests that the eastern breach was connected to it, flooding the area during the tidal cycle and maintaining the channel. After 2010, the saline lagoon appear to have been infilled by sediment and/or water; indicating the reduction of the flow velocities and the accretion in the eastern side.

6.2. Paull Holme Strays morphological changes and processes

The Paull Holme Strays managed realignment site is characterised by its two totally different regions. As was presented in the results chapter, the western section has a larger breach located

at elevations lower than the MHWN tide level in 2004. This section of the site has experienced an accretionary trend and the clear development of tidal creeks.
According to the data reported in the results, the western section of the site has increased is elevation especially in its higher parts. Accretion rates are expected to be negatively related to the height of the surface. However, the lower part of the western side of Paull Holme Strays has accreted less than the higher one. Elevations which were initially below the MHWN tide level along the front of the site accreted a maximum of 0.25 metres between 2004 and 2005; while the elevations which were above the MHWN tide level accreted up to 2.75 mODN (noting a relatively low margin of error associated with the all the site data (+/- 15cm)). According to Oenema and DeLaune (1987) research, accretion is greatly increased during spring tides and storms when the suspended sediment concentrations and flooding period increase. Under such conditions, the higher elevations of the site are also flooded. Neap tides flood only the low lying regions, but these flood volumes have much lower suspended sediment concentrations. The larger elevations in this western section were no higher than 2.8 mODN in 2006, and therefore under the influence of high neap and all spring tides, allowing frequent tidal exchange and sediment supply. Furthermore, the sheltered location of these higher grounds allowed the deposition of the sediment from the water column. The influence of the western breach could, on the other hand, directly affect the lower areas decreasing the sediment capacity to settle. Although estuaries are often considered protected environments, waves can have significant sedimentological effects by eroding and re-suspending fine sediments so that they can be dispersed by currents (Carroll, 2012); since the lower areas of the western part of the realignment site have not accreted up to the MHWN tide level over the survey period of 6 years, thus a more energetic environment influenced by wave action could be one explanation.
The results obtained for this section of the site (west) are very similar to those reported by the Paull Holme Strays monitoring programme (Environment Agency. 2009). According to this, the higher accretion rates were found in the higher region of the western side of the site, reaching 0.44 m by 2008. Furthermore, the results are also consistent with the reported by Mazik *et at.* (2007) in a study which also analysed the development of the recently breached site.
The eastern section of the site has shown a different behaviour. From the initial configuration, the eastern side had a higher elevation, ranging from 3 to 3.5 mODN, with places even higher than the MHWS tide level in the central part of it. According to the results, this higher area of the site has been subject to a small erosional trend over the years. Firstly, the development of the eastern tidal channel led to great erosion (almost 2 metres in 2 years) probably related to high flow velocities. On the other hand, the elevation of the site does not allow every tide to flood it, decreasing the sediment availability.
In addition, a relation between the flood and drain period of the site could explain the erosion rates observed in the eastern region. Due to the position of Paull Holme Strays in the estuary, the flooding tide would enter the side preferably by the western breach. During the ebb period following HW, a larger volume of water than expected could force its way out through the

eastern breach, closer to the estuary mouth. This increased water volume through the eastern breach has not only led to the erosion of the breach itself, but also the channel passing through it. Moreover, the presence of standing water in this eastern section of the site, similar to the lagoon decided in the case of Welwick, could also have contributed to the erosional trend observed.

According to the site monitoring programme undertaken until 2008, this erosion trend of the eastern side was not reported, probably due to the survey method based on the monitoring of fixed samples sites along a series of transects, mainly located in the western section of the site, twice a year. On the other hand, the study undertaken by Mazik *et at*. (2007) reported negative accretion rates (erosion) in the southern-eastern region of the site and close to the embankments during the study period (2004-2006), similar to the results found during this research.

6.3. Chowder Ness morphological changes and processes

Chowder Ness managed realignment site presented a continued accretion rate over the period of analysis. The site had two originally low areas, as was described in the results chapter. These areas, located in the front and eastern part, accreted between 0.25 to 1 metres during the first year after breaching (2006-2007) (noting however the fairly large margin of error associated with the 2006 data (+/- 50cm)), from elevation below the MHWN tide level to approximately 2.5 mODN. The processes driving this accretionary trend are very similar to those one described for the front part of Welwick: the lower the elevation, the more frequent the sediment supply and the more rapid its accretion combined with the decrease in current velocity in order to reach a deposition threshold and to allow sedimentation form the water column.

After 2007, the low areas had an elevation similar to the rest of the site surface, however, the accretion continued, over the entire site. According to the volume results, the site experienced relatively high accretion rates until 2009, and opposite to what has been observed in the two previous sites, the volume change over the last survey (2010-2011) was similar to that observed during the first year after breaching (Figure 38). The large suspended sediment concentrations of above Hull (Townend and Whitehead, 2003) together with the small configuration of the site appear to have resulted into a more constant accretion over the time.

The narrowing of the main tidal channel indicates that the flow velocities are not high enough to re-erode deposited sediments, in accordance with previous observations. In addition, the configuration of the site, based on the removal of the frontal defences, has allowed a large tidal exchange, increasing the availability of sediment and the high deposition rates.

On the other hand, the erosion of the lowered remaining embankments has been reported. This loss of material could be related to the interaction between the tide and remaining embankment and it decreased over the period of analysis, suggesting that the processes moved toward equilibrium after the initial change.

Furthermore, the decrease in elevation of the rear side of the site was observed, especially during the first year after breaching. This decrease could be related to the loss of material from the slope of the new embankments. Similar to the sites previously analysed, the consolidation of the new seawalls due to the settlement of the earth material is observed during the first years, decreasing over the time.

6.4. Alkborough

The Alkborough site is unusual due to the constrained breach with a sill level over MHWN levels. Meaningful analysis of the LiDAR data proved difficult, due to the large areas of standing water over the site, resulting in "artificial" erosion/accretion of the surface, affecting the accuracy of the analysis.

The site appears to have accreted, the infilling of the lagoon areas and higher elevation was recorded; however, a more detailed analysis is required in order to rely in the results obtained, therefore, the site will not further discussed.

6.5. Managed realignment sites comparison

The managed realignment sites analysed during this research are located in the same estuary; they are under the influence of similar processes and all of them have experienced an accretional trend over the study period. The shape of the hypsometric curves indicates that the sites have shallow channels and a large intertidal storage configuration, favouring flood dominance and the import of sediments (Bosboom and Stive, 2012).

However, differences have been observed, possibly related to the position in this big estuary. The Humber Estuary has a length of 62 km, and is often split into 4 distinct morphological areas (more details can be found in Appendix 1) with specific characteristics, tidal regime, waves height and suspended solid concentrations. These properties, together with the design and shape of the sites, have meant that the four realignment schemes have been subject to a different combination of processes.

Both Paull Holme Strays and Welwick are located on the northern bank of the estuary, Welwick in the Outer Humber and Paull Holme Strays in the Middle section – although they are located in fairly close proximity (approx. 20 km). In both sites an accretion rate was recorded since breaching, however, Welwick accreted a maximum of 1 m in its lower areas during the first year; Paull Holme Strays presented lower rates of maximum deposition, 0.60 m between 2003 and 2004 (it should be noted that the site was breach during 2003). Furthermore, the larger accretion rates of Paull Holme Strays are located at the higher and sheltered elevation in the western part of the site, as was previously mentioned in Section 6.2.

According to Le Hir *et al.* (2000), wind waves generated within the estuary are an important factor in the re-suspension of sediments in mudflats; furthermore, small waves can have an important influence on sediment transport, because, in shallow waters, the stress they cause on the bed is comparable with the stress associated with a quite substantial tidal current. Under this assumption, the lower accretion of Paull Holme Strays could be related to a more exposed location of the site, however, according to the wave data of Chapter III, Welwick site, situated in the Outer estuary, is the one under the higher waves influence (0.3 to 1.5 m high) with the larger fetch (larger than 10 km in the S/SE direction). On the other hand, Paull Holme Stray has wave heights of 0.2-0.6 m with a usual fetch of 3.5 km SW; smaller values than Welwick; however, the prevailing winds of the region are from the south-west (ABPmer, 2011c), thus could be the cause a more frequent wave climate, higher energy level and the lower accretion rates in this site. Furthermore, the bigger sites will be subjected to greater levels of internally generated wind-driven waves that play an important role in remobilizing deposited and unconsolidated sediment (Mazik *et al.,* 2010), also explaining the lower accretion rates observed in Paull Holme Strays.

In addition, GeoSea Consulting (1990) (ABPmer, 2011c) identified a general counter clockwise circulation pattern incorporating Foul Holme Spit in the Middle Humber, located just below Paull Holme Strays. This sediment circulation could result in the reduction of the sediment availability for the managed realignment site and it could contribute an explanation for the observations.

In addition, the deposition rates are directly related to the SSC in the water column. The Humber Estuary is characterised by high values of SSC (average of 200 mg/l at all depths according to ABPmer (2011c)) due to its macro-tidal nature combined with the dominance of muddy bed sediments. These concentrations are subject to natural variability, due to the influence of tide, wave and seasonal changes, with concentrations above Hull being twice as high as those found down-estuary (ABPmer, 2010). Both Paull Holme Strays and Welwick are located below Hull, however, the larger SSC above this point could explain the large and continuous accretion rates observed in Chowder Ness site. Besides, it should be noted that Chowder Ness site is a banked realignment scheme that allows the exchange of water along the whole frontal area, increasing the connectivity with the estuary.

Alkborough, on the other hand, due to its constrained breach at a fixed level (higher than the MHWN tide), is a site difficult to compare and analyse. As previously mentioned, the standing water on it increases the uncertainties of the results; however, it is evident that the site has experienced accretion over the period of analysis.

6.6. Prognosis of site evolution

One of the main objectives of a managed realignment scheme is to re-create habitats in order to compensate for the losses caused by coastal squeeze and coastal developments. Two of the sites analysed during this project (Welwick and Chowder Ness) were undertaken mainly to create mudflats. Mudflat habitats tend to typically occur between LAT and approximately the MHWN tide level, whilst saltmarshes tend to be found at higher elevations (i.e. between MHWN and MHWS).

Due to the high level of SSC found within the Humber Estuary, accretion rates can be high if there is sufficient tidal exchange between the estuary and the realignment sites (following breaching). These high accretion rates are particularly evident at Welwick and Chowder Ness, where large amounts of mudflat habitat accreted up to saltmarsh level over the first one to two years, thus highlighting the difficulty of creating sustainable mudflat habitat within the Humber Estuary; with the estuary being more naturally suited to saltmarsh creation.

According to Morris (2013) current evidence derived from sites that are predominantly less than 100 ha in extent (as all the study sites of this research are with the exemption of Alkborough) suggests that saltmarsh will dominate after a relatively short period, especially where suspended sediment loads are particularly high (as in the Humber Estuary).

The results presented in Chapter V illustrate that the sustainable large scale creation of mudflats in the Humber Estuary will be difficult, however, the utilisation of more stable/appropriate breach dimensions along with the further adoption of varied yet suitable design criterion (e.g. regulated tidal exchange and dendritic channels) has the potential to reduce sedimentation rates in future sites; thereby possibly improving the sustainability of future mudflat habitats. This being said, saltmarshes offer a great number of benefits (Baily and Pearson, 2007; Dixon *et al.*, 1998), not only from the ecological point of view, but also, both socially (walking, cycling, fishing, etc.) and economically (reduction coastal defences cost, flood management strategies, etc.). The successful colonisation of saltmarsh can be regarded as a valuable outcome, especially as there has been significant saltmarsh loss on the Humber in the past. Thus the managed realignment sites in the estuary have contributed to the restoration of this important habitat. Nevertheless, such an outcome should not be interpreted as an acceptable alternative to mudflat development in areas where continued land claim for urban and industrial development is taking place (Mazik *et al.*, 2010). However, some mudflat has been maintained in the sites along channels.

Furthermore, considering the sea level rise prediction for the future, the saltmarsh habitat is expected to continue to dominate the realignment sites, as their sedimentation rates generally exceed contemporary sea-level rise, especially in an environment with high sediment availability as the Humber Estuary.

6.7. LiDAR uncertainties and accuracy issues

The LiDAR method has several advantages over ground based surveys. These include it being relatively quick, covering large study areas and providing data with high resolution (0.5-2 m) and improved vertical accuracy (15 cm). However, some issues and errors are related to this survey technique, as was frequently observed during this study. Thus, caution should be observed when interpreting LiDAR data.

Firstly, LiDAR is not an all-weather sensor; it cannot be flown above clouds and should not be flown with standing water on the ground. These characteristics limit its use in coastal environments due to the presence of water, in some area even during low tide – as was observed at all the studied sites.

Secondly, the errors of the method can be summarized into horizontal and vertical accuracy. The horizontal error is related to the inaccurate positioning of aircraft by the GPS; it is more difficult to assess and it is generally not provided.

The vertical error is related the accuracy of the equipment and the nature of the surface in terms of vegetation cover, human artefacts, presence of water and reflective mud surfaces. Alkborough managed realignment site was a clear example of the inaccuracy issues related to the presence of standing water. As was mentioned previously, the constrained breach and the low surface elevations do not allow the full drainage of the site and drainage could possibly not have been completed during low tide surveys. Thus, in the tidal habitats, the presence of water can cause significant errors both during the LiDAR surveys and the data analysis.

The vertical accuracy of LiDAR is commonly specified as the Root Mean Square Error, a statistical value equal to the square root of the average of the squares of the differences between known points and modelled points in the LiDAR surface (Shillenn and Umansky, 2011). UK LiDAR accuracy, as was previously mentioned is generally +/-15 cm; however, the potential inaccuracy of the 2006 DTMs for Chowder Ness and Welwick was higher (+/-50 cm), thus caution needs to be applied during the interpretation of the results.

Furthermore, as was mentioned in the methodology chapter, the LiDAR data provided by the Environment Agency has been filtered removing vegetation and human artefacts. This process is undertaken by automated routines with a typical efficient of 90-95% (Shillenn and Umansky, 2011), hence adding an extra source of error. In addition, data uncertainties increase with increment of vegetation coverage, height and relief (Saye *et al.*, 2005).

All the above described inaccuracies of LIDAR data mean that there are uncertainties in relation to the results of this study.

This particularly relates to volume calculations. Information from previous studies (see Gares *et al.*, 2006) indicates that volume calculation based on LiDAR may misrepresent the actual change by 10-15% on non-vegetated terrains, dunes and beaches In addition to this percentage of error, managed realignment sites have the uncertainties related to the presence of standing water and reflective mud surfaces.

After the initial large change observed in the sites, the elevation changes decrease to values smaller than 10 cm. Considering that the claimed accuracy of the LiDAR data is 15 cm and adding the uncertainties related to the coastal environments, the changes observed following the initial accretion, are smaller than the accuracy range of the data and therefore should be treated with caution. However, the results indicate that these small changes in elevation continue over the time, presenting a long term constant signal in the elevation analysis that indicates that the small accretion recorded is not a product of the uncertainties of the data.

6.8. Monitoring techniques recommendations

As presented in the previous sections, one of the main problems related to LiDAR data in the study area is the presence of standing water. The elevation changes and volume calculation in areas covered by standing water are not reliable, thus interfering with the monitoring and evolution analysis of a site.

In order address this problem LiDAR survey should be undertaken during low tide conditions ideally during similar stages of the tide. However, this is not always the case/practicable, likely particularly when large areas are flown. Furthermore, the metadata of the LiDAR should contain specific information about the day and time of the flight to enable correlation with likely conditions during survey. For the data used in this study, this information was provided in terms of relatively long periods of time (Table VI), which did not allow the tracing of the specific time and day, impeding any tide consideration and correction.

In addition, the presence of standing water tends to be in low-lying areas subject to no/very little drainage, as in the case of the saline lagoon in Welwick or the lower parts of Alkborough. In order to correct the errors derived by the presence of water, a topographic ground survey based on transect with georeferenced elevation measurements through the low lying area should be undertakens. The elevation data recorded in the site should be used to correct and to calibrate the LiDAR data in order to improve its accuracy. Generally, ground truthing of LiDAR is considered prudent.

Finally, long term datasets for monitoring purposes are recommended, even if the larger changes occur during the first years after breaching, the monitoring of the site over a longer period of time will allow the analysis of the long term evolution of managed realignment schemes and provide insights into how the sites adapt to sea level rise.

Chapter VII: Conclusions

The aims of this study were to describe in detail the evolution of the four managed realignment sites in the Humber Estuary using LiDAR data, to relate the changes observed to the typical physical processes of the estuary and to assess both the future evolution of the sites as well as the monitoring techniques used to date. In the following section, the key finding of the research are presented together with some recommendation related to future work in managed realignment sites.

7.1. Key findings

Managed realignment schemes are a valuable contribution to sustainable coastal management and can potentially offer social and economic benefits as well as environmental gains.

The managed realignment sites in the Humber Estuary all presented an accretionary trend over the period of analysis, characterised by high deposition rates, when compared to sites elsewhere in the UK where lower SSC are typical of the estuarine environment (e.g. Tollesbury on the Blackwater Estuary (Morris, 2013)). Accretion rates have been particularly high during the first years after breaching, and at all sites the rates of accretion seem to have levelled over the analysis period, this would mainly be related to the higher elevation levels of the sites in the later surveys.

Even though the four realignment sites are located in the same estuary, significant differences in their morphological evolution have been recorded, this is thought to mainly be related to the different configurations of the schemes, as well as their location along the Humber Estuary.

The elevation changes of the managed realignment schemes of the Humber Estuary appear to have been mainly driven by inundation frequencies. The tidal exchange determines the amount of sediment that can be moved into site where it is deposited in the lower-sheltered areas due to the decrease in flow velocities. However, waves may have also contributed.

Due to the high concentration of suspended sediments in the estuary and the rapid accretion rates identified, the sustainable development of mudflats in the future will be difficult; with the estuary being more naturally suited to saltmarsh creation. Taking SLR into account, the establishment of saltmarsh habitats should still expected to dominate managed realignment sites due to the rapid vertical accretion rates observed in the sites.

Managed realignment sites are subject to large morphological changes in the first years after breaching, afterward the rates of accretion/erosion decrease; however the monitoring of the site, even after the initial changes, is essential to understand the processes and long term evolution of the schemes.

Although not without issues, LiDAR elevation data are thought to be extremely valuable for comparing and analysing morphological changes in managed realignment sites.

The accuracy of the LiDAR data should be included in the analysis, considering not only the horizontal and vertical accuracy provided by the supplier, but also the uncertainties created by the presence of standing water and reflective mud, which cause that the claimed data accuracy is not often achieved.

In order to improve the accuracy of LiDAR data analysis, information about the exact day and time of the flight should be provided. In addition the calibration of the data using ground points is required in order to increase the quality of the analysis, especially in areas of standing water.

7.2. Recommendation for future work

The analysis undertaken during this study demonstrates the variety of information which can be extracted from LidAR data. Nevertheless, more in-depth study of these aspects could be undertaken. For example, channel development could be studied in more detail. Primary data from the official monitoring programmes could also be consulted to compare the results of different techniques of measuring elevation changes. Also, it may be interesting to correlate benthic and plant development with elevation changes.

Further investigating ways in which longer term sustainable mudflats might be created in high suspended sediment concentration environment such as the Humber Estuary would also be valuable. The generation of saltmarshes undoubtedly has benefits, however, mudflat habitat losses due to development and coastal squeeze should ideally still be compensated. Further research should address ways to increase the energy in the sheltered areas of the managed realignment sites in order to decrease the deposition rates, building on initial insights gained during this study (see previous section).

Lastly, the uncertainties related to LiDAR data also need further attention. A detailed analysis of LiDAR accuracy should improve the method, not only in the monitoring of realignment site, but also for any other LiDAR application. The presence of water and the error associated to it, the true vertical accuracy of the data as well as the horizontal one, and the effect of reflective mud surfaces should be quantified using statistical techniques and ground surveys. Few research studies have been undertaken in order to define the accuracy of the LiDAR methods, most of the studies related to this technique and the coastal environment briefly mention the uncertainties of the data, so a study related to this topic would be of great importance to both the scientific community and the policy/decision makers.

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Appendixes

1. Appendix 1: Literature Review

1.1. The Humber Estuary

The main characteristic of the estuary are presented in Table AI.

Table AI. Humber Estuary key characteristics (Townend and Whitehead, 2003)

Parameter	Values for the Humber
Length	62 km to Trent Falls; 147 km to tidal limit on River Trent
Area	Cross-sectional area at mouth 85538 m^2 to Mean tidal level Plan area 2.8 X 10^8 m^2 at HighWater (HW); 1.8 X 10^8 m^2 at Low Water (LW) Intertidal area 1 X 10^8 m^2 Saltmarsh area 6.3 X 10^6 m^2 (all between Spurn and Trent Falls)
Volume	Total volume 2.5 X 10^9 m^3 at HW and 1.1 X 10^9 m^3 at LW Tidal prism, springs 1.5 X 10^9 m^3 and neaps 0.8 X 10^9 m^3
Width and depth	Width at mouth 6620 m; hydraulic depth at mouth 13.2 m Width at tidal limit 52 m; hydraulic depth at tidal limit 2.9 m Average width 4265 m; average hydraulic depth 6.5 m
Form description	Area=84exp(6.7x/l); r^2=0.99 Width = 198exp(3.7x/l); r^2=0.89 Depth = 0.55exp(3x/l); r^2=0.91 (length, l=145 km)
Freshwater flow	Average flow 250 m^3 s^{-1}; high flow 1600 m^3 s^{-1}

1.1.1. Background studies and monitoring

Over the last decade, extensive research programmes have been undertaken on and around the Humber catchment, ranging from the fundamental research under the UK Natural Environment Research Council (NERC) Land Ocean Interaction Study (LOIS), through strategic studies of the estuary by the Environment Agency, to local studies in support of developments by Associated British Ports and others. Much of this work has been aimed at trying to improve understanding of the morphological behaviour of the estuary system in order to be better able to predict change both natural and anthropogenic. A particular focus of the strategic studies has been the synthesis of a wide range of methods to develop an understanding that is consistent across a range of spatial and temporal scales (Townend *et al*., 2007).

In 1996 the Environment Agency began to develop a comprehensive strategy for managing the flood defences of the Humber Estuary. This strategy was to be based on am sound understanding of the physical processes taking place in the Humber. In January 1998 the Agency appointed a consortium to undertake a range of geomorphological studies of the estuary (Townend and

Whitehead, 2003). The results of these studies were subsequently used to formulate the first draft of the Shoreline Management Plan and a preliminary Coastal Habitat Management Plan or CHaMP (Townend and Whitehead, 2003).

Whilst initial studies reveal that estuary volumes have remained roughly constant since the 1850's, the more recent analysis has identified a long-term trend of an increase in estuary volume. All the studies found the form of the Estuary to be changing, with the high-water plan area reducing and the low water plan area increasing slightly. Together these changes mean that up until 1985 there had been a gradual loss of intertidal areas, particularly in the Outer Estuary. However, it appears that intertidal areas throughout the whole Estuary have begun to increase in extent nowadays (ABPmer, 2010).

An analysis of the energy flux indicates that as a whole, the Estuary is developing slowly towards a 'morphological equilibrium', although on a smaller scale some sections appear to be moving away from this equilibrium state (ABPmer, 2011c).

1.1.2. Morphology

The coastal and estuarine processes around the Estuary are particularly dynamic in nature. This large area of open water has fast-flowing currents, shifting sands and shallow waters, and the bathymetric charts of the Estuary are constantly changing (ABPmer, 2010).

The Humber Estuary is highly dynamic in its morphology, particularly in areas where there are no constraints (either geological or man-made). This dynamism manifests itself in cyclical variations in the positions of channels and banks throughout different regions of the Estuary. The processes experienced by many of these regions appear to be interconnected. The dominant influences on morphological change are tides, waves, freshwater flows, tidal surges and biological activity. These influences produce changes in SSC, deposition rates, bed composition and ultimately channel/ bank configurations (ABPmer, 2010).

The Estuary can be divided into four regions (Eurosion, 2003), described following, Figure A1 illustrates them.

- **The Inner Humber (Trent Falls to Humber Bridge)**

  Downstream of Trent Falls, where the Rivers Trent and Ouse merge, the Estuary is characterised by a number of extensive intertidal banks composed of sand/ silt (ABPmer, 2010). The construction of the training works at Trent Falls in the 1930s has relatively stabilised the upper part of this section as far as Whitton. The rest of the section remains unstable and the channel migrates between two extreme positions, one lying along the north bank and one along the south. Channel instability in the inner estuary appears to be triggered by high freshwater flow coinciding with periods of large tidal range. In recent years this area has been more stable than in the past (ABPmer, 2011c).

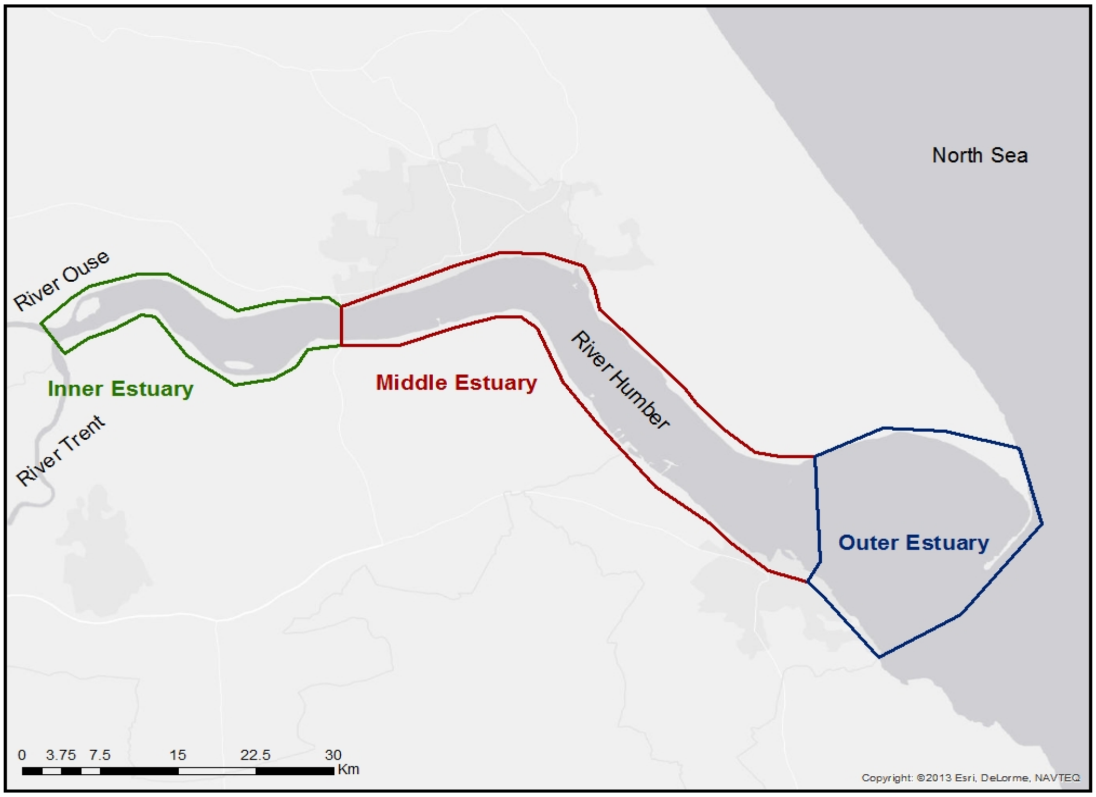

Figure A1. Humber Estuary regions

- **The Middle Humber (Humber Bridge to Grimsby**)

The Middle Humber is similar in its characteristics to the Inner Humber, having a number of banks and channels that have a preferred configuration (ABPmer, 2010). It appears that the foreshore at the outer part of this section is currently relatively stable. The inner area nearer Hull on the north bank is also relatively stable, but is heavily constrained by the existing coastal defences. Considerable subtidal change has occurred in recent years resulting in almost the complete removal of Foul Holme Spit at Chart Datum (CD), substantial deepening throughout Halton Middle, particularly the northern section, and a change to the configuration of Skitterness, Hull Middle and Halton Flats. Up estuary of Immingham, intertidal accretion has been dominant, resulting from the Immingham developments, although a new equilibrium has now developed (ABPmer, 2011c).

- **The Outer Humber (Grimsby to Spurn Point)**

The Outer Humber is dominated by a three-channel system at the mouth, a large submerged sandbank (the Middle Shoal), and a single deep channel leading to the Middle Humber (ABPmer, 2010).

This section is more exposed to wave action than the rest of the estuary, particularly the southern shore which is predominantly sandy rather than muddy in nature. The flow patterns in the area exhibit a marked counter clockwise circulation, with the main current crossing from one side of the Estuary to the other on the flood and the ebb. These features, along with a number of others suggest that this part of the estuary may act more like a coastal inlet or bay and that, in effect, the true mouth of the Estuary is nearer Grimsby. The subtidal section of the estuary is variable in terms of morphology in both short and long timescales (ABPmer, 2011c). The presence of boulder clay deposits in the Outer Humber provides a geological constraint that influences the position of some of the sand banks, intertidal areas and Spurn Point itself (ABPmer, 2010).

- **Tidal River**

  Both the River Trent and the River Ouse are deemed to be tidal rivers and are fully canalised with extensive erosion protection works on the banks. The canalisation maintains the meander system that was present when the works took place, largely in the 18th and 19th centuries (ABPmer, 2011c).

The dynamic nature of the Humber is illustrated by the interactions existing between the various bank systems in the Inner and Middle Estuary. Channel migration in the Inner Estuary region releases sand, which forms banks off Barton and New Holland in the upper Middle Estuary. Furthermore, there is a sediment exchange between Barton Ness Sand and Skitter Sand lower down the Humber, which ultimately helps determine the shape and levels across Halton Flat ABPmer, 2011c).

1.1.3. Hydrodynamic regime

The tidal levels, currents and waves of the Humber Estuary, focusing on the four managed realignment sites are presented in the next section. Due to the lack of information of the hydrodynamic regime within the sites, the information was obtained for the closest locations showed in Figure A2.

1.1.3.1. Tidal levels

The Humber Estuary is the largest macro-tidal coastal-plain estuary on the British North Sea Coast. At its seaward end there is a large tidal range due to the position of the mouth within the North Sea basin and the estuary is dominated by tidal conditions, despite the significant freshwater inputs (Townend and Whitehead, 2003).

The estuary has a mean spring tidal range of 5.7 m at Spurn Head increasing to 7.4 m at Saltend then decreasing to 6.9 m at Hessle, which is 45 km inland. During the neap spring tide sequence at Saltend the tidal range varies from 5.8 m to 7.4 m. Tides are semi-diurnal with a slight diurnal inequality, amounting to a 0.2 m difference in high water spring tides at Immingham (ABPmer, 2010).

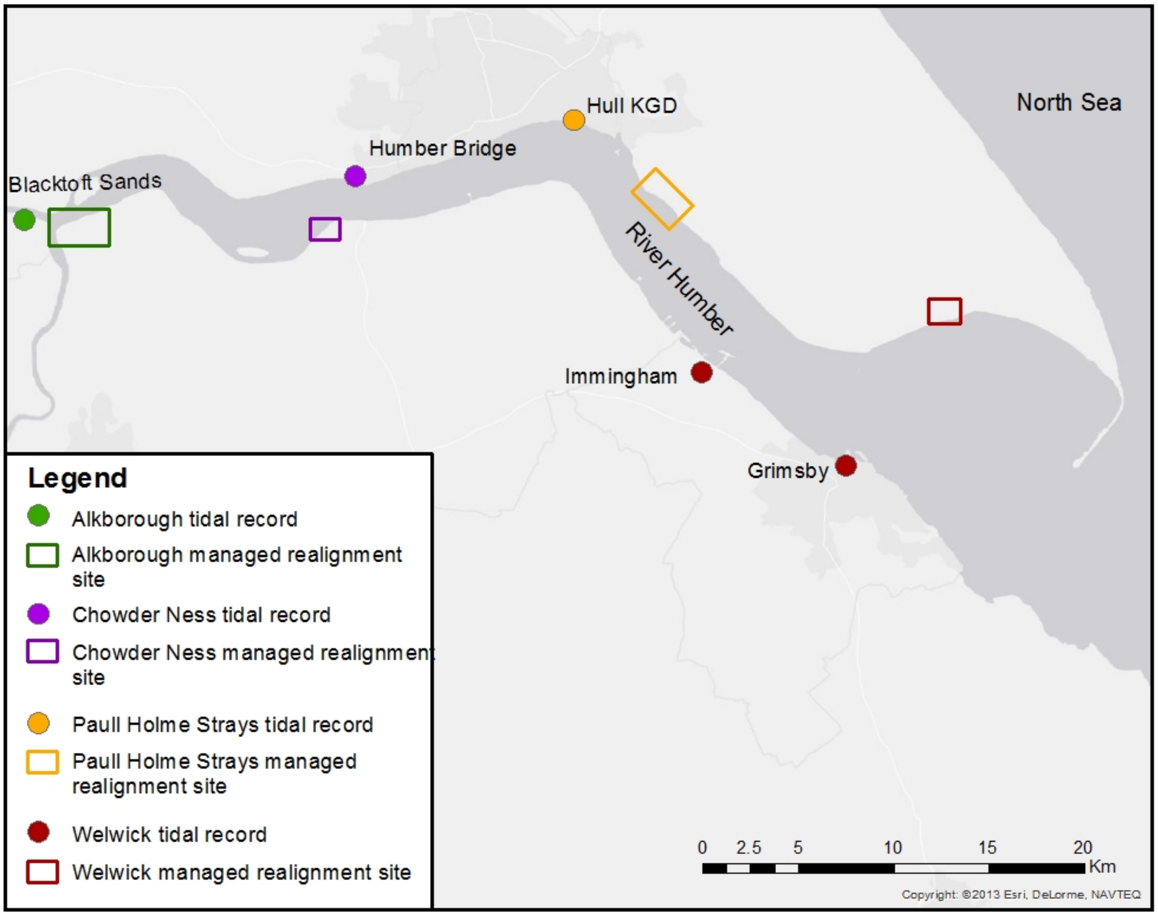

Figure A2. Location of the tidal records of the managed realignment sites

The Humber tides are driven by the amphidromic system centred off the west coast of Denmark in the central North Sea. As the tide passes south of North Shields, it enters shallow water conditions, which amplify the range from 4.3 m to 4.6 m at the River Tees entrance and 5.7 m at Spurn (ABPmer, 2010). On spring tides, the length of the flood tide becomes progressively shorter than the ebb in an up-estuary direction. On neap tides, however, the flood phase is longer than the ebb by an average of about 35 minutes at Spurn. This difference reduces up-estuary, becoming approximately equal in length at Hull. Further up-estuary the flood tide progressively shortens with respect to the ebb length in a similar manner to the spring tides (ABPmer, 2011c).
Morphological measures of the tidal asymmetry suggests the Estuary as a whole has become more flood dominant over the last 150 years, however this is more attributable to the area up-estuary of the umber Bridge, since in the reaches down estuary of Hull there has been increased ebb dominance (ABPmer, 2010). It is possible that flood dominance could spread further down the channel in the future, with enhanced capability for retaining sediment transported on the flood tide (Eurosion, 2000).

Table AII presents the tidal levels for the Estuary according to Environment Agency (2012).

Table AIIXVI. Tidal data for Humber ports near managed realignment sites (UKHO Admiralty Tide Tables from Environment Agency (2012))

Tidal Data (mODN)		Immingham	Grimsby	Hull	Humber Bridge	Blacktoft Sands
Closed realignment site		Welwick		Paull Holme Strays	Chowder Ness	Alkborough
Tidal Level	MHWS	3.4	3.2	3.7	3.9	4.2
	MHWN	1.9	1.8	2.1	2.1	2.5
	MLWN	-1.3	-1.3	-1.4	-1.4	-1.1
	MLWS	-3	-2.8	-3.2	-3	-1.7
Tidal Range	MHWS to MLWS	6.4	6	6.9	6.9	5.9
	MHWN to MLWN	3.2	3.1	3.5	3.5	3.6

1.1.3.2. Tidal currents

The Humber is a well-mixed estuary. This is largely a reflection of high tidal current velocities. As saline water moves into the Estuary it meets the seaward flow of freshwater from the Rivers Ouse and Trent, and the more dense saline water tends to flow beneath the less dense fresh water. The high velocities of the tidal currents cause almost total mixing of the two water bodies, except under conditions of very high freshwater flows (ABPmer, 2010).
Table AIII presents the tidal current velocity for the Estuary according to ABPmer (2011c).

Table AIIIXVII. Tidal current velocities for the Humber Estuary (ABPmer, 2011c)

Location	Maximum Flood Velocity (m/s)	Maximum Ebb Velocity (m/s)
Seaward of Spurn	1.6	1.2
Immingham	1.8	2.1
Saltend	2.1	2.16
Hessle	2.16	2.38
Blacktoft	2.4	1.98

1.1.3.3. Waves

Within the Humber Estuary wave action generally reduces landward due to the meandering of the tidal channels, the tendency of waves to refract towards the shoreline, and energy losses due to shallow water effects. In the Humber the effect of waves propagating from offshore is limited to the Outer Estuary. In terms of locally generated waves, significant wave energy can be generated from the fetches within the Estuary, particularly in the area of Spurn Bight and the rear of Spurn, due to the prevailing south-westerly winds (ABPmer, 2010).

ABP R&C (1986) analysed waves recorded at Bull Sand Fort at the entrance to the Humber Estuary between 1984 and 1986. The results illustrated that the significant wave height only exceeds 1 m for 11% of the time, although there was seasonal variability. The maximum significant wave height was 2.8 m. Waves from the south-east cause localised wave energies with a maximum impact on the southern shore to the east of Grimsby. There is a further area of increased wave energy, which extends approximately 5 km east and west of Hawkins Point. For identical wave conditions from the north-east, wave energy is more spread along the southern shore with moderate levels of energy reaching as far as Immingham (ABPmer, 2011c).

1.1.4. Sediment transport

The sediment transport of the estuary is presented in the next section addressing the main pathways in Section 1.1.4.1 and the sources, sinks and stores in Section 1.1.4.2.

1.1.4.1. Sediment pathways

Erosion of the Holderness coast, caused by waves, introduces sediment to the coastal transport system. The coarser material eventually contributes to the supply to the Spurn Peninsula, estimated at circa 100,000m³ per annum. The remainder, circa 280,000m³ per annum of sand and the finer suspended material, is moved southwards towards Easington and Kilnsea where it tends to drift offshore. The material then supplies offshore bars or sink holes in the areas of The Binks, New Sand Hole, the Humber Estuary, particularly Donna Nook, and beyond towards the Lincolnshire coast and The Wash (ABPmer, 2011c).

A part of the finer sediments released from the Holderness cliffs is transported, in suspension, into the Humber Estuary where it becomes available for deposition on the mudflats and saltmarshes whilst the rest is transported towards the Wash and the German Bight. The silt fraction is representative of muddy intertidal sediments found within the estuary whilst the sandy sediments are found throughout the subtidal sections of the estuary (ABPmer, 2011c).

Within the estuary sediment transport pathways are complex and probably continually changing as indicated by the secular and cyclic changes in the historical bathymetry throughout the estuary. A general counter clockwise circulation pattern incorporating Foul Holme Spit in the Middle Humber and a clockwise circulation of sediments based around the Middle Shoal within the Lower Humber with little indication of a direct link between the two areas has been identified. On the muddy intertidal, down-estuary transport was reported on both sides of the estuary. East of Grimsby the dominant direction of movement along the Cleethorpes foreshore was towards the estuary (ABPmer, 2011c).

1.1.4.2. Sediment budget

A sediment budget is a balance of the quantity of sediment entering and leaving a selected segment of coast or estuary. It is based on quantification of the sediment transport, erosion and deposition within a given control volume, where, typically, the quantities are defined in terms of sources, sinks and the processes that give rise to additions and subtractions (US Army Corps, 1992). An estuary provides a readily defined control volume. Point sources/sinks exist in the form of rivers, other terrestrial outfalls and the open sea; line sources/sinks may be defined in terms of transfers on and off the intertidal zone, erosion from cliffs and transfers to or from saltmarshes /wetlands. It is also necessary to consider the subtidal bed of the estuary as an important source/sink. In addition, material is stored in suspension within the volume of water that moves back and forth under tidal action within the estuary (Townend and Whitehead, 2003).

According to Townend and Whitehead (2003), the Humber Estuary's sediment budget is complex due to its highly variable nature. Their work shows that the exchange between the rivers and the sea is an order of magnitude smaller than the flux of sediment through the mouth on each tide and that the inputs and outputs on each tide are very much smaller than the volume of sediment held in suspension within the Estuary (ABPmer, 2010). They define the main components of the sediment budget of the Estuary as presented in Table AIV and Figure A4.

In summary, the Humber Estuary has three main sediment sources: its tributaries, the North Sea (in the form of suspended sediment) and the eroding Holderness coast.

Table AIV. Sediment budget for the Humber estuary (Townend and Whitehead, 2003)

Element	Typical dry solids estimate (t/tide)	Rate (m^3/year)
Fluvial input	335	7.9 X 10^9
Suspended load in estuary	1.2 X 10^6	-
Erosion from cliffs	7	3900
Supply to saltmarshes	11	1.26 X 10^4
Deposition on intertidal zone	200	2.69 X 10^5
Deposition on subtidal zone	230	1.91 X 10^5
Tidal flux at mouth	1.2 X 10^5	0.8-1.5 X 10^9
Output from Holderness	5200	3.12 X 10^6
Net marine exchange	~100	-

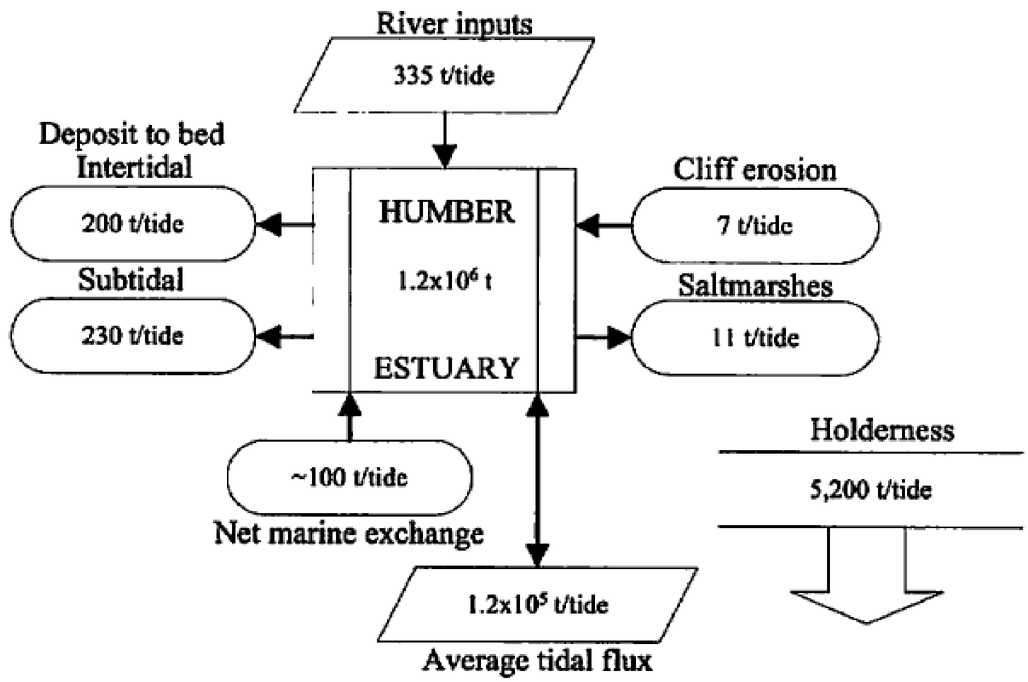

Figure A4. Sediment budget for the Humber estuary (Townend and Whitehead, 2003)

1.1.5. Erosion and Accretion

A general trend of accretion within the Estuary was observed during 1851-1936. During this period the main areas of accretion were located at Grimsby Middle, Middle Shoal, Foul Holme Sand and around Read's Island. Since 1936 however, many areas have been seen to erode whilst the Estuary as a whole has displayed a tendency for landward transgression. This has been achieved by the greater erosion of the intertidal area near Grimsby and greater accretion in the Inner Estuary (ABPmer, 2010).

According to Environment Agency (2000), erosion and accretion in the Humber in the near future is likely to be a response to accelerated sea level rise. An erosion of the upper intertidal zone and sides of the channel in the outer estuary will provide sediment to the inner estuary where it will be deposited on the intertidal allowing the estuary to migrate landward. Furthermore, the middle and outer estuary, perhaps seaward of Skitter Ness, will suffer progressive erosion of the upper intertidal areas. This erosion is already occurring along the southern banks of the estuary and on exposed banks in the north, such as at Hawkins Point.

Accretion in the estuary is predicted to occur on the upper intertidal areas, particularly the saltmarshes, of the inner estuary, perhaps landward of the Bridge but increasing into the tidal rivers. The restricted area of such saltmarsh in the Humber, as a result of the extensive reclamation in the past, will mean that deposition sites are limited and the excess sediment may be either deposited in the subtidal channels or exported from the system (Environment Agency, 2000).

2. Appendix 2: Study Area

2.1. Welwick

2.1.1. Site background

Welwick lies on the northern shore of the outer reach of the Humber, some 9 km from the estuary mouth. The site is located towards the western end of Sunk Sand and Trinity Sand, an extensive area of intertidal flats, which themselves lie in the lee of Spurn Head. Immediately in front of the site, the estuary is around 9 km wide at high water mark, but narrows to around 5 km just to the west. The flood defences comprised an earth embankment topped in places by gabion baskets and fronted with light rock armouring (approximately 300–500 mm diameter). The area in front of the current flood bank is composed of mudflat and saltmarsh, which forms part of the Humber Estuary SSSI, the Phase I Humber Flats Marshes and Coast SPA and Ramsar Site and the Humber Estuary SAC (Pontee *et al*., 2006).

Analysis of old Ordnance Survey (OS) maps shows that in 1892 the site was composed of mudflats with a low-density creek network draining towards the estuary. Landwards of the mudflat at this time there was saltmarsh with a more developed drainage system. The first stage of reclamation took place before 1910, when the fields landwards of the current site were enclosed by an embankment. By 1951 the original reek system had been replaced by field drains and another embankment had been built (Pontee *et al*., 2006). By 1971 the site was completely reclaimed, covering a total area of some 54 ha with an originally elevation from around 2 to 8 mODN (Pontee, 2007).

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2.1.2. Objectives

The primary objectives at Welwick were to create between 15 and 38 ha of intertidal mudflat, together with 12-28 ha of saltmarsh and 4-10 ha of grassland (ABPmer, 2011).

Specific objectives for the site are presented fallowing (Pontee, 2007):

- To create compensatory mudflat habitat;
- To leave the existing saltmarsh in place;
- To create additional saltmarsh on the site;
- To create a transition from mudflat to saltmarsh;
- To avoid removing sediment from the site; and
- To avoid excessive earth movement on site.

2.1.3. Realignment approach and construction

To avoid disturbance of overwintering and breeding birds at Welwick, works were restricted to the months between April and August, with the site being constructed over a 2 year period and completed by 2006. For its creation, new flood defences were constructed to the rear of the site with a minimum height of 6.1 m above ODN. The 70,000 m^3 of material required for the defences was obtained from within the site (combination of re-profiling and creation of

temporary borrow pits), with the new embankment seeded and left to stabilise for a year (IECS, 2008a).
The existing seawall was removed in stages over a length of 1,400 m and the wholesale removal rather than creation of solitary breaches was chosen in order to improved connectivity with the wider estuary, to achieve a more accurate re-creation of the type of environments which existed prior to reclamation; to allow the whole cross sectional area of the estuary including the realignment site to respond to estuary wide changes; and to increased energy levels within the site, thereby improving the probability that mudflat habitat will be maintained (ABPmer, 2011).
Breaches were created in the existing saltmarsh in front of the site to increase wave energy. The fronting marsh could not be removed completely because they are designated. The breaches would allow the site to flood and drain sufficiently. The location of the breaches were chosen to minimise marsh losses (approximately 0.4 ha), their width having been assessed by calculating the discharge and considering the critical threshold for erosion of sediment. As such, the suggested breach size was considered large enough for the velocities to be below the critical threshold for erosion (IECS, 2008a).
Re-profiling of the site was required to ensure that a large area of the site stays below the level where marsh vegetation becomes established, thereby ensuring the creation of mudflat habitats. The re-profiling included the creation of a gentle slope from the fronting, existing, mudflats to the rear of the sites (ABPmer, 2011). Levels within most of the site were altered by 0 to 1 m and the material was used to construct the new defences and landscape other areas of the site (Pontee *et al.*, 2006).

2.1.4. Previous assessments of site evolution

An initial 10 year monitoring programme is currently being undertaken to describe both changes to habitat fronting the realignment (in relation to bathymetry, saltmarsh evolution, invertebrates and waterfowl), and to the realignment site itself (in relation to topography, saltmarsh composition, changes to intertidal invertebrates and waterfowl usage)(IECS, 2008a).The monitoring includes Laser / LiDAR topography surveys to determine the degree to which accretion and erosion has generally occurred across the site. The Laser surveys were undertaken for the baseline surveys. The survey was repeated in March 2007, June 2008, April 2009 and June 2011 using LiDAR and comparisons between the resulting elevation models have since been made (Environment Agency, 2012).
According to Environment Agency (2012), the monitoring has found an accretionary trend over the survey period between 2007 and 2011, with an average difference between 2007 and 2011 of +14 cm. The degree of accretion was found to have decreased over time. The main change in elevation took place in the initial year following the breach, with typical elevations increasing by between 0 and 50 cm between 2006 and 2007. The change in elevation in subsequent years has decreased, although increases of up to 40 cm have still been observed at some locations across the site between the 2009 and 2011 surveys. Over the survey period, the majority of change in elevation (accretion) has occurred in lowest (seaward) parts of the site. On the other hand,

erosion was initially noted in the creeks, and continually towards the rear of the site within the created saline lagoons (Environment Agency, 2012).

2.2. Paull Holme Strays

2.2.1. Site background

Paull Holme Strays is situated on the north bank of the Humber, approximately 10 km to the east of Hull and 35 km from the North Sea at Spurn Point, in the middle region of the estuary. The tidal range in this area is approximately 6.4 m with salinity ranging from 11–23 practical salinity units (psu) (Mazik *et al.,* 2007). The scheme is within and/or adjacent to the Humber Flats Marshes and adjacent to the Humber Estuary Special Protection Area (SPA), Ramsar Site and possible Special Area of Conservation (pSAC) (Environment Agency, 2005).

Prior to the creation of the managed realignment site, the land behind the tidal defence was predominantly Grade 2 agricultural land. A number of scattered farms, houses and a gas distribution compound were situated in the flood risk zone with a number of gas pipelines crossing the foreshore. The Paull Holme Strays defences are also necessary to protect a major gas distribution station. As a result of protecting these important built assets, the benefits of ensuring a high flood defence standard at Paull Holme Strays (at about 1 in 200 years) greatly outweigh the costs (Cunningham *et al.,* 2005). Seaward of the defences there was a narrow strip of saltmarsh and an extensive mudflat. The intertidal zone throughout the whole of the reach is within the Humber Estuary pSPA, pRamsar site and pSAC. Post inundation the site has become intertidal mudflat and saltmarsh has started to colonise the site (Environment Agency, 2005).

The defences at Paull Holme Strays are an essential part of the North Humber flood protection system. This protects a large area of floodplain stretching inland and including suburbs of Hull. The flood defence standard at Paull Holme Strays deteriorated during the 1990s. As relative sea level rose, saltmarsh was lost from the seaward side of the earth flood defence banks. In places, mudflat extended right up to the toe of the embankment, which as a result was subject to increased wave action and erosion. The standard of flood protection fell to less than 1 in 10 years (Cunningham *et al.,* 2005).

2.2.2. Objectives

The objectives of the scheme were to provide cost effective flood risk management for the area as well as providing compensatory habitat for flood defence schemes and coastal squeeze losses on the estuary. It was initially anticipated that the site would ultimately create approximately 45 ha of mudflat and 35 ha of saltmarsh (Environment Agency, 2012).

The specific objectives of the managed realignment site were (IECS, 2008a):

- To provide cost effective flood risk management for the area;
- To create intertidal habitat to compensate for that lost through implementation of this and other flood defence schemes in the middle estuary which is compensated on a 1:3 ratio of

habitat loss to creation for direct construction related losses from defence improvement works; and

- To address additional habitat losses arising from coastal squeeze as identified in the Coastal Habitat Management Plan (CHaMP) which is compensated on a 1:1 ratio of habitat loss to creation for coastal squeeze.

2.2.3. Realignment approach and construction

The existing sea wall, protecting the former agricultural land from inundation, was breached at the eastern (50 m wide) and western (150 m wide) sides of the site, approximately 1.5 km apart. Two breaches in the old sea wall were made in order to maximise incursion and drainage whilst avoiding high velocities of a single breach. No sill protection was used on the breaches and large borrow pits were dug in the south-eastern part of the site and opposite the western breach to provide the earth for construction of the new sea wall (IECS, 2008a).

The elevation of the eastern breach is greater than that in the west and, as such, flooding in this part of the site is less frequent and current speeds are low. In contrast, water enters and drains the site on every tide through the western breach and as a result of the strong currents in this area, a deep channel was initially scoured through the existing mudflat and around the area immediately inside the breach (Mazik *et al.*, 2010).

2.2.4. Previous assessments of site evolution

A five-year monitoring programme, which concluded in 2008, included an intensive sedimentation monitoring programme, it was carried jointly by the Institute of Estuarine and Coastal Studies (IECS) and the Centre for Ecology and Hydrology (CEH) (Mazik *et al.*, 2007) and it was the most comprehensive and extensive in the Estuary (Environment Agency, 2012).

The monitoring found a strong correlation between ground level and accretion at the numerous sample locations which were monitored within the scheme. The greatest accretion rates were observed at the sites which initially were at the lowest ground levels. Sites which were initially at mudflat levels (below 2.3 mODN), accreted the most, by 64 cm on average (Environment Agency, 2012).

For elevations typical of mudflats (2.0-2.3 mODN), the accretion during the first year was high (0.23 m), but declined significantly over time (0.06 m at the last year of the monitoring program). For elevations typical of saltmarsh (2.6 m – 3.0 mODN), the initial accretion rates were lower (0.03 m), but also experienced a slower decline overtime (0.02 m at the end of the fifth year) (Environment Agency, 2012). The maximum accretion was observed at elevations between 2.41-2.6 and 2.61-2.8 mODN with up to 0.91 m in any year. (Environment Agency, 2009)

Furthermore, the rate of accretion in the north of the realignment site has been greater than was expected from assumptions made during design. The estimated (including back extrapolation) mean total accretion since the time of the breach to September 2008 was 44.7 cm (lowest site estimate at least 80 cm) for the northern part and 6.65 cm for the southern part (Environment Agency, 2009).

The Paull Holme Strays site is crossed by subterranean gas pipes. It was also important that these pipelines remained securely buried under the sediment of the site. Measurements over the gas pipeline during the monitoring program showed sediment accretion at most stations over the pipe with some scouring immediately around the base of some of the posts, but with no overall cause for concern (Environment Agency, 2007).

2.3. Chowder Ness

2.3.1. Site background

Chowder Ness managed realignment site is located on the south bank of the Inner Humber Estuary upstream from the Humber Bridge.

Prior to the creation of the managed realignment site, the land behind the tidal defence was predominantly Grade 2 agricultural land with an approximate elevation of 2.8 mODN. To the rear of the site there is a track, farm buildings and a road leading to the village of Barton Waterside. A footpath used to run along the crest of the previously sea defence, across one of the fields within the site and behind part of the site on the raised ground.

The land at the rear of the site rose rapidly from 4 mODN to an elevation greater than 7.6 mODN (3 m above HAT), although this gradient decreased from west to east. A raised area ran through the centre of the site in a NNE-SSW direction with elevations rising to over 4 mODN.

2.3.2. Objectives

The initial objective of Chowder Ness was to create 10.5 ha of mud and 0.8 ha of saltmarsh to support a variety of invertebrate and bird species (ABPmer, 2011b).

2.3.3. Realignment approach and construction

As mudflat creation was the main objective of the schemes, and as the sites were largely too high for this to occur, the land was re-profiled to increase the extent of lower areas where mudflat could develop (i.e. below Mean High Water Neap (MHWN)). These works included the creation of a gentle slope from the fronting, existing, mudflats to the rear of the sites to assist drainage (ABPmer, 2011b).

New flood defences were created at the rear of the site to a minimum height of 6.7 mODN. The material for these defences was obtained from within the site from a combination of re-profiling and creation of temporary borrow pits (these were later infilled with material obtained from the seawall removal) (ABPmer, 2011b).

The existing seawall was removed over a length of 570 m (some 200 m remain), to a level of around 1.6 to 2 mODN. This removal, rather than the creation of solitary breaches, was chosen for the same reason described in Welwick case (Section 3.1.1).

The old defence was removed in a series of stages: firstly, removing the rear of the embankment; secondly, the concrete wave return, the bitumen and rock face; and finally, the overall lowering of the embankment (to levels around 1.6 to 2 mODN).

As Chowder Ness was considered relatively small-scale in relation to the estuary as a whole any predicted changes to the hydrodynamics and sediment dynamics were expected be extremely localised and relatively small in magnitude (ABPmer, 2011b).

2.3.4. Previous assessments of site evolution

As with Welwick case, described in Section 3.1.1 an initial 10 year monitoring programme is currently being undertaken to describe both changes to sites fronting the realignment (bathymetry, invertebrates and waterfowl), and to the realignments site itself (topography, saltmarsh composition, changes to intertidal invertebrates and wildfowl usage) (IECS, 2008a). The monitoring programme includes Laser and LiDAR topography surveys to determine accretion and erosion on site. The baseline surveys were undertaken by both Laser and LiDAR. The LiDAR survey was repeated in June 2008, April 2009 and June 2011 and comparisons between the resulting elevation models have since been made (Environment Agency, 2012).

In general, the monitoring results show that there has been an overall accretionary trend, with an average increase between 2007 and 2011 of 43 cm and general values in the order of 10 and 100 cm (IECS, 2008a). The monitoring found continued evidence of creek development at the western end of the site. The majority of this change took place over the first two years following the breach of the site (Environment Agency, 2012).

Errors associated to the LiDAR data were found during this monitoring programme, appearing to occur where vegetation is or has been present. Although vegetation differences should have been filtered out of the LiDAR data it is clear that the accuracy of these measurements may have been affected. However it is assumed that the overall trends within the data sets are accurate (Environment Agency. 2012).

It is important to mention, that the lowest accretion rate of the Humber realigned sites have been found at Chowder Ness.

2.4. Alkborough

2.4.1. Site background

The Alkborough site is located on the south bank of the inner Humber Estuary in Lincolnshire at the confluence of the River Ouse and the River Trent. The flats lie below the village of Alkborough, adjacent to the Trent and Humber and in the parish of Alkborough. The adjacent parishes include Whitton and West Halton. To the rear of the flats is a natural escarpment, which made the flats an ideal location for managed realignment as the rising ground contained the floodwaters. The flats consist of 440 hectares of low-lying agricultural land surrounded by a flood embankment, which was built in 1956 following extensive flooding in 1954. Due to a combination of bank settlement, erosion, and sea level rise the embankment will be compromised within the next ten years.

As the largest realignment site on the Humber, Alkborough realignment scheme formed a key part of the sustainable flood defence strategy detailed within the Humber Estuary Shoreline Management Plan (Environment Agency). This large capacity for water storage will reduce tidal levels throughout the upper estuary, thus delaying the need to raise other flood defences (IECS, 2009).

2.4.2. Objectives

The scheme's main objective was to act as a flood storage area in the event of an extreme flood event. It has been estimated that during a 1 in 200 flood event, the scheme could reduce extreme water levels by more than 150 mm. Providing flood storage at Alkborough has made it possible to defer improvements to other flood defences in the tidal rivers upstream of the site that would otherwise be needed to counter the effects of sea level rise. By creating at least 150 ha of intertidal habitat, the site also aided in compensating for anticipated habitat losses due to coastal squeeze; the new wetlands at Alkborough also aided the Environment Agency in meeting all of their national BAP targets for saltmarsh and mudflat habitat creation for 2006-2007 (Environment Agency, 2012).

2.4.3. Realignment approach and construction

Engineering works began on site in 2005 and in August 2006 the final stage of construction was completed. Much of the inland boundary runs to rising ground, so relatively little new banking was required. The process implied a breach 20 m wide with boulder sill and 1.5 km of lowered defences. In addition the modification to the creek network inside site was required (IECS, 2008a), a long (1.6 km) 'distributor' channel was cut from the breach into the site and it initially had a minimum bed level of around 2.5 mODN. The breach is very narrow and fixed at an elevation which is 30 cm above the level of MHWN; hence, the site is not flooded during every tide and very little wave energy can enter it (Environment Agency, 2012).

On 6th September 2006, the old flood defence bank was breached and on the next high tide, inundation occurred (IECS, 2008a).

2.4.4. Previous assessments of site evolution

A five year monitoring programme, examining the physical and biological development of the newly created habitat at Alkborough site, began in November 2007 (IECS, 2009).

As is common in managed realigned site, initially high rates of accretion were recorded. Accretion rates had continued on the second and third years of monitoring across the site at a slower rate, with the exception of one area (IECS, 2011). Average accretion ranged from 0.02 m to 0.09 m, compared to values of up to 0.06 m during the first year.

The areas of highest elevation and accretion were found along/around the distributor channel where elevations were predominantly greater than 3.2 mCD, reaching a maximum of 3.4 mCD in some parts in 2009. A significant increase in elevation had occurred in most sectors of the site since implementation (Environment Agency, 2012). During the fifth year of monitoring, due to colonisation by vegetation, together with areas of standing water, it was not possible to survey the site as extensively as in previous years, however, in 2011 in the majority of the site elevation is greater than 3.3 m with some areas reaching 3.5 m, particularly in the north eastern part of the site and to the north of the distribution channel. Elevation had reached a maximum in 2010 in most sectors but there was very little increase in it between 2010 and 2011 (IECS, 2011).

Accretion levels on the mudflat outside the site were considered stable and most of the area had remained at an elevation of 0 – 2.6 mODN with the exception of the infilling of a particularly low lying section of the mudflat where significant accretion had taken place (IECS, 2009). A significant decrease after 2008 was observed, in 2010, a negative mean elevation has been recorded with most of this area being between 0 and -1.5 mCD. A further decrease in elevation was recorded in 2011. It is apparent that the mudflats in this area undergo frequent cycles of erosion and deposition (IECS, 2011).

The sediments both inside and outside the realignment site are described as fine-coarse silts, with fine sands being present in some areas, and are typical of the area. No changes in particle size were noted over time although water content and sediment organic content decreased inside the site between 2007 and 2008 (IECS, 2008).

It is important to notice that there has been an accretionary trend throughout most of the realigned site, with an average difference between 2008 and 2012 of +17 cm. It appears that the data may have been negatively biased by a lack of repeatability between some of the surveys for the site (Environment Agency, 2012).

3. Appendix 3: Results

3.1. Welwick

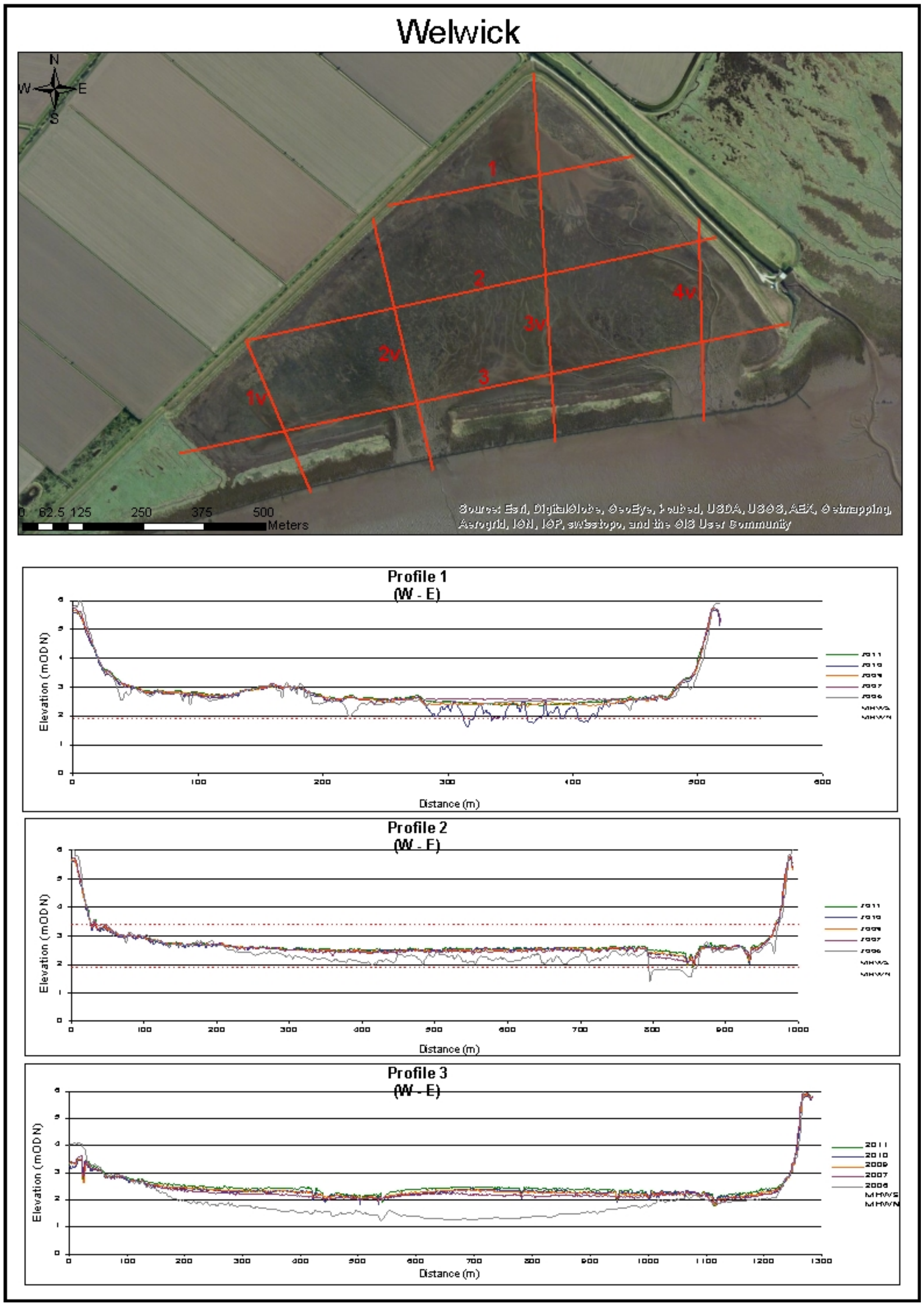

Figure A5. Welwick cross section profiles

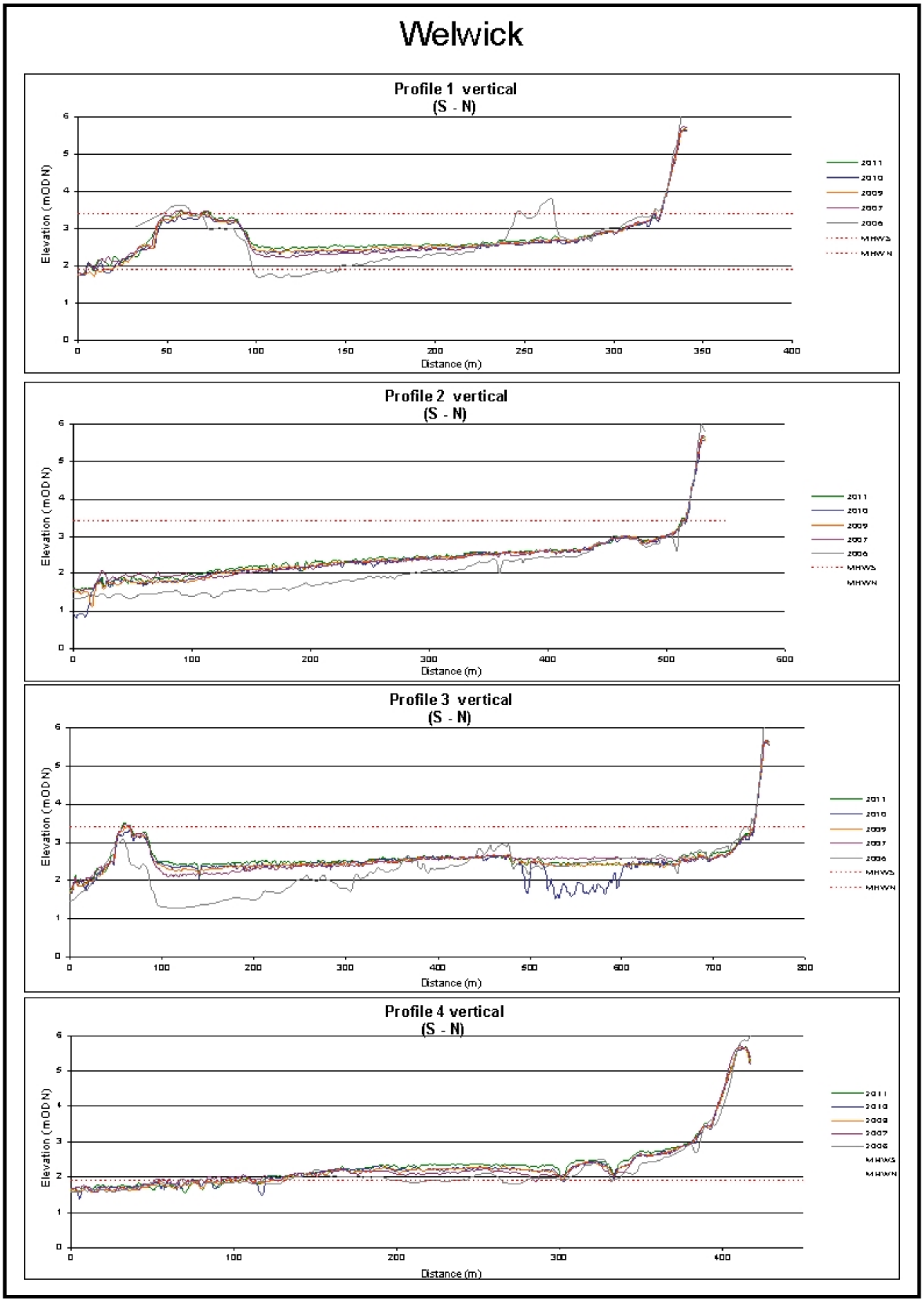

Figure A6. Welwick cross section profiles

3.2. Paull Holme Strays

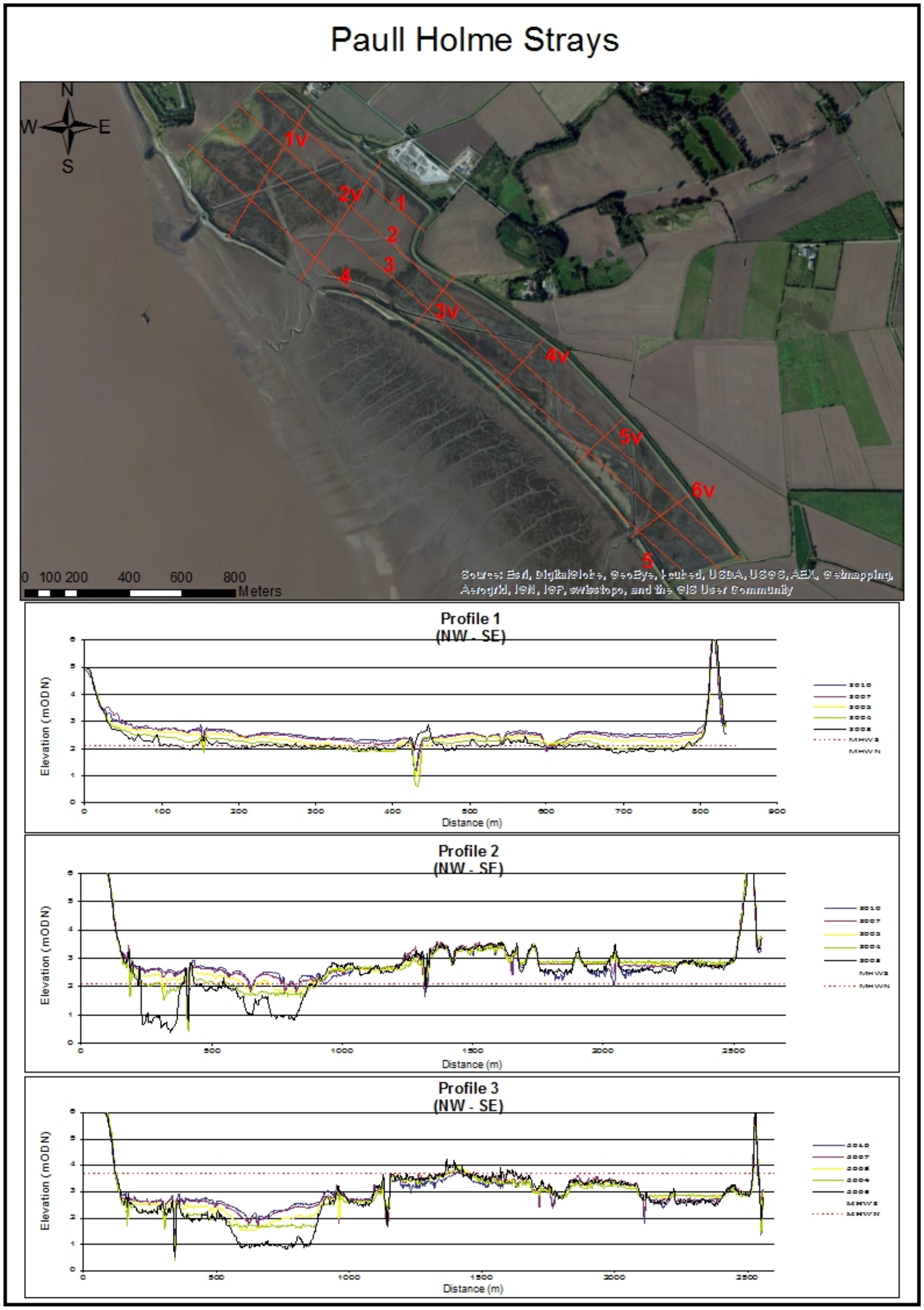

Figure A7. Paull Holme Strays cross section profiles

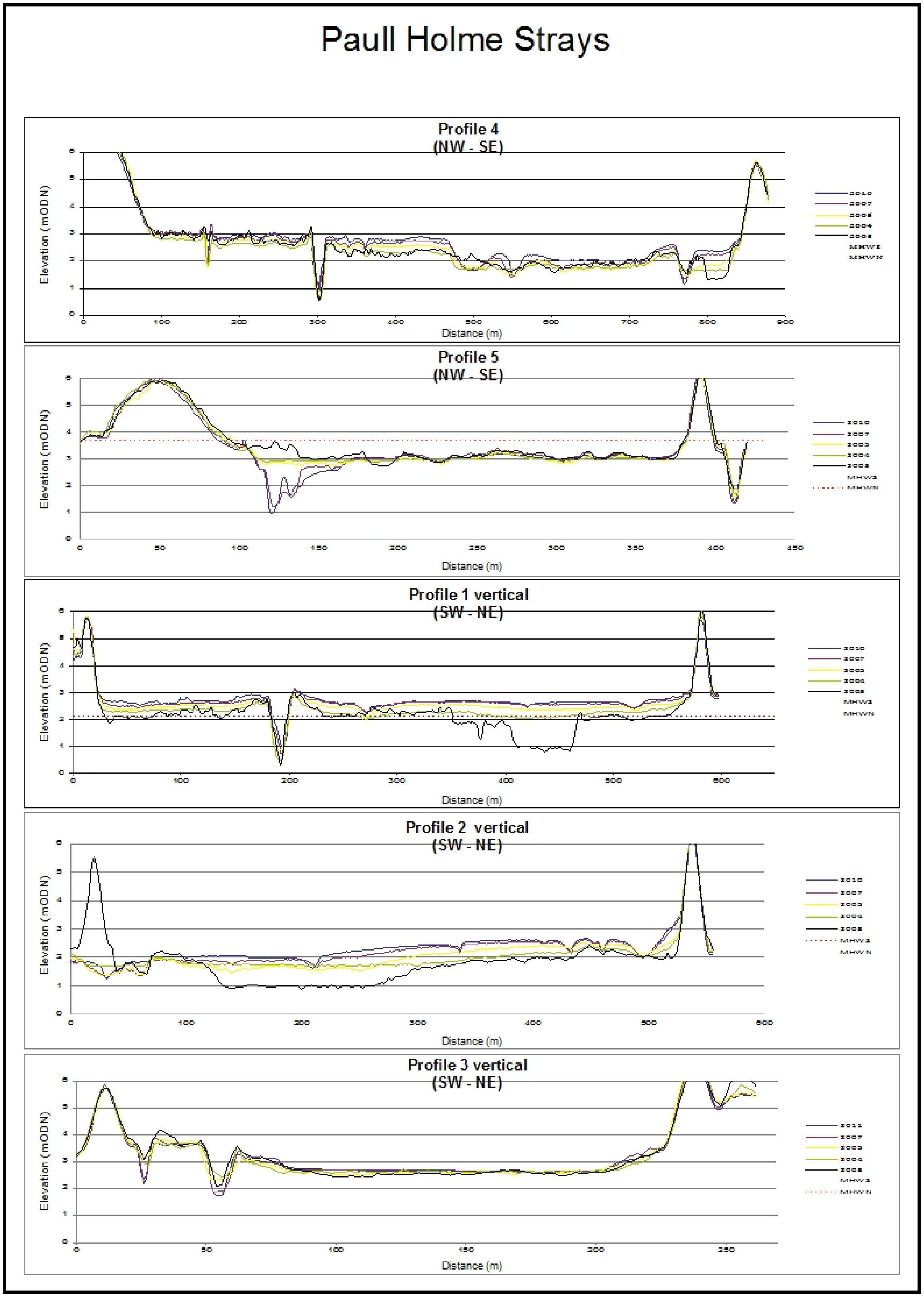

Figure A8. Paull Holme Strays cross section profiles

Paull Holme Strays

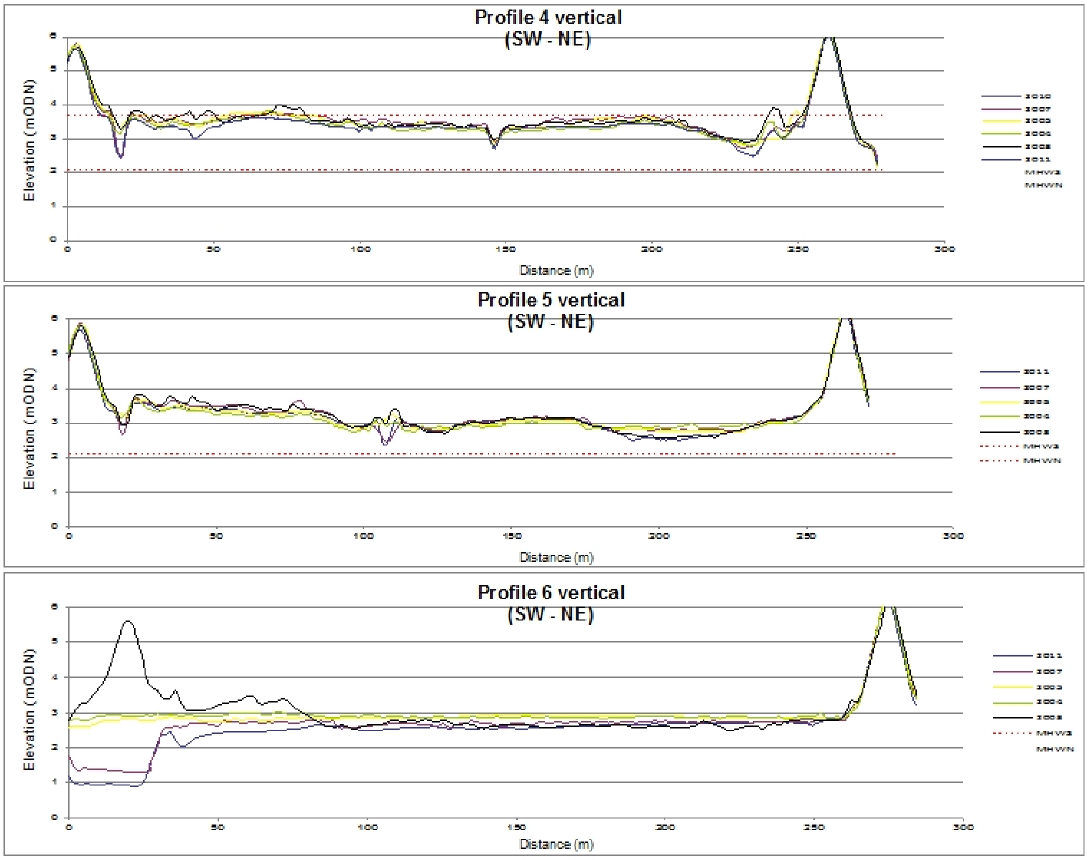

Figure A9. Paull Holme Strays cross section profiles

3.3. Chowder Ness

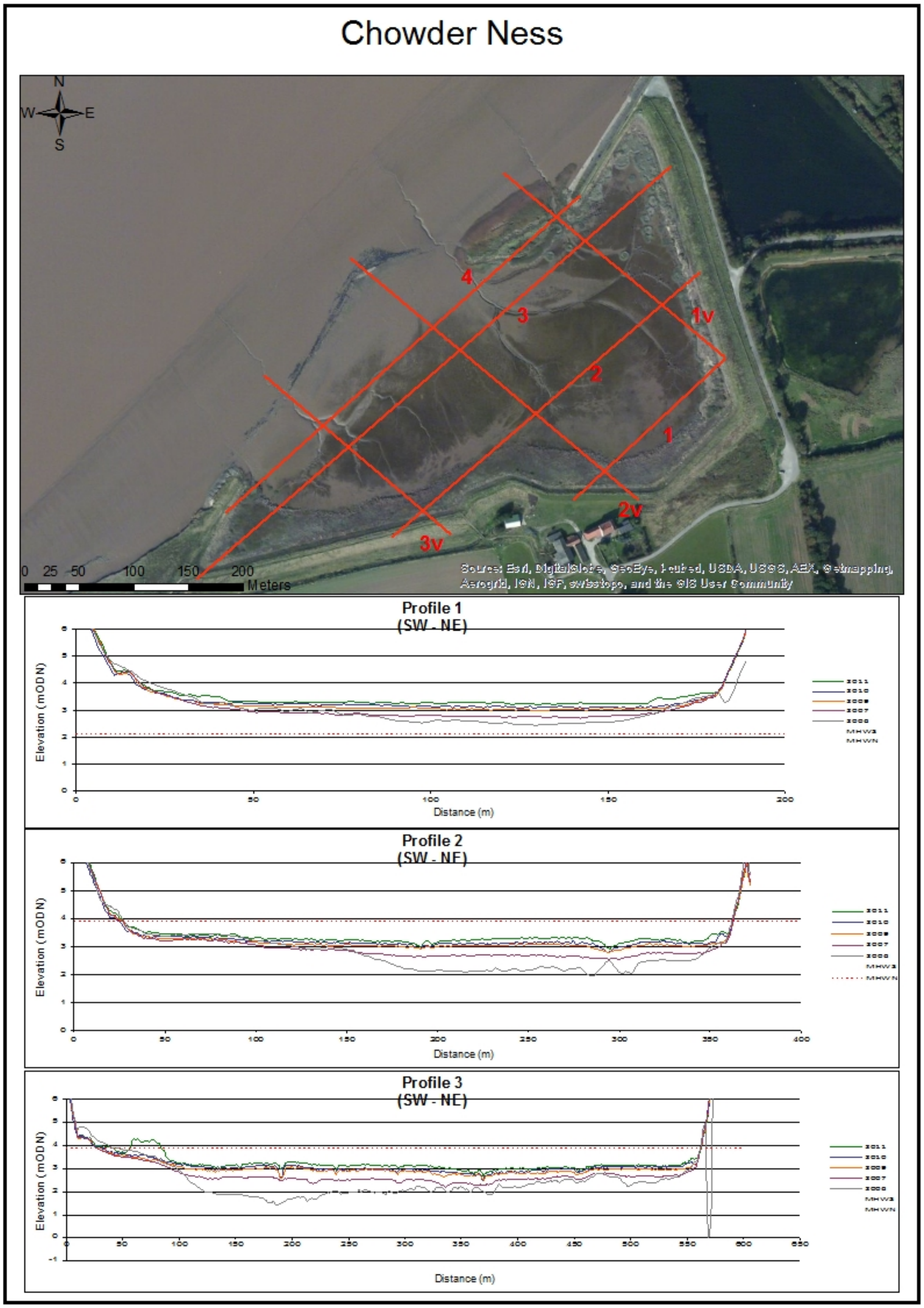

Figure A10. Chowder Ness cross section profiles

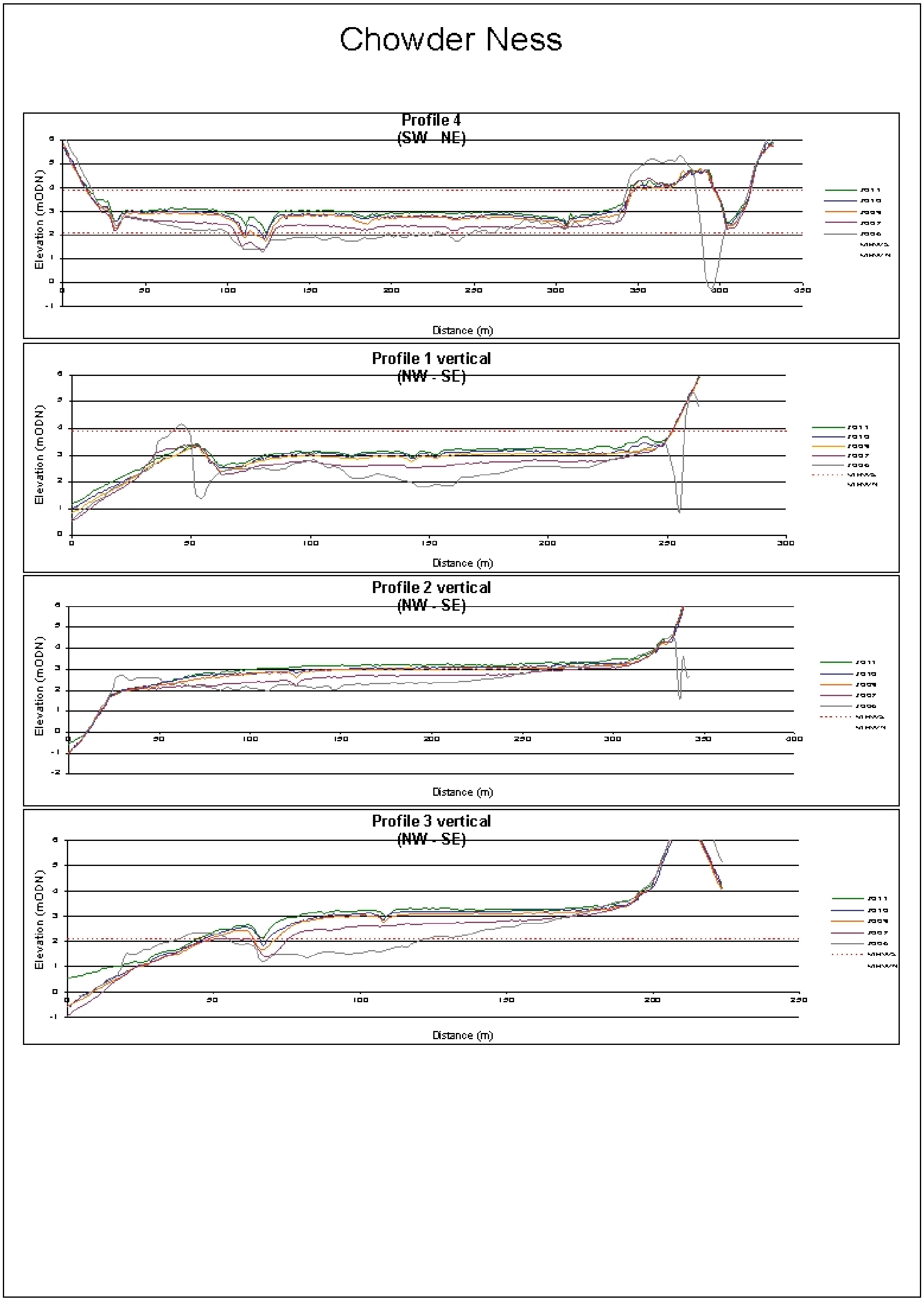

Figure A11. Welwick cross section profiles

3.4. Alkborough

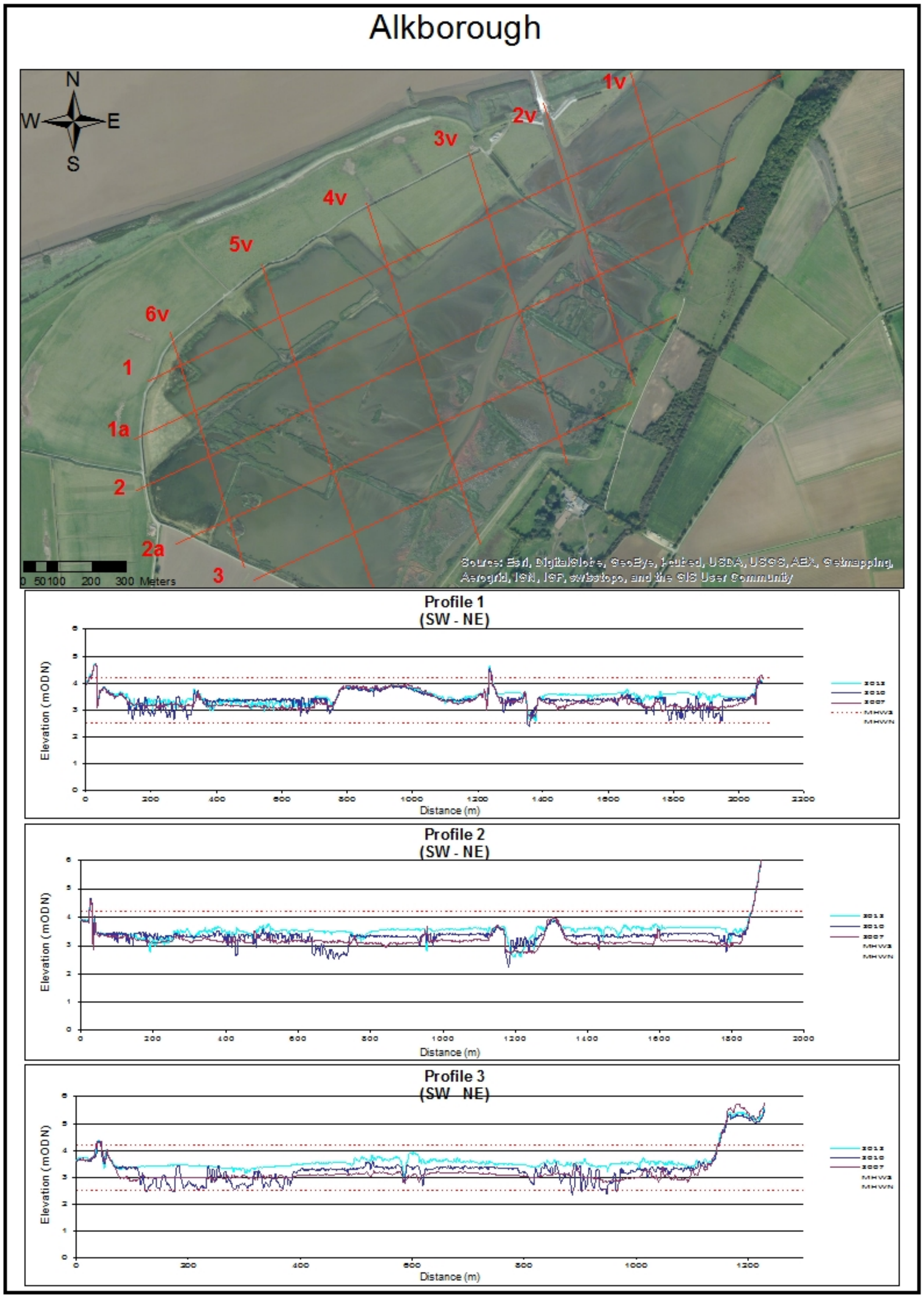

Figure A12. Alkborough cross section profiles

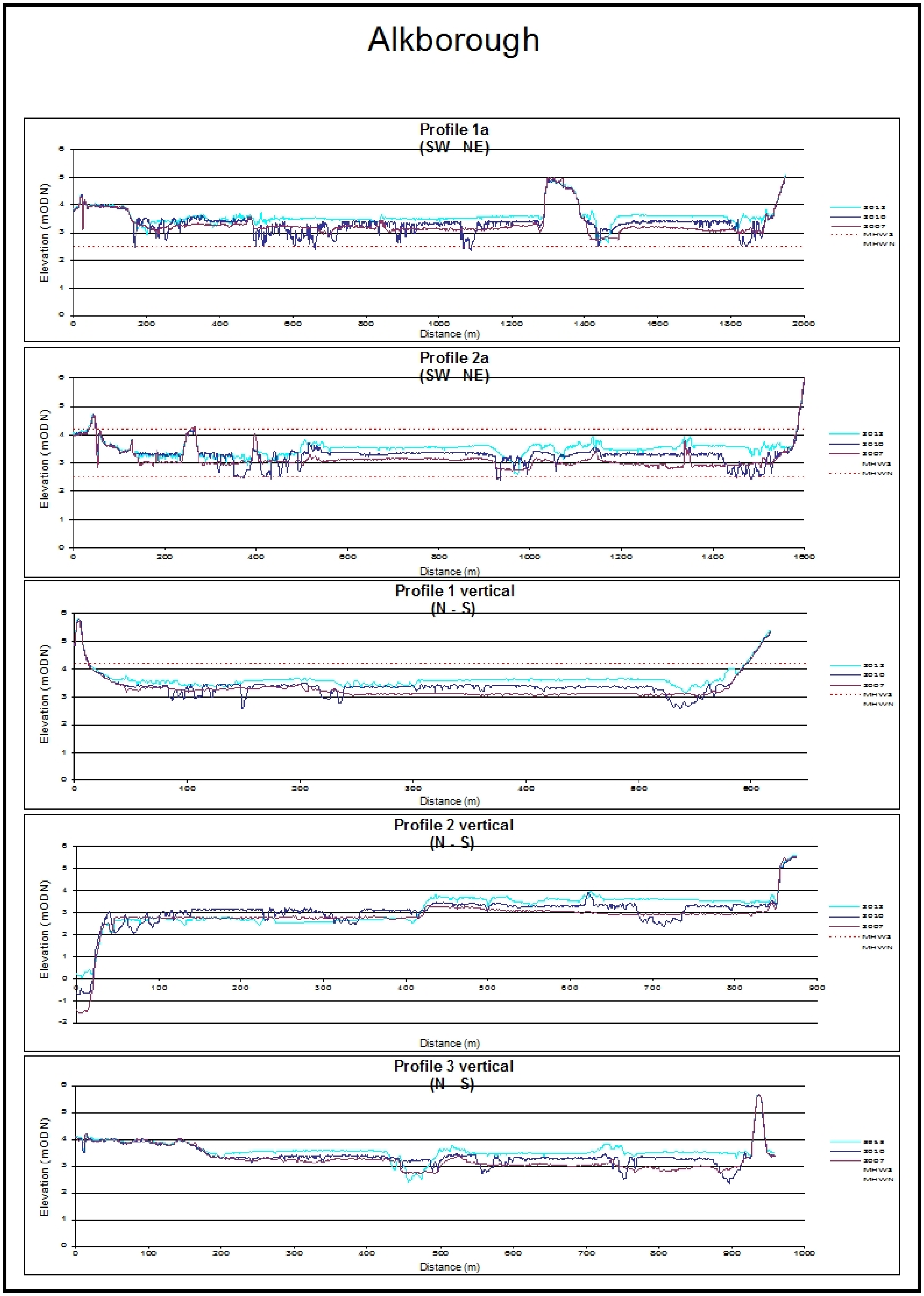

Figure A13. Alkborough cross section profiles

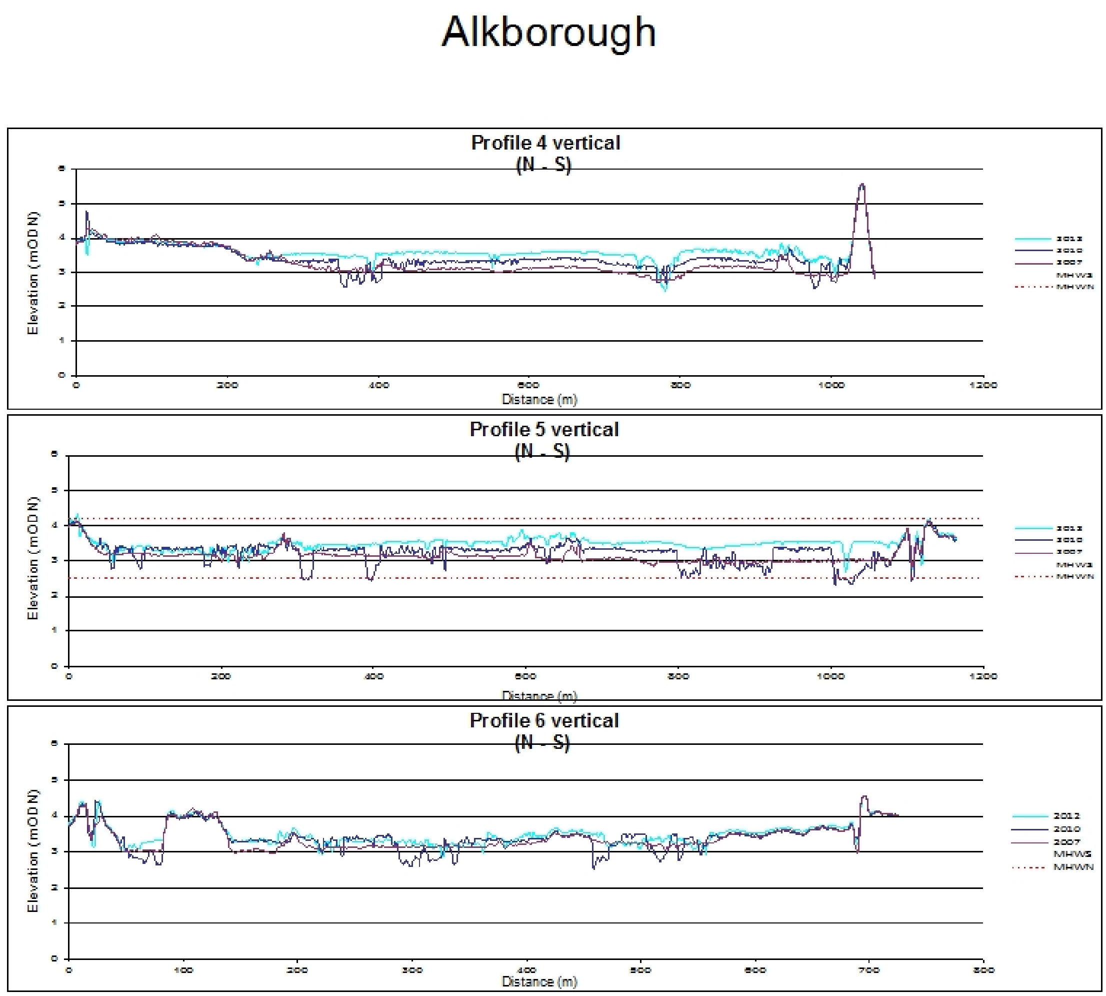

Figure A14. Alkborough cross section profiles