Bawdsey

Coastal Process Assessment

DDR5548-RT001-R03-00

September 2016

Document information

Document permissions	Confidential - client
Project number	DDR5548
Project name	Bawdsey
Report title	Coastal Process Assessment
Report number	RT001
Release number	R03-00
Report date	September 2016
Client	The Crown Estate
Client representative	Dr Mike Cowling
Project manager	Dr Belen Blanco
Project director	Jonathan Simm

Cover photograph courtesy Mike Page, July 2016

Document history

Date	Release	Prepared	Approved	Authorised	Notes
16 Sep 2016	03-00	BLB	AHB	AHB	Incorporating minor typos and comments made by stakeholders
09 Aug 2016	02-00	BLB	AHB	AHB	Incorporating minor typos and comments made by Client
29 Jul 2016	01-00	BLB	AHB	AHB	Draft for Client comments

Document authorisation

Prepared	Approved	Authorised

Executive Summary

The Crown Estate (TCE) wishes to improve its knowledge of the complicated coastal processes at East Lane, Bawdsey and its immediate surroundings in order to help inform a coastal management option appraisal for the frontage. HR Wallingford carried out this study of the coastal processes of the area using data analysis and numerical modelling.

The work completed within this study involved three interrelated tasks, namely a desktop review of past shoreline, profile and seabed changes, a wave assessment to derive a set of nearshore time-series and numerical modelling of shoreline evolution to investigate how the longshore shingle transport and the plan-shape of the beaches are likely to change in the future.

Sources of beach sediments

Starting with the origins of the shingle beaches between Shingle Street and the Deben, this study has concluded that as well as longshore drift from the north past Orford Ness, there has been a local source of beach sediment from the coastal cliffs at Bawdsey between East Lane and the mouth of the Deben estuary that has not been emphasised in previous studies. Both these sources have provided shingle to the beaches and could do so again depending on future wave conditions.

Some southward transfer of beach sediment from the mobile banks across the mouths of Deben and Ore/Alde estuaries occurs episodically, its transport being influenced by tidal flows in and out of the estuaries, by unpredictable meandering of the main entrance channels and by wave action. As a consequence the balance between the gains of shingle from the north and the losses to the south is highly variable and difficult even to measure let alone predict.

The available evidence from surveys of the nearshore seabed does not suggest to us any significant offshore losses of gravel from these beaches, where it would presumably have otherwise resulted in a noticeable accumulation on the seabed.

Recent shoreline changes

Since 1945, the overall impression of shoreline changes between East Land and Shingle Street is a ‘seesawing’ of the coastline around a hinge point in the centre of Hollesley Bay between those two locations, with beach sediment transferring from one end of the frontage to the other together with gradual landwards recession of the coastline over this same period. However both here and at Shingle Street, there seems to be evidence of periods during which very little changed followed by more active times when the beach plan-shape altered more noticeably.

To the south of East Lane, substantial recession of the shoreline at and just to the south of East Lane is the most striking difference between recent shoreline and that of 1881. The much smaller recession of the coastline further south is also noteworthy. The beaches just the south of the coastal defences at East Lane have gone through phases of both advance and retreat, but recession has dominated with the latest surveys showing the most landward shoreline position over the last 130 years.

Examining the topographic beach surveys provided by the Environment Agency’s Anglian Coastal Monitoring project the suggests that since 2012 there has been a continuing movement of beach sediment northwards from the vicinity of East Lane, with that sediment moving along the coastline in the centre of Hollesley Bay and accumulating at or just south of Shingle Street. We therefore interpret the overall pattern of changes in beach widths along the coastline on either side of East Lane, Bawdsey as being caused by a recent change in the direction of longshore beach sediment transport in Hollesley Bay from southward to northward, particularly since summer 2013.

An important consequence of the recent trends in beach morphology is the increased possibility of outflanking of both ends of the seawall at East Lane, with the attendant greater risks of erosion or flooding of the hinterland. These localised problems contrast with rather stable beach widths both in the centre of Hollesley Bay and the Bawdsey cliffs frontage.

Changes in the seabed bathymetry

Bathymetric chart comparisons carried out by Helene Burningham (UCL) only cover the period prior to 1990, so they cannot directly provide any indication of possible causes of changes near East Lane in the last 25 years. Our impression is that the historic changes prior to this date may have contributed to a gradual increase in wave energy along the frontage each side of East Lane as the Cutler Bank has moved offshore and the shore-platform gradually lowered. This would be expected to have led to a long-term tendency for the erosion of cliffs and landward retreat of the shingle barrier beach in Hollesley Bay. However, there is no evidence for rapid movements or changes in nearshore banks that might have caused different responses in the beaches over short stretches of the coastline near East Lane.

Comparison of more recent cross-sectional surveys of the beaches and the nearshore seabed undertaken as part of the Environment Agency’s Anglian Coastal Monitoring programme have shown, in contrast, that a little further north, particularly near Orfordness, large changes in the nearshore seabed have occurred at the same time as localised changes in beach widths.

Wave conditions

Waves approaching this part of the East Anglian coast arrive from one of two main directions, i.e. from N and NE and from the SW sector. This bimodality complicates the behaviour of the shoreline: the difference in persistence and strength of waves from each of these directions governs the evolution of the beaches at and near East Lane.

Analysis of the offshore wave data showed two years since 1981 where the offshore wave height exceeded for more than 1% of the year was substantially higher than the average. Very strong winds during the winters of 1989/90 and 2014/15 resulted in considerable damage over much of the UK. Substantial changes in the study shoreline were observed and measured during these winters.

Further analysis revealed that during these winters, the proportion of waves approaching from the south-west almost doubled and many fewer waves arrived from the north-east sector. Both the increased intensity of large waves and the change in their direction seem to be linked to an increased value of the North Atlantic Oscillation (NAO) index which meteorologists use to characterize (high-altitude) atmospheric pressure and wind patterns over that ocean (in the way that the El Niño / La Niña weather patterns occur over the Pacific Ocean).

The longshore drift regime

The ‘traditional’ view of the longshore drift regime, based on studies going back some 70 years, is that the long-term net drift direction along this part of the Suffolk coastline is southwards, but with periods of a reverse drift both along the spit that extends south from Ordfordness as well as along almost the whole frontage between the Ore/Alde and the Deben.

As a consequence of this traditional view of the drift regime, it is to be expected that the beach just north of the artificially-maintained headland at East Lane would remain well-stocked with sediment but there would likely be a problem of erosion to the south of it since the projection of the seawall and the lack of beach sediment in front of it would greatly reduce the longshore drift rate. However, beach changes in recent years strongly suggest a net northwards transport of shingle from East Lane towards Shingle Street.

Longshore drift rates in Hollesley Bay and along Bawdsey cliffs are very variable. In general, in most years, there seems to be a drift divide point somewhere in between East Lane and Bawdsey Cliffs (the position of this point varying throughout the years). From the winter of 2013 there has been an increased northerly drift at all the points studied except one close to Bawdsey Manor. In the last two years, the northerly drift increased to about double its average value and the southerly drift has been less than its average value. The result has been a large net northerly drift which would be responsible for the changes seen in the beach survey data. It is worth pointing out that the increase in northerly drift causing the erosion at the north of East Lane is mainly due to natural but unpredictable causes i.e. an increase of the waves from the SW and reduced waves from N and NE.

The main changes in the behaviour of the beaches near East Lane in recent times are concluded to be the result of changes in offshore wave conditions that have altered the direction of the alongshore sediment transport.

While the variations in the net drift rate have dominated the short-term changes in the beach plan-shape, especially in recent years, the magnitude of that net rate, in the centre of Hollesley Bay for example, has been modest.

Predicted future shoreline evolution

A beach plan-shape model of the coastline from just south of Shingle Street and extending almost to Bawdsey Manor has been set up and calibrated. A great amount of time and effort was spent in the model calibration, especially in trying to find the final best nearshore wave sequence that produced beach changes as observed. With the model calibrated for the specific study area, it was then applied to predict possible future changes in shoreline position. This exercise was aimed at identifying what potential changes in the current situation might result from changes in the mean offshore wave direction, from changes in the sequencing of wave events or from an increase in sea level (relative to the land), all of which could be a consequence of climate change.

The aim of this modelling was to examine where problems may develop in the future, both north and south of East Lane, in terms of possible erosion or flooding risks.

Of course it is impossible to predict the future nearshore wave climate for the next 50 years let alone predict the sequencing of the individual wave events that will occur under any climate. Due to this, a series of 40 plausible long-term time-series of nearshore wave conditions have been developed in order to predict a range of possible shoreline positions over the next 50 years.

These alternative future scenarios indicated that on their own sea level rise (relative to the land) and the sequence of wave events are not major influences in the development of the plan-shape of the beaches. The locations and rates of change of beach width will however be influenced by changes in the proportion of waves arriving from the NE and SW sectors, and this cannot be predicted with any confidence.

Recommendations

The substantial historical changes discussed throughout this report make a strong case for continuing the monitoring of the beaches in the area (currently undertaken by the Anglian Monitoring System), and possibly increasing the frequency of the surveys which involve bathymetric surveying of the nearshore seabed designed to record the levels of the nearshore seabed approximately as far out as the -10m OD contour.

Turning now to possible intervention options, the main concern resulting from changes to the morphology of the beaches between the mouths of the Ore/ Alde and Deben estuaries is the possible outflanking of one or even both ends of the seawall at East Lane, Bawdsey. Analysis of past changes to the beaches and our modelling of how those beaches may later in the future point to the possibility of rapid and localised erosion in these two areas.

It should first be pointed out that the drift rate in Hollesley Bay, which has been northwards in recent years may reverse naturally, leading to a return of at least some of the shingle that has moved away from the northern end of this seawall to the north in recent times. While this would reduce the risk of outflanking of the seawall at its northern end, this would not necessarily lead to a reversal of the erosion problems just to the south of that seawall.

The problems of erosion and cliff recession just to the south of the coastal defences at East Lane seem to have been less of a concern in the past. In general the loss of cliff top land has smaller economic consequences than flooding. This is likely to have been the case when comparing the relative importance of problems in the past. However the potential for rapid beach loss and cliff recession, accompanied by lowering of the shore-platform at the base of the cliffs, may be of greater concern if this is the location chosen to bring ashore cables.

Because of this, there may be a case for reducing the risks of erosion in front of and just beyond both ends of the existing seawall at East Lane. The normal solution to this problem, for example as used at the southern end of the seawall at Aldeburgh, is to retain a beach between groynes (or less frequently breakwaters) along the frontage(s) at greater risk.

This study has shown that the drift rates towards and either side of the East Lane headland are variable in both magnitude and direction. In this context it is not straightforward to assess the possible advantages or disadvantages of installing groynes to help reduce the changes in beach width to the north or to the south of the East Lane headland. In general, groynes can help spread a localised and intense erosion problem over a greater length of a frontage allowing more time to intervene and remedy a loss of beach sediment. Given the extent to which the seawall at East Lane already projects seaward, and the lack of beach sediment in front of it, this structure is -reducing the transfer of shingle from one side of the headland to the other. Further modelling of beach changes between and on each side of any proposed groyne system would be needed to clarify their likely effectiveness.

Contents

Figures

Tables

1. Introduction

The Crown Estate (TCE) wishes to improve its knowledge of the coastal processes at East Lane, Bawdsey and its immediate surroundings in order to help inform a coastal management option appraisal for the frontage. HR Wallingford carried out this study of the coastal processes of the area using data analysis and numerical modelling.

At East Lane, Bawdsey, coastal defences have been installed to protect a small headland which was the site of an anti-aircraft battery in World War II. Figure 1.1 shows the location of the study area and Figure 1.2 a snapshot of changes in the positions of the cliffs (or defences) between 1945 and 2012, indicating the recession that has occurred over this period. To the north of East Lane, in particular, there is a concern that further erosion of the beach could lead to the risk of flooding of an extensive area of very low-lying land, with the long-term potential for a breakthrough to the estuary of the Deben. There have been discussions over many years regarding the advantages and disadvantages of continuing to defend this part of the coastline and how changes in its management might affect adjacent areas.

A coastal processes review has recently been completed by Mott MacDonald (Mott MacDonald, 2015) on behalf of the Environment Agency (EA). Their study report comprises a brief review of the contemporary coastal problems at Bawdsey, based on existing studies, as well as a comprehensive chronological sequence of coastal protection measures implemented to offset erosion since the early 1900s. The report also includes a description of the processes responsible for coastal change in the area. The report provides a good summary of past changes and the general coastal process issues at the site. However, because it relies heavily on past studies and reports that have been undertaken at a larger-scale (macro) level, it does not provide a more detailed understanding of the processes at the site. In particular, it does not address:

- Conflicting discussions regarding the net sediment transport direction. Previously studies have generally concluded it to be North to South, yet recent shoreline changes to the north of East Lane suggest a net northerly transport;
- How the longshore transport of beach sediment presently varies annually and seasonally;
- How this transport and therefore the plan-shape of the coastline are likely to change in the future.

Mott MacDonald recognised that this detailed understanding is limited. For example in Section 3.4 (Mott MacDonald 2015) they recognise the potential importance of offshore banks and that to understand this further would require numerical modelling. The modelling carried out in this study has been focused on addressing the questions raised above.

This study builds on the Mott MacDonald (2015) report, the most recent Shoreline Management Plan (Royal Haskoning, 2010), Environment Agency monitoring and morphology reports (Environment Agency 2007a, 2007b, 2010, 2011) and other background information, but it goes a step further by examining alongshore sediment transport rates along the coastline in greater detail, both for present day and future scenarios. Our approach to this study is set out in Section 1.1 together with a more detailed description of the coastline and study frontage in the Section 2.2.

Figure 1.1: Location plan

Source: Contains Ordnance Survey data © Crown copyright and database right [2014] and Google Pro

Figure 1.2: Shoreline change 1945 (yellow line) to 2013 (imagery)

Source: Google Pro

1.1. Study approach

Based on the issues outlined above, the scope of this study was discussed both with The Crown Estate and the Bawdsey Coastal Partnership and after discussion the study approach was agreed in mid-December 2015. Our work has involved completing three different but interrelated tasks that are briefly described as:

Task 1 – Desktop review of past shoreline, profile and seabed changes

First we examined the existing knowledge and interpretations regarding the long-term geomorphology of the coastline, particularly in respect of the sources and movements of beach sediments and changes in shoreline position. As discussed in Section 1, this revealed often incomplete and sometimes conflicting views, particularly in regard to the long-term (centuries) patterns of longshore transport of sand and shingle.

The next part of the study, described in Section 3 was a review of information on the changes in the beaches at and either side of East Lane, and of changes in the nearshore seabed. For some aspects of this review, significant research has already been undertaken, so that when possible we have built on and used existing studies and findings. However to gain a better understanding of recent changes both in the plan-shape of the coastline, e.g. beach widths, and the cross-sectional profile of the beaches, we have obtained and analysed beach survey data from the Environment Agency's Anglian Monitoring System.

The main concerns regarding the change in the coastline at East Lane relate to the erosion and recession of the shingle beach and the cliff-tops. However, other research has suggested that changes in the bathymetry of the seabed beyond the low tide mark might also be influential. We therefore included, in Section 3.5, a review of such changes in the first part of this study, based on published papers and survey data.

Task 2 – Wave assessment

Detailed wave modelling was carried out in order to derive a series of nearshore wave conditions to fully understand the spatial variability of waves along the frontage. The input for this was a long term time series of offshore wave and wind conditions purchased from the Met Office. Analysis of these offshore waves is described in Section 4.3.1.

Time-series of nearshore waves representing the past 35 years were then generated using the most recent bathymetric data. In order to efficiently derive the nearshore time series, as required for the beach plan-shape modelling, a meta-modelling technique, as used in the recent EA National Flood Risk Assessment – State of the Nation (SoN) project, was applied. The inter-annual variation of the nearshore wave conditions was studied in Section 4.4.1 in order to relate it to the erosion problems seen in the area.

The nearshore wave data was then validated with measured wave conditions available from WaveNet, which is described in Section 4.5.1.

The wave data derived were then used in the following beach plan-shape modelling task.

Task 3 – Beach plan-shape modelling

Potential longshore transport rates were calculated at numerous points along the frontage based on the predicted nearshore wave conditions for the past 35 years. Variations alongshore, as well as inter-annual and intra-annual variations were assessed and reported in Section 5.2. This analysis showed that this area has a considerable net drift, which is composed of a moderate to medium southerly and northerly drifts. Along the years, the balance between both components has shifted at various times, producing either northerly drifts or southerly drifts.

A numerical model of the area was then set up in order to study the beach plan-shape evolution. In order to tune the model to a certain area, the model needs to be calibrated with the available data, a process which is reported in Section 5.3.

The beach shoreline model is going to be applied for 50 years in order to ascertain the likely future shoreline positions. As it is impossible to predict the future wave climate and even more so the sequencing of these wave conditions, a considerable amount of 50 years synthetic sequences have been derived from the present day wave climate, as explained in Section 5.4, in order to drive the numerical model.

The results from the numerical model are then described in 5.5, looking at the sensitivity of the different components to the creation of the synthetic time series in the results.

2. Coastal geomorphology

2.1. Regional overview – Weybourne to Felixstowe

An appreciation of the long-term evolution of the coastline of eastern Norfolk and Suffolk is helpful in studying recent and potential future changes at and close to East Lane, Bawdsey.

The geology of this part of East Anglia is dominated by sedimentary rock which offers little resistance to the action of waves and tides. The southern part of the North Sea only flooded around 5,000 to 10,000 years ago at the end of the last Ice Age. Ever since that time, the coastline and the nearshore seabed have been eroding and this process will continue in the future where waves can act on the ‘soft’ rock. The marine erosion is perhaps most noticeable along those parts of the coast where there are high cliffs, predominantly of glacial till. In places the landward recession of the edge of these cliffs can average several metres per year over decades. This erosion, however, does provide a quantity of sand and gravel that forms beaches that can not only protect the face of these cliffs but also prevent flooding of low-lying land lying between the areas of higher ground.

In general at any point along this coastline, beach development tends to be dominated by waves arriving from the north and north-east sectors. Waves approaching from the east and south-east have been generated over the shorter fetch lengths across the North Sea to continental Europe, and while these occur more frequently are less able to move beach sediment along the coastline. As a result, it is generally the case that beach sediment moves southwards along this whole coastline. As a consequence, for example, erosion of the cliffs between Sheringham and Happsiburgh provides sediment for the beaches that prevent marine flooding of the low-lying coastal plain that extends south to Great Yarmouth and includes the Norfolk Broads.

Coastal defences to reduce the risks of flooding and/ or the rates of cliff recession have been a feature of this coastline for several hundred years, initially to enhance or increase the area of agricultural land and later to protect coastal resorts. The planning and management of such defences, however, has been complicated by variations, both over time and along the coastline, of the rates of shoreline change.

The fluctuations in beach widths, and hence in the rates of recession of cliffs to landward of them, in this part of East Anglia contrasts to other coastlines which have apparently similar geology and experience similar wave conditions (e.g. the Holderness coast in Yorkshire) but which rarely if ever show so much variability.

It is worth mentioning a few examples as a precursor to more specific discussion of the frontage either side of East Lane Bawdsey, namely:

- **Gorleston,** near Great Yarmouth, where the beaches just south of the mouth of the Yare have recently accreted dramatically, obviating the need for improved coastal defences that were being designed less than 20 years ago.
- **Pakefield,** near Lowestoft, where cliffs were eroding more quickly than anywhere else in the UK before the Second World War. At present these same cliffs have a wide beach in front of them.
- **Dunwich** where much of the town was destroyed by erosion in the Middle Ages. Even in the early years of the 20th century it was noted that the rates of recession were much slower than reported historically and that during the 19th century erosion 'has probably not been continuous with periods when little or no erosion has apparently occurred' (Royal Commission, 1911). The rates of cliff recession here have been very small in recent times.
- **The Dip, Felixstowe**. Here beach widths just south of the mouth of the Deben estuary have varied dramatically over time, sometimes requiring intervention and at others accreting and extending seaward beyond the end of the groynes.

There have been many papers and reports that have presented information on coastline changes over time, but few of these have gone on to provide a convincing explanation of why this has occurred. Sometimes coastline changes are linked to the movements of nearshore and usually shallow sub-tidal sand banks. Where such banks are formed at the mouths of estuaries, for example the ebb shoal delta of the River Deben, it is not surprising that the beach widths on either side of the entrance vary. This is the case for the beach at The Dip, Felixstowe, where movements of the main ebb-dominated channel not only affect the transport of beach sediment across the estuary mouth but also the banks (The Knolls) to seaward of the mouth, in turn affecting wave conditions for some distance along the coastline either side of it.

Elsewhere parts of the East Anglian coastline are affected by the movement of 'nesses', i.e. large accumulations of beach sediment that form small headlands. Nesses, for example at Kessingland and Winterton-on-Sea, typically have a sandbank to seaward of them; it is still a matter of debate whether the movement of these banks along the coastline causes migration of the nesses or vice versa. The change in the fortune of the beaches and cliffs at Pakefield has been a result of the northward movement of such a ness from Benacre northwards to Kessingland.

At Gorleston, the changes in beach width in recent times, and previously, appears to have been caused by movements of the extensive sandbanks lying offshore of the Yarmouth Roads that have altered the wave climate that the beaches experience.

Similarly at Dunwich, there is a nearshore shingle bank, apparently formed from sediment eroded from the cliffs in the past, which now provides shelter to part of that coastline. As with other banks, Dunwich Bank appears to be mobile so that wave conditions along the beaches will continue to change in the future.

Elsewhere coastal processes are apparently not affected by nearshore banks but noticeable changes in cliff top recession rates have still occurred. In some instances this variability has been linked to changes in the prevailing wave climate over periods of a decade or more (Cambers, 1983). Such variability will affect the amounts of sediment released to the beaches, and this in turn will alter the rates of longshore sediment transport as well as the changes n wave conditions.

The above examples indicate possible natural causes of recent changes in the behaviour of the beaches near East Lane, Bawdsey. They can be summarised as follows:

- Changes in <u>offshore</u> wave conditions, which can alter rates of cliff erosion as well as altering the rate and even the directions of alongshore sediment transport;

- Changes in the seabed contours, for example the movement or change of a shape of a sand-bank, that alters the wave conditions reaching the coastline to landward;
- Changes in the amount of beach sediment crossing the mouths of estuaries caused for example by meandering of tidal channels and currents.

In addition, there may be anthropogenic causes for coastal changes, for example installing, altering or removing coastal defences.

2.2. The study frontage – River Ore / Alde to River Deben

2.2.1. Context

The area of greatest interest in this study lies between Shingle Street and the Deben (see Figure 1.2). At the centre of this study area is the former gun emplacement and 'hard point' of East Lane, Bawdsey. The headland here is protected by a seawall. To the north, Bawdsey Beach extends from East Lane to Shingle Street. It has a concave plan-shape and its shingle ridges, overlying a clay shore-platform are backed by a clay embankment that protects a large extent of low lying land. To the south, Bawdsey Cliffs, between East Lane and the mouth of the Deben is a convex frontage with a shingle beach similarly perched on a clay shore-platform. At the southern limit of Bawdsey cliffs, there is a spit, which is generally agreed to be the source of material for the Knolls, the banks (ebb tidal delta) across the mouth of the River Deben estuary.

To the north of the Martello Tower at East Lane, the existing beach provides flood protection to the low lying hinterland and the defences are predominantly overseen by the EA as they provide flood protection benefits. To the south, however, the land is higher and the beach provides protection against cliff recession rather than flooding. Here the coastal defences predominantly fall under the powers of Suffolk Coastal District Council (SCDC).

From the above, it is clear that reductions in beach width, brought about by a reduction in the volume of sediment, have the potential to increase the risks of flooding or erosion or both. The starting point for our review of how beach volumes have and may continue to change is to consider the source(s) of the shingle, i.e. a mixture of sand and gravel, which forms the main part of those beaches.

2.2.2. Shingle sources – beaches and cliffs

In many locations along the East Anglian shoreline, the beaches have been supplied with sediment from the coastal cliffs just landward of them. According to Walkden and van Baanen (2013), the northern part of the Bawdsey cliffs consist of a soft, partially consolidated silty material, with little sand or gravel, while their faces along southern part have been armoured to prevent erosion. Their view is that the erosion of these cliffs (or presumable the geologically similar nearshore seabed) would supply very little in the way of beach sediments, i.e. sand and gravel.

A somewhat different view can be found in the SMP2 (Royal Haskoning, 2009), namely:

> "The cliffs at Bawdsey could, if the fronting shingle beach were to be overtopped, provide small inputs of London Clay material and some shelly sand from the overlying Early Pleistocene, Red Crag deposits. These were undoubtedly an important source before the shingle beach had elongated sufficiently from the north to protect them", and:

> "The silty clays to silty sands that comprise the softer elements of the London Clay do provide some material under the action of strong tidal and wave activity, on exposed areas of the seabed, but as even the coarsest grain size from the London Clay is < 0.250mm…".

Probably the most authoritative view however is that of the British Geological Survey's (1996) report commissioned by the Environment Agency. This report provides a quantitative basis for estimating the volume and proportion of mud, sand and gravel input from coastal cliffs between the north shore of the Thames Estuary and the Wash. Their results, based on sampling from many locations, estimate the volume of each of these types of sediment that would be released by a one metre recession of the cliffs at various locations between those two estuaries.

They describe the Bawdsey cliffs, which stretch along about 3km of the coastline between East Lane and the Deben, as (Pleistocene) Red Crag overlying London Clay. The former is dominant, in places up to 13 m thick. In contrast, the London Clay at the base of the cliffs, while up to 6 m deep in places, is generally less than 3m thick. It is the Red Crag that can provide beach sediments, having gravel and shell components varying from 25% to 30%.

By combining information on the rock type, the height of the cliffs (up to 16m) and their length, their study indicates a uniform recession of the Bawdsey cliffs could provide around 5,000 cubic metres of gravel (particles diameters greater than 2.0 mm) and around 18,0000 cubic metres of sand (particle diameters between 0.063 and 2.0 mm). While recession of these cliffs has been modest in recent times, as indicated in Figure 1.2, in the past this may have provided a significant contribution to the beaches.

This local source of beach sediment has not been emphasised in previous studies. In general it had previously been concluded that Bawdsey Beach has been supplied with sediment (shingle) that has travelled from the north past Orford Ness. The often substantial deposits at Shingle Street just south of the mouth of the Ore/ Alde estuary mouth were argued to provide further evidence for this supply mechanism as explained in more detail later.

Steers (1946) describes this part of the coastline and refers to the changes at the end of the shingle spit that extends south-westward from Orford Ness to North Weir Point, saying:

> "Here the spit is thin and unstable, and in the great storm of 1897 a mile or more was cut off. This shingle was piled up in quantities at Shingle Street, the effect of the 1897 storm being to add to that already existing there and at the same time to form the lagoon between the old and the new shingle. The same material continues to the south and protects the marshlands as far south as Bawdsey Cliff (London Clay and Red Crag). It still moves southwards and forms a small and fluctuating bar across the Deben."

This assessment is supported by Mott Macdonald (2015) which states:

> "The evidence of southerly directed net alongshore sediment transport around Orford Ness (estimated to be between 70,000 and 130,000 m^3/year by 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".

However there is still doubt about this transport being the only source of shingle between Shingle Street and the Deben. It is worth noting a recent conclusion drawn by Professor Ken Pye (pers. comm., 2016) on the basis of his analysis of how the size of the gravel varies along the beaches either side of East Lane, namely that:

> “Before the shoreline around East Lane was hardened in the 1920s the shoreline had a more gentle curvature and the littoral drift along the northern part of the Bawdsey shore, south of East Lane, was also northwards while that at the southern end of the Bawdsey shore was southwards towards the Deben entrance. Offshore transport of sediment from the beach during storms also seems to have been important in that area, and probably still is. The Shingle Street area, and neighbouring parts of Hollesley Bay, have acted as a long-term sink for shingle–dominated sediment, receiving material drifted alongshore from the south and also receiving sediment transferred from North Weir Point via the knolls – a very dynamic area all round with complex cycling of material on multi-annual to decadal timescales.”

Perhaps the best that can be made of the above is that, in the past, both sources have provided shingle to the beaches between Shingle Street and the Deben, and could do so again in certain circumstances.

2.2.3. Other sources of shingle

While the normal ‘sources’ of sediment for a beach are either adjacent beaches or the cliffs (or dunes) behind them, it is worth considering other possibilities. It can be confidently concluded that the modest freshwater outflows from the Ore/ Alde or the Deben have not and will not supply any significant quantities of sand or gravel to the coastline between Shingle Street and the Bawdsey Manor frontage.

Another possible source of shingle for the beaches either side of East Lane is the offshore seabed. Figure 2.1, based on the bathymetry used for the wave modelling in this study, shows the main features of the nearshore seabed off the study coastline (for convenience the location of the headland at East Lane, Bawdsey is marked by a red triangle).

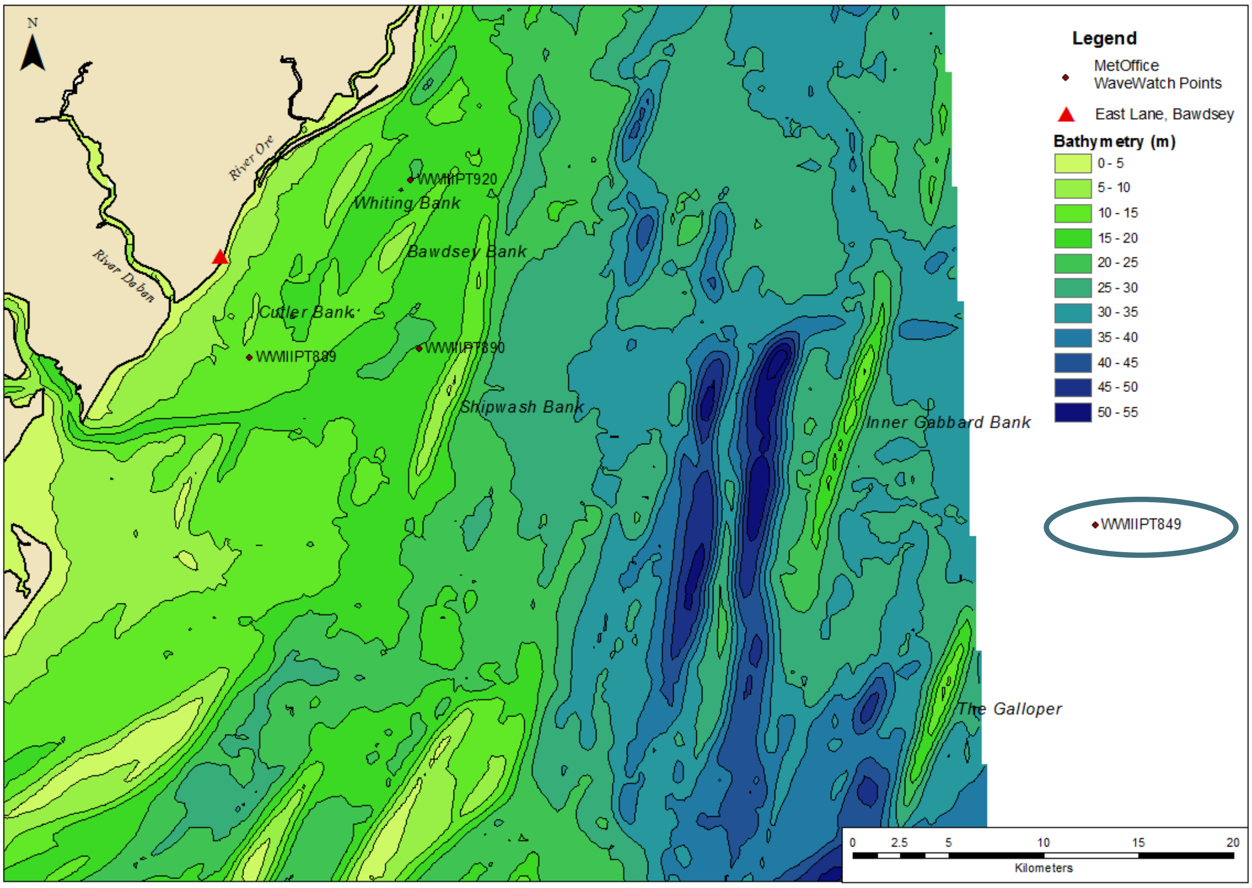

Figure 2.1: Nearshore bathymetry

Source: HR Wallingford/Seazone

Note: The position of the Met Office European WaveWatchIII ReMAP Hindcast offshore point used in this study, as described in 4.3, is shown as WWWIIIPT849 highlighted by a blue oval.

Offshore of the frontage, there are several shallow banks and these bathymetric features will influence the nearshore coastal processes. These include: Cutler Bank, opposite Bawdsey Cliffs, Whiting Bank offshore of the Hollesley bay channel, Bawdsey Bank opposite Hollesley Bay (and Bawdsey Beach), and finally the Shipwash and Inner and Outer Gabbard Banks further offshore. These banks are understood to be mobile and it has been mooted that subtle changes in the banks could affect the gross and net transport rates along the beaches to landward of them and this point is returned to later. At this stage however we are concerned about the possible interchanging of sediment between the banks and the beaches.

All the nearshore banks are formed from fine to medium sand, though Cutler Bank (the most recently formed) is composed of coarse to medium shelly sand. In the HR Wallingford *et al.* (2015) report on the Southern North Sea Sediment Transport Study, it was concluded that these sediments closely matched those making up the cliffs along the Bawdsey frontage. There is stated to be abundant evidence of a Pleistocene Crag derivation, with distinctive shells indicating their source. This is also the case particularly in the sands of the Whiting and Bawdsey Banks, and in the sand-wave fields that lie between the Shipwash and Bawdsey Banks. It is noteworthy that there appears to be no gravels present in these banks. Note however that the source of these sediments in these banks is not necessarily the coastal cliffs at Bawdsey.

The geology of these cliffs is likely to be very similar to that of the nearshore seabed which also will have been eroded by the action of waves and currents over the past few millennia.

The possible (present-day) interactions between the nearshore seabed and the coastline were further considered by Mott Macdonald (2015). They commented in detail on the nearest bank to East Lane, saying:

> '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'.

HR Wallingford *et al.* (2002) concluded that the Whiting Bank, lying close to and partly in the lee of Orfordness, 'might be receiving sand winnowed from the mobile sandy shingle of Orfordness Spit. Also due to the close proximity of the Whiting Bank to the coast there may be some sediment interchange under severe wind-generated current action'. This latter sentence referred to the results of computer modelling of sand transport during tidal surges in the Southern North Sea.

Bearing this and other evidence in mind, Mott MacDonald (2015) concluded that:

> "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 *et al.*, 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".

From this it is unlikely that gravel found along the beaches between the Ore/Alde and the Deben has come from erosion of the seabed directly offshore or from the various banks on that seabed. It is also worth noting that rather than suggesting a contribution of shingle to the beaches from the offshore seabed, previous geomorphological studies have indicated the opposite, i.e. an offshore loss of gravel and sand (see for example the quoted text from Professor Ken Pye at the end of Section 2.2.2). Any justification for such a conclusion, however, is not easy to find.

Some transfer of sediment to the beaches from the mobile banks across the mouths of these estuaries does occur. Here its transport is influenced by tidal flows in and out of the estuaries as well by wave action. So shingle from the spit ending at North Weir Point on the northern side of the mouth of the Ore/Alde estuary will travel onto the shallow banks across the mouth of that estuary (knolls) and the same occurs at the southern end of Bawdsey Beach where shingle moves onto The Knolls at the mouth of the Deben. What is less certain is how much, if any, of this shingle is permanently lost from the coastline before it is transferred to the beaches to the south of these estuaries.

However, the available evidence from surveys of the nearshore seabed does not suggest to us any significant losses of gravel from the beaches to the seabed, where it would presumably have otherwise resulted in a noticeable accumulation.

2.2.4. The longshore drift regime

Understanding and quantifying the processes causing movement of beach sediments and the rates of that transport along this coastline is critical to predicting the likely future evolution of the coastline on each side of East Lane, as well as in examining possible coastal defence management options. Before describing the modelling carried out in this study it is therefore worth briefly reviewing past studies of the longshore transport of beach sediments and in particular the rates and directions of that transport.

As already discussed in Section 2.2.2, conclusions based on the geomorphology of the coastline, for example the presence of spits and analysis of the types and origins of the beach sediment, have differed in the past. While Steers ((1946) clearly had the view that the net drift between Shingle Street and the Deben was southwards, Pye (2016) has reached a different view which for convenience is repeated here:

> ‘the evidence shows that long-term (at least 200 years) net littoral drift has been northwards to the north of East Lane and over the past 60 – 70 years have been southwards to the south of East Lane. Before the shoreline around East Lane was hardened in the 1920s the shoreline had a more gentle curvature and the littoral drift along the northern part of the Bawdsey shore, south of East Lane, was also northwards while that at the southern end of the Bawdsey shore was southwards towards the Deben entrance’.

These differing views have different implications about the original source of the gravel found on the beaches either side of East Lane and the amount of shingle deposited in the Shingle Street area. Further research, perhaps comparing the geological/ chemical characteristics of the gravel clasts, might help resolve these issues. In this report we do not try to reconcile these different views about the sources, the long-term net directions of the longshore movement of beach sediment (shingle) and its ultimate fate. Rather our aim is to understand how and why the beaches either side of East Lane have changed in the last 20 years or so, and to postulate possible future changes.

Estimates of the mean annual drift rate made in earlier studies of this coastline have varied, in part perhaps because of changeable weather and wave conditions. A previous review of predictions of drift rates along the North Norfolk coastline can be found in the Southern North Sea Sediment Transport Study (SNS2) (HR Wallingford *et al.*, 2002) and the following text is adapted from Appendix 11 of the final report of that study.

*As normal in such studies, the longshore drift rate was calculated in the Southern North Sea Sediment Transport Study (SNS2) using a simple formula that estimates the instantaneous rate of sediment transport caused by any wave condition. By repeated use of this formula for the whole wave climate, as predicted for a chosen location at the coast, the total volume of longshore drift at that location is estimated. Most of the studies that calculated drift rates in this way used a variation of a formula developed by Komar and Inman (1970) and widely known as the CERC formula because of its use in the Shore Protection Manual (*U.S. Army Coastal Engineering Research Center*, 1984). This approach is still widely used, albeit with refinements in the modelling. However, it is important to realise that the longshore drift rates calculated by this numerical method are subject to a considerable degree of uncertainty unless a site-specific validation can be carried out. In addition, estimates made using information on waves over one period can vary dramatically from subsequent estimates made using wave information for a different period. Moreover, despite the fact that there have been many studies estimating longshore drift rates, there is no way of physically measuring the rates of sand transport along the coastline. Any drift rates quoted must therefore be treated as estimates rather than absolute values.*

Longshore transport rates around East Anglia were modelled in the pioneering studies by the University of East Anglia in the late 1970s and early 1980s (Vincent, 1979, Clayton et al., 1983, Onyett and Simmonds, 1983). They developed a model for longshore transport that was applied to the whole of East Anglia and some of Essex. Many of the regions were not modelled again for several years. However, following the requirement for Shoreline Management Plans, many areas have been modelled in more detail, using more *up-to-date techniques and site-specific model settings. Therefore the SNS2 study proved to be an opportune moment to extend and update the work of UEA and to apply it to a greater area.*

Predictions of longshore transport rates along the coastline between the Ore/Alde and the Deben were summarised in the SNS2 study are reproduced in Table 2.1.

Table 2.1: Previous estimates of longshore drift rates near East Lane, Bawdsey

mE	mN	Location	Dir (˚N)	Net Q (m^3/yr) (southwards)	Source
636500	242000	Shingle Street	207	83,000	Onyett & Simmonds (1983)
636300	241300	Shingle Street	198	64,000	Vincent (1979)
636900	242650	Shingle Street	031	83,300	Posford Duvivier (2000)
634121	237377	Bawdsey	234	8,500	HR Wallingford (1997)
633150	237450	Bawdsey	230	210,000	Onyett & Simmonds (1983)

Source: HR Wallingford et al. (2002)

In the Table 2.1, the assumed beach orientation is given at each location defined by the National Grid coordinates. The direction of the net longshore drift is to the south in all these studies. The estimated average annual net drift rate is given followed by the source of the estimate.

The likely results of such calculations will depend on the assumed orientation of the beach, the accuracy to which wave directions can be estimated and to the period of time over which wave conditions were retrospectively forecast.

It can be seen from the table that both the date of the predictions (and hence the wave conditions that were available to be used in the modelling) and the beach orientations assumed in those predictions vary. The latter is particularly noticeable at Shingle Street, reflecting changes in the position and shape of the shingle ness there. In addition, different researchers have made different assumptions about the beach sediments, which can substantially affects the calculation of drift rates. Under the same wave conditions, the drift rate along a shingle beach is typically only 5 – 10 % of that along a sand beach. This point was made in HR Wallingford et al. (2002) which notes that:

> *'The Vincent (1979) and Onyett and Simmonds (1983) results were calculated for sand, in an area where the beaches are almost entirely of gravel. The high transport rates and low amount of sand present implies that any sand entering this stretch of coastline is rapidly transported through the area without settling to form sand beaches'.*

A further important source of inaccuracy in the calculations of longshore transport rates is that this rate will depend on the presence or absence of beach sediment that is available to be transported by the breaking waves and the currents they produce. The CERC formula mentioned above assumes that, at all times, there is ample sediment on all parts of the beach profile, from the limit of wave uprush down to and beyond the seaward limit of the breaker zone. At times and along parts of the coastline, especially near East Lane at present, this is patently not the case. Even close to Shingle Street, where the beach has been and is still well-stocked with shingle, the longshore drift rate can be expected to vary depending on the amount of sediment that has crossed the mouth of the Ore/ Alde estuary.

Overall these previous studies have concluded that the net drift along the coastline was to the South, with the source of the sediment being eroding cliffs further north. Clayton, McCave and Vincent (1983) states there was a supply of sediment of around 40,000m^3/year from the eroding cliff at Dunwich for example.

Wallingford et al. (2002) goes on to say:

> *'The percentage of shingle on the beach increases to virtually 100% at Orfordness. It is believed that sand leaves the coast at Orfordness. There is southwards net movement of shingle along Orfordness, although the direction of transport can reverse under appropriate wave conditions.*
>
> *The predicted longshore transport rates at Bawdsey Manor, just north of the River Deben were all to the south-west, implying that beach material from in front of Bawdsey Cliff may be carried across the River Deben entrance. This ties in with observations of downdrift erosion south of the old military fort at East Lane, Bawdsey in 1996'.*

This long-held view has influenced decisions made about managing the coastal defences at East Lane. For example, in a report on the options for future management of the coastline near Bawdsey (Haskoning, 2010) says:

> *'At East Lane the defences impose a significant downdrift control of the shoreline to the north…'*
>
> and
>
> *'East Lane … acts as a dam allowing the bay to the north to fill before allowing a supply of*
>
> *sediment to the south'.*

These statements clearly reflect a view of a net southward longshore drift towards East Lane from further north in Hollesley Bay although that report goes on to modify this view by saying:

> *'Over Hollesley Bay, the angle of the bay is in net equilibrium. Under north to east wave conditions material will progress south. South easterly wave conditions can cause northerly drift.'*

This indicates a near-zero net drift rate, but taken together with the previous statement the report goes on to conclude that removal of the defences at East Lane would change the situation and increase the chance of a net southerly drift past that location. It seems likely that similar views on the net longshore drift direction influenced the option of using groynes as a coastal defence measure at East Lane because they might restrict the transport of shingle further south.

The 'traditional' view of the longshore drift regime, based on studies going back some 70 years, is therefore that the net drift direction along this part of the Suffolk coastline is southwards. The main source of the sediment for the shingle beaches lies further north, but its rate of arrival near Shingle Street is variable, depending on transport processes across the mouth of the Ore/Alde estuary and the rate of movement of shingle along the spit between Orfordness and North Weir Point. It has also been recognised that this net long-term transport rate alters from time to time, with most past reports indicating periods of a reverse drift direction both along the spit that extends south from Ordfordness as well as along almost the whole frontage between the Ore/Alde and the Deben.

As a consequence of this traditional view of the drift regime, it is to be expected that the beach just north of the artificially-maintained headland at East Lane would remain well-stocked with sediment but there would likely be a problem of erosion to the south of it since the projection of the seawall and the lack of beach sediment in front of it would greatly reduce the longshore drift rate at that point.

However, as discussed later, beach changes in recent years strongly suggest a net northwards transport of shingle from East Lane towards Shingle Street, in line with the views of Pye (2016) that *'long-term (at least 200 years) net littoral drift has been northwards to the north of East Lane'*.

Further investigation of such recent changes is clearly warranted to help explain the causes of the past changes in the behaviour of this part of the coastline and to inform decisions regarding any future changes and whether or not to intervene.

3. Coastline changes near East Lane

3.1. Introduction

As noted in Section 2, there has been considerable debate regarding long-term drift rates of the beach sediments along the coastline on either side of East Lane and how those rates have altered over time. Of more direct interest and concern is how that part of the coastline is changing, or more pointedly how quickly and why it is eroding. While coastal geomorphologists tend to concentrate on processes and changes over hundreds if not thousands of years, coastal managers and engineers are much more interested in changes over the last few years (and if possible the next few).

The normal starting point for coastal managers investigating coastal erosion is a comparison of Ordnance Survey maps and aerial/ satellite images which give a broad overview of their perspective on 'long-term' rates of coastline change. Shoreline changes since 1881, depicted in Figure 3.1 and Figure 3.2, were provided to this project by Helene Burningham of University College, London (UCL) and show the evolution of the coast north and south of East Lane respectively. Despite the difficulties associated with analysing infrequent and not always particularly accurate maps, it is worth starting this section of the report with an assessment of the changes that have taken place over about 130 years since the first Ordnance Survey map (see Sections 3.2 and 3.3). For this purpose we have divided the coastline into two overlapping sections either side of East Lane, where the orientation of the coastline has always changed substantially.

Of the very different orientations of the beaches north and south of East Lane, Royal Haskoning (2010) said:

> *'The cliff backed frontage south of East Lane, changes orientation from the typically NNE / SSW of the southern section of Hollesley Bay, to a more NE /SW orientation down to the mouth of the Deben, at Bawdsey Manor. The harder London Clay nearshore area of this section slopes more gently seaward than that of the northern section of Hollesley Bay and Orford Spit.'*

This difference in the wave-cut clay shore-platform underlying the beaches reflects the topography of the land behind them. It is not surprising that the nearshore seabed in front of the cliffs along the Bawdsey Manor frontage has a different character to that to seaward of the low-lying coastal plain that stretches north from East Lane to Aldeburgh. The different orientation of the seabed contours north and south of East Lane alters the direction of waves approaching the coast and this in turn affects the orientation of the beaches. In general, and given long enough, shorelines either evolve to face the average wave direction so reducing the rate of longshore transport of beach sediment to zero or to an orientation that results in an average net rate that is (roughly) constant along the coastline. It is this latter situation that is likely to be relevant to the coastline between the mouths of the Ore/Alde and the Deben in recent times.

3.2. Changes north of East Lane (1881-2012)

The most striking change shown in Figure 3.1 is the substantial recession and straightening of the shoreline near East Lane between 1881 and 1945. It seems likely that the great majority of the erosion here took place between 1881 and the 1920s when coastal defences were apparently first installed at East Lane.

While Figure 3.1 shows that to the north of the seawall at East Lane shoreline recession has continued after 1945, this has not been continuous; rather there have been periods of recession followed by phases of beach accretion and advance, for example with the 1973 shoreline further seaward than that in 1958.

Halfway between East Lane and Shingle Street, Figure 3.1 shows very modest changes in the position of the shoreline over a period of about 130 years. Further north, as might be expected given the complicated sediment transport processes across and on either side of the mouth of the Ore/ Alde estuary discussed earlier, the beach widths have varied dramatically in front of Shingle Street. The 2012 shoreline here is well seaward of that in 1881 having advanced substantially since 1973 at this location.

Since 1945, the overall impression of shoreline changes between East Land and Shingle Street shown by this comparison is a 'seesawing' of the coastline around a hinge point between those two locations, with beach sediment transferring from one end of the frontage to the other. It is likely that here, as is generally the case along the coastline of Suffolk, that there is a underlying slow trend for recession of the shoreline caused, for example, by the gradual erosion of the nearshore wave-cut shore platform and by sea level rise relative to the land.

Even during the periods when the shoreline just north of East Lane had advanced, however, the orientation of the beaches there has generally not matched that recorded in 1881 when the shoreline was closer to north-south. While this change in angle is modest, typically less than 10˚, it nevertheless could have altered the average net drift rate of beach sediments. Assuming that average winds and hence wave conditions, in the southern North Sea have not altered over the last 130 years, this change in the shoreline would have increased the rate of longshore transport caused by waves arriving from the East (say from 75˚ to 105˚) and decreased the rate when waves approach from the south-east (say 120˚ - 150˚). The overall result of this reorientation is therefore likely to have been an increase in the southward drift of beach sediments and a decrease in their intervening periods of northward transport. The effects of this on the coastline south of East Lane, however, will have depended on factors such as the supply of sediment from further north and on variations in wave conditions as discussed in Section 2.

To the north of East Lane, Figure 3.1 shows that changes in beach width have been greatest at Shingle Street with periods of accretion and of erosion between 1945 and 2012. Just north of East Lane, there is little or no evidence of periods of beach volumes increasing. Instead there has been a gradual landwards recession of the coastline over this same period. However both here and at Shingle Street, there seems to be evidence of periods during which very little changes followed by more active times when the beach plan-shape alters more noticeably.

It is also clear that the maximum beach widths at Shingle Street shown on this figure occur in 2011 and 2012 at the same time as the narrowest beach widths just north of East Lane. This immediately raises the suspicion that there has been a transport of beach sediment northwards from one end of this frontage to the other in the preceding years, i.e. a net northward longshore drift.

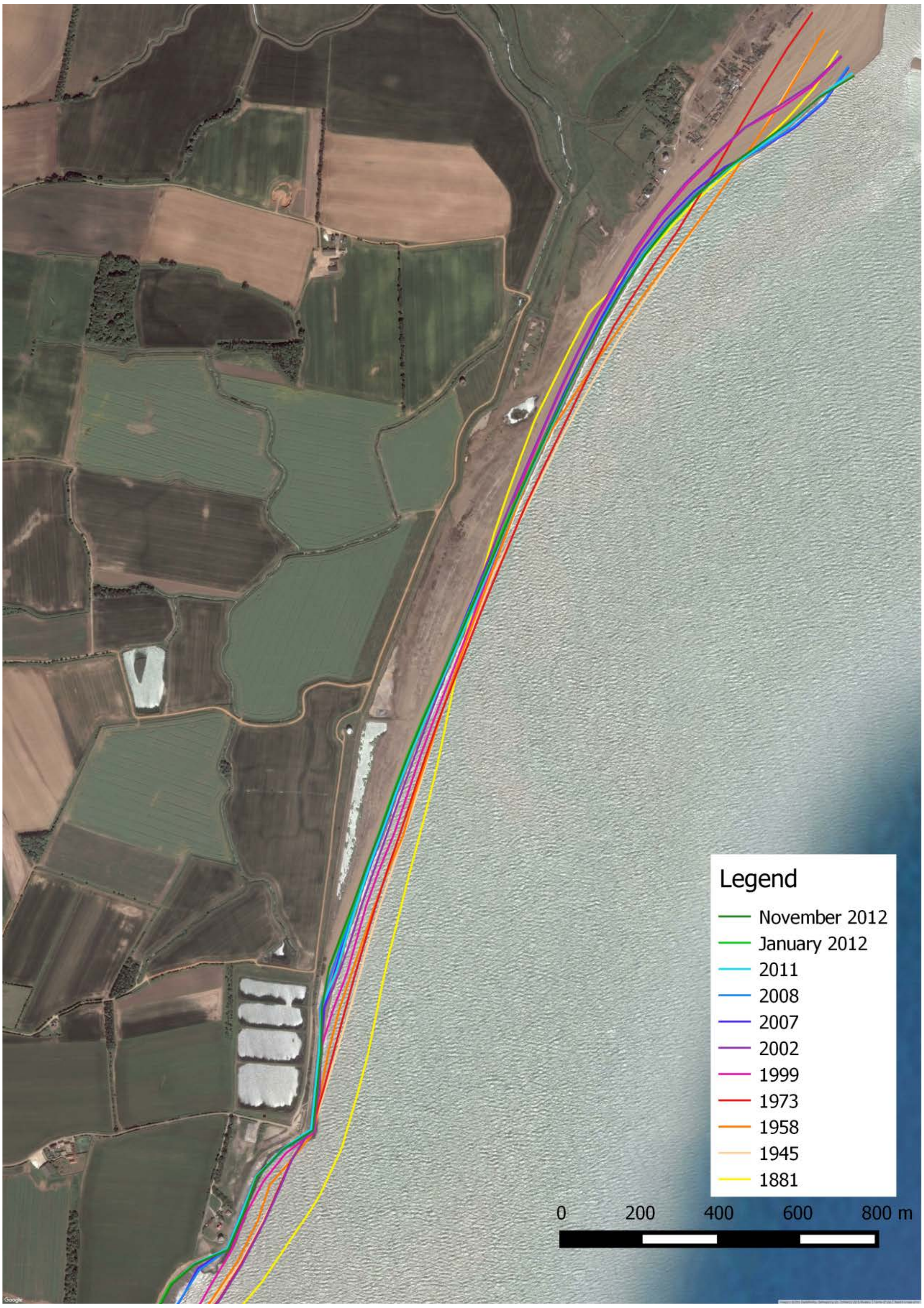

Figure 3.1: Historical shoreline positions – Shingle Street to East Lane, Bawdsey

Source: UCL (Burningham, pers. com. 2016)

Figure 3.2: Historical shoreline positions – East Lane, Bawdsey to River Deben

Source: UCL (Burningham, pers. com. 2016)

3.3. Changes south of East Lane (1881-2012)

Figure 3.2 is also based on the information provided by Helene Burningham of UCL. As in Figure 3.1, the substantial recession of the shoreline at and just to the south of East Lane is the most striking difference between recent shoreline and that of 1881. This general recession has reduced the change in coastline orientation near East Lane and it would be easier now, under the influence of south-easterly waves, for beach sediment to travel to the north of East Lane than in 1881. While the defended headland at East Lane does act as a headland today, it is much less noticeable a feature than the natural headland that existed in the same area in 1881.

The much smaller recession of the coastline further south is also noteworthy. Given the inevitable inaccuracies in mapping an every varying coastline, it would be very hard to obtain a reliable recession rate for the cliffs to the north of Bawdsey Manor from this comparison.

As for the beaches further north, those just to the south of the coastal defences at East Lane have gone through phases of both advance and retreat but recession has dominated with the latest surveys showing the most landward position of the shoreline over the 130 year period. At the same time, however, beaches roughly halfway between Bawdsey Manor and East Lane have accreted and advanced since 1958 and remained healthy up until 2012. As would be expected, the beach widths near the mouth of the Deben have fluctuated and appear to have been wider in 2012 than at any previous date shown in this comparison.

Overall the impression given by changes in recent years is of rapid erosion just south of East Lane with some of the sediment depositing at least temporarily further south before reaching Bawdsey Manor as well as just at the entrance to the Deben.

However, it can be misleading to reach firm conclusions on the basis of very infrequent surveys that were not specifically designed to record changes in beach morphology. A more satisfactory source of data is a carefully-designed and controlled programme of beach surveys, as discussed next.

3.4. Beach profile changes

3.4.1. Introduction

More detailed information on recent changes to the coastline of interest in this study is available from specific beach surveys. This monitoring is described in more detail in a report published by the Environment Agency (2011) and sections of that report are repeated here for convenience.

> ‘The Shoreline Management Group (SMG) based within the Environment Agency’s (Anglian Region) Flood and Coastal Risk Management section has undertaken regular strategic coastal monitoring of the Anglian coast since 1991.
>
> The Anglian Coastal Monitoring programme … has collected a variety of data including:
>
> - Annual aerial photographs
> - Bi-annual strategic topographic beach surveys (winter and summer) at 1km intervals
> - Bathymetric surveys (extension of beach survey lines out to approximately 10m depth offshore)
> - Continuous wave and tide recording (nearshore and offshore)
> - Scheme specific beach topographic surveys at closer intervals.

Beach topographic profiles have been undertaken at 1km intervals, twice yearly in summer and in winter, along the coast since 1991. Generally speaking the main aspect of interest is the average rate of beach erosion or accretion along the coast. In addition to this, gradual change to the gradient or steepness of the beach is often of particular interest to coastal managers'.

The results of the repeated surveying of the beach profiles between the Deben and (just to the north of) the Ore/Alde have been obtained for this study from the Anglian Coastal Monitoring programme. The locations of the original cross-section locations (prefix SO) considered in this report are shown in Figure 3.3 together with the locations of extra cross-sections (prefix HL) which were first surveyed in early 2009 or later.

Data from the 26 cross-sections shown in this figure have been analysed to provide an understanding of the character of those beaches and how they have changed between early 1991 and late 2015. Appendix A contains figures showing the survey results at each of these cross-sections each showing the time-history of changes in the beach profiles.

Usually, these surveys only extend down to approximately low tide level, and from the viewpoint of assessing changes in the width and height of a beach this is adequate to judge any changes in the standard of protection it provides against flooding or coastal erosion. Analysis of these 'topographic' beach surveys is returned to in Section 3.4.3. However, the monitoring programme also includes less frequent surveys that extend below the low tide mark and it is these surveys that we examine first.

3.4.2. Assessment of nearshore bed level changes

The beach profile surveys which involved bathymetric surveying of the nearshore seabed were designed to record the levels of the nearshore seabed approximately as far out as the -10m OD contour. These bathymetric surveys were intended to provide extra information on how and why the beaches were changing. There are three important reasons for undertaking such surveys, namely:

- To monitor any nearshore bathymetric features such as sandbanks that, as they change shape and position, will alter waves and the morphology of the beach to landwards of them.
- To determine the lower limit of the beaches, i.e. at what depth their profile ends. For UK beaches there is usually a fairly well-defined level at which the rather steep beach face ends and the much flatter shore-platform, with little or no sediment cover, begins. The level of this beach 'toe' is important since it is used to relate changes in the volume of beach sediments to the changes in beach width, for example when planning beach recharge or recycling operations.
- To monitor any 'down cutting' of the shore platform on which the beach sediment rests. Abrasion of the nearshore seabed by waves and tidal flows, assisted by the 'sand blasting' effect of sediment moving over its surface, is a continuing long-term process. The rate of lowering can be expected to be greater in areas like Suffolk where the shore-platform is of 'soft' rock, e.g. London Clay, than where the nearshore seabed is of older and more durable rock such as granite.

Eight profiles along the whole area of the study frontage have been chosen to provide information on how nearshore seabed levels as well as beach profiles change. These extended profiles extend seawards to below the -5 m OD contour (but not always to the intended -10 m OD contour) and have been surveyed four times so far. The data collected are presented in Figure 3.4 (August 1992- shown in red, August 1997- green, July 2003- blue and July 2007- mauve) and show the variability of the recorded bed levels extending on the shore-platform. Care has to be taken in interpreting these surveys given the likely inaccuracies involved in bathymetric surveying undertaken using a small boat in often choppy water close to the coast.

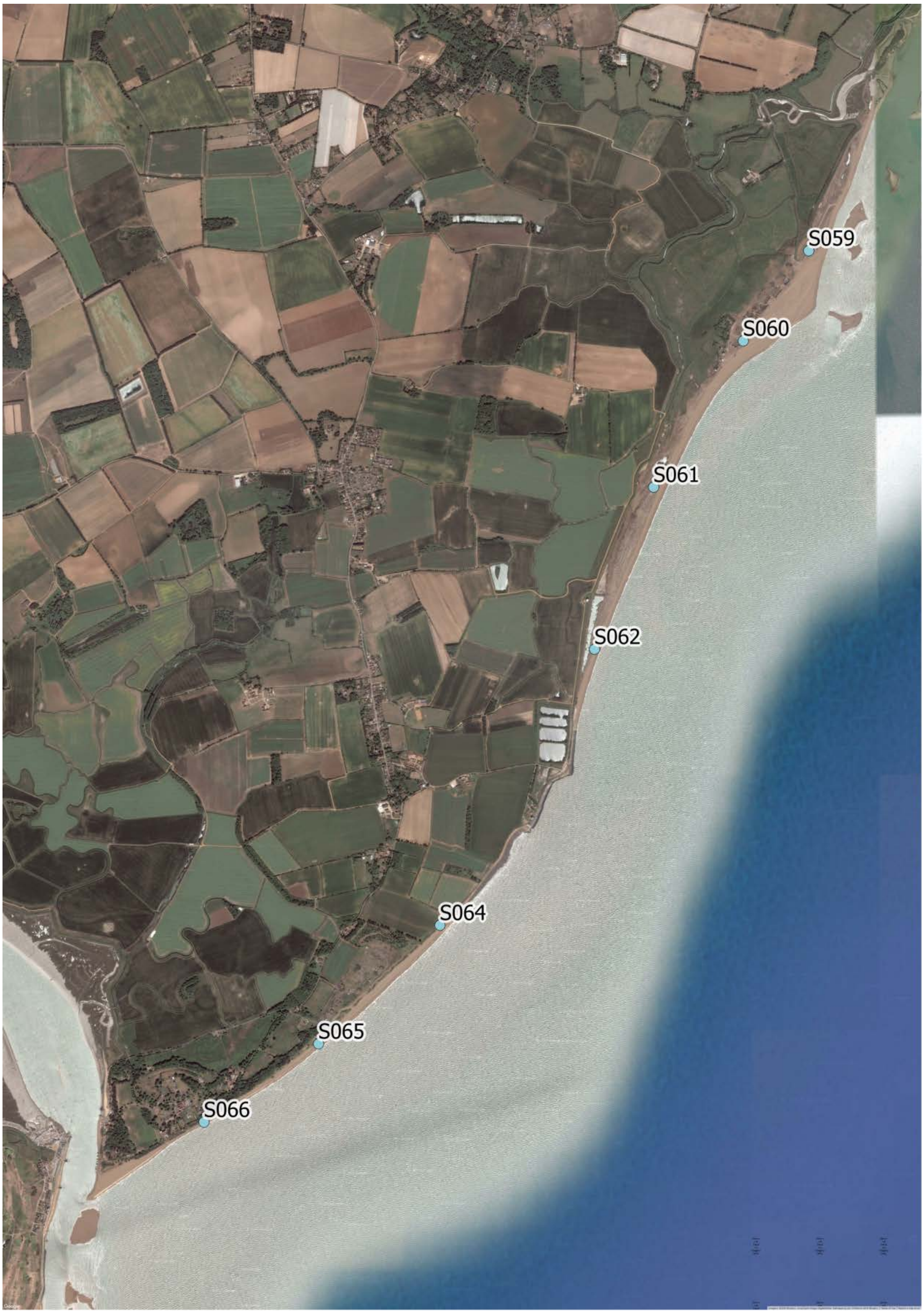

Figure 3.3: Locations of profile cross-section surveys

Source: Google Pro & Anglian Coastal Monitoring programme

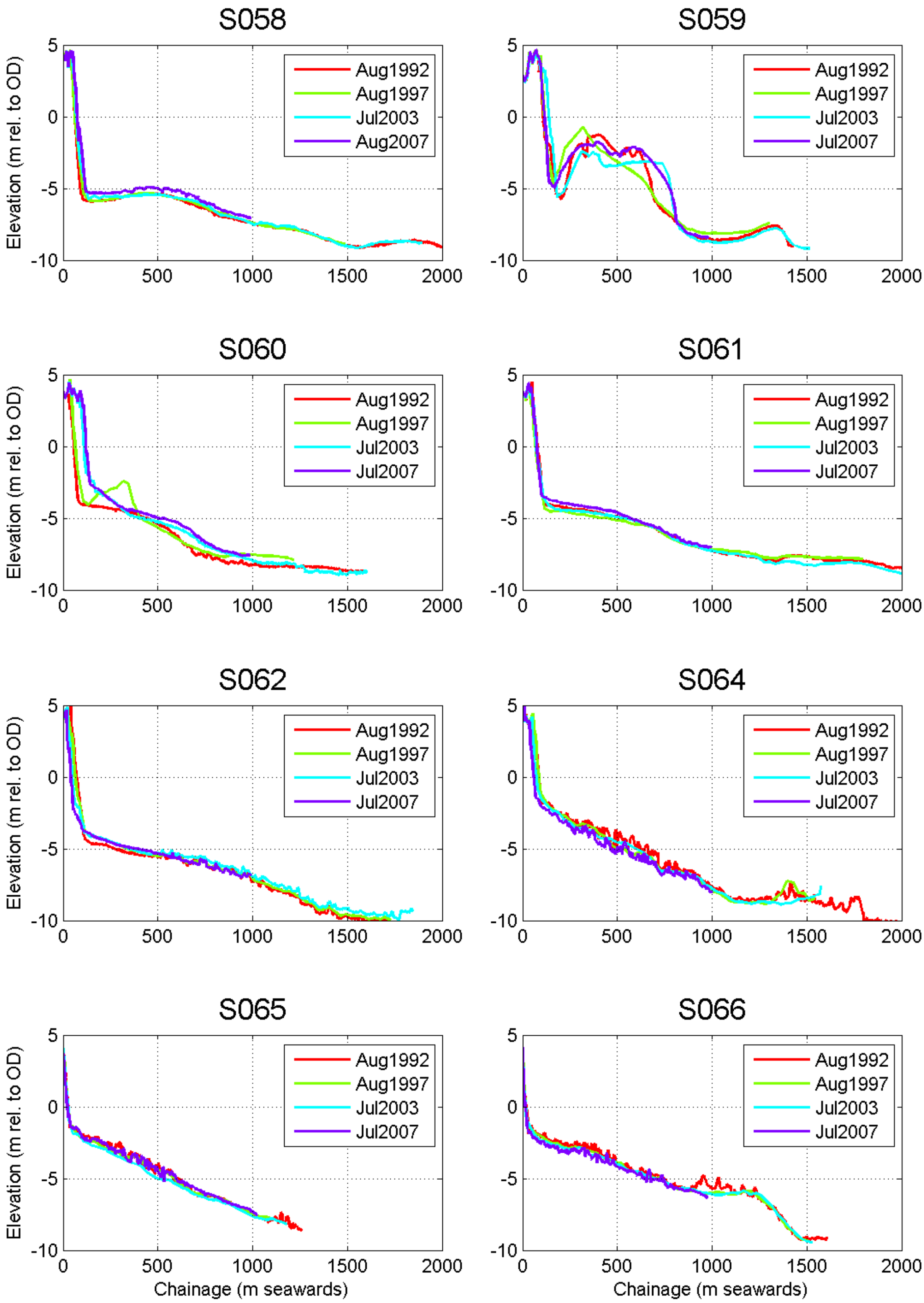

Figure 3.4: Comparison of long cross-sectional profiles (Ore/ Alde to Deben)

Source: Anglian Coastal Monitoring programme

Errors can arise from measuring water depths, reducing such soundings to Ordnance Datum using information on tidal levels at the location and time of the soundings and from positioning errors which (before high precision GPS) were considerable especially when up to 2 km offshore.

Because of these likely inaccuracies, the assessments of these surveys presented in Table 3.1 should be treated as 'best guesses' rather than firm conclusions.

Table 3.1: Assessment of topographic/ bathymetric surveys

Profile code	Upper beach	Beach toe level (m OD)	Nearshore bathymetry features	Shore platform changes
SO 58	Accreting (faster below MSL) over time	-6 to -5 m	An accreting low profile 'hump' / 'bank', perhaps from onshore-offshore transfer of shingle.	No evidence to seaward of bank (below -7 m).
SO 59	Widest in 2003 but variable	-5 m (± 0.5 m)	Substantial & changeable nearshore bank with crest just under low tide.	No evidence to seaward of bank (below -8 m).
SO 60	Accreted between 1997 and 2003	-4 to -3 m	Temporary bank in 2003 perhaps showing offshore-onshore movement of shingle.	Perhaps being covered by shingle beyond bank (down to -7m or -8 m OD).
SO 61	Stable	-4.5 to -3.5 m	Possible accretion 2003-2007.	No evidence below -6 m OD.
SO 62	Eroding (since 1997)	-4.5 to -4.0 m	Nothing significant.	Little change – steeper and rugged beyond -5 m OD.
SO 64	Eroding (since 1997)	-2.5 to -2.0 m	Nothing significant.	Steep/ rugged below -3 m Perhaps lowering (0.5 m over 16 years).
SO 65	Stable	-2.5 to -2.0 m	Nothing significant.	Steep/ rugged below -2.5 m. Lowering slightly?
SO 66	Stable	-2.5 to -2.0 m	Nothing significant.	Steep/ rugged below -2 m. Perhaps lowering (0.5 m over 16 years).

Source: Anglian Coastal Monitoring programme

From these comparisons, the following tentative conclusions can be drawn:

- Along the Orfordness spit just north of the mouth of the Ore/Alde (S058), there seems to have been some accretion on the platform since 2003, perhaps indicating offshore transport of beach shingle.
- Just north of Shingle Street (SO59) the bathymetric surveys reveal a substantial nearshore bank with its crest just below or at low tide level. This bank, which extends some 800 m seaward of beach, has changed considerably in volume and profile shape, probably reflecting its likely movement alongshore as much as the result of onshore-offshore sediment movement. Changes in the morphology and position of this bank must have a significant effect on the beach to landward of it. There is also an apparently stable hump on the seabed some 1300 m seaward of the beach face that may or may not be of shingle.

- Just south of Shingle Street (S060) there has been some accretion of the upper beach following the temporary appearance of a nearshore bank in 2003. It may well be that this behaviour is the result of shingle crossing the Ore/Alde and travelling first along the coast and then onshore in this area.
- In the middle of Hollesley Bay (SO61) there is little evidence of changes in either the beach face profile or the nearshore seabed. That said there is some indication of accretion on the shore platform between 2003 and 2007 perhaps indicating onshore shingle transport.
- Just to the north of East Lane (SO62) the profiles indicate a change in the character of the nearshore seabed. Close inshore, up to 400 m from the toe of the beach, the bed is smooth and has a shallow slope. Further seaward, beyond about the -6 m OD contour, the slope becomes steeper and the seabed surface is rugged. There is little evidence of change of the inshore section (after 1997) and it is difficult to draw reliable conclusions about any changes further seaward. While the surveys, at face value, suggest an increase in bed levels in 2003, there is very little difference between the 1991 and 2007 surveys.
- Just to the south of East Lane (SO64) the long profile surveys show erosion of the upper beach and that the steep nearshore seabed extends closer inshore, virtually to the toe of the shingle beach. At this profile, in particular, there is evidence of this rugged nearshore being lower in 2007 and 1991 although it is difficult to separate any lowering over the intervening 16 years from the apparent variations in bed levels. Our view is that the jagged appearance of the seabed shown in this and adjacent profiles is a reflection of an irregularly eroded seabed rather than the movement of sedimentary features such as sand ripples. The difference in levels over time at any point may well be a result of small differences in the position of the survey vessel rather than indicating genuine vertical variations in the seabed profile.
- Further south along the Bawdsey Manor frontage (profiles SO65 and SO66), beaches have changed little but their toe level (as at Profile SO 64) is much higher than north of East Lane. The nearshore seabed slope is somewhat gentler at SO66 than at SO65 and SO64 but has the same rugged appearance.

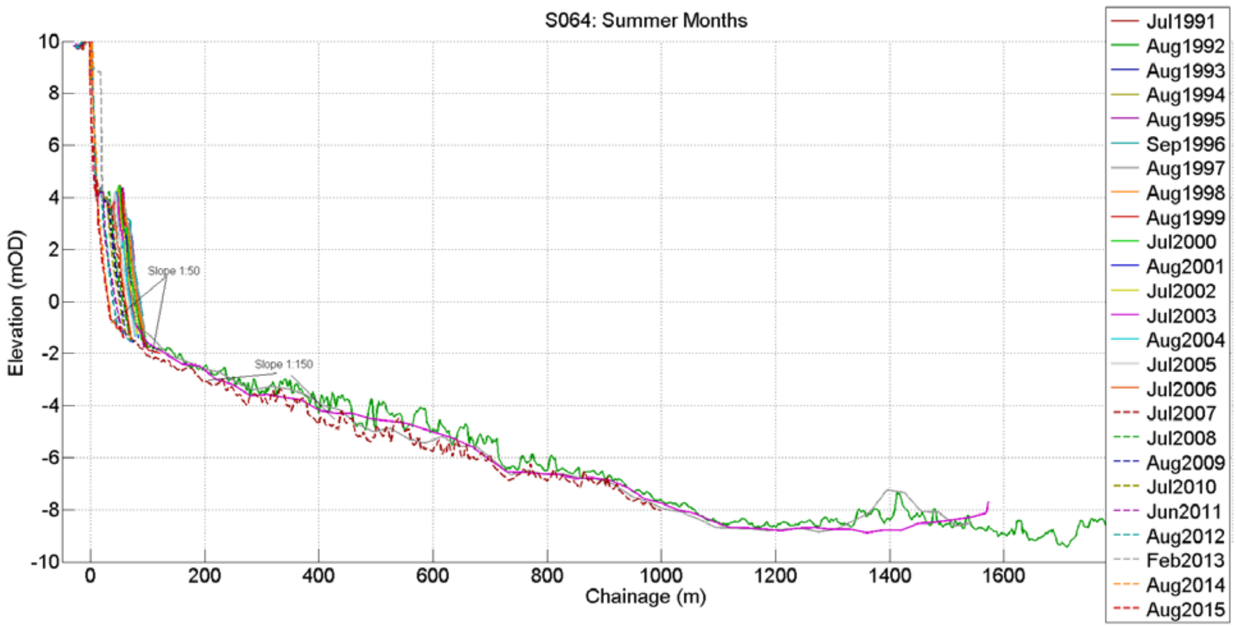

Figure 3.5: Comparison of summer surveys at Profile SO64 (south of East Lane)

Source: Anglian Coastal Monitoring programme

It should be noted here that there have only been four surveys that extend beyond the seaward end of the beach profiles, all surveyed in the summer, and none in the last eight years. It is potentially dangerous to draw conclusions on how recent erosion near East Lane relates to changes in the nearshore seabed.

However some further insight into both links between the width and toe level of beach and the character of the underlying shore-platform can be gained from Figure 3.5. At this location, just to the south of East Lane, Bawdsey (see Figure 3.3), the beach width in recent years has reduced to the extent that even the topographic surveys sometimes reach the shore platform beyond the toe of the beach. This allows a better appreciation of the level and gradient of the shore platform that underlies the shingle beach, showing for example that close inshore this substrate has a slope of around 1:50 compared to a more typical value of about 1:150 further offshore. The appreciable gradient of this underlying shore-platform is unusual; most computer models of beach evolution assume a horizontal 'base' on which the beach sediments rest. Because of this it can be expected that modelling beach changes, just south of East Lane in particular, may not reflect the actual situation because of this unusual characteristic of the coastline.

3.4.3. Analysis of topographic beach surveys

The repeated topographic surveys of the beach profiles undertaken for the Anglian Coastal Monitoring programme provide much more frequent updates on how the coastline either side of East Lane has been changing. At the time of writing this report, survey data collected up to the end of 2015 has been obtained and analysed. As is always the case, these surveys (shown in Appendix A) show considerable short-term variability in response to changing weather conditions. In general the recorded beach profiles tend to be steeper in summer and slope more gently in winter in response to the number of large wave events preceding each survey. This behaviour can produce quite large variations in the position of the beach crest or the high water mark without necessarily reflecting the quantity of beach sediment at any location; essentially the same volume of sediment is naturally rearranged to produce a profile that is more closely in equilibrium with the incoming waves.

Seasonal changes in the position of the 0 m OD contour (roughly mean tide level) are less than those of the beach crest, and therefore provide a better indication of how the amount of sediment (i.e. the beach cross-sectional area) is changing over time. Figure 3.6 uses information from the original (SO prefix) cross-sections between the Ore/Alde and the Deben to show how the beach width has changed during the period 1992 to 2015 along the whole study frontage. Notice that these widths are shown relative to a fixed location well landwards of the beach; it is the changes in the distances from these fixed locations to the 0 m OD contour that are of principal interest.

The stormy winