

Coastal Processes Study: East Lane, Bawdsey, Suffolk

Final Report

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Contents

Executive Summary

Focusing on the coastline and coastal processes in the vicinity of East Lane, Bawdsey, Suffolk, this report examines the causes and consequences of past and recent coastal erosion and coastal management. It draws on the evidence base from academic and practitioner studies. Having established the past coastal behaviour the report then suggests how coastal evolution may proceed in the future with due consideration given to the present coastal management and engineering structures, historical trends, limits to prediction and uncertainty.

The report provides a brief review of the contemporary coastal erosion problems at Bawdsey and the chronological sequence of coastal protection measures implemented to offset erosion since the early 1900s. Processes responsible for coastal change in the vicinity of East Lane, including tides and extreme water levels, tidal currents and waves, are examined. Information about the local geology, the behaviour of the primary coastal landforms, and the alongshore erosion, transport and accretion of sediment is used to explain the observed historical and contemporary morphodynamic behaviour of the coastline. Conclusions and recommendations for further investigations are presented.

The key report findings are:

- The major sources, pathways and sinks of sediment affecting the Bawdsey frontage span a geographical range extending from Orford Ness in the north to the mouth of the Deben Estuary in the south.

- As a sediment store and supply system operating at a wide range of time- and space scales, the role of Orford Ness in the wide-area sediment dynamics of the coastline cannot be overlooked and must be accounted for in any coastal management strategy.

- The ‘hard point’ on the coast at East Lane, created by more than a century of coastal management interventions, no longer promotes active alongshore sediment transport due to unfavourable coastal orientation, seaward projection and wave reflection.

- Sediment supply from the north has reduced during the most recent cycle of spit progradation from Orford ness and the accompanying accretion at Shingle Street and has added to sediment starvation to the south contributing to erosion pressure along the Bawdsey frontage.

- There is no paucity of beach sediments between Orford Ness and the Deben Estuary. However, they are unevenly distributed with large amount presently held in the spit extending from Orford Ness and at Shingle Street a little further south.

- It is believed that a plentiful supply of sediment previously received at East Lane will be restored by a natural process of breaching Orford Ness spit at some undefined time in the future. However, reliance on this natural process to restore beach volumes carries a high risk with regards to coastal management.

- The *ad hoc* series of defence works carried out in response to ongoing erosion pressures at East Lane have been a reaction to circumstances. Without a radical change in management policy the defences will require continued maintenance as well as further extension if coastal processes continue to erode the coastline in the manner they have for the past few decades. Since resources to support capital and maintenance works is limited and increasing hard to secure, this is clearly an unsustainable situation.

- It is considered to be unlikely that traditional hard coastal engineering at East Lane can be justified in the future on economic or environmental grounds and it is now timely to begin to seek an alternative sustainable solution while at the same time ensuring the present level of flood defence. It is considered that in the future a coastal realignment, possibly combined with beach recharge, is the most viable low-risk, long-term solution for the frontage.

1 Purpose of Report

Using the evidence base from existing studies, and the local experience and knowledge from the Environment Agency, this report focusses on the coastline at East Lane, Bawdsey and reviews contemporary coastal processes in order to better understand recent coastal erosion and how the engineered and natural sections of the coastline are likely to evolve in the future.

As the local behaviour of a coastline is frequently controlled by processes occurring at larger spatial and temporal scales, Bawdsey cannot be considered in isolation from the wider coastal environment of Suffolk. Furthermore, in order to understand the history of shoreline changes at Bawdsey, it is necessary to have an appreciation of the wider geological setting and sediment supplies, and the marine and meteorological forces and other factors that control and drive coastal changes. This will also help to understand the risks and uncertainties associated with forecasting future shoreline change.

In order to develop, and provide evidence to support an improved conceptual understanding of contemporary and future coastal evolution along the frontage at East Lane, and along the adjacent coastlines, this review has accessed a suitably broad range of reports and other relevant materials. The literature on the hydrodynamics and morphodynamics of the Suffolk coast is extensive, and a good understanding of the main drivers of broad-scale coastal changes has been established. However, this report deliberately focusses on those aspects of the physical environment that are less-well understood and have a direct bearing on local coastal processes and historical erosion problems at Bawdsey. This information has been used to inform an assessment of the potential future coastal evolution at Bawdsey and will in turn contribute to the understanding required to develop options to help alleviate the present erosion problems in the future.

The report comprises the following sections:

- **Section 2: Introduction**: describes the physical setting of Bawdsey, the role of responsible authorities and defines the geographical limits to the present study area;
- **Section 3: Bawdsey Coastal Erosion Review**: presents a review of the contemporary coastal erosion problems to the north and south of East Lane and the coastal protection measures implemented to offset erosion;
- **Section 4: The Coastal Environment:** describes the geology, seabed sediments and features and examines the historical and

contemporary behaviour of the primary coastal features including Orford Ness, Shingle Street, Hollesley Bay, the East Lane frontage, the Bawdsey Manor frontage and the mouth of the Deben Estuary;

- **Section 5: Coastal Processes:** reviews the coastal processes that drive coastal evolution at Bawdsey including tides and extreme water levels, tidal currents and waves;
- **Section 6: Coastal Morphodynamics:** draws on the information in Sections 3 – 5 and describes the present understanding of sediment transport and shoreline behaviour based on historical and contemporary evidence;
- **Section 7: Future Coastal Evolution:** reviews briefly the key evidence presented in the proceeding sections and considers to extent to which prediction of future coastal evolution is possible;
- **Section 8: Conclusions**: presents a summary of the key findings from the study and looks briefly at a range of potential coastal management actions to address the ongoing coastal erosion problem along the frontage; and
- **Section 9: Recommendations**: identifies key elements required to advance the present incomplete understanding of coastal processes at Bawdsey.

Reference works quoted in the report along with a glossary, list of acronyms and notation are provided in Sections 10 to 13, respectively and three Appendices provide: (a) information on the chronological history of East Lane defences; (b) an interesting photographic record of erosion in 2005; and (c) results of detailed shoreline change analysis.

2 Introduction

The primary focus of this report is the artificially maintained headland at East Lane, Bawdsey, Suffolk, located between the mouths of the Rivers Alde/Ore and Deben (Figure 2.1). The headland is identified in the Shoreline Management Plan (SMP, Royal Haskoning, 2010a, b) and is considered to act as a control point on the coast providing some shelter from the dominant NE waves. It is thought also to regulate the net north to south alongshore transport of beach sediments between Aldeburgh and Felixstowe (Halcrow, 1998). Other key locations referred to in this report are shown in Figure 2.2.

The Environment Agency (EA) has responsibility for the coastline to the north of the ditch line immediately to the north of Rose Cottage at East Lane, behind which land is protected against flooding. Further to the north of East Lane, additional defences protect low-lying coastal floodplains dominated by agriculture. The Suffolk Coastal District Council (SCDC) has responsibility for the frontage to the south of this point which comprises low cliffs which are susceptible to losses through coastal erosion. To the south of the headland additional coastal defences protect a Martello Tower (a scheduled ancient monument) and two residential properties.

Figure 2.1: Location of Bawdsey, Suffolk, UK

Source: Mott MacDonald and Ordnance Survey

The Bawdsey frontage is within the administrative area covered by Suffolk Coastal District Council (SCDC). Operational responsibility of coastal defence is shared with the Environment Agency (Anglian Region). Flood defence falls under the remit of the Agency, using powers under the Water Resources Act 1991, whilst coastal protection is empowered to SCDC by the Coast Protection Act 1949. At the northern end of Hollesley Bay, the present management policy for

Shingle Street (Figure 2.3a) is Managed Realignment (MR) leading to *Hold the Line* (HTL). From Shingle Street to East Lane, along Hollesley Bay, MR is advocated. At East Lane the policy is HTL. The policy for the frontage to the south of East Lane along Bawdsey cliffs is *No Active Intervention (NAI).*

Figure 2.2: key locations referred to in the report

Source: Ordnance Survey

In order to define the geographical extent of the present study area, the major sources, pathways and sinks of sediment have been considered. At the local scale the primary study area is indicated in the right panel of Figure 2.1. However, coastal processes affecting this location have origins that extend well beyond these limits, and to reflect this at the larger scale, the northern boundary is defined at the apex of Shingle Street (Figure 2.3a) and the southern boundary at the mouth of the Deben Estuary (Figure 2.3b). Further, the role of Orford Ness in the wide-area sediment dynamics of the coastline cannot be overlooked and is also examined in subsequent sections with reference to its role in coastal sediment control, storage and supply. Similarly, the complex system of gravel shoals that comprise the ebb tidal delta of the Deben Estuary have a role in alongshore sediment exchanges and are also considered (Figure 2.3b).

Figure 2.3: (a) Shingle Street looking north towards Orford Ness; and (b) mouth of the Deben Estuary looking north towards Bawdsey.

Source: Haskoning, 2010a, courtesy of Mike Page.

3 Bawdsey Coastal Erosion Review

In this section the past and recent coastal evolution at Bawdsey is reviewed alongside a narrative describing the coastal management actions undertaken in response to coastal changes. A chronological summary of coastal events and management interventions between 1881 and the present day is provided in Appendix A.

3.1 History: East Lane, Bawdsey

Historically, Bawdsey has been a site for National defence including: (a) Martello Towers built during the Napoleonic War between 1805 and 1808 (Figure 3.1); (b) first World War pillbox, field coastal battery and a gunnery observation tower (Figure 3.2); and (c) a Second World War field gun battery. Hard defences to protect WW1 installation from coastal erosion were installed around 1915. Additional coastal defences comprising timber groynes were installed around 1920 in response to increasing beach erosion along the frontage. Historical evidence of ongoing erosion indicates that these were only partially successful in intercepting alongshore sediments. More substantial coastal erosion defences to WW2 features were installed around 1939. These hard defences were constructed to stabilise the coast and resist erosion, thereby protecting the military interests at East Lane. Over time the defences have acted as a ‘hard point’ creating a headland with a ‘soft’ coastline on either side subject to erosion. Selected images showing parts of the original defences are shown in Figure 3.3.

The existing WW1 and WW2 defences were repaired as required during the period 1949 to 1971. In the subsequent period up to the early 1980’s defences were maintained in a piecemeal fashion as damage occurred. During this time, erosion of the coastline to the north and south of East Lane continued making the headland more pronounced as the land either side was set back. It is important to note that the local changes in coastal orientation brought about by the erosion immediately north of the headland, as well as the further development of the headland feature acted to reduce the wave incidence angle thereby reducing the alongshore transport rate. This in turn contributed to a net loss of beach material to the south as the sediment supply was reduced. Furthermore, the accompanying lowering of beach levels to the south promoted more effective erosion by wave action at the base of the cliffs resulting in accelerated erosion during high-tide and/or storm conditions in particular.

With erosion ongoing up to the mid-1980s the defences at East Lane were deemed by the Anglian Water to be at the end of their useful life and were programmed for rebuilding. However, no significant work was undertaken at that time due to a lack of funding.

Around 1990 the Martello Tower (Figure 3.1) was protected by a shingle beach (width *c*. 20 m) and *c*. 25 m of land. At this time old wooden groynes were in a very poor state and had little control on rates of alongshore transport of beach sediments. It is reported that ongoing coastal erosion in 1996, and a major storm in 1997, removed the entire beach and some of the cliff.

Figure 3.1: Martello Tower at East Lane, Bawdsey (with Phase 2 defences in place).

Source: http://www.nvcc.org.uk/tag/east-lane-trust/ (from Mike Page) and Mott MacDonald (2015)

Figure 3.2: WW1 and WW2 defences, East Lane, Bawdsey

Source: http://www.nvcc.org.uk/tag/east-lane-trust/

Figure 3.3: Selected images of parts of the original defences

Source: Mott MacDonald, February, 2015

In response to the damage to the defences and to severe coastal erosion during the period 1996 to 1997, when further sections of the beach were lost, SCDC carried out emergency works to prevent further damage. This involved repairs to the concrete wave return wall running around the East Lane promontory and to the north, and emplacement of a temporary '*Kentstone*' block work revetment. Two partial collapses of the defences around this time were in-filled with rock armour under emergency maintenance works initiated by the NRA Operations Department. To the south of the sheet piling area (Figure 3.3), approximately 200 m of rock was deployed in order to provide protection to the earth embankment and soft cliffs further south. This had the primary objective of halting the erosion of the cliffs which had escalated at that time to unprecedented rates in excess of 1 metre per month.

While improving the local coastal erosion protection, these works also served to exacerbate erosion immediately to the south. With the residual design life for the temporary revetment only 3-5 years, and the poor condition of the EA flood embankment to the north of East Lane, the inland villages of Bawdsey and Alderton were exposed to increase the flood risk (as well as the potential loss of the Martello Tower), and thus it was evident that a long-term solution to the coastal erosion problem was well overdue.

In the 2003 PAR to address the problem (Royal Haskoning, 2003), the preferred option (Option 9) comprised:

- Strengthening/extension of the rock revetment around the promontory, keying into the existing revetment and where possible re-using existing rock, to a 1:100 year standard of defence (Year 0, EA responsibility);
- Construction of a more robust rock armour revetment along the soft cliff line in front of the East Lane properties (Year 0, SCDC responsibility); and
- Construction of a more robust rock armour revetment along the earth embankment to the south of the promontory in year 10.

In pursuit of a solution it was found that the 'priority score', defined by grant-in-aid funding criteria, was not sufficient to guarantee funding for a combined long-term approach to the erosion problems. Taking matters into their own hands, a group of local landowners and residents set up the East Lane Trust (ELT) in 2004 with the stated aim of promoting, facilitating and raising funds for the rebuilding and maintenance of the local flood protection and coastal defences. The core initiative of ELT was to acquire and then sell land at development value to generate the required funds for the implementation of a new coastal defence scheme.

Meanwhile, erosion south of East Lane point by 2005 (Figure 3.4; Figure 3.5) created some immediate problems (e.g. by 2005 the Martello Tower stood only 10 m from the cliff edge), and to delay the inevitable loss of the EA flood embankment, Suffolk Coastal District Council (SCDC) undertook further emergency works along the frontage while grant-in-aid funding or other means was sought.

Figure 3.4: Coastal erosion south of East Lane point: (a) 1996; and (b) March 2005.

Source: (a) HR Wallingford, 2008; (b) Environment Agency.

Figure 3.5: Details of coastal erosion south of East Lane point, November 2004.

Source: Terry Oakes Associates Limited

Figure 3.6: South of East Lane point (a) before repairs in 2005; (b) after repairs in 2015 (from approximately the same vantage point).

Source: (a) EA (2010); and (b) Mott MacDonald, February 2015.

The rate of erosion in the embayment to the south of the Martello Tower during 2005 was captured by the artist Bettina Furnée in a work called '*Lines of Defence'*. With Bettina's permission monthly snapshots of the cliff recession are included in Appendix B. It is noted that in total, the cliff receded 17 m in 12 months. The tide/surge/wave conditions during

2005 were essentially the same as those pertaining in previous or subsequent years, and thus the extreme erosion recorded in 2005 was probably related to the very low beach levels at that time which frequently exposed the cliff base to wave attack. This process was probably further exacerbated by the nature of the defence termination which may have acted to reduce sediment delivery into the embayment from the north. Unequivocal evidence to support this view is unavailable at present.

In 2007, the EA undertook *Phase 1* emergency improvements to their defences north of East Lane Point (Figure 3.7). Despite the increased rate of cliff cut-back to the south threatening the loss of the Martello Tower, and a significant increase to the flood risk to the inland villages of Bawdsey and Alderton, *Phase 2*, which included the EA and SCDC frontages to the north and south of the Point, respectively, could not be implemented because grant-in-aid funding was still not available.

Figure 3.7: EA Phase 1 repairs, north of East Lane point.

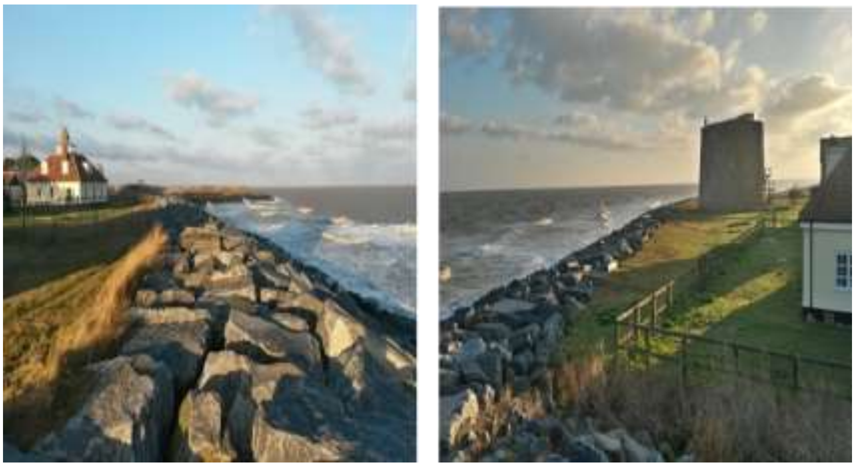
Source: Mott MacDonald, February, 2015

Through the use of a Planning Agreement (Section 106) the SCDC were assured of receiving the profits from the sale of the land initiated by the ELT and therefore had the confidence to pursue the design and necessary approvals for the *Phase 2* coast protection scheme. The ELT donated proceeds from the sale of three parcels of land to the Council who then let and managed the Works Contract valued at £2.2m. As their contribution to the scheme the Environment Agency agreed to cover any contingency costs. This was a landmark initiative (Morris *et al*., 2014) brought about by a strong Partnership between ELT, SCDC, EA, Senior Elected Members and the local MP, land owners, three Parish Councils (Bawdsey, Alderton and Hollesley); and the residents.

English Heritage and Natural England were consulted during the development and approval stages of the scheme.

With all the necessary permissions in place, work on *Phase 2* commenced on site in October 2008 and was completed in the summer of 2009. The scheme involved the construction of rock armour revetment in front of soft cliffs. This was intended to reduce erosion at this location. In total 22,000 tonnes of *'granite*[1]*'* (according to the press) were brought by barge from Norway, each boulder weighing *c.* 6 tonnes, to make 'rock armour' for *c.*350 m of cliff protection. The works have a design life of 50 years and were completed at a cost of *c.* £2.4m in the summer of 2009 (Figure 3.8).

Figure 3.8: Sections of the Phase 2, south of East Lane point.



Source: Mott MacDonald, February, 2015

Since 2009 the focus of erosion has merely shifted *c.*150 m southwards. Within 2 months of completing *Phase 2*, waves still reached the base of the cliffs and regular cliff falls were still taking place. Although at present the 'rock armour' is ''*holding up well and performing as intended*'' (Fell-Clark, letter to the Editor, East Anglian Daily Times 6.2.10), the shingle beach in front of the revetment appears to be denuded.

The southern end of the revetment south of East Lane has proven to be especially problematic. Figure 3.9 shows the erosive conditions at the termination in 2006 and the accompanying erosion of the embayment.

[1] In fact, much of the material is Larvikite and Gabbro, with a large proportion of French Carboniferous Limestone

In response to this problem the southern end of the defences was terminated with a rock armour ‘fishtail’ groyne (Figure 3.10). There is some evidence that this structure has reduced the rate of erosion along the northern end of the embayment.

Figure 3.9: Erosion at the southern termination of the defended frontage in 2006.

Source: http://www.stacey.peak-media.co.uk.

Figure 3.10: The rock armour groyne southern termination of the defended frontage in 2007.

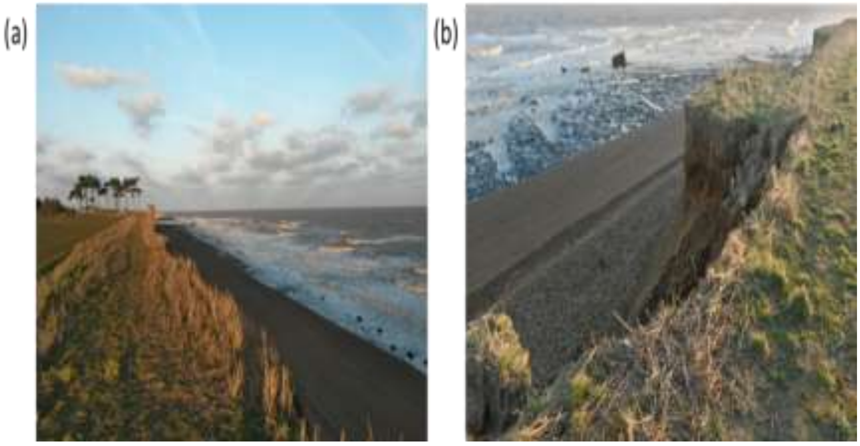
Source: http://www.stacey.peak-media.co.uk.

Figure 3.11: Beach conditions south of the rock armour fishtail groyne termination in February: (a) 2007; and (b) 2015.

Source: http://www.stacey.peak-media.co.uk and Mott MacDonald, 2015.

Sediments in the embayment south of the Martello Tower (Figure 3.11) have varied significantly in depth and width. It is understood that gravel-size beach materials, presently comprising the bulk of the beach material in the embayment south the Martello Tower, originate from the material eroded from the cliffs, offshore sources and possibly a small contribution from the north. Should this be transported away by whatever means, the cliffs would again be exposed to wave attack and erosion would again precede quickly until such time a beach re-establishes. Further, given the present deficit of beach sediments to the north of the frontage, and the significant projection of the East Lane 'headland' from the 'natural' coast, there is little evidence to suggest that significant quantities of sediment can be delivered to this location from the north and thus any losses must be replenished from cliff erosion (or possibly by sediment from the south during infrequent favourable wave conditions). At the present time, the embayment beach appears to be relatively healthy and affording some protection to the cliffs (Figure 3.11b). In part this can be attributed to the performance of the fishtail groyne at the northern end of the embayment.

Figure 3.12: Present day cliff erosion along the embayment: (a) last year's cereal crop on the cliff edge; and (b) a typical example of cliff failure.



Source: Mott MacDonald, 2015.

However, although the beach may be reducing local cliff erosion, there is still compelling evidence that the cliffs along the embayment to the south of the Martello Tower are still actively eroding, with the stalks of last years (2014) cereal crop evident on the cliff edge (Figure 3.12a) and recent cliff falls (Figure 3.12b) along the frontage.

Figure 3.13: The remaining section of the Quilters Wall in 2010.

Source: Mike Page, 2010.

In February 2010 a further 12,000 tonnes of rock was brought in to reinforce coastal protection using emergency funding of £1.5m. In 2012 to 2013 further loss of beach shingle along the northern section of the frontage required further emergency works to be implemented at the (Figure 3.13). A landward widening of the embankment was implemented with reinforcement of the seaward face. Repairs to the northern end of the defence line were also undertaken involving installation of a reinforced clay bund to rear of the existing embankment line and the addition of *Armourloc* block work protection to the seaward face over approximately 50 linear meters.

In 2014 further emergency works involved the importation of fill material to reinstate the seaward embankment profile. The work involved overlaying a geotextile with approximately 4,000 tonnes of graded rock armour to construct a rock revetment. Initial works to the northern end of the site covered approximately 80 m of the wall and a small 20 m section was also in-filled slightly further south where an existing gap in the revetment was present (Figure 3.14). The remaining work was complete in March 2015. The emergency works to the remaining section of the Quilters Wall to the north of East Lane were completed in 2015 (Figure 3.15).

Figure 3.14: The remaining section of the Quilters Wall in 2015.

Source: Mott MacDonald, February, 2015.

Figure 3.15: Completion of the last scheme, April 2015: (a) looking north; and (b) close-up the sheet pile/rock revetment section.

(a)

(b)

Source: Mott MacDonald (2015)

3.2 The situation north of East Lane, Bawdsey

Although the report returns later to examine shoreline changes in detail, it is helpful in this historical section to present visual evidence of coastal changes north of the present sea defences at East Lane. Figure 3.16

shows photographs from 2008 of a healthy shingle beach extending northwards from East Lane towards Shingle Street.

Figure 3.16: The beach north of Bawdsey in 2008

Source: Environment Agency

However, since 2008, the beach to the north of East Lane has continued to erode. This is considered to reflect either a reduction in supply from the north to replenish losses or a (temporary) reversal in the net sediment transport direction. A comparison between the beach north of East Lane in 2008 with the same beach in February 2015 is shown in Figure 3.17. There is clear evidence that the beach has narrowed significantly and reduced in elevation. Beach profile measurements presented below confirm this visual interpretation. At the present time, the designated brackish lagoons behind the shingle beach ridges appear vulnerable to coastal squeeze and to a lesser extent inundation by salt water and sediment ingress by overwashing during storms or by breaching in the most extreme case (Figure 3.17). This important habitat is therefore considered to be under threat at the present time.

Figure 3.17: The beach north of Bawdsey in 2008 (left) and 2015 (right).

Source: Environment Agency (2008) and Mott MacDonald (2015)

Figure 3.18: Completed defences in March 2015. The inset shows the defence termination with the natural shingle beach.

Source: Mott MacDonald (2015)

The termination between the most recent costal defence works and the beach running northwards is incomplete (Figure 3.18). In this figure the unnatural angle between the natural beach extending northwards towards Orford Ness and the Bawdsey coastal defences is seen clearly. In late March, 2015 the natural shingle beach was observed to abut the newly completed defences, albeit at an unnatural angle. It will be interesting to see if shingle accretes at this location. It is noted that the present width and height of the shingle beach immediately to the north of the recently completed defences makes it potentially vulnerable to over washing and possible breaching during a severe storm event.

The present condition of these emergency works, and the northern termination in particular, remains a concern for the BCP as the frontage immediately to the north, comprising the natural shingle beach and clay embankment, remain vulnerable to storm impacts if the beach level remains low. As expressed above the normal supply of beach sediments from the north has either been reduced or possibly reversed. It is noted that such changes in the direction and magnitude of natural sediment transport along the frontage are contrary to historical trends and the evidence in all studies published to date and could not have been foreseen during scheme design.

On the basis of this understanding, and the clear evidence presented above, the suggestion that the erosion now evident to the north of the most recent costal defence works is attributable to the EA rock revetment interventions between 2006 and 2015 is not supported by the evidence and is primarily a consequence of the present sediment deficit. How long this deficit may persist remains open to speculation and a clear cause-effect relationship cannot be established without a comprehensive study to provide the data required to quantify processes. It is noted that providing a definitive cause effect relationship at this complex coastal location cannot be expected when the basic data are missing.

3.3 South of East Lane, Bawdsey

While the most dramatic coastal changes have occurred south of the present defences, where erosion has resulted in a deep embayment described and illustrated above, further south, the beach width increases and establishes what appears to be a healthy profile that protects the cliff from erosion (Figure 3.19). Consequently, the well-vegetated cliffs appear to have established a stable profile.

Figure 3.19: The healthy beach south of Bawdsey in 2015.

Source: Mott MacDonald (2015)

Figure 3.20: The sheet pile wall at Bawdsey Manor

Source: Mott MacDonald (2015)

The beach remains wide and well-established until the frontage of Bawdsey Manor, where sheet piles have been installed to protect the property from erosion (Figure 3.20). Unfortunately, primarily due to modification of the wave climate by wave reflections from the face of the sheet pile wall, the beach in front to the piles has been progressively lowered to the extent that waves now regularly reach the sheet piles and prevent the accretion of any sediment transported south from Bawdsey. It is noted also that damage to the groynes occurred during installation of the sheet piles which reduced their ability to retain sediments on the beach.

Further south, on the northern side of the Deben Estuary, there is an appreciable accumulation of shingle and a healthy beach, indicating that coastal processes at this location are able to maintain a balance between alongshore sediment losses and gains, with perhaps more gain than loss judging by the morphology seen during a field visit in February 2015 (Figure 3.21). Sediments lost from this section of the beach pass the mouth of the estuary in a series of dynamic shoals called The Knolls described well by Burningham & French (2006; 2007). The Knolls are considered further below.

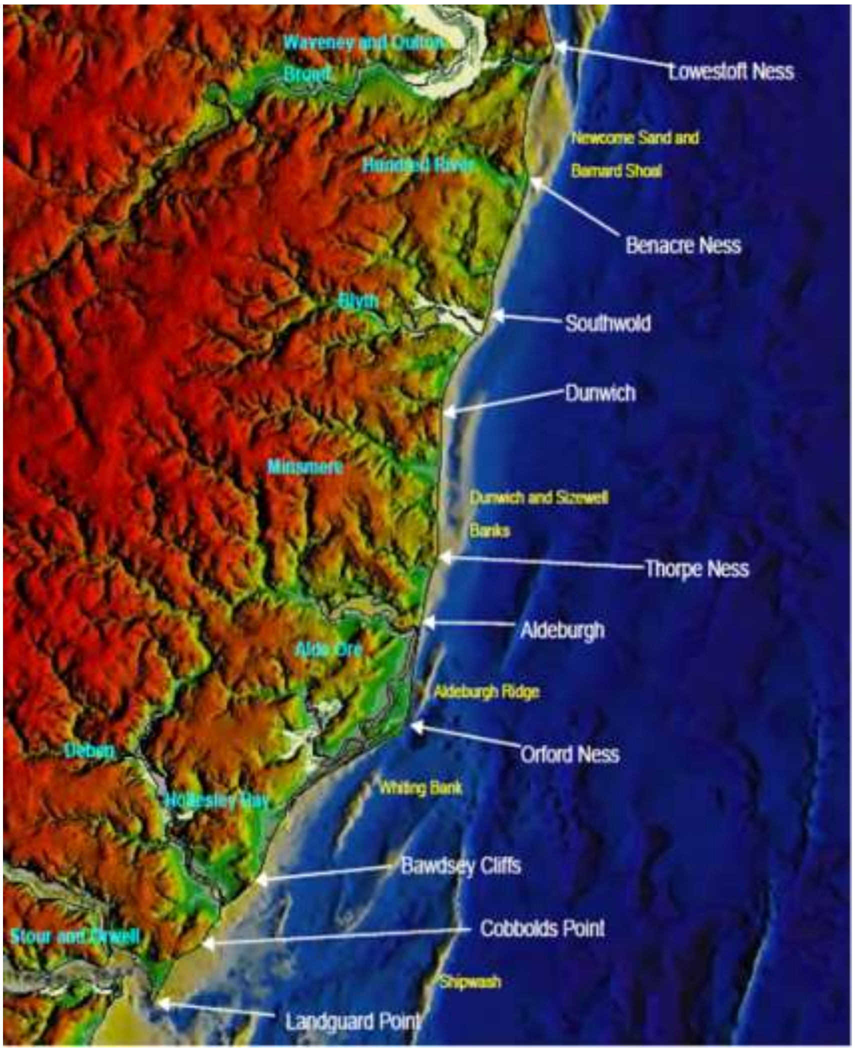
Figure 3.21: The wide beach south of the sheet pile wall at Bawdsey Manor

Source Mott MacDonald, 2015.

4 The Coastal Environment

A general view of the primary topography and bathymetry of the Suffolk coast is shown in Figure 4.1. A point to interest, and a characteristic feature of the Suffolk coast, is the repeated series of embayments between the headlands at Lowestoft Ness, Benacre Ness, Southwold, Thorpe Ness, Orford Ness, Bawdsey and Cobbolds Point.

Figure 4.1: General view of the primary topography and bathymetry of the Suffolk coast.



Source: Royal Haskoning, 2010a, Appendix C.

4.1 Geology

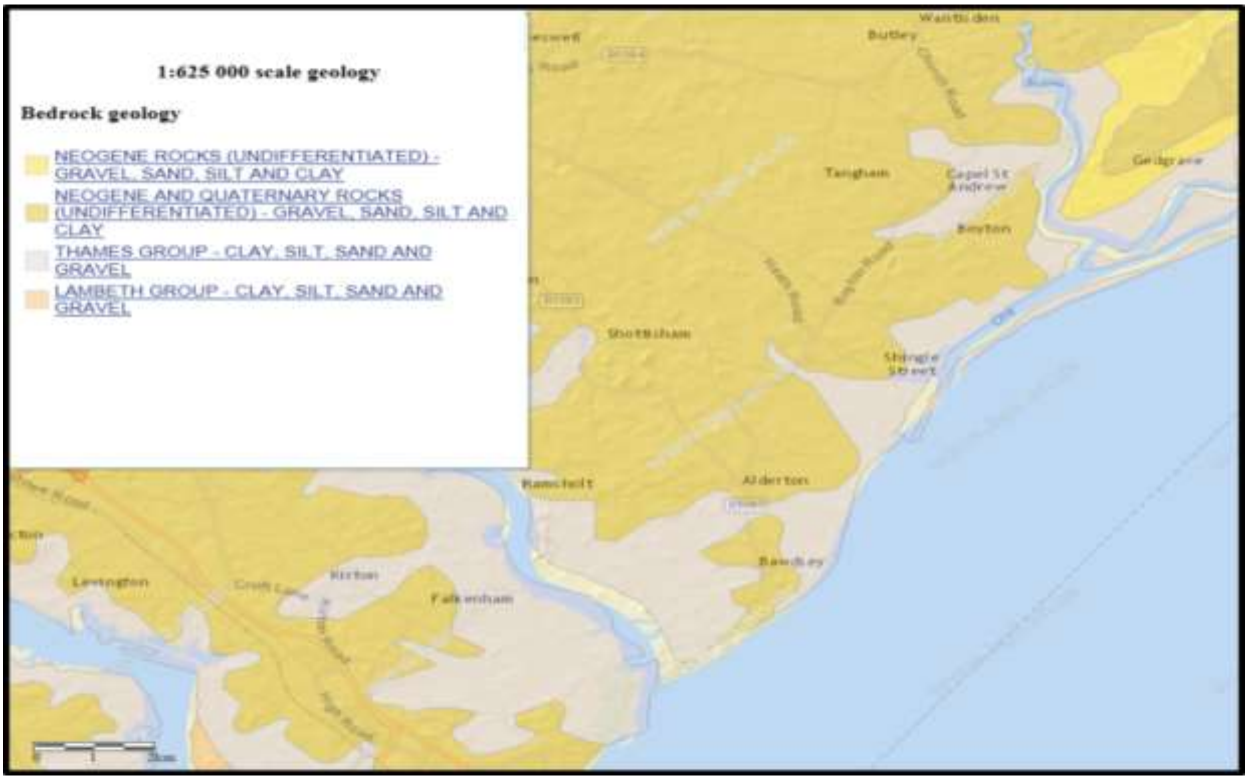
The regional geology provides a context for understanding patterns of change to the East Anglian coastline. Solid and drift geology maps are shown in Figure 4.2 and Figure 4.3, respectively. Here only the most recent marine transgression from the last glacial maximum when sea level was approximately 120 m lower than in the present day is considered. During the period 8000-6000 before present (BP) the sea level rose rapidly and established an overall morphology and bathymetry similar to the present day (Lees, 1980; Eisma *et al.*, 1981; Shennan *et al.*, 2000). From 4000 BP to present, sea level rise has occurred at a rate of 1-1.5 mm/year. There is evidence of accelerating relative sea-level rise in recent years with an average rate of 2.59 mm/year (1956–2009) and 4.65 mm/year (1993-2009) (BEEMS TR139). For the past 50 years, a rate of 2.57 mm/year has been measured at the Lowestoft tide gauge (Woodworth *et al.* 2009). The general effect of sea-level rise is to push the soft shoreline landwards, except at places where coastal processes favour sediment accumulation.

The historic evolution of the Bawdsey frontage is dominated by the evolution of the shingle bank which forms Orford Ness and supplies sediment along the coast to the south. In considering the historic evolution of the Hollesley to Bawdsey shoreline, and Orford Ness to the north, Posford Duvivier (2000) suggest that sea level rise caused offshore sediment to be gradually driven onshore in a generally south west direction. The shingle component was probably initially driven onshore as a ridge to the north of what is now Orford Ness. On reaching the shore, the dominant wave climate forced the shingle southwards towards and beyond what was formally a gentle headland to the north of Hollesley Bay. At the same time the ridge was also being rolled back landward as sea level continued to rise. The consequence of the southward drift and roll-back over the shoreline geomorphology at that time resulted in the formation of a shingle spit. The subsequent growth of the spit southwards forced the River Alde estuary to re-orientate southwards so that by the time Orford Castle was constructed in AD 1165, the spit had grown as far south as the northern tip of Havergate Island.

The dominant stratigraphy comprises: (a) Eocene London Clay which underlies the area; (b) outliers of mid-Pliocene Coralline Crag which lies unconformable on the clay; and (c) late Pliocene Red Crag which overlies both these deposits unconformable. There is evidence also of later Early and early Middle Pleistocene proto-Thames Kesgrave Sands and Gravels. Suffolk's Pliocene Coralline Crag, deposited approximately 3.75 Ma, outcrops as a 12 km inlier ridge running from the north of Aldeburgh south-westwards to the Butley River, with further small outliers, including Sutton, to the southwest, and rests unconformable on the London Clay. The Red Crag is of late Pliocene age, around 2.5 Ma, unconformable overlying the Coralline Crag and London Clay. It was formed in a high energy, shallowing sea dominated by strong tidal currents, with submarine sand waves piling up against the shoreline to the west. Further details of these units are provided in Dixon (1979; 2006).

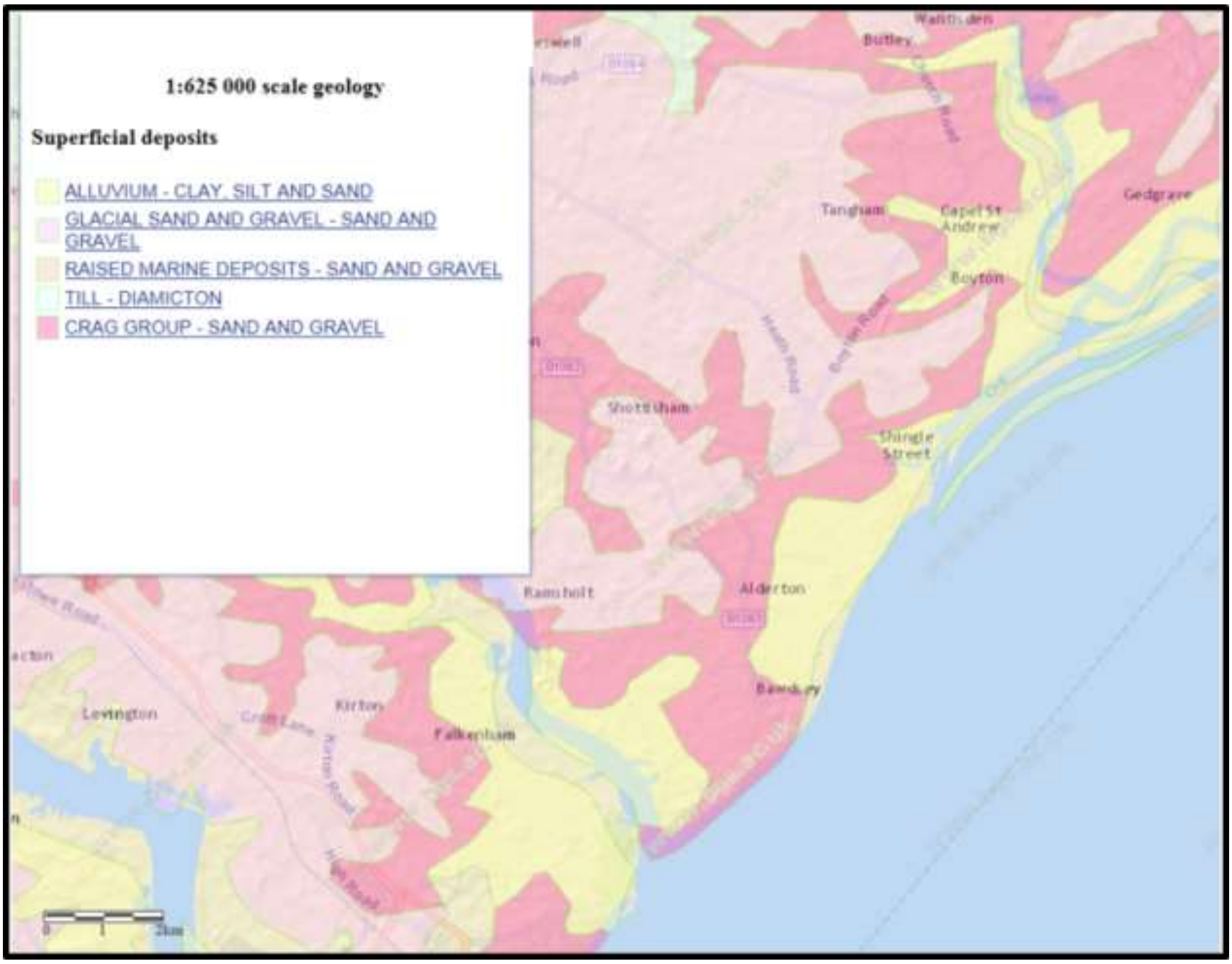
Present day erosion of the cliffed areas to the north of Orford Ness periodically provides large quantities of shingle, sands and clays. These deposits include the medium grained Chillesford Sand, the Chillesford Clay, the Easton Bavents Clay and the sandy, shingle rich, Westleton Beds, collectively termed the Norwich Crag.

Figure 4.2: Bawdsey solid geology



Source: Source: British Geological Survey

Figure 4.3: Bawdsey drift geology

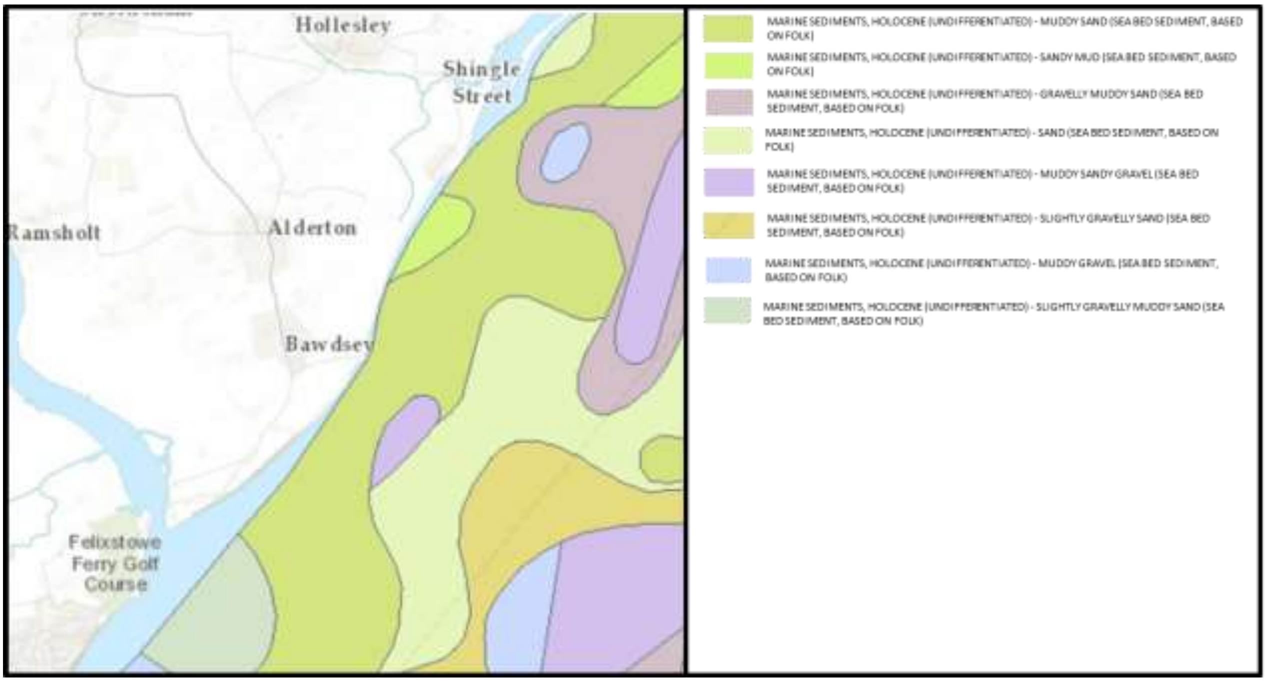


Source: Source: British Geological Survey

4.2 Sea Bed Sediments

Surficial sea bed sediment maps for the southern North Sea have been produced by Cameron *et al.* (1992) and the British Geological Survey (BGS, 1996). A simplified version of this work in the Bawdsey locality is shown in Figure 4.4. Here offshore, the seabed is composed of clayey, silty, fine sands of the Westkapelle Ground Formation overlying the shelly, medium to coarse grained, sands of the Red Crag. The offshore bed is a mix of mud, fine sand and broken shell. There are outcrops of London Clay and channels covered with fine sediment (HR Wallingford, 2002; Burningham & French, 2006). The Environment Agency, National Marine Monitoring Team carried out a sediment survey following the approximate line and bearing of the topographic profiles identified in this study, only mud, sand and London Clay was identified. This makes progression of shingle from bank to bank or offshore unlikely.

Figure 4.4: Seabed sediments



Source: Source: British Geological Survey

4.3 Sea Bed Features

Offshore, elongated banks and channels follow the tidal stream orientated from the southwest to northeast. Whiting Bank, Bawdsey Bank and Shipwash lie 3 km, 7 km and 12 km offshore, respectively, and have a minimum crest depth of 1 m or less below LAT. Closer to the shoreline, The Cutler is a small 3 km-long nearshore bank composed of crushed shells and sand situated just offshore from Bawdsey cliff. While HR Wallingford (2002) suggest links between The Cutler and Bawdsey Cliff, it is clear that the transport is dominantly offshore and the bank neither has nor supports shingle transfer to the beach.

The most important roles of the banks concerns their impact on the nearshore wave climate where bottom friction, refraction and diffraction, and possible wave breaking processes, act to reduce wave energy arriving at the beach, especially storm waves. These processes in turn have influence on the littoral drift of sediments along the shoreline. Further investigation of the role played by these offshore features in the behaviour of the Bawdsey frontage would require numerical modelling of the waves, tidal flows and sediments in order to elucidate the processes and to quantify the amounts of sediment transport.

4.4 Orford Ness

While sea level rise has generally resulted in erosion of the soft coastal geology of Suffolk, sediment accretion has occurred at some locations where coastal processes act to favour accumulation. One such area, called Orford Ness, is situated approximately 13 km north of Bawdsey village. The net flow of beach material along the Suffolk coast from north to south is controlled by Orford Ness (Figure 4.5). Of particular significance to the beaches of Hollesley Bay is the transfer of sediment across the mouth of the Ore onto Shingle Street and its passage southwards thereafter. The Suffolk CHaMP report (Haskoning, 2002) describes Orford Ness a terminal sediment feature and major sediment source of 'primary control status'. The geomorphology and sediment dynamics of Orford Ness are therefore described here in detail.

Figure 4.5: (a) Orford Ness; and (b) North Weir Point

Source: Mike Page

Orford Ness is a shingle cuspate foreland that shows evidence of changes in sea-level rise during its formation (Birbeck College and Babtie (2000, henceforth BC&B). The growth of the ness is evidenced by the past shorelines that remain preserved as shingle ridges. Orford Ness has gone through many variations in plan shape and remains extremely sensitive to wave climate

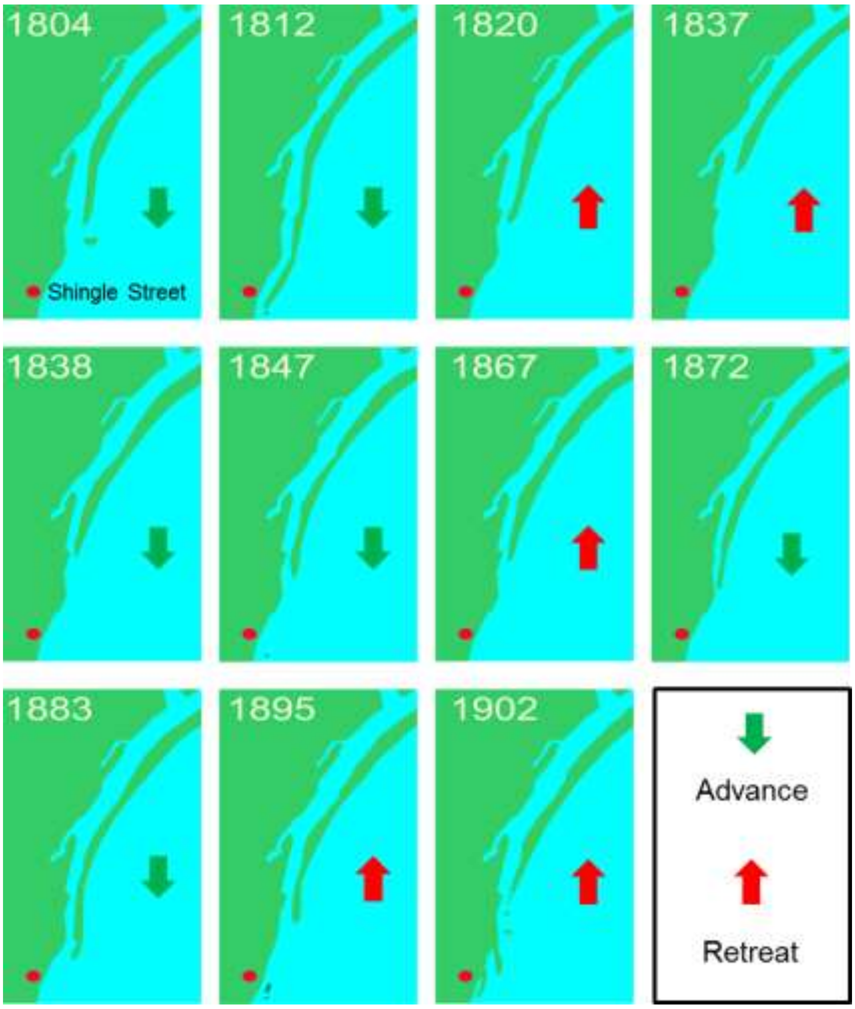
Following the emplacement of Orford Ness during the most recent period of sea level rise, evidence indicates that the spit continued to develop in a southerly direction towards Bawdsey. The earliest available map of the Orford Spit area dates back to the reign of Henry VIII (e.g. Carr, 1969) and appears to show that the mouth of the River Ore was at Chantry Point just to the south of Orford. The whole of the mainland frontage south of Chantry Point is shown as being exposed to the sea. The map also indicated the presence of 'sandbanks' (or more likely gravel) to the south of Orford Ness, opposite what is now known as Havergate Island. However, although a clear spit feature is not shown on the map, comments were made around this time regarding the deterioration of the navigability of the River Ore due to a developing spit and the sever effects on the port of Orford. Carr (1969) demonstrates that subsequent maps produced between the 1600's and 1800 show the spit to have grown beyond Orford and Havergate Island so that by the late 1800's the spit had grown almost to its present length. It is noted that in a report considering the frontage between Orford Ness and Aldeburgh, Clayton (1987) draws attention to the long-term trend for erosion along this frontage.

Cobb (1957) describes the cyclic nature of Orford Spit, which consists of a period of growth lasting for about one hundred years, followed by retreat. Orford Spit is known to have undergone at least two periods of growth followed by collapse since the beginning of the 19th century. In support of this Cobb (1957) states that the spit reached a maximum length in 1811 and again in 1893. In both cases the most southerly location is reported to have been approximately opposite the Martello Tower at the southern end of Shingle Street. The alignment of the shingle ridges along the Shingle Street frontage also supports this theory. Historical changes to Orford Ness spit between 1804 and 1902 are shown in Figure 4.6. These images were derived by Carr (1969) from a wide range of map sources and support the historical view of the spit evolution cycle described above.

It has been widely suggested that there is a critical length the spit reaches prior to breaching. For example it is reported that the end of the spit elongation cycle in 1893 coincided with a sever autumn between the 18th and 20th November which resulted in a breach, followed by progressive retreat in which the isolated portion of the spit formed a series of islands and banks. Over the following two decade these features were driven onto the Shingle Street frontage by wave action creating a series of lagoons which remain partially preserved today. At the same time the spit retreated *c.* 2 km to reach its most northerly known location by 1912. As this retreat distance was almost twice that recorded at the end of the 1811 cycle, and historical evidence indicates that breaching only occurs when the spit reaches its critical length, Posford Duvivier (2000) suggest that this explains why the most recent cycle of spit growth has lasted so long (currently 122 years).

There are three primary mechanisms for spit breaching that may act independently or together: (a) increased hydraulic gradients through the spit caused by a reduction in the hydraulic efficiency of the estuary; (b) direct wave attack, especially during surge/spring tide conditions; and (c) partial blockage of the estuary mouth by storm deposits that increase the hydraulic gradient between the estuary and the open sea at low water. In all cases, an existing weakness in the spit structure is likely to be exploited. Interestingly, the severe storm of 1953 did not cause breaching of the spit indication that storm direction as well as spit length may play a role in the process.

Figure 4.6: Historical changes in Orford Ness spit from 1804 to 1902 (modified from Carr, 1969).



Source: Carr (1969)

Papers by Carr (1965; 1969; 1970; 1971; 1972) provide good summaries of previous work on the dynamics of the spit and consider the role of currents within the estuary, inshore waves and tide levels on morphodynamics. In particular, the discussion by Carr (1986) of historical changes at the mouth of the River Ore over the thirty year period up to 1985, considers the mechanisms of spit growth and decay and how material is transported onto the Shingle Street frontage.

The evidence of southerly directed net alongshore sediment transport around Orford Ness (estimated to be between 70,000 and 130,000[2] m^3/year, Carr, 1972), and the consequential extension of the spit is indisputable. However, the mechanism by which sediment is transferred from the distal end of the spit to Shingle Street is less easily identifiable. If the possibility of sediment supply from offshore to the beaches between Shingle Street and East Lane, Bawdsey, is discounted, (and there is evidence to indicate that this in the case), beaches to the south of the Ore Estuary must receive sediments from Orford Ness via mechanisms that transfer sediment from the spit to Shingle Street. Evidence to support this is provided by the complex of shingle shoals in the mouth of the Ore which are observed to change their morphology frequently (Figure 4.7). Historical changes in this area between 1881 and 1926 shown in Figure 4.8 illustrate well the complex and dynamic nature of the Weir Point area.

Figure 4.7: Shingle shoals in the mouth of the Ore Estuary

Source: http://www.gofishing.co.uk/Sea-Angler/Section/wheretofish/England2/Suffolk/Orford-Ness

[2] Approximately equivalent to the volume of 260 average size UK homes.

Figure 4.8: Historical changes in the Weir Point area between 1881 and 1926: (a) High water line; and (b) low water line.

Source: Environment Agency and Ordnance Survey.

In a study to investigate the shingle transfer mechanism, Steers (1957) reports experiments using a radioactive tracer (Barium 140 - Lanthanum 140) to measure shingle movement at the mouth of the River Ore near Shingle Street. Around 2,000 pebbles were deployed on the main beach of Orford Ness and on off-shore shingle banks of the ebb delta and about 600 marked pebbles were deposited about 700 m off shore in a water depths between 6 m and 10 m. Initially, in January 1956, south, southwest and south-east winds prevailed and the tracer pebbles that could be detected moved northwards an mean distance of around 600 m (max. distance was *c.* 2.2 km) During 20 - 26 February, the wind was generally in the north-east (mean speed *c.* 8 m/s with wave heights *c.* 60 cm) and the northerly drift of pebbles was arrested and reversed. Marked pebbles were found not only on the Orford beach, but on the isolated shingle banks in the haven mouth, and on the beach at Shingle Street.

On the basis of this evidence it was concluded that waves from a northerly quarter, combining with the tidal current, which at springs may reach a velocity of 4 m/s on the ebb in the entrance to the River Ore according to Steers (1957), can move shingle from North Weir Point across to the opposite bank. The path of beach material is considered to be either: (a) up river under the influence of waves and the flood current, or, alternatively; (b) to the shingle banks off shore, aided by the ebb tide. It is suggested that the pebbles which reached the beach at Shingle Street had all arrived by way of the off-shore banks.

The experiment described here, alongside other reported by Kidson *et al.*, (1958) and Kidson & Carr 1959) using labelled pebbles, demonstrated emphatically that shingle moves over the sea floor across a river mouth where ebb and flood currents may be very strong indication strongly that Shingle Street sediments could easily have been transported from the other side of the haven mouth. Interestingly, no movement of the pebbles deployed offshore was detected during the observational period. Here hydrodynamic conditions are very different to those in the river mouth and no direct comparison between the two locations is possible.

By considering the predicted average sediment transport rates of 100,000 m^3/year along Orford Beach, and observed growth of the spit, and using the approach documented by Posford Duvivier (2000) it is possible to calculate how much material crosses the mouth of the estuary. Assuming a typical cross-section for Orford Spit a sediment volume of around 35,000m^3/year is sufficient to sustain a typical spit growth rate of 20m/year (Posford Duvivier, 2000). This indicates that on average only 35% of the material travelling down Orford Beach contributes to the growth of Orford Spit and the remaining material must cross the estuary mouth and reach the Shingle Street frontage. This might be anything between 35,000 and 95,000 m^3/year, depending on the wave conditions. The growth of Shingle Street tends to support this conclusion.

In a study of contemporary behaviour, BC&B used an analysis of beach profile data from 1991 to 1997 to conclude that there is erosion on the northern side of the ness and accretion along the southern side. Erosion appeared to be greater than accretion at the apex, indicating a longer term erosion (or southwards translation) of the ness.

4.5 Shingle Street

Shingle Street is convex coastal projection immediately south of Weir Point formed primarily of shingle-sized sediments (Figure 4.9). Barnes & Heath (1980) discuss the geomorphological history of the Shingle Street frontage, including the results of carbon dating of peat samples from within the bed of the Ore and shingle samples from drillings on Havergate Island. The morphology of Shingle Street is brought about by the net convergence of sediment transported from the north by the mechanisms identified above, and periodically from the south by alongshore transport during southerly wave conditions. Historically, periods of accretion and erosion have resulted in considerable changes to the morphology of Shingle Street. Figure 4.9 shows a clear sequence of beach ridges orientated approximately parallel with the southern shore of the feature indicating accretion and growth southwards. In these photographs, there is also a well-defined storm ridge running parallel to the shoreline around the entire feature demonstrating cross-shore sediment exchanges. Shingle Street is considered to act as a reservoir for beach sediments and has a role in the supply of beach sediments to the south.

The morphological behaviour of the Orford Ness spit and Shingle Street is closely connected and affect the rate of sediment delivery to the south by alongshore transport processes. When the spit is in its most southerly location it provides protection to Shingle Street from north easterly storm waves and Shingle Street accretes by the sediment exchanges mechanism described above. However, when the spit is breached and retreats northwards, increased exposure of Shingle Street to north easterly waves results in erosion and the eroded sediments are then transported southwards into Hollesley Bay. The changing coastal orientation relative to the dominant wave climate along the Hollesley Bay frontage results in a decrease in alongshore transport efficiency towards Bawdsey leading to a gradual widening of the beaches.

The 2003 PAR (Royal Haskoning, 2003, p. 11) states that "*the defence in front of Shingle Street relies on the shingle bank, with the bank adapting naturally, changing in profile and level, to maintain a defence standard in excess of 1:100. As with the main shingle bank around the bay, the size and integrity of the natural defence at Shingle Street relies on the control provided to the coast by East Lane*". This comment is at odds with the net north to south direction of net sediment transport between Orford Ness and the Deben Estuary noted in all documents accessed during the preparation of the present report. Although a notion exists that East Lane Bawdsey acts to hold sediments in place along Hollesley Bay, there is little evidence to support this as demonstrated clearly by the present deficit of beach sediments at the northern end of the East Lane defences.

Shingle Street shows clear geomorphological evidence of accretion from both northern and southern sources and is presently protected from north-easterly waves (most effective for alongshore transport) by the elongation of Orford Ness Spit and the associated shoals.

Figure 4.9: Shingle Street: (a) Looking north towards Orford Ness; and (b) well-developed gravel ridge beach structures.

Source: Mike Page.

4.6 Hollesley Bay

As Orford Ness was evolving in the manner described above, the coastline in Hollesley Bay, between Shingle Street and the mouth of the River Deben, was also developing and retreating in response to sea level rise (Figure 4.10). Here the majority of the coastline comprised low-lying land and low sand and gravel cliffs which were easily eroded by wave action. In some place the rate of coastal recession was checked by the presence of more resistant underlying clay deposits. Posford Duvivier (2000) suggest that underlying harder outcrops of clay have restricted the overall retreat of the coastline, forming shallow bays separated by small headlands, such as that currently observed at East Lane. While there is little evidence to support this view provided by geological mapping of the area which shows main changes in rock resistance to erosion occur around 0.75 km south of East Lane, local geology may be more resistant in the vicinity of East Lane and may have contributed to headland development.

Figure 4.10: Hollesley Bay and related primary coastal features

Source: Mike Page.

4.7 East Lane: Present day

While in recent history the coastline between Orford Ness and the Deben Estuary has been largely undefended, hard defences at East Lane, Bawdsey have existed for over seventy years and follow earlier attempts to stabilise the shoreline using timber groynes. The structures built to protect the military interests at East Lane have created a ‘hard point’ on the coast that has been resistant to erosion. To the north and south of this artificial promontory the “soft” coastline on either side has retreated, most markedly to the south due to the promontory intercepting the net north-to-south alongshore sediment transport. This interception has starved the beach to the south of sediment and has resulted in beach lowering which in turn has allowed waves to attack the soft cliffs at high water.

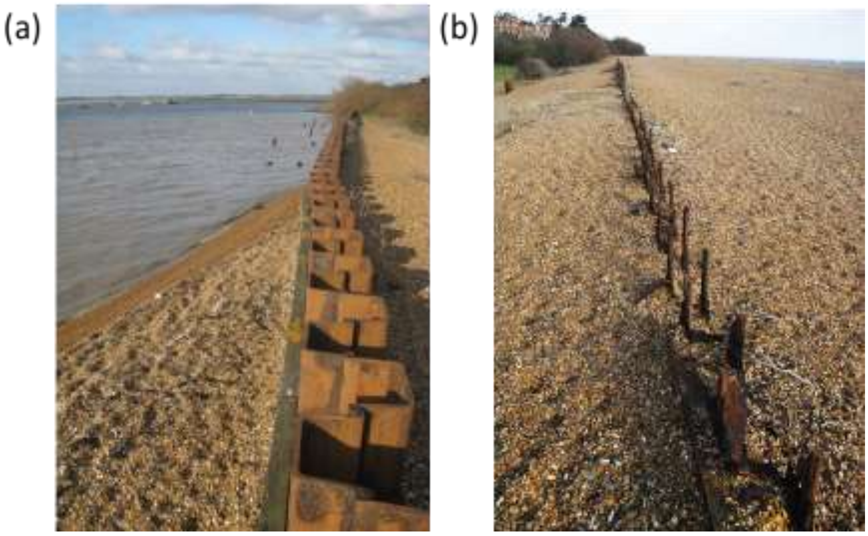
4.8 Groyne field to the north bank of the Deben Estuary

A variable width shingle beach with groynes backed by low cliffs occupies the northerly 930 m of this frontage. The 310 m Bawdsey Manor frontage is defended by a Frodingham steel sheet pile wall 3 m from the toe of the cliff (Figure 4.11) and an older timber groyne field seaward of the piles is in a poor state of repair. The beach at present is depleted of sediments. To the south of Bawdsey Manor there is a 325 m length of shingle beach with steel sheet pile walls at the crest. The parts of these walls not covered by sediment are in very poor condition and have, in many locations, completely corroded (Figure 4.12). The north bank of the Deben Estuary is characterised by a large accumulation of shingle.

Figure 4.10: Frodingham steel sheet pile wall defending Bawdsey Manor.

Source: Mott MacDonald, 2015.

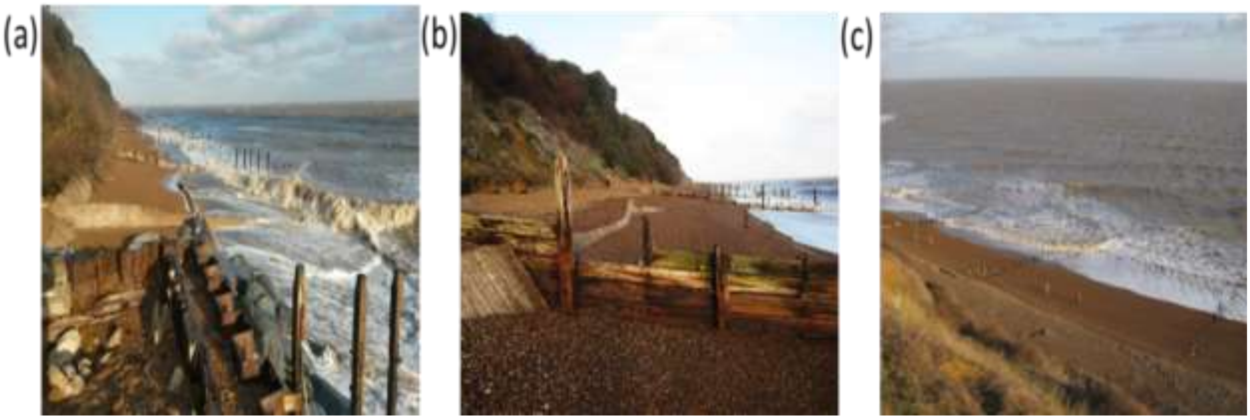
Figure 4.10: Sheet pile defences at the mouth of the Deben Estuary: (a) good condition; and (b) badly corroded.



Source: Mott MacDonald, 2015.

Immediately north of Bawdsey Manor, the sheet pile wall gives way to a series of shore-normal and shore-parallel concrete defence structures (like Figure 3.4a) and timber groynes in poor repair (Figure 4.13). The groynes continue northwards for approximately 1 km from this location.

Figure 4.11: Defences north of Bawdsey Manor: (a) at the termination of the Frodingham sheet pile wall, (b); timber groynes and unexplained concrete structures and (c) the last timber groynes before the undefended beach south of East Lane Point.



Source: Mott MacDonald, 2015.

4.9 Deben Estuary

The estuary extends south-eastwards for over 12 km from the town of Woodbridge to the sea just north of Felixstowe (Burningham & French, 2006). It is narrow and sheltered and has a limited amount of fresh water inputs. The seabed in the offshore area contains a mixture of mud, fine sand and broken shell. The main characteristics of the bathymetry are the influence of the ridges of London Clay and sub-marine river channels, which are now buried and filled with fine sediments (HR Wallingford, 2002). The tidal length in the Deben estuary is approximately 18 km and the estuary has a mean spring tidal prism of around 17x106 m^3. The peak spring tidal discharges through at the estuary inlet exceed 2000 m^3/s (NRFA, 2014). At 2 km upstream of the tidal limit, the mean flow of the River Deben is around 0.79 m^3/s and thus the estuary is well-mixed (NRFA, 2014).

The inlet region has a landward flood tidal delta (Horse Sand) and a seaward ebb tidal delta (The Knoll). A single bar/spit extends from time to time from the Bawdsey foreland, (Figure 4.14). The orientation of the offshore sandbanks located near the estuary mouth is controlled by the strong tidal streams in the area. In the estuary inlet there is small wave propagation, and only fetch-limited wind waves are locally generated inside the estuary.

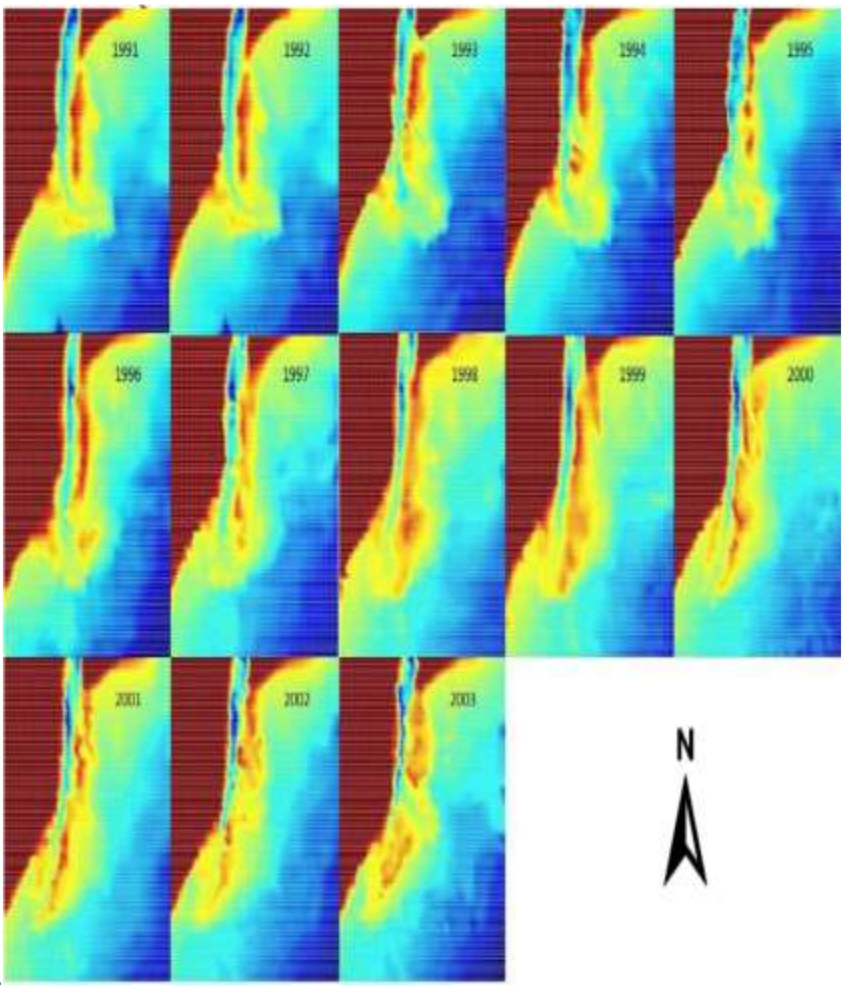
Figure 4.12: Mouth of the Deben Estuary: (a) Looking north towards Bawdsey; and (b) Looking south towards Felixstowe.

Source: Royal Haskoning, 2010a.

Land reclamation of more than 2000 ha of intertidal mudflats and saltmarshes (approximately 25% of the tidal area), completed during the early 19th century, has changed considerably the Deben estuary (Beardall *et al.*, 1991). At present there is more than 25 km of defences in the estuary protecting 16 compartments from tidal inundation (more than 1400 ha). According to Posford Duvivier (1999) many of the defences are in a poor state and realignment to restore tidal action in the compartment areas has been considered. If this happens, the stability of the shoreline downdrift of the area and the behaviour of the ebb-tidal delta may be modified due to an increase in the tidal prism.

The bathymetry of the Deben estuary is well documented (Ordnance Survey and Hydrographic charts). Burningham and French, 2006 define the main morphological characteristics of the estuary as follows: (a) the middle and upper reaches of the estuary are tidally dominated, entirely intertidal (upstream) and characterised by a single meandering channel with muddy intertidal flat and saltmarsh on the flanks; (b) landward of the estuary mouth the channel divides around the partly intertidal Horse Sand and the main inlet channel between Bawdsey and Felixstowe Ferry is only 180 m wide (Hayes, 1975); and (c) the course of the subtidal channel (offshore) is defined by the position and extent of a historically mobile system of intertidal shoals known locally as The Knolls. Bathymetry within and between the channels around the flood–tidal delta implies flood dominance to the northeast and ebb dominance to the southwest of Horse Sand. It is noted that an interesting new modelling study of the Deben Estuary is presented by Horrillo-Caraballo *et al.*, (2014). Their work is supported by the observed bathymetric changes recorded in the mouth of the Deben Estuary between 1991 and 2003 (Figure 4.13). Although the outputs from the modelling provide little useful information to help understanding of the Bawdsey frontage they provide insight into the estuary mouth sediment exchange mechanism that have much in common with those operating in the mouth of the Ore.

Figure 4.13: Morphological changes in the mouth of the Deben Estuary 1991 to 2003



Source: Horrillo-Caraballo *et al.*, 2014

It is understood that locally there is a view that the shingle volume of the Knolls is presently greater than has been in the past. However, this is not supported by available evidence from monitoring and modelling work. While it might be speculated that the beach lowering that has occurred along the Bawdsey Manor frontage has probably contributed to an increase in the sediment flux across the Deben Estuary, and indeed to the very wide 'healthy' beach immediately north of the estuary mouth, there is no robust evidence of increased accretion in the mouth of the estuary.

To the north of the Bawdsey manor sheet piles, groyne embayments show little evidence of any significant net alongshore transport. Should there be a deficit of sediment delivery from the north some degree of sediment asymmetry in the distribution of sediments in the groyne embayments would be expected. This is not observed and implies that either the net sediment flux alongshore is close to zero or the sediment retaining ability of the groynes has been compromised due to their age.

5 Coastal Processes

5.1 Tidal water levels

Tidal levels within the North Sea basin are generated by the tidal wave moving in from the Atlantic. It enters the North Sea both from the north of Scotland and through the English Channel. The tidal wave, in effect, travels along the Suffolk coast in a southerly direction. The Bawdsey shoreline is exposed to a microtidal range (mean tidal range = 2.1 m, Posford Duvier, 2000) so that wave energy is focused onto a relatively narrow band of the beach. Consequently, the beaches at Bawdsey are more vulnerable to erosion during storms than beaches in macrotidal and megatidal ranges where wave energy is distributed over a larger beach area. The tidal levels given in Table 5.1 are predicted astronomical tide levels, and do not take account of tidal surges caused by meteorological factors. Such surges can be in the order of 2 m above the astronomical levels.

Table 5.1: Tidal Water Levels at Bawdsey

Reference	Level (m CD)
MHWS	3.4
MHWN	2.8
MLWN	1.0
MLWS	0.3

Source: Posford (2000)

As already noted the beaches at Bawdsey are very sensitive to variations in water level, particularly when a surge is superimposed on the tide as a consequence of:

- Persistent northerly winds blowing over the North Sea which act to ‘pile up’ water levels in the southern North Sea;
- An abrupt switch between a strong southerly to a strong northerly wind potentially releasing a series of surge waves into the southern North Sea; and
- Storm surges entering the North Sea round the north of Scotland and progressing down the North Sea.

Extreme water levels at Bawdsey for the stated return periods are shown in Table 5.2.

Table 5.2: Extreme Water Levels at Bawdsey

Return period (years)	Extreme water level (mODN)
1:10	2.99
1:25	3.20
1:50	3.36
1:100	3.51
1:250	3.72
1:500	3.88
1:1000	4.03

Source: Royal Haskoning (2007)

5.2 Nearshore currents

In the vicinity of Bawdsey, nearshore tidal currents affecting the beach and nearshore sediments are generated by a combination of astronomically forced tidal motions, wave action (including wave set-up, wave-generated offshore-directed sub-surface currents and wave-generated alongshore currents), and storm-associated currents.

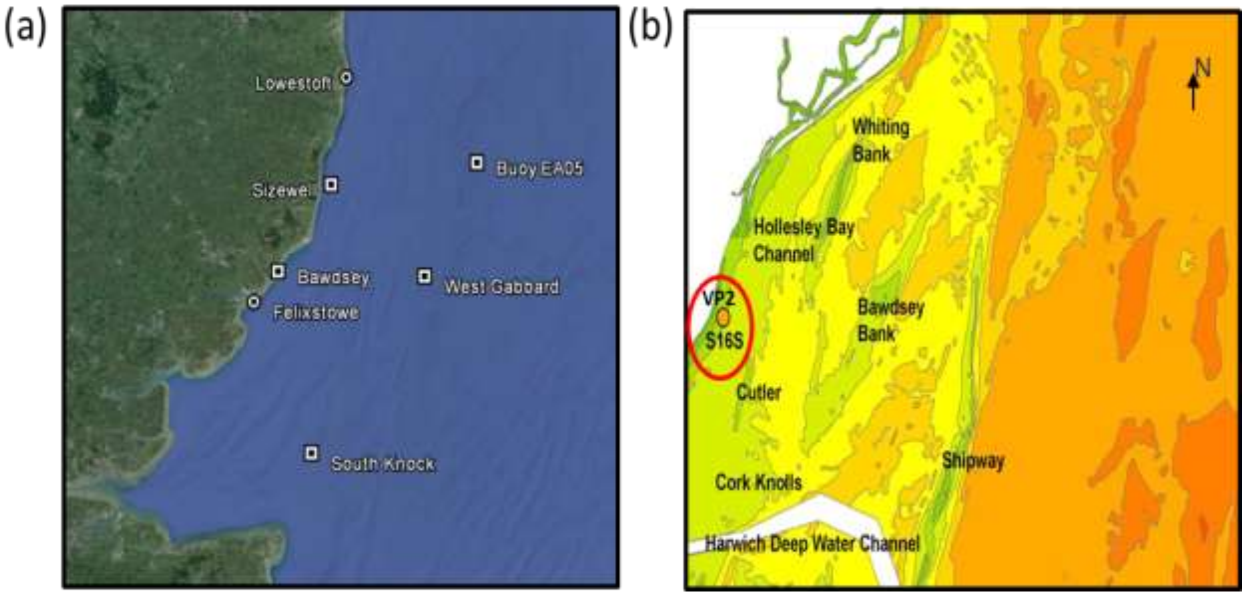
The local tidal system is slightly ebb dominant, with ebb and flood tides running approximately parallel to the coast in a southerly and northerly direction, respectively. Spring tide velocities are typically of the order of 0.8 m/s, but rise to 1.3 m/s off Orford Ness. The ebb tide flows are closely similar to the flood tide flows, but the velocities tend to be slightly higher (*c.* 5%). The tidal currents are rectilinear, with an ellipticity of *c.* 5%. The pattern of neap tide currents follows a very similar pattern to the spring tide, but the velocities are typically two thirds the magnitude. At the mouths of the Rivers Deben and Ore the tidal velocities can locally be up to 2.5 m/s, but are more widely of the order of 1.0 to 1.5 m/s running parallel to the shoreline.

5.3 Waves

Along the frontage between Orford Ness and the Deben Estuary, the coast is subject to the wave climate of the southern North Sea. The nearshore region of London Clay is wide and shallow and the net wave energy is orientated more to the east-southeast, giving the relatively stable configurations of Hollesley Bay. In general, available data show that Suffolk has a moderate wave climate with offshore waves from the northeast and southeast sectors being dominant. Less frequent waves from the north-northeast sector tend to be larger.

The Environment Agency (2008) report that mean wave heights along the coast of Suffolk range from 0.4 m to 0.9 m and note an increase in the measured mean wave heights compared to those detailed in previous literature, such as the Coastal Management Atlas (Anglian Water, 1988) which states that the mean wave height at North Southwold is 0.3 – 0.4 m. The average offshore wave height is 0.96 m, with modal directions of 50% from the northeast and 32% southwest (Burningham and French, 2006). According to HR Wallingford (2002) waves from the Northeast are associated with the littoral drift pattern in the area. As there are no long-term (>15 years) 'nearshore' wave observations from the Suffolk coast or adjoining offshore areas, wave model hindcast data has been used in previous studies (e.g. Halcrow, 2001a, b).

Figure 5.1: (a) Location of wave data and tide gauges; and (b) location of gauges VP2 and S16S at Bawdsey showing the sea bed features Shipway, Cutler, Bawdsey Bank and Hollesley Bay Channel.

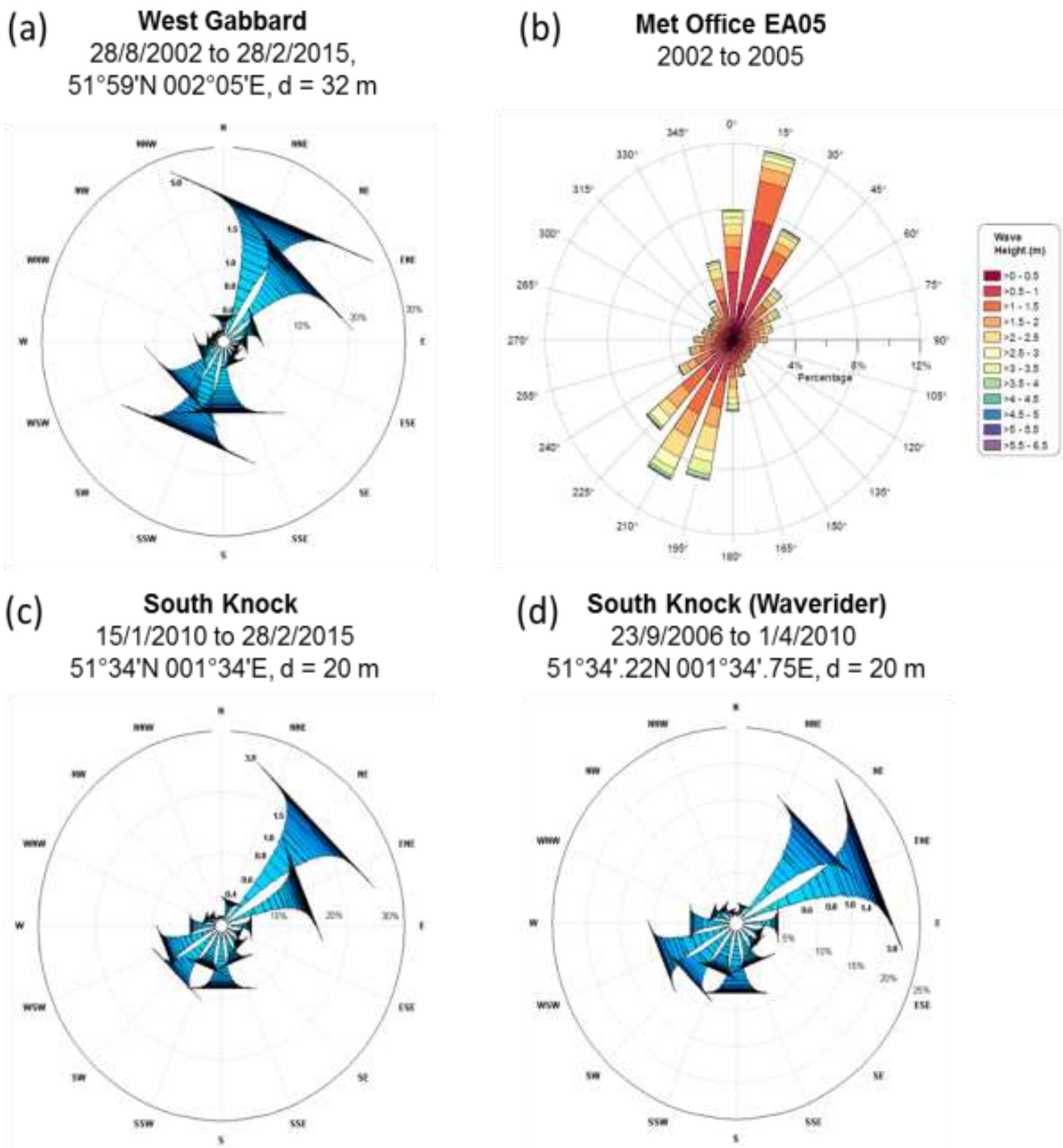


Source: Environment Agency (2008).

5.4 Offshore wave data

In order to better understand the wave climate at Bawdsey and the related influences on coastal processes this report makes use a number of wave data sets. These include Wavenet sites (West Gabbard, South Knock and Sizewell), EA wave gauge deployments at Bawdsey and the Met Office wave model prediction point EA05, (Figure 5.1). Wave roses from West Gabbard (28 August 2002 to 28 February 2015), South Knock (Wavenet, 15 January 2010 to 28 February 2015 and Waverider, 23 September, 2006 to 1 April, 2010) and EA05 (2002-2005) are shown in (Figure 5.2). Owing to the longer fetch, waves generated by a given wind speed from the northeast are larger than those from the southeast for the same wind speed. The observational and hindcast wave data show no direct correlation between wind speed/direction and waves indicating that swell waves may play a role in defining the wave climate during some periods (BEEMS, 2012). Importantly, in a given year, the differences between wave energy levels from each sector can mean that sediment transport under extreme waves differs in direction from that under more frequent moderate waves.

Figure 5.2: Figure 5.2: Wave rose for offshore locations: (a) West Gabbard (28 August 2002 to 28 February 2015); (b) EA05 (2002-2005); (c) South Knock (15 January 2010 to 28 February 2015); and South Knock (23 September 2006 to 1 April 2010).



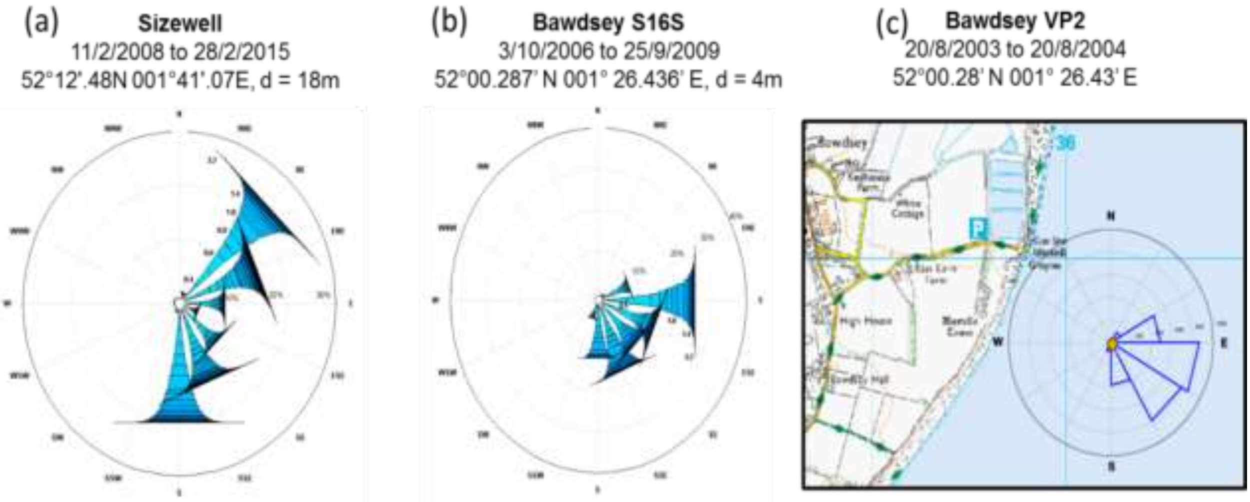
Source: CEFAS and Environment Agency

5.5 Inshore wave data

Inshore wave data close to Bawdsey is available from two sources: (a) an (incomplete) wave record from a Valeport 730D wave, tide and current monitor (identified as VP2) deployed 0.6 km from East Lane Bawdsey by the Shoreline Management Group for the period 20 August 2003 to 20 August 2004 (Royal Haskoning, 2009); and (b) an AWAC acoustic Doppler wave (and current) gauge deployed just south of the headland of Bawdsey at the southern end of Hollesley Bay in a depth of 4 m (CD) at 52° 00.287' N, 001° 26.436' E for the period 3 October 2006 to 25 September 2009 (hereafter called S16S), (Environment Agency, 2008). The approximate deployment location is shown in Figure 5.1b. Additional inshore wave data are also available from the Wavenet Sizewell deployment (Figure 4.1b).

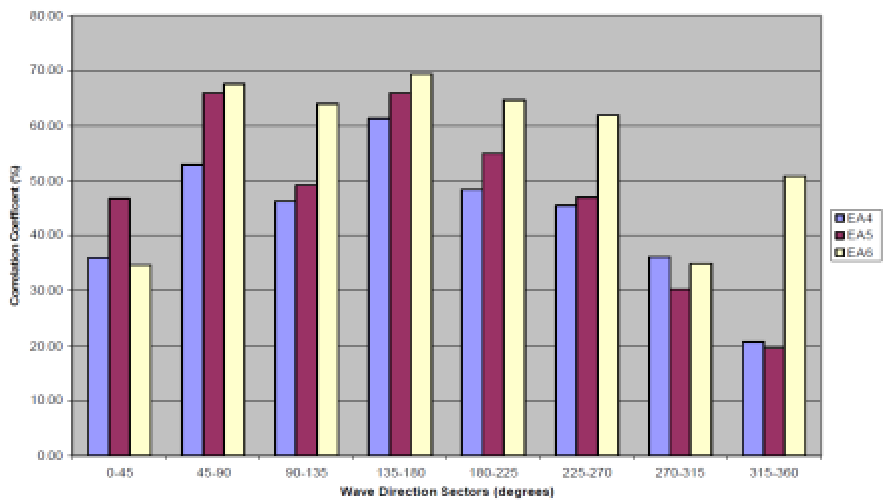
Wave roses derived from data from Sizewell, S16S and VP2 are shown in Figure 5.3. The correlation between offshore (EA05) and inshore (VP2) wave conditions for different wave sectors reported by Royal Haskoning (2009) is shown in Figure 5.4. While overall correlation is relatively good for wave directions between north and east, this declines significantly with wave direction south of east due to coastal orientation and the shelter provided by offshore banks.

Figure 5.3: Wave roses derived from data from VP2 (20 August 2003 to 20 August 2004) and S16S (3 October 2006 to 25 September 2009) at Bawdsey.



Source: Source: CEFAS and Environment Agency

Figure 5.4: Correlation between offshore (EA05) and inshore (VP2) wave conditions for different wave sectors. Also shown are correlations with Met Office model locations EA04 (north of EA04) and EA06 (south of EA04) not referred to in the text.



Source: Royal Haskoning (2009)

The characteristics of three storm events recorded at East Lane between 2003 and 2004 are summarised in Table 5.3.

Table 5.3: Three storm events recorded by the Valeport 730D deployed 0.6 km from East Lane Bawdsey by the Shoreline Management Group for the duration 20 August 2003 - 20 August 2004.

Date	H_{max} (m)	H_s (m)	T_p (s)	T_z (s)	Direction (deg)
08/01/2004	3.8	2.4	6.9	4.6	140
29/11/2003	3.5	2.2	6.5	4.6	168
20/02/2004	3.8	2.1	5.2	3.6	94

On approaching the coastline, incoming waves are modified as they cross a number of eastern banks and deeps including: Inner Gabbard and Outer Gabbard, Shipway and Bawdsey Bank (Figure 4.1). Comparison between offshore wave records from West Gabbard and inshore wave data from Bawdsey therefore provide an opportunity to assess the impact of these offshore seabed features on the local wave climate at Bawdsey, albeit for a limited period. It is noted that the Bawdsey AWAC was located in an area of shallower bathymetry which modified the wave climate further.

Haskoning (2002) state the net wave energy direction offshore is from the east, comprising principal components from the northeast and the southwest. For the period 1978 -1986 Halcrow (1988) report annual significant wave heights, Hs, at Bawdsey as being 0.2 - 0.3 m. Looking at more recent data Pontee (2005) suggests that Hs is more typically 0.4 - 0.5 m with a peak period, Tp, of 6 s. Futurecoast (2002) state that the dominant waves direction is from the north-northeast along the line of maximum fetch in the North Sea for long swell waves. Burningham & French (2006) state mean offshore Hs values of 0.96 m, with 50% coming from the northwest and 30% have a southwest modal direction.

A number of authors have attributed the shape of the Suffolk coast to the variation in wave energy along it (e.g. Pethick, 1999; Royal Haskoning, 2009). Such variability can contribute to changes in the direction of net alongshore sediment transport over daily to annual time-scales. The Environment Agency (2008) report that Bawdsey is well sheltered, and consequently wave heights are significantly lower in the southern part of the Suffolk coast. Approaching waves are modified both in height and direction by the Inner Gabbard banks, and also by the nearshore banks of Shipway and Bawdsey Bank. A similar pattern in wave height reduction between offshore and nearshore locations is observed along the Suffolk coast. However, measured wave heights do not decrease to the same extent at all locations. For example, for approximately the same offshore wave conditions, the inshore wave heights at Southwold are approximately one metre higher than wave heights at Bawdsey, reflecting different amounts of wave dissipation.

Thus while the inshore wave climate of the Suffolk coast overall is shown to be well-correlated with the offshore conditions for wave directions between north and east, the net wave energy acting on different sections of the coast appears to change along the coast. A summary of Hm0 values for inshore waves at stated return periods is shown in Table 5.4.

Table 5.4: Return periods of nearshore wave heights at specified water levels

Wave height return period (years)	*Hm0* (m)	Water Level return period (years)	Water level (m AOD)
1	2.19	1	3.64
1	2.25	1	3.64
5	2.31	5	4.00
5	2.43	5	4.00
5	2.44	5	4.00
10	2.50	10	4.16
10	2.52	10	4.16
10	2.53	10	4.16
20	2.60	20	4.31
20	2.61	20	4.31
20	2.62	20	4.36
50	2.72	50	4.51
50	2.73	50	4.51
100	2.73	50	4.51

Source: Royal Haskoning, 2009

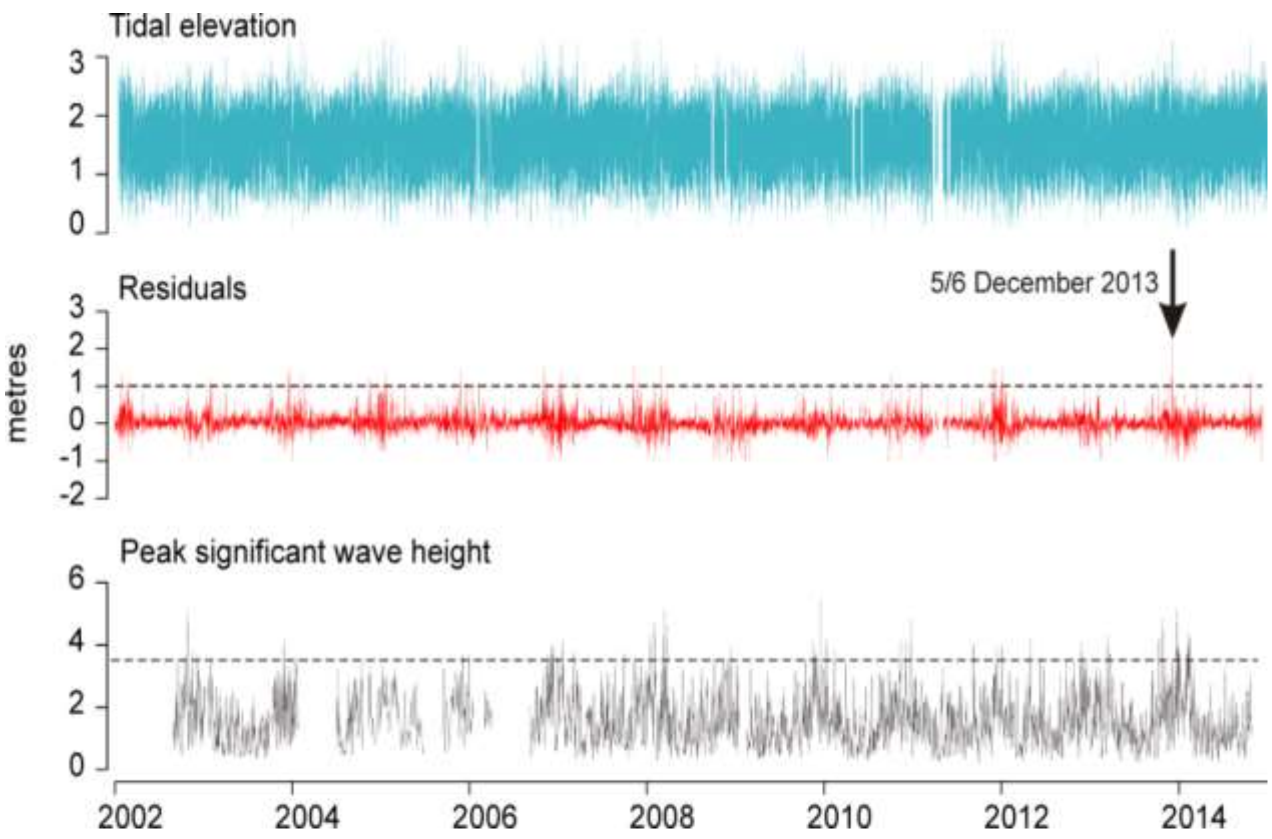
The breaking wave height along the frontage at the Mean High Water Spring water level has been determined using the method from the US Army Corps of Engineers (Shore Protection Manual, 1984). Table 5.5 shows the breaking wave height and the wave crest level at approximately the lowest beach level (-1.0m AOD) for a number of typical wave periods.

Table 5.5: Calculated theoretical breaking wave height associated with MHWS still water level

Wave Period (s)	Breaking Wave Height (m)	Wave Crest Level (m AOD)
10.6	1.36	1.66
8.0	1.33	1.64
6.0	1.28	1.59

For a 1:50 year wave height and 1:50 year water level the maximum wave run up is estimated to be 5.83 m AOD for a beach slope of 1:3.5 at the toe of the present defence structure.

Figure 5.5: Time-series plot showing tidal elevation and tidal residuals from Lowestoft and daily peak significant wave height measured at West Gabbard for the period 2002 to 2015.



Source: Source: British Oceanographic Data Centre and Cefas (Wavenet).

Figure 5.5 shows time-series tidal and wave data from the Lowestoft Class A tide gauge and from the West Gabbard buoy, respectively. The extreme surge event on 6 December, 2013 is indicated by the arrow and arbitrary ‘threshold’ values for surge elevation and wave height of 1 m and 3.5 m, respectively, are indicated by the dashed lines for discussion purposes only. Visually, Figure 5.5 shows that during the period from January 1 2002 to 31 December 2014, surge events, as expected are most frequent during the winter months and that these events are coincident with higher than average wave events.

The most significant observation from the data shown in Figure 5.5 is that the magnitude and frequency of surge elevations and significant wave height exhibit essentially the same seasonal behaviour. The winters of 2007 and 2008 are characterised by coincident higher than average surges levels and wave heights. The 5-6 December 2013 surge event is clearly exceptional. However, caution should be exercise when attempting to relate these data to the coastal responses at Bawdsey since there is a significant geographical separation between the measurement locations and the Bawdsey frontage. The conditions here may be markedly different to those at Lowestoft and West Gabbard.

6 Coastal Morphodynamics

In this section the evidence presented in Sections 3 to 5 related to coastal processes is used to develop a conceptual understanding of the coastal morphodynamics for the study area. Coastal morphodynamics is the study of coastal geomorphology and its change under the influence of waves, tides and sediment transport at a range of temporal and spatial scales. The information from this study is then used to inform the evaluation of potential future coastal evolution in the short (annual) to medium-term (decadal) discussed in Section 7.

6.1 Alongshore Sediment Transport

At a large scale the Southern North Sea Sediment Transport Study SANDFLOW model (HR Wallingford *et al.*, 2002) shows that on a spring tide the net tidal residual sediment (median grain diameter, D50 = 0.1 mm) flux is up to 100 kg/m/tide in a northerly direction. The model also indicates that coarser 2 mm gravel is only transported in a northerly direction within approximately 20 km of the shore. With storm-generated surge and wind waves the net tidal residual sediment flux is reversed to a southerly direction with between 1000 and 10000+ kg/m/tide (D50 = 0.1mm) and 10 - 1000 kg/m/tide for D50 = 2 mm.

Between Orford Ness and the mouth of the River Ore, modelling by Posford Duvier (2000) (Figure 6.1) shows that drift is almost exclusively southwards, under all wave conditions (except southerly). Immediately adjacent to the mouth of the estuary there is more potential for northwards drift, due to the present alignment of the distal point of the spit (which is constantly fluctuating).

Between the Rivers Ore and Deben the transport regime is more complex (Figure 6.1) with north and south transport directions possible depending of the wave direction. However, the net result is an overall southerly drift along most of Hollesley Bay. However, of particular significance is the observation that the East Lane headland creates an alongshore drift divide. To the north of East Lane limited amounts of alongshore transport occur directed the north or south depending on the wave direction. To the south of East Lane much larger amounts of sediment are transported exclusively southwards. Thus while beach sediment volumes to the north of East Lane may fluctuate, once passed the East Lane promontory sediments have a tendency to continue southwards towards the River Deben.

Figure 6.1 Schematic illustration of alongshore transport rates and directions

Source: Adapted from Posford Duvivier

Alongshore sediment transport between Orford and Bawdsey has been studied by Posford Duvier (2000), Vincent (1979), Onyett & Simmonds (1983) and Motyka & Brampton (1993) and the estimated rates presented in Table 6.1. Although the rates along Shingle Street are similar, the Posford Duvier (2000) transport direction is opposite to that predicted by Vincent (1979) and Onyett & Simmonds (1983). The reason offered to explain this difference was that the local beach angle restricted the supply of sediment from the north. However, it may be possible that the offshore wave point used in the study was too far south to adequately represent the inshore waves at that point. Furthermore, the Vincent (1979) and Onyett & Simmonds (1983) rates were calculated for sand in an area where the beaches are almost entirely of gravel.

In 1966/7 a beach recharge scheme moved 350,000 m^3 of shingle northwards from Orford Ness to Aldeburgh to replenish the eroding shingle ridge. Taylor & Marsden (1983) reported that after 15 years most of the recharge had disappeared, implying a sediment transport rate of shingle of the order of 20,000 m^3/year.

Table 6.1: Estimated alongshore sediment transport

mE	mN	Location	Direction (degrees)	QLST (m3/yr)	Forcing	Reference
641300	246600	Orford	242	195,000	Wave	Vincent (1979)
644200	248150	Orford Ness	242	132,700	Wave	Posford Duvier (2000)3
638750	245150	North Weir Point	231	67,200	Wave	Posford Duvier (2000)
636500	242000	Shingle Street	207	83,000	Wave	Onyett & Simmonds (1983)
636300	241300	Shingle Street	198	64,000	Wave	Vincent (1979)
636900	242650	Shingle Street	31	83,300	Wave	Posford Duvier (2000)
633150	237450	Bawdsey	230	210,000	Wave	Onyett & Simmonds (1983)
633150	237450	Bawdsey East Lane	230	83,300	Wave	Posford Duvier (2000)
633150	237450	Bawdsey south	230	141,000	Wave	Posford Duvier (2000)
634121	237377	Bawdsey	234	8500	Wave	HR Wallingford (1997)4

The estimated values for alongshore transport shown in Table 6.1 should be interpreted with caution for the following reasons:

Only *potential* transport rates were calculated, assuming that at all times there was a sufficient volume of material to be transported. In some locations this is not the case:

- Many of the transport rates are for medium sand – even when the beaches were of mixed sand and shingle, or even of pure shingle. The potential sand transport rate will be far higher than the transport rate for shingle at the same site;

[3] Values obtained using the UNIBEST-LT model through various formulae for calculating the transport rate of sand or shingle due to predefined wave climate and tidal regime. Wave data were input to the model from the Southern Met Office offshore wave station.

[4] Values obtained using the DRCALC model to give the total alongshore drift produced by the wave climate using the CERC formula. The model was run using an assumed size of shingle. The magnitudes of the transport rates are therefore uncertain, but the relative size and direction should be consistent.

- The majority of model results are driven by waves only and the effect of the tide is generally ignored. In many cases this approach is fine. However, in some cases it has been shown to make a difference of up to 10%;
- Physical measurements of the sediment transport along the coastline are not available. Any drift rates quoted must therefore be treated as estimates rather than absolute values; and
- All calibrations of sediment transport formulae using point measurements exhibit a large degree of scatter.

A useful summary of work addressing alongshore sediment transport is given by HR Wallingford, (2002).

6.2 Cross-shore sediment transport

There are no data available to enable an unambiguous commentary about cross-shore sediment exchanges. Beach profile changes discussed below for example reflect changes in beach volumes brought about by both alongshore and cross-shore transport processes and it is not possible to distinguish between the two processes. However, the 'sudden' appearance of significant coarse beach sediments south of East Lane reflect significant episodic cross-shore exchanges that suggest either a reservoir of sediments offshore, or effective transfer from the north East Lane since there are no beach sediments of any significance along the defended frontage.

6.3 Shoreline behaviour

A range of data sources have been accessed in order to assess and quantify historical and contemporary shoreline behaviour along the frontage. In the initial analysis, the behaviour of the coastline between Orford Ness and the mouth of the Deben Estuary has been considered with a view to identifying any underlying long-term, broad-scale trends that might control the more local coastline behaviour at East Lane. Subsequent analyses have focussed on the areas extending approximately 1 km to the north and south of East Lane. While some new analyses are presented, reference is also made to a number of published studies that have used aerial photographs and data from beach profile and maps to determine trends in coastal evolution.

6.3.1 Historical analyses

Historical maps from epoch 1 (1881), 2 (1904) and 3 (1926) shown in Figure 6.2 to Figure 6.4, respectively. For clarity these maps have been split into north and south sections and superimposed on aerial photograph of the site from 2015. These images therefore allow visual evaluation of the historical changes in the vicinity of East Lane. In particular they have been used here to look for evidence of interactions between old coastal defence structures and the coastline.

The second epoch map of the frontage (1904, Figure 6.3) shows significant shoreline recession, especially in the northern section. The coastal control measures have had little effect in controlling erosion. Figure 6.3 also shows that a groyne field was built between the period 1881 and 1904 spanning the entire frontage (33 groynes in total). If the cartography is accurate, the map shows accretion on the southern side of many groyne embayments (especially just south of East Lane point). This provides strong evidence of the net southerly alongshore drift discussed above. The step-like erosion in the 5 groyne embayments south of East Lane point also shows that in that area is faster than elsewhere and may be the precursor of the further severe erosion in this area up to around 1990.

The earliest reliable map of the frontage (1881, Figure 6.2) illustrates well the large changes in shoreline position over the last 134 years. However, although the beach was wide at this time, the northern section of the map indicates the presence of ‘structures’ assumed here to beach early examples of beach control measures. Further information about these features has not been found.

Figure 6.2: The OS map of 1881 overlain on an aerial photography from 2015 showing the historical and contemporary coastline to the north and south of East Lane, Bawdsey.

Source: Ordnance Survey & Mott MacDonald.

Figure 6.3: The OS map of 1904 overlain on an aerial photography from 2015 showing the historical and contemporary coastline to the north and south of East Lane, Bawdsey.

Source: Ordnance Survey & Mott MacDonald.

Figure 6.4: The OS map of 1926 overlain on an aerial photography from 2015 showing the historical and contemporary coastline to the north and south of East Lane, Bawdsey.

Source: Ordnance Survey & Mott MacDonald.

The third epoch map of the frontage (1926, Figure 6.4) shows further significant shoreline retreat. Between 1905 and 1926 the groyne field shown on the 1905 map was replaced by an even longer groyne field spanning the frontage. In 2015 there is little visual evidence left of these structures and clearly they have not performed the intended function of retaining beach sediments and protecting the shoreline.

The historical shoreline changes discussed above are summarised visually in Figure 6.5. In the area north of the present day embayment south of the Martello Tower, the shoreline position shows retreat at each period examined. To the south of the embayment, the map evidence indicates some accretion between 1881 and 1905. This may possibly be attributed to erosion protection afforded by the groynes. Equally plausible, however, is that the accretion simply reflects an alongshore redistribution of sediments eroded from the frontage a little further to the north. These provide some temporary coastal protection until they are also transported south. This view is supported by the observation that by 1926, erosion again dominates the frontage with the 1926 shoreline position west of the 1881 and 1905 locations.

The historical map evidence shows that while groyne systems were present along the frontage, they did very little to stop erosion, although it remains an open question whether or not they reduced the rate of erosion. The present day contention that the reinstatement of groynes along the frontage would prevent erosion, or at least slow it down significantly, must therefore be challenged.

Figure 6.5: Shoreline positions defined by the high water mark derived from the OS map for 1881, 1904 and 1926 overlain on an aerial photography from 2015, East Lane, Bawdsey.

Source: Ordnance Survey & Mott MacDonald.

6.3.2 Contemporary analyses: aerial photographs

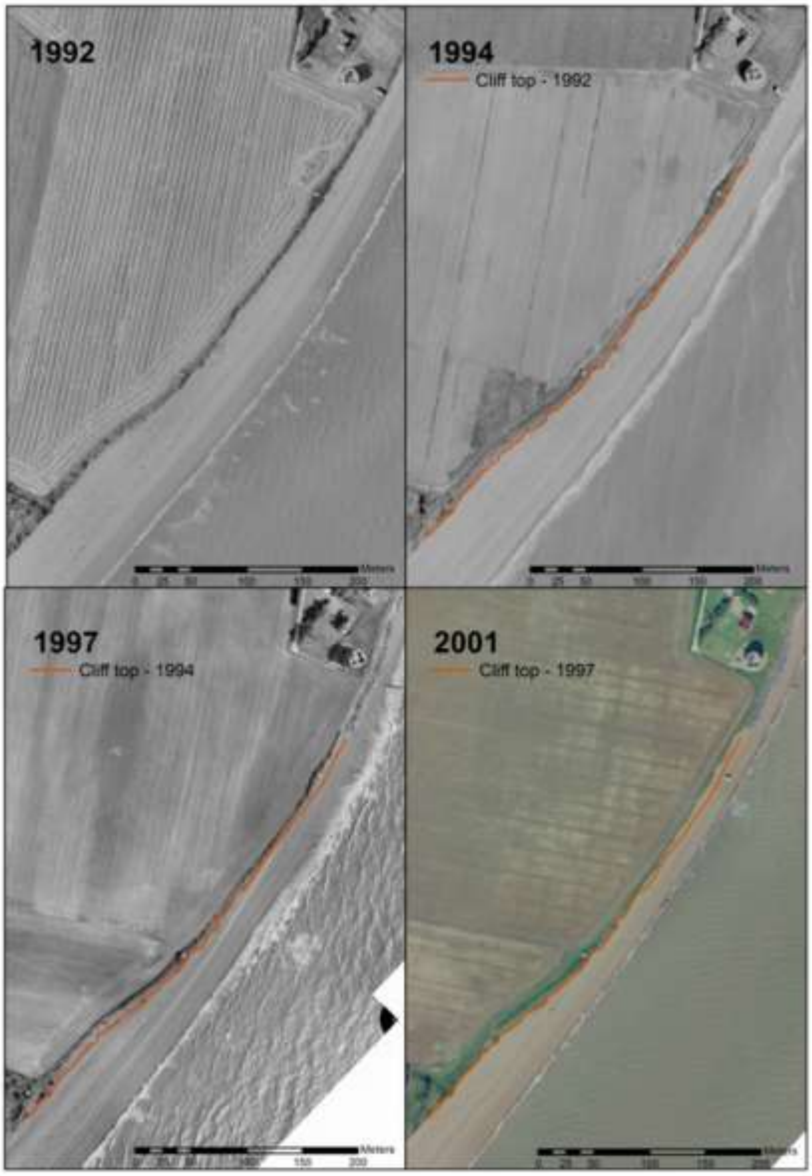
A paucity of data on shoreline behaviour between 1926 and around 1990 prevent detailed analysis of coastal changes. However, it is clear that erosion continued during this period, reflected by the construction of hard defence structures (Appendix A). The changes in the coastline morphology during the period 1992 to 2014 are documented in the sequence of aerial photographs shown in Figure 6.6 to Figure 6.9. Here the focus is on the coastline south of the Martello Tower where erosion has been the most severe. It should be noted that in these photographs the location of the cliff line from the proceeded photograph is shown to demonstrate the shoreline retreat.

Changes in shoreline location occurring between 1992 and 1994 along this frontage are relatively minor. By 1997, coastal defences have been built along the frontage extending from East Lane Point to just south of the Martello Tower. Around this time the rate of shoreline retreat begins to accelerate. For example, the Pill Box located on the cliff top in 1997 is observed on the beach by 2001. Interestingly, the shoreline position approximate 200 m south of the Martello Tower shown little change during this period.

Although by 2004 a new ‘wrap-round’ termination is added to the rock revetment defending the Martello Tower, erosion of the embayment to the south proceeded unchecked and the beach width reached its lowest value around 2005. In the period 2006 to 2007 the beach re-established. The source of this new material has not been established but is thought to originate from the south. A second ‘fishtail’ termination was constructed in 2009 in a further attempt to control erosion. Interestingly, rocks placed on the beach for the construction in 2009 (Figure 6.8) promoted the development of a secondary embayment which persisted up to 2011.

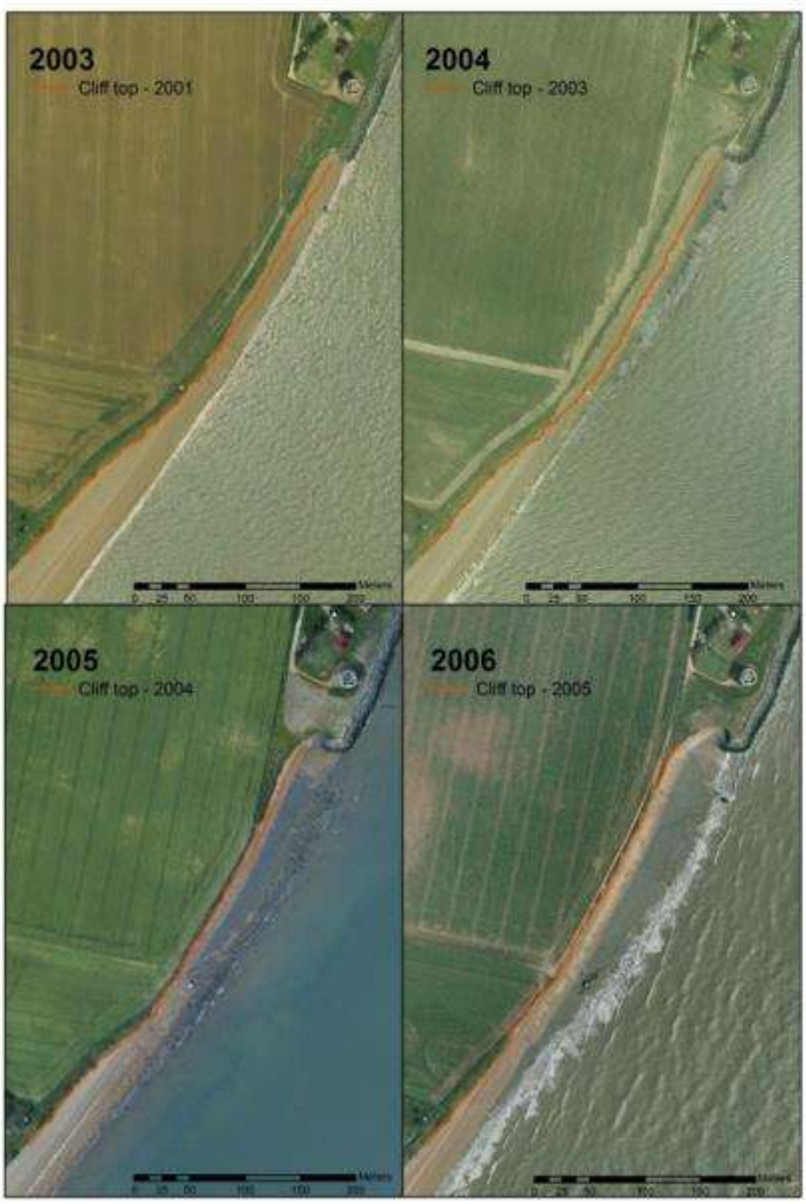
Between 2009 and 2011 erosion was severe with a maximum cliff recession of the order of 50 m. Subsequently, between 2012 and 2014 the rate of erosion has reduced significantly, primarily due to the re-establishment of a shingle beach along this frontage which acts to protect the cliffs from wave attack. Although visual evidence gathered in March 2015 indicated that the frontage remains relatively stable, its present status is maintained only by a relatively narrow shingle beach. If this is removed in the manner shown in the recent historical record, high rates of coastal erosion are likely to result, possible leading to outflanking of the present defences.

Figure 6.2: Sequence of annotated aerial photographs from 1992 to 2001, East Lane, Bawdsey.



Source: Environment Agency & Mott MacDonald

Figure 6.3: Sequence of annotated aerial photographs from 2003 to 2006,



Source: Environment Agency & Mott MacDonald

Figure 6.4: Sequence of annotated aerial photographs from 2007 to 2010, East Lane, Bawdsey.

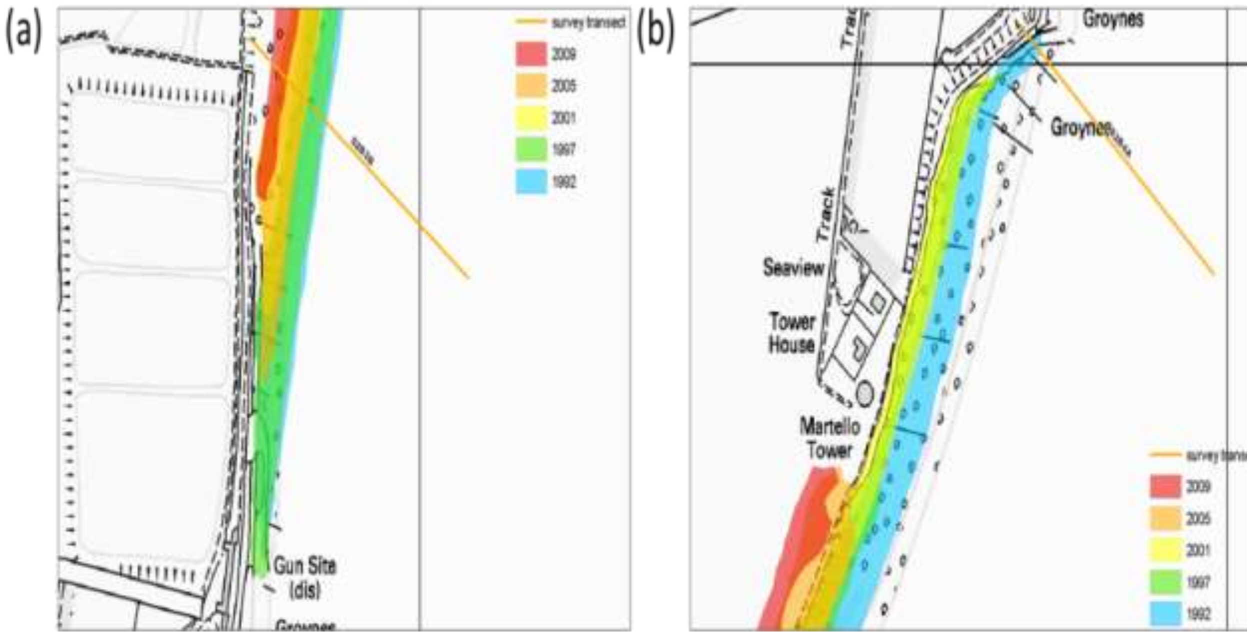
Source: Environment Agency & Mott MacDonald

Figure 6.5: Sequence of annotated aerial photographs from 2011 to 2014, East Lane, Bawdsey.

Source: Environment Agency & Mott MacDonald

A summary of an analysis of aerial photographs published by the Environment Agency, (2010) is shown in Figure 6.6 for locations (a) north of East Lane and (b) south of east lane. Figure 6.6a shows that until the end of the 1990s the beach extended up to the gun emplacement on the hard point of East Lane. However, over a period of 17 years from 1992 the beach receded and by 2009 only comprised a narrow beach of about 50 m width at transect S2B3B (Figure 6.19). South of the gun emplacement Figure 6.6b shows as described above that beach erosion between 1992 and 2009 was extensive and rapid. During this period the beach disappeared from in front of the Martello Tower and erosion to the south of the defences has resulted in the embayment previously described (Figure 3.9).

Figure 6.6: Beach erosion maps derived from aerial photographs between 1992 and 2009: (a) north of East Lane; and (b) south of East Lane.



Source: Environment Agency (2010) & Ordnance Survey

6.3.3 Quantifying rates of shoreline retreat

Changes in shoreline position documented on historical maps and aerial photographs have been quantified using the Digital Shoreline Analysis System (DSAS) extension within the Environmental Systems

Research Institute (ESRI) Geographic Information System (ArcGIS) software. DSAS is used here to compute the rate-of-change statistics for the shoreline. In the first part of the analysis, the top of the cliff line was identified on the available aerial images (1994-2014) and historical maps (1881, 1904 and 1926). This was selected as being the most easily identifiable reference point on the maps and photographs. Following standard practice, an error in cliff top position of +/- 1 m was assumed in order to account for shadows, vegetation, landslides, etc. The resulting cliff lines derived from all the maps and photographs are shown in Figure 6.11.

In the DSAS software the rate of shoreline change calculated is related to an established location (i.e. the black line in Figure 6.11). Cross-shore transects were generated from this baseline every 5 m along the shoreline. It is noted that transects are perpendicular to the baseline and therefore, not always perpendicular to the different shoreline orientations. However, sensitivity tests have been undertaken in order to determine the effect of the transect spacing and the baseline orientation and very similar results were obtained. It was assumed that all transects have the same erosion capacity and there are no geological differences in the study area. The transects defined for this study are shown in Figure 6.12.

Figure 6.7: Cliff line positions derived from aerial images (1994-2014) and historical maps (1881, 1904 and 1926).

Source: Environment Agency & Mott MacDonald

Figure 6.8: Transects defined every 5 m for the study area.

Source: Environment Agency & Mott MacDonald

The DSAS analysis provides three useful shoreline change statistics:

- The Shoreline Change Envelope (SCE, Figure 6.9) is the distance between the latest and the older shoreline for each transect. This represents the total change in shoreline movement.
- The Linear Regression Rate (LRR, Environment Agency & Mott MacDonald

- Figure 6.10) is a rate-of-change statistic determined by fitting a least-squares regression line to all shoreline points along a given transect. This represents a linear erosion rate over the period of time of the analysis.
- The End Point Rate (EPR, Figure 6.11) is calculated by dividing the distance of shoreline movement by the time elapsed between the oldest and the most recent shoreline. This represents an average rate of change during the period of interest.

Supplementary statistics are also generated by the software to support the LRR including:

- The confidence of the End Point Rate (ECI) estimate which adds the uncertainty of the two shorelines used to calculate the EPR and expresses the uncertainty in the EPR. However, the value is not relevant in this case because the same uncertainty was added to all shoreline (i.e. +/- 1m);
- The Standard Error of Linear Regression (LSE) measures the accuracy of the predicted values and provides a standard error of the estimate in order to assess the accuracy of the best-fit regression line;
- The Standard Error of the Slope with Confidence Interval (LCI) describes the uncertainty of the reported rate of shoreline change. Here a confidence level of 95.5% (2σ) was selected to represent the band of confidence around the reported rate of erosion for each transects; and
- The R-squared (LR2) statistic, or coefficient of determination, is the percentage of variance in the data that is explained by a regression. It is a dimensionless index that ranges from 1.0 to 0.0 and measures how successfully the best-fit line accounts for variation in the data.

These statistics are presented in a Table in Appendix C. Please note that the Transects are numbered south to north.

The results of the DSAS software show that the highest rates of shoreline recession of the order of 130 m are found immediately south of the Martello Tower (Figure 6.9), thereby confirming and quantifying visual assessments reported above. Further south, the rate and magnitude of shoreline change decreases to minimum values of the order of 30 m (Figure 6.9). Similar, the highest erosion rates of around 1 m/year are also found south of the Martello Tower and decline to values of the order of 0.5 m/year in the most southerly location. Average annual erosion rates derived using the EPR method are closely similar to those from the LRR method. It is noted that these rates are averaged over the period 1881 to 2014 and much faster erosion has occurred during some periods as has been described above.

Figure 6.9: Results of the SCE analysis

Source: Environment Agency & Mott MacDonald

Figure 6.10: Results of the LRR analysis

Source: Environment Agency & Mott MacDonald

Figure 6.11: Results of the EPR analysis

Source: Environment Agency & Mott MacDonald

6.3.4 Contemporary analyses: beach profiles

Beach topographic profiles have been measured regularly since 1991 at locations along the Suffolk coastline. In many cases these data allow quantification of temporal changes to the different section of the cross-shore beach morphology so that trends in accretion or erosion can be identified. Although the coastal processes bringing about changes in beach profiles are expressed by cross-shore and alongshore sediment transport, beach profile analysis alone is unable to distinguish between the two net transport directions. However, by examining the simultaneous temporal behaviour of the adjacent profiles, it can be possible to identify coherent spatial changes in beach morphology associated with the alongshore transport of beach sediments. The location of Suffolk coastal beach profiles considered in this report are shown in Figure 6.16.

Figure 6.12: The geographical location of Suffolk coastal beach profiles.

Source: Environment Agency

During the period 1991 to the present day, the naming convention for the profiles was changed (Figure 6.12). To avoid confusion, Table 6.2 shows the old and new profile name and geographical location.

Table 6.2: EA beach profile naming convention and geographical locations

Old profile name	New profile name	Location
S2B1S	S059	North Shingle Street
S2B1	S060	South Shingle Street
S2B2A	S061	Alderton
S2B3A	S062	North Bawdsey
S2B3B	-	North East Lane
S2B4A & S2B4	S063	East Lane
S2B4B	-	South Bawdsey
S2B5	S064	Bawdsey Hall
S2B6	S065	Bawdsey Beach
S2B7	S066	Bawdsey Manor

A number of studies have analyses the beach profile data with the aim of understanding past changes in shoreline position and changes in beach volume. Shoreline evolution trends identified can then be interpreted to provide guidance on the likely future evolution of the coastline. However, the past trends can never be used as a reliable guide to how the coastline might evolve in the future and thus estimates must be treated with care.

Figure 6.13: Beach erosion and accretion trends from 1991 to 2006 for the northern, middle and southern sections of the frontage between Shingle Street and Bawdsey Manor.

Source: Environment Agency, 2007.

In Figure 6.13 the changes in the shoreline are rather crudely distinguished by coloured arrows that indicate net erosion (yellow to dark red) and accretion (light green to dark green). The numbers refer to the changes in the location of the high water line. In broad terms, the northern section around Shingle Street is characterised by accretion of the order of 4 m. Both the middle and southern sections are characterised by erosion, with the largest rate (*c*. -6 m) recorded to the north of East Lane.

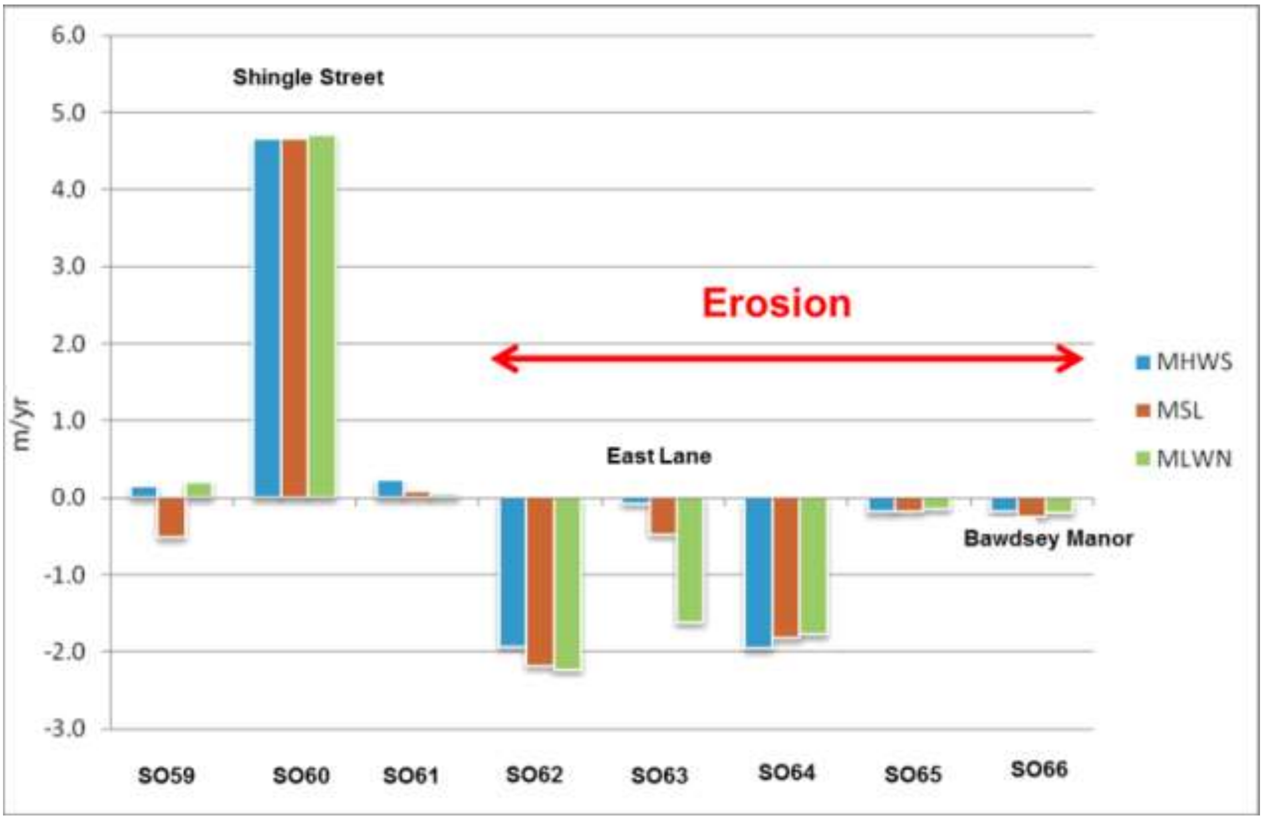
An improved beach profile analysis spanning the years 1991 to 2010 is presented in Table 6.3 for 8 locations between Shingle Street and Bawdsey Manor. The changes in shoreline position determined from this analysis are shown graphically in Figure 6.14.

Table 6.3: Beach foreshore trends determined through the foreshore change parameter, 1991-2010.

Old ID	New ID	Defence	Location	Movement (m/year) MHWS	MSL	MLWN	Mean rate (m/year)	Foreshore change parameter (FCP)
S2B1S	SO59	Shingle ridge	North Shingle St.	0.14	-0.51	0.2	-0.1	1
S2B1	SO60	Shingle ridge	South Shingle St.	4.65	4.66	4.7	4.7	6
S2B2A	SO61	Shingle ridge, embankment	Alderton	0.23	0.09	0.05	0.1	3
S2B3A	SO62	Shingle ridge, embankment	East Lane	-1.93	-2.17	-2.22	-2.1	-6
S2B4A	SO63	Rock armour, stone revetment, sheet piling	East Lane	-0.07	-0.47	-1.61	-0.7	-1
S2B5	SO64	Low crag cliff	S. Bawdsey Beach	-1.95	-1.82	-1.77	-1.9	-4
S2B6	SO65	Crag cliff, buried groynes	S. Bawdsey each	-0.18	-0.17	-0.13	-0.2	0
S2B7	SO66	Crag cliff, relic groynes, sheet pile wall	Bawdsey Manor	-0.18	-0.24	-0.19	-0.2	0

Source: Environment Agency (2010). Note: Positive Foreshore Change Parameter (FCP) values indicate a beach system advancing seaward and negative values show a system retreating landwards. The individual FCP numbers indicate flattening, steepening or no rotation.

Figure 6.14: Measured change in shoreline location relative to MHWS, MSL and MLWN during the period 1991 to 2010 (Table 6.3).



Source: Modified from Environment Agency, 2010.

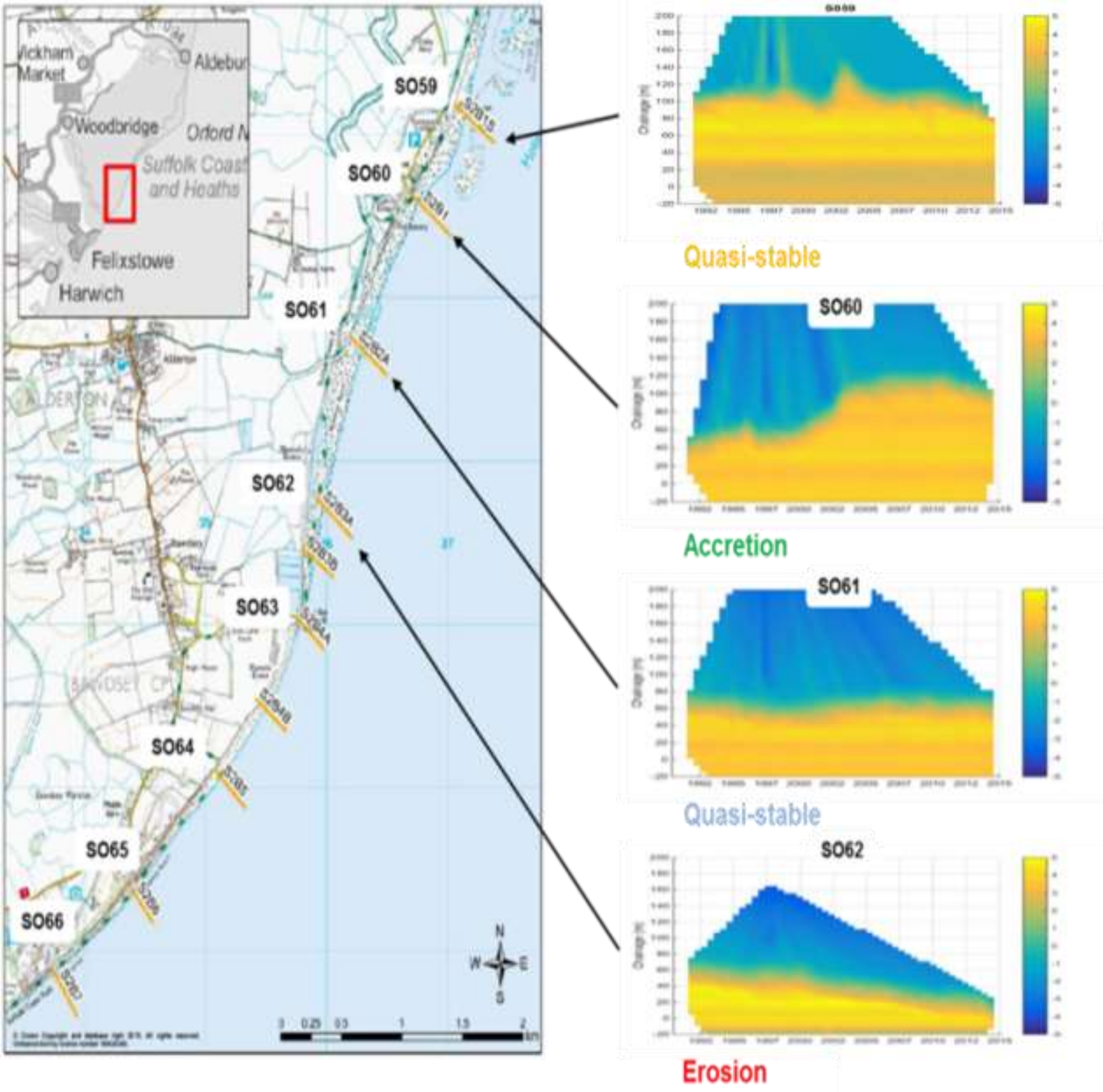
Figure 6.14 shows clearly that Shingle Street is dominated by accretion, and erosion has occurred between 1991 and 2010 at all locations south of and including profile SO62. During this period, the greatest erosion is recorded north of East Lane.

A further analysis of beach profiles was undertaken for this report spanning the years 1991 to 2015. In this new analysis beach profiles extending seaward from approximately -20 m chainage to around -1m AOD and have been ‘time-stacked’ and contoured using Matlab software in order to show clearly temporal changes in profile elevation. Four profiles from the northern and southern section of the frontage are shown in Figure 6.15 and Figure 6.16, respectively.

In the most northern location studied (SO59) the exhibits quasi-stability with a small accretion spike around 2003 (note this record is incomplete). At Shingle Street (SO60) the beach width has generally increased at variable rates between 1991and 2015. However, there is an indication of a decrease in beach width since 2012. This is supported by local anecdotal evidence from residents familiar with the area.

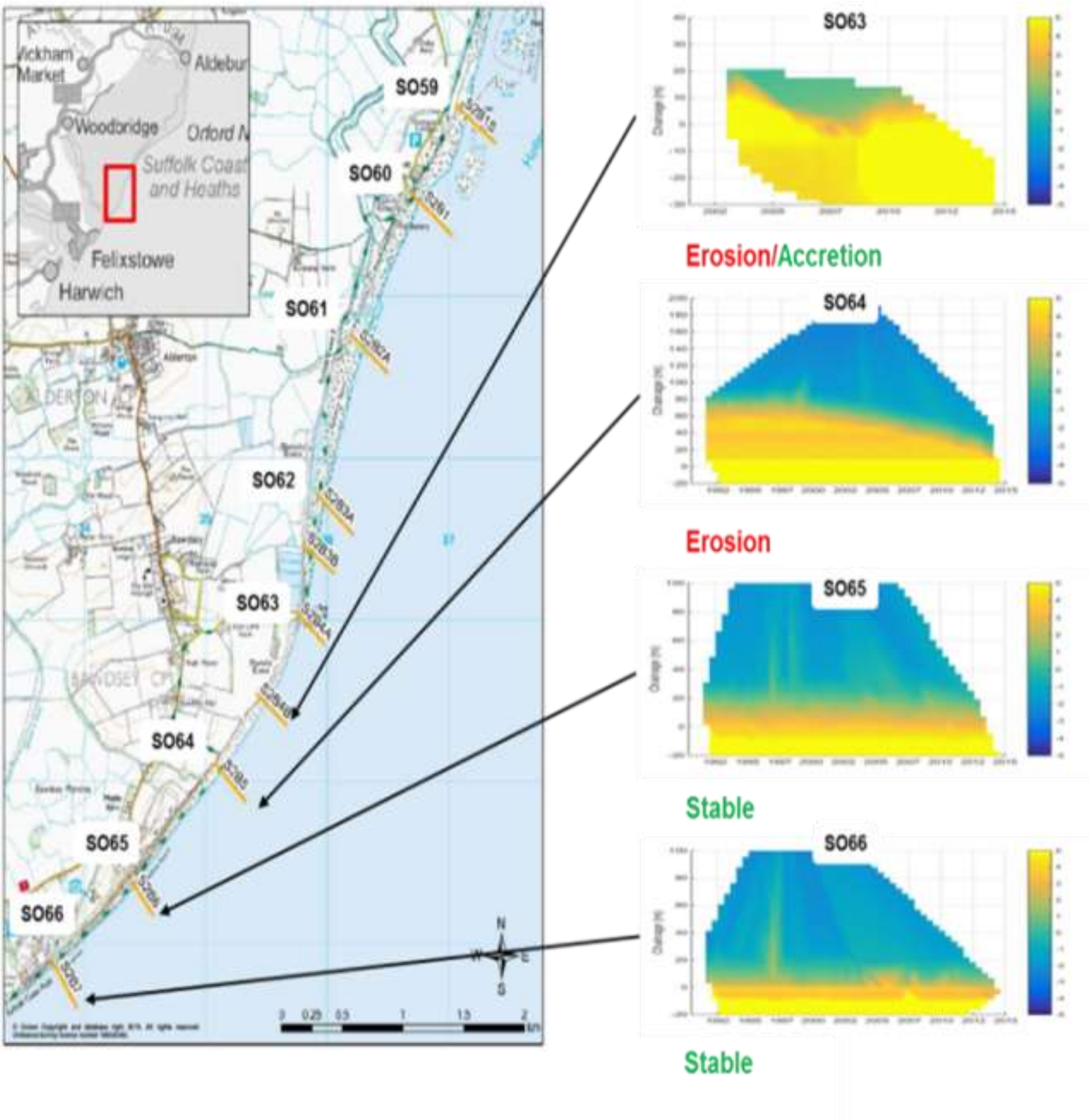
The beach width at SO61has been relatively stable between 1991 and 2015, with a minor recession between 1997 and 2001. At location SO62, just to the north of the most recent coastal defence construction, the beach width has decreased at an almost uniform rate since 1991. Given that the net sediment drift is from north to south along the frontage, and that little sediment transport around East Lane is evident in any data examined in this report, this suggests that sediment may be moving northwards at this location.

Figure 6.15: Time-stacked beach profiles from the northern frontage (Shingle Street to East Lane) spanning the period 1991 to 2015.



Source: Mott MacDonald & Environment Agency

Figure 6.16: Time-stacked beach profiles from the northern frontage (Shingle Street to East Lane) spanning the period 1991 to 2015.



Source: Environment Agency

To the south of East Lane (SO63) the beach eroded between 2002 and 2007 before accreting and reaching quasi-stability (note this record only spans the years 2002 to 2015). Further south profile SO64 shows a trend of acceleration erosion since 1991. Further south still, profiles SO65 and SO66 are stable during the period 1991 to 2015 further supporting the view that erosion at East Lane in localised and related to coastal defence work disrupting the natural sediment processes.

7 Future Coastal Evolution

In common with many other coastal locations worldwide, there is a great uncertainty in any predictions of future changes to the Bawdsey frontage owing to interaction between multiple factors including hydrodynamics, geology, sediment dynamics, hydrology and coastal defences. While extrapolation of past coastal behaviour can provide a useful guide (e.g. Bray & Hooke, 1997), it is not necessarily the key to predicting the present-day or future behaviour. Nevertheless, the projection of past trends into the future is a common approach used to evaluate potential coastal evolution and in the absence of a better alternative it forms the basis of the approach adopted in this chapter concerning guidance on probable coastal erosion trends.

The potential baseline erosion rates derived by Haskoning (2010a) from beach profile analysis between the years 2010 and 2011 are summarised in Table 7.1. In addition to present day conditions, this analysis further assumes sea level rise rates of: 0.06 m to year 2025; 0.34 m to year 2055; 1 m to year 2105. The uncertainty in these derived figures is clear when looking at the 100 year erosion range (e.g. 160 to 300 m in Hollesley Bay). Therefore on their own, these figures provide only an approximation of the future changes to the coastline.

Table 7.1: Potential baseline erosion rates assuming sea level rise rates of: 0.06m to year 2025; 0.34m to year 2055; and 1m to year 2105.

Location	Base rate (m/year)	Comments	100 year erosion range
Orford Ness	1.0	Dependent of occasional feed from the north.	33 to 186
Orford Spit	0.0	Still affected by sea level rise.	5 to 15
North Weir Point	0.3	Subject to breaching.	17 to 115
Shingle Street	0.5	Allowing for variation due to sediment supply.	40 to 115
Hollesley Bay	1.0	Influenced by sediment supply.	160 to 300
Bawdsey Cliffs	0.1	Influenced by storms.	15 to 70
Bawdsey Ferry	1.1	Influenced by behaviour of the Knolls.	60 to 100

Source: Haskoning (2010a)

The historical record leaves little doubt that erosion dominates the long-term coastal evolution trend for the frontage between Orford Ness and the Deben Estuary (and probably beyond). Nevertheless, there is sufficient local variation in rates of erosion and accretion as to leave uncertainty about how a particular location will evolve in the short- to medium-term. Setting aside the potential impacts of climate change for the time being, it is considered that the primarily reason for this uncertainty in coastal evolution predictions stems from the present incomplete understanding of the coastal sediment transport regime between Orford Ness and the Deben Estuary. It has been shown that even on relatively short time-scales (e.g. 1991 to the present day) erosion and accretion dominate along different sections of the frontage.

The sediment exchanges processes between Weir Point and Shingle Street, and the cyclical breaching of the spit that extends from Orford Ness is particular, is pivotal in controlling the supply of sediment to the south. Further, the wave climate in a given year may favour either net northerly or southerly alongshore sediment transport at a given location so that the ‘normal’ drift may be temporally halted or reversed leading to sediment starvation at other locations. At the present time Weir Point continues to prograde, albeit slowly, continuing a cycle begun over 120 years since the last recorded breach and spit break-up. At the same time, large volumes of sediment have been added to Shingle Street, so that this feature is larger now that at any time in recorded history. The historical beach erosion/accretion records show that there is a ‘hold-up’ at the present time in the alongshore sediment supply from Shingle Street to the Bawdsey frontage leading to a deficit in the local sediment budget.

Past evidence shows that the spit extending from Orford Ness has breached on at least three occasions. This has then increased the exposure of the sediment at Shingle Street to waves (especially from the north east) and erosion of this feature has ensued with (it is assumed, given the dominant wave climate) a redistribution of sediment to the south. Should this occur again, it is anticipated that the same cycle will repeat leading to natural replenishment of beach sediments along Hollesley Bay. However, at Bawdsey, the combined effect of coastal orientation, which now favours low rates of alongshore transport, combined with the defended headland at East Lane will provide in the short-term an effective barrier to alongshore transport under present climatic conditions. It is considered that sediments transported southwards along the Hollesley Bay frontage will tend to accumulate on the northern side of the defences until such time as the beach build sufficiently to align with the defended sections and weak alongshore transport to the south can be re-established. However, there is no guarantee that sufficient sediment will reach this location before the supply is again cut by the accretion of the Orford Ness spit and the accompanying accretion at Shingle Street.

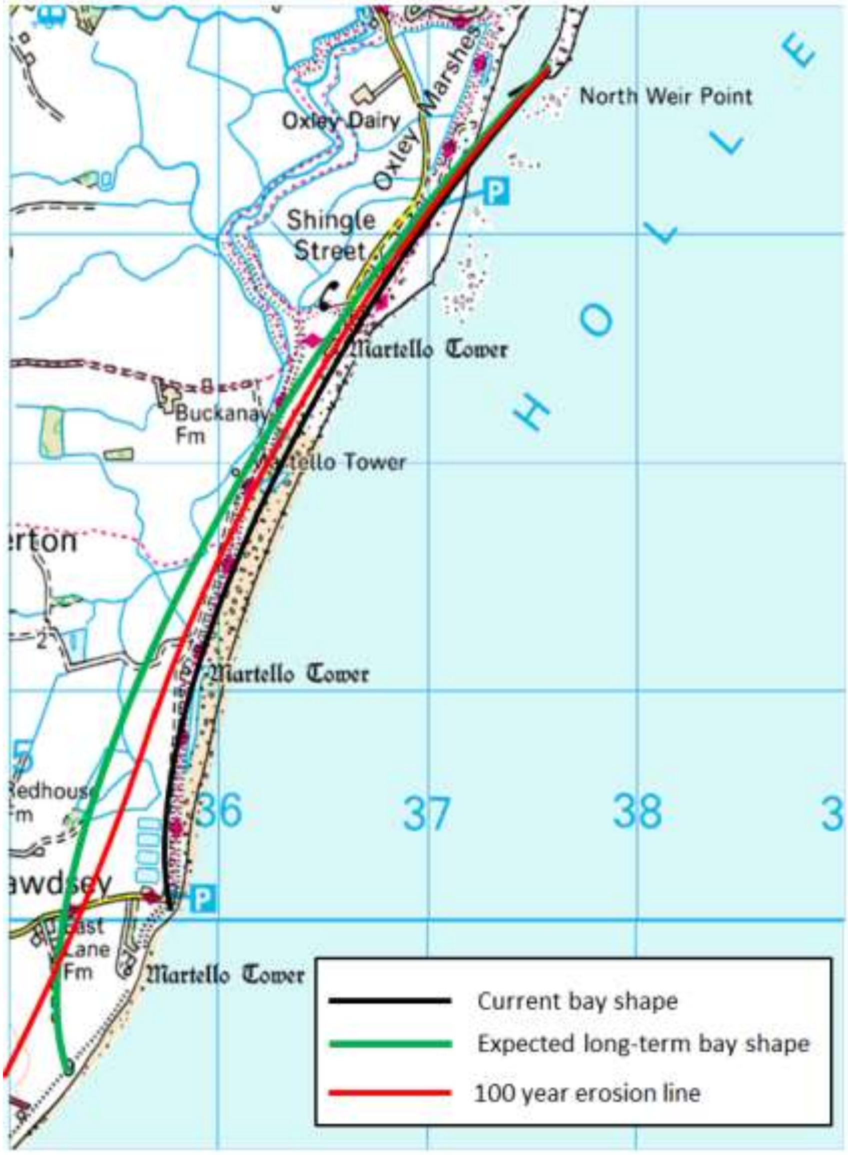
All available evidence indicates that without intervention, erosion will proceed at the present ‘hotspot’ to the south of the Martello Tower at East Lane. At present a moderate protection to the cliffs at this location is provided by a narrow shingle beach. However, it is probable that this feature is ephemeral in nature, having a limited supply from the north, and its present dynamics are governed by the action of the fishtail defence termination at the southern end of the rock revetment, and possible an intermittent supply of sediment from the south, as well as from local cliff erosion/recession. Removal of these beach sediments by north easterly waves during a storm will again expose the cliffs to waves and rapid erosion would be anticipated until such time as a beach can re-establish. Similarly to the north of the East Lane defences, the beach width is narrow and has a potential to erode further and possibly breach during an extreme event. This could then potentially expose the existing flood defences running north to wave attack at high water which in turn could compromise the defence integrity if action is not taken. Further, a breach here would also impact on the designated habitats behind the beach. To prevent this, action will be required to extend the northern extent of the existing defences.

Without active and substantial coastal management to moderate further the coastal processes along the Bawdsey frontage, the rate of erosion will probably accelerate in response to sea level rise and to changes to storm magnitude, duration, grouping and frequency. However, without knowledge of the changes likely to occur in the forcing terms, predictions of future coastal behaviour in response to climate change are subject to great uncertainty. That said it is clear that present day coastal erosion trends will continue and probably accelerate as rising sea level brings waves closer to the shoreline thereby increasing the erosion potential. Although there is little doubt that climate change will have impact on the frontage, there are far more immediate pressures to consider as the next big storm occurring during spring tides may lead to serious coastal impacts that could potentially threaten lives and property.

Consideration has also been given briefly to the future shape of the coastline in the absence of any coastal defences (or at least no further engineering interventions). Figure 7.1 shows projected coastal positions for the long-term bay shape and 100 years of erosion based on historical trends (Haskoning, 2010a). However, it is unclear how these shoreline positions were derived and thus their validity cannot be assessed here. It is assumed that they are based on the understanding of past coast changes and on well-established methods of projection trends in geomorphology evolution.

The overall shape of the predicted future coastline approximates to one that might be expected given the dominant coastal processes along the frontage. It provides also an impression of how coastal evolution might proceed if the present coastal defences at East Lane are absent/removed and thus represents a natural shoreline realignment that would place the shoreline in a natural equilibrium with sediment supply and forcing conditions.

Figure 7.1: Projected change in shoreline location.



Source: Haskoning (2010a)

8 Conclusions

The work documented in this report aims to contribute to the development of a sustainable, cost-effective, longer-term coastal management strategy providing the best outcomes for local residents, visitors and the environment. It has placed the Bawdsey coastline within a regional context and has identified important geological and geomorphological controls and a number of physical processes and events that characterise the present day and historical behaviour of the Bawdsey coastline. Although at the present time and stage in the investigations of coastal dynamics at Bawdsey a good understanding of local coastal processes has been established, there still remain gaps in knowledge that add risk to coastal defence designs. The main conclusions from the report are:

- The major sources, pathways and sinks of sediment affecting the Bawdsey frontage span a geographical range extending from Orford Ness in the north to the mouth of the Deben Estuary in the south.

- In any consideration of coastal management strategies for the frontage, the role of Orford Ness in the wide-area sediment dynamics of the coastline cannot be overlooked with respect to its role in coastal sediment storage and supply over a range of time-scales.

- East Lane, Bawdsey, has been defended by a range of coastal structures for at least the past 120 years. This has created a 'hard point' on the coast which no longer promotes active alongshore sediment transport due to unfavourable coastal orientation and wave reflection. Further, sediment supply from the north has reduced during the most recent cycle of spit progradation from Orford ness and the accompanying accretion at Shingle Street. It is considered that this has reduced the sediment supply to the south.

- It is clear from maps and aerial photographs that there is no paucity of beach sediments between Orford Ness and the Deben Estuary. However, they are unevenly distributed with large amount presently held in the spit extending from Orford Ness and at Shingle Street a little further south.

- Coastal management at East Lane has lacked a coherent strategy and for pragmatic reasons has been characterised by a series of mixed approach defence works in reaction to ongoing erosion pressures. Thus through time, the defence structures, comprising primarily rock revetments, have been extended to the north and south of East Lane as the proceeding defences have been outflanked, or where erosion has begun to compromise flood defences. The works have been a reaction to circumstances and without a radical change in management policy will require continued maintenance as well as further extension if coastal processes continue to erode the coastline in the manner they have for the past few decades. Given that resources to support capital and maintenance works is limited, and increasing hard to secure, this is viewed as being an unsustainable situation.

9 Recommendations

Ad hoc reactionary management of the coastal erosion and flood defences should be abandoned as soon as practicable in favour of the long-term strategy developed from a detailed options appraisal.

The strategy should have the full support of all stakeholders and funders. Continuation of the present partnership between BCP, EA, SCDC, EH and NE is recommended to ensure an outcome that protects the environment and meets the needs and aspirations of the residents and local businesses.

The strategy should be initially informed by a high-level appraisal of all the coastal defence options for the Bawdsey frontage. This should include traditional engineering approaches as well as more radical approaches such as realignment/recharge and/or Orford Ness spit breaching.

The strategy must be underpinned by a sound understanding of the coastal processes and account must be taken of projected climate change impacts to reduce risks and ensure resilience.

'Local' coastal management solutions must also consider far-field consequences to avoid adverse knock-on effects of any local schemes. Partnership working arrangements will ensure all interests are accounted for.

Numerical modelling to better understand and quantify alongshore transport and potential impacts of engineering is recommended at an early stage in any options appraisal study.

A dialogue with the primary stakeholders NE, EH and local land owners should begin early in the options appraisal process to ensure buy-in and to alert the process to any issues that might limit options.

The development of the future coastal defence strategy has the potential to be ground-breaking and to serve as demonstration project for innovation. Clearly, the hard defences at East Lane have had a profound impact on the coastline to the south and north and will continue to adversely affect alongshore sediment transport necessary to maintain a healthy natural beach. Since climate change is likely to exacerbate this situation, it is recommended that coastal managers step back from the present hold the line approach and consider instead an approach that works with natural processes to establish a stable coastal configuration that will require minimal maintenance in the future.

10 References

Anglian Water, 1988. Anglian Coastal Management Atlas. Sir William Halcrow & Partners, Swindon, November 1988.

Barnes, R. S. K., & Heath, S. E., 1980. The shingle-foreshore/lagoon system of Shingle Street, Suffolk: a preliminary survey. Transactions of the Suffolk Naturalist Society, 18(168), 81.

Beardall, C.H., R.C. Dryden & T.J. Holzer. 1991. The Suffolk Estuaries. Segment Publications, Colchester. 77 pp.

BGS, 1996. Saxmundham England and Wales Sheet 191, Solid and Drift Geology, 1: 50,000. British Geological Survey, Keyworth, Nottingham.

Birbeck College & Babtie, 2000. Spits and Nesses: basic processes and effects on long-term coastal morphodynamics. Report prepared for DEFRA by Birbeck College.

Black & Veatch, 2005. Minsmere Frontage: Dunwich Cliffs to Sizewell Power Stations Coastal Processes Report. Report to the Environment Agency. Redhill, Surrey, U.K.: Black & Veatch Consulting Ltd., 100p.

Bray, M. J., & Hooke, J. M., 1997. Prediction of soft-cliff retreat with accelerating sea-level rise. Journal of Coastal Research, 453-467.

Burningham, H., & J. French. 2006. Morphodynamic behaviour of a mixed sand-gravel ebb-tidal delta: Deben Estuary, Suffolk, UK, Marine Geology, 225, 23–44.

Burningham, H., & French, J. R., 2007. Morphodynamics and sedimentology of mixed-sediment inlets. Journal of Coastal Research, 50, 710-715.

Cameron T. D. J., Crosby, A., Balson, P.S., Jeffrey, D.H., Lott, G.K., Bulat, J. & Harrison, D.J., 1992. United Kingdom Offshore Regional Report: The geology of the southern North Sea. British Geological Survey. HMSO, London, 152 pp.

Carr, A. P., 1965. Shingle spit and river mouth: short term dynamics. Transactions of the Institute of British Geographers, 117-129.

Carr, A. P., 1969. The growth of Orford spit: cartographic and historical evidence from the sixteenth century, Geographical Journal, 135, 28-39.

Carr, A. P., 1970. The evolution of Orfordness, Suffolk before 1600 A.D.: geomorphological evidence. Zeitschrift fur Geomorphology, 14, 289-300.

Carr, A. P., 1971. Orford, Suffolk: further data on the Quaternary evolution of the area. Geological Magazine, 108, 311-16.

Carr, A. P., 1972. Aspects of spit development and decay: the estuary of the river Ore, Suffolk. Field Studies, 4, 633-653.

Carr, A. P., 1986. The estuary of the River Ore, Suffolk: three decades of change in a longer-term context. Field Studies, 6(3), 439-458.

Clayton, K., 1987. Orfordness: coastal stability and coastal defences, Report to Nature Conservancy Council, Peterborough

Cobb, R. T., 1956. Shingle Street: Suffolk. Annual Report of the Field Study Council, 57, 31-42.

Dixon, R.G., 1979. Sedimentary facies in the Red Crag (Lower Pleistocene, East Anglia). Proceedings of the Geologists' Association 90, 117–132.

Dixon, R.G., 2006. Sutton Knoll. Transactions of the Suffolk Naturalists' Society 42, 97–101.

Dixon, R., 2011. Field Meeting to the Bawdsey Peninsula, Suffolk, England, 22nd May 2010, to examine London Clay, Coralline Crag and Red Crag deposits: Leaders: Roger Dixon and Bob Markham. Proceedings of the Geologists' Association, 122(3), 514-523.

Environment Agency, 2007 Coastal Morphology Report Bawdsey (1991 – 2006). RP001/S/2007, Shoreline Management Group, Environment Agency, Anglia Region, Peterborough.

Environment Agency, 2008. Suffolk sea state report, Year 2 Oct 2007 – Sept 2008. Shoreline Management Group, Environment Agency, Anglia Region, Peterborough, 48pp.

Environment Agency, 2010. Coastal Morphology Report Bawdsey, RP015/S/2010, 27pp.

Environment Agency, 2013. East Lane, Bawdsey: Assessment of current situation and options, 9pp.

Fuller, R. M., & Randall, R. E., 1988. The Orford Shingles, Suffolk, UK—classic conflicts in coastline management. Biological Conservation, 46(2), 95-114.

Futurecoast, (2002). Futurecoast CD. Produced by Halcrow Group Ltd for Defra, Swindon, UK.

Green, C. P., & McGregor, D. F., 1990. Orfordness: geomorphological conservation perspectives. Transactions of the Institute of British Geographers, 48-59.

Halcrow, (1988). Anglian coastal management atlas. Report produced by Sir William Halcrow and Partners for Anglian Water, Swindon, UK.

Halcrow, 1998 Shoreline Management Plan, for sub-cell 3c Lowestoft to Harwich. Report for Suffolk Coastal District Council, Waveney District Council & Environment Agency. Halcrow, Swindon.

Halcrow Group Limited, 2006. Bawdsey-East Lane Sea Defences: Study to Inform Appropriate Assessment, Environment Agency Anglian Region, March 2006, 106pp.

Hayes, M.O., 1975. Morphology of sand accumulation in estuaries: an introduction to the symposium. In: Cronin, L.E. (Ed.), Estuarine Research. Academic Press, New York, pp. 3– 22.

Horrillo-Caraballo, J. M., Karunarathna, H. U., Reeve, D. E., & Pan, S., 2014. A hybrid-reduced physics modelling approach applied to the Deben Estuary, UK. Coastal Engineering Proceedings, 1(34), sediment-76.

HR Wallingford, 1996. Sea defences: East Lane Bawdsey, Site visit report. Report EX 3369. Report for the Environment Agency, Anglian Region. H. R. Wallingford, Wallingford.

HR Wallingford, BEEMS, U. E. A., Haskoning, & D'Olier, B., 2002. Southern North Sea Sediment Transport Study, Phase 2. HR Wallingford Report, EX, 4526.

HR Wallingford, 2008. Understanding the lowering of beaches in front of coastal defence structures, Phase 2. Mitigation methods, 49pp.

McGregor, D. F. M., & Green, C. P., 1990. Composition of the Orfordness shingle. Proceedings of the Geologists' Association, 101(3), 259-263.

Morris, J., Beedell, J., & Hess, T. M., 2014. Mobilising flood risk management services from rural land: principles and practice. Journal of Flood Risk Management. DOI: 10.1111/jfr3.12110

Kidson, C. & Carr, A. P., 1959. The movement of shingle over the sea bed close inshore. *Geographical Journal*, 380-389.

Kidson, C., Carr, A. P., & Smith, D. B., 1958. Further experiments using radioactive methods to detect the movement of shingle over the sea bed and alongshore. *Geographical Journal*, 210-218.

Motyka, J. M., & Brampton, A., 1993. Coastal management: mapping of littoral cells. Technical Report. HR Wallingford, 115 pp.

NRFA, 2014. National River Flow Archive. http://www.nwl.ac.uk/ih/nrfa/.

Onyett, D. & Simmons, A., 1983. East Anglian Coastal Research Project Final Report, Geobooks, Norwich, 125 pp.

Pontee, N. I., (2005). Management implications of coastal change in Suffolk, UK. *Maritime Engineering 158, Issue MA2, pp.69-83.*

Posford Duvivier, 1999. Suffolk estuarine strategies: river Deben. Strategy Report: Volume 1 Main Report. Environment Agency: Anglian Region, CP505(163). 61 pp (plus appendices).

Posford Duvier, 2000. Hollesley to Bawdsey Sea defences, Coastal process report. Report for the Environment Agency. Posford Duvivier, Peterborough.

Posford, 2002: Suffolk coast and estuaries Coastal Habitat Management Plan. Final report. Produced by Posford Haskoning for English Nature & Environment Agency. October 2002, Peterborough, UK.

Royal Haskoning, 2003. East Lane Project Appraisal. Hollesley to Bawdsey Sea Defences, Environment Agency Project number 3E3461, 56pp.

Royal Haskoning, 2009. Shoreline Management Plan, Sub cell 3c, Lowestoft Ness to Felixstowe Landguard Point, Appendix C, Review of coastal processes and geomorphology. Draft report for Suffolk Coastal District Council. Royal Haskoning, Peterborough.

Royal Haskoning, 2010a. Suffolk SMP2 Sub-cell 3c Policy Development Zone 6 – Orford Ness to Cobbold's Point, Suffolk Coastal District Council/Waveney District Council/ Environment Agency, 66pp & Appendices.

Royal Haskoning, 2010b. Suffolk SMP2 Sub-cell 3c Policy Development Zone 7 – Cobbold's Point to Felixstowe Port (south),Suffolk Coastal District Council/Waveney District Council/ Environment Agency, 36pp & Appendices.

Steers, J. A., 1926. Orford Ness: a study in coastal physiography. Proceedings of the Geologists' Association, 37(3), 306-IN6.

Steers, J. A. 1951. Notes on erosion along the coast of Suffolk. Geological Magazine, 88(06), 435-439.

Steers, J. A., 1957. How are beaches supplied with shingle? Coastal Engineering Proceedings, 1(6), 18.

Taylor, H. R., & Marsden, A. E., 1983. Some sea defence works in eastern England. In Shoreline protection (pp. 133–144). London: Thomas Telford. London.

Vincent, C. E., 1979. Longshore sand transport rates—a simple model for the East Anglian coastline. Coastal Engineering, 3, 113–136.

11 Glossary

Bathymetry – The measured shape and depth contours of the sea bed.

BP – Before present**.**

Fetch - The uninterrupted distance over water which the wind acts to produce waves.

Intertidal – The coastal area between the Lowest Astronomical Tide (LAT) and Highest Astronomical Tide (HAT).

Maximum wave height (Hmax) – Statistic of the maximum wave height recorded in a period of time.

Mean direction (Mdir) – The average or main direction from which waves have come, measured over a period of time.

Mean Sea Level - Generally refers to 'still water level' above a fixed datum (excluding wave influences), averaged over a period of time such that periodic changes in level (e.g. due to the tides) are smoothed out.

Mean wave period (Tz) – Also referred to as the zero crossing period, a description of the average wave period over duration of time.

Neap Tide - The tide that occurs when the tide-generating forces of the sun and moon are positioned at right angles to each other. The neap tide has the lowest tidal range.

Ordnance Datum (OD) – A specific datum or plane to which depths or heights are referred to.

Peak period (Tp) – Also called dominant wave period and Tpeak, it is the wave period (time for two successive waves to pass a point) associated with the largest wave energy, obtained from the spectral "peak frequency" i.e. the frequency band that has the largest energy.

Residual surge level – The difference from the predicted (astronomical / harmonic tide level) and the observed / instrument measured level. A surge can be negative or positive relative to the mean sea level.

Return period – A statistical interpretation to describe the frequency an event will occur, for example a 2.5 m wave that may be expected once in every 5 years would have a 1:5 years return period.

Sea (waves) – Waves generated at a storm system, under a height of 2 m.

Significant wave height (Hs) – Statistical calculation of Hm0 taken from the spectral analysis to describe the average wave height.

Spring tide - The tide that occurs when the tide-generating forces of the sun and moon are in alignment and results in a higher than average tidal range.

Storm surge - A storm surge is the additional sea level accounted for by a storm. The rise in water level causes a propagating bulge of water on the open coast caused by the action of wind stress and atmospheric pressure on the sea surface.

Storm waves – Wind driven waves associated with a storm system, these waves have a higher frequency than swell waves and therefore can cause multiply frequency peaks in the spectra. In a multiple peaked spectrum the mean wave period (Tz) may not be a measure of the frequency where the peak energy occurs.

12 Acronyms

AOD	Above ordnance datum
BP	Before present
Ch	Chainage
DSPR	Directional spreading (waves)
EA	Environment Agency
HAT	Highest astronomical tide
IPCC	Intergovernmental Panel on Climate Change
JPA	Joint probability analysis
LAT	Lowest astronomical tide
PAR	Project Appraisal Report
MHWS	Mean high water spring
MHW	Mean high water
MHWN	Mean high water neap
MLWN	Mean low water neap
MLW	Mean low water
MLWS	Mean low water spring
MSL	Mean sea level
ODN	Ordnance Datum Newlyn
SCDC	Suffolk Coastal District Council
SLR	Sea level rise
SMP2	Second Shoreline Management Plan

13 Notation

D50	Median grain size (mm)
Hm0	Significant wave height (m)
Pw	Wave power (J/m/s)
Tp	Peak wave period (s)
Uw	Bottom wave orbital velocity (m/s)
θ	Mean wave direction (degrees N)
θ_b	Mean beach angle

Appendices

Appendix A. Chronology of events and reference material in the study

1881	The first Ordnance Survey (OS) County Series map of 1881 shows a wide shingle beach with no major coastal defences present.
1808-1810	Martello Tower was built.
1886	Bawdsey Manor was built.
1904	Two Martello Towers at East Lane are shown in the 1904 OS map. No information about when the second tower was built, but probably together with the first one around 1808.
1926	Only one Martello Tower remains in the OS map indicating that due to coastal erosion between 1904 and 1926 one of the towers was lost. In addition, the map indicates that a significant concrete seawall, originally constructed by the local landowner Sir William Eley Cuthbert Quilter, have been built and the area has begun to form the point or promontory. The wall is locally known as the Quilters Wall.
WW1	During the first word war a pillbox, field coastal battery and a gunnery observation tower were built in the study area.
WW2	Initial defences comprised a gun battery and the anti-invasion installations were built during the Second World War era. These consisted of 'dragons teeth' metal spikes and 'anti-tank' concrete blocks.
1949-1951	First major repair of the above defences were undertaken.
1992-1992	Repair defence works were undertaken in the area. Anti-tank' blocks were placed in the void left after the promenade deck collapsed.
1995-1996	Emergency works to repair concrete wave return wall, running around the promontory and to the north, with a 'Kentstone' block work revetment in front were undertaken. Two partial collapses at this time were in-filled with rock armour under emergency maintenance works initiated by the then National Rivers Authority's

	(now the Environment Agency) Operations Department. To the south of the sheet piling area, approximately 200m of rock provides protection to the earth embankment and soft cliffs further south were built as part of the emergency works with the aim of halting the erosion of the cliffs, which had escalated, at the time, to rates in excess of 1 metre per month.
2003	East Lane Project Appraisal: Hollesley to Bawdsey Sea Defences. Recommendations: (a) Strengthening / extension of the rock revetment around the promontory, keying into the existing revetment and where possible re-using existing rock, to a 1:100 year standard of defence (Year 0, EA responsibility); (b) construction of a more robust rock armour revetment along the soft cliff line in front of the East Lane properties (Year 0, SCDC responsibility); and (c) construction of a more robust rock armour revetment along the earth embankment to the south of the promontory in year 10.
2004	Defra declines funding (9.3 CB ratio / 19 Points). A group of local landowners and residents formed East Lane Trust. Landowners identified numerous potential housing plots above the 5 metre flood contour and abutting village boundaries which could be gif ted to East Lane Trust. The concept of East Land Trust is discussed with SCDC.
2005	Suffolk Coastal District Council (SCDC) undertook 'low-cost' short-term emergency works along the frontage south of the Point. EH revision to Defra (8.4 CB ratio / 19.2 points).
2006	Priority points raised above 20 for Defra.
2007	The Environment Agency was able to carry out emergency improvements to their defences north of the Point (Phase 1, Figure 2). Phase 2, which included the Environment Agency and SCDC frontages to the south of the Point, was more difficult to implement because grant-in-aid funding was still not available. This was despite the increased rate of cliff cut back to the south threatening the loss of the Martello Tower and a

	significant increase to the flood risk to the inland villages of Bawdsey and Alderton.
2007	CDC Cabinet meeting - consideration was given to proceeding with a Coast Protection scheme at East Lane, Bawdsey. A planning application is submitted to SCDC and planning consent obtained.
2008	East Lane Trust (ELT) given charitable status.
2008	Phase 2: SCDC as the local maritime authority agreed that they would act to promote the scheme under the Coast Protection Act. Works commenced on site in October 2008. A scheme was completed in the summer of 2009 which involved the construction of rock armour revetment in front of soft cliffs to protect the vulnerable area of the coast at Bawdsey and reduce longer-term erosion. This scheme provides protection for the next 50 years (Figure 3).
2009	December 2009 a situation emerged at East Lane where beach levels dropped significantly as a result of moderate south-easterly gales.
2010	Emergency works were undertaken in Jan/Feb of 2010 which consisted of the placement of rock armour in front of the affected section of sea wall to mitigate against fluctuating beach levels. North end tie-in complete.
2012/13	Further emergency works scheme was implemented to the south of this site. Once again this was due to shingle loss in front of the defence due to storms. On this occasion a landward widening of the embankment was implemented with reinforcement of the seaward face. Repairs to the northern end of the defence line, installation of a reinforced clay bund (2,000tonnes, £30k of imported clay) to rear of existing embankment line and addition of armourloc blockwork protection to the seaward face over approximately 50 linear meters. Blockwork mattresses and geotextile used from surplus on other jobs, only major costs were the clay labour and plant.

2014	Emergency works to complete the remaining section of the Quilters Wall.
2014/15	Emergency works involved the importation of fill material to reinstate the seaward embankment profile, then being overlain with geotextile and approximately 4,000 tonnes of graded rock armour to construct a rock revetment. Initial works to the northern end of the site covered approximately 80 linear metres of the wall and a small 20m section was also in-filled slightly further south where an existing gap in the revetment was present. Site Works, reinstatement and demobilisation were substantially complete by the 19th March 2014.

Appendix B. Lines of Defence: a work by Bettina Furnée[5]

Winter

January 2005

February 2005

March 2005

[5] (http://www.ifever.org.uk/camera/).

Spring

April 2005

May 2005

June 2005

Summer

July 2005

August 2005

September 2005

Autumn

October 2005

November 2005

December 2005

Appendix C. Shoreline change analysis

Table C1 and Figure C1 presents results from the shoreline change analysis. This shows the following statistics for each transect: End Point Rate (EPR); confidence of End Point Rate (ECI); Shoreline Change Envelope (SCE); Linear Regression Rate (LRR); R-squared (LR2); Standard Error of Linear Regression (LSE); and Standard Error of the Slope with Confidence Interval (LCI, 95.5%).

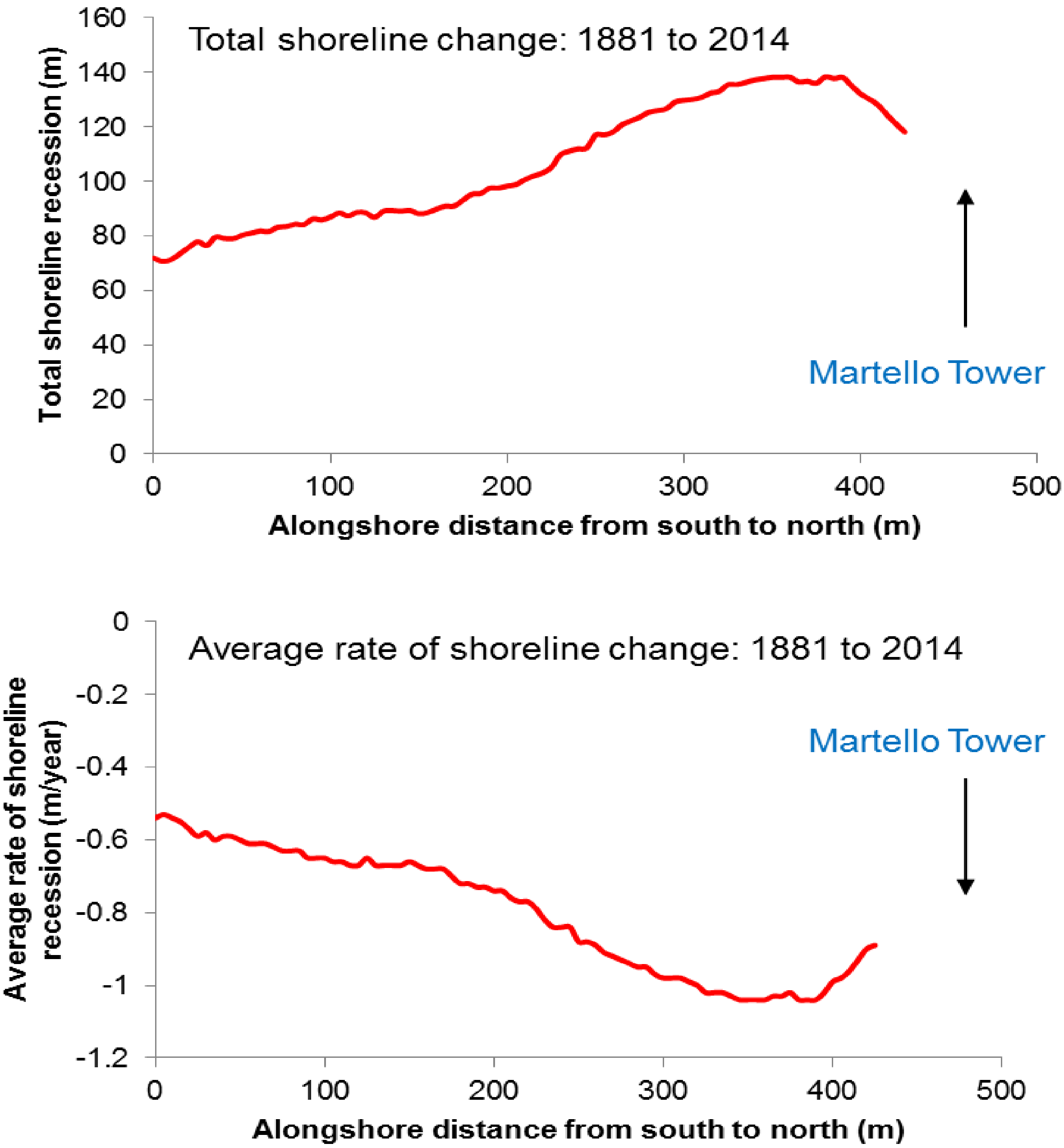
Table C.1: Results from the shoreline change analysis

TRANSECTS	EPR	ECI	SCE	LRR	LR2	LSE	LCI, 95.5%
1	0	0.061	0.02				
3	-0.54	0.011	71.88	-0.4	0.81	8.14	0.107
4	-0.53	0.011	70.67	-0.39	0.8	8.03	0.106
5	-0.54	0.011	71.37	-0.41	0.8	8.44	0.11
6	-0.55	0.011	73.55	-0.42	0.79	8.63	0.112
7	-0.57	0.011	75.86	-0.42	0.77	9.14	0.119
8	-0.59	0.011	77.85	-0.4	0.7	10.57	0.137
9	-0.58	0.011	76.48	-0.4	0.73	10.03	0.13
10	-0.6	0.011	79.57	-0.44	0.77	9.83	0.128
11	-0.59	0.011	79.07	-0.44	0.75	10.23	0.133
12	-0.59	0.011	79	-0.44	0.75	10.23	0.133
13	-0.6	0.011	80.24	-0.44	0.74	10.77	0.14
14	-0.61	0.011	80.99	-0.44	0.71	11.35	0.147
15	-0.61	0.011	81.78	-0.44	0.71	11.45	0.149
16	-0.61	0.011	81.61	-0.44	0.71	11.49	0.149
17	-0.62	0.011	83.09	-0.45	0.71	11.5	0.149
18	-0.63	0.011	83.42	-0.44	0.7	11.86	0.154
19	-0.63	0.011	84.3	-0.45	0.7	11.93	0.155
20	-0.63	0.011	84.12	-0.44	0.67	12.65	0.164
21	-0.65	0.011	86.24	-0.45	0.67	12.75	0.165
22	-0.65	0.011	85.88	-0.45	0.68	12.53	0.163
23	-0.65	0.011	86.91	-0.45	0.67	12.93	0.168
24	-0.66	0.011	88.44	-0.45	0.65	13.52	0.175
25	-0.66	0.011	87.37	-0.46	0.63	14.14	0.183
26	-0.67	0.011	88.62	-0.48	0.61	15.35	0.199
27	-0.67	0.011	88.49	-0.49	0.63	14.93	0.194
28	-0.65	0.011	86.78	-0.47	0.65	13.98	0.181
29	-0.67	0.011	89.1	-0.48	0.61	15.34	0.199
30	-0.67	0.011	89.32	-0.47	0.59	15.77	0.205
31	-0.67	0.011	89.07	-0.47	0.59	15.96	0.207
32	-0.67	0.011	89.35	-0.48	0.61	15.49	0.201

TRANSECTS	EPR	ECI	SCE	LRR	LR2	LSE	LCI, 95.5%
33	-0.66	0.011	88.11	-0.48	0.59	16.18	0.21
34	-0.67	0.011	88.53	-0.47	0.55	17.2	0.223
35	-0.68	0.011	89.85	-0.48	0.56	17.14	0.222
36	-0.68	0.011	90.9	-0.48	0.57	16.87	0.219
37	-0.68	0.011	90.94	-0.49	0.58	17.14	0.222
38	-0.7	0.011	93.12	-0.51	0.58	17.42	0.226
39	-0.72	0.011	95.26	-0.55	0.61	17.54	0.228
40	-0.72	0.011	95.55	-0.57	0.62	17.94	0.233
41	-0.73	0.011	97.49	-0.58	0.62	18.22	0.237
42	-0.73	0.011	97.55	-0.58	0.63	18.19	0.236
43	-0.74	0.011	98.3	-0.59	0.64	17.86	0.232
44	-0.74	0.011	98.83	-0.6	0.62	19.07	0.247
45	-0.76	0.011	100.65	-0.62	0.62	19.48	0.253
46	-0.77	0.011	102.01	-0.64	0.62	19.99	0.259
47	-0.77	0.011	103.07	-0.65	0.64	19.76	0.256
48	-0.79	0.011	105.11	-0.67	0.62	21.06	0.273
49	-0.82	0.011	109.64	-0.68	0.64	20.48	0.266
50	-0.84	0.011	111.09	-0.7	0.63	21.52	0.279
51	-0.84	0.011	111.88	-0.71	0.63	21.97	0.285
52	-0.84	0.011	112.27	-0.71	0.64	21.72	0.282
53	-0.88	0.011	117	-0.73	0.63	22.59	0.293
54	-0.88	0.011	117.03	-0.73	0.63	22.63	0.294
55	-0.89	0.011	118.16	-0.75	0.63	23.29	0.302
56	-0.91	0.011	120.81	-0.77	0.62	24.27	0.315
57	-0.92	0.011	122.2	-0.78	0.62	24.65	0.32
58	-0.93	0.011	123.54	-0.79	0.62	24.9	0.323
59	-0.94	0.011	125.32	-0.8	0.63	25.16	0.327
60	-0.95	0.011	126	-0.81	0.62	25.47	0.33
61	-0.95	0.011	126.65	-0.82	0.63	25.56	0.332
62	-0.97	0.011	129.09	-0.83	0.63	26.09	0.339
63	-0.98	0.011	129.76	-0.84	0.63	26.08	0.339
64	-0.98	0.011	130.12	-0.85	0.63	26.14	0.339
65	-0.98	0.011	130.81	-0.86	0.64	26.27	0.341
66	-0.99	0.011	132.38	-0.87	0.64	26.46	0.343
67	-1	0.011	133.05	-0.88	0.64	26.65	0.346
68	-1.02	0.011	135.47	-0.89	0.64	26.85	0.348
69	-1.02	0.011	135.49	-0.9	0.64	27.05	0.351
70	-1.02	0.011	136.33	-0.91	0.65	27.16	0.352
71	-1.03	0.011	137.21	-0.92	0.65	27.3	0.354

TRANSECTS	EPR	ECI	SCE	LRR	LR2	LSE	LCI, 95.5%
72	-1.04	0.011	137.68	-0.92	0.65	27.07	0.351
73	-1.04	0.011	138.16	-0.93	0.66	26.87	0.349
74	-1.04	0.011	138.14	-0.93	0.66	26.82	0.348
75	-1.04	0.011	138.2	-0.93	0.67	26.61	0.345
76	-1.03	0.011	136.51	-0.93	0.67	26.38	0.342
77	-1.03	0.011	136.72	-0.93	0.67	26.24	0.341
78	-1.02	0.011	136.01	-0.94	0.68	26.05	0.338
79	-1.04	0.011	138.33	-0.96	0.69	26.11	0.339
80	-1.04	0.011	137.72	-0.96	0.69	25.85	0.335
81	-1.04	0.011	138.08	-0.97	0.69	26.25	0.341
82	-1.02	0.011	135.02	-0.95	0.73	23.68	0.307
83	-0.99	0.011	132.08	-0.95	0.74	22.84	0.296
84	-0.98	0.011	130.15	-0.95	0.75	22.03	0.286
85	-0.96	0.011	127.95	-0.94	0.76	21.57	0.28
86	-0.93	0.011	124.37	-0.92	0.77	20.56	0.267
87	-0.9	0.011	121.09	-0.91	0.78	19.43	0.252
88	-0.89	0.011	118.08	-0.86	0.8	18.81	0.255

Figure C.1: Computed total and rate of shoreline changes.



Source: Mott MacDonald, 2015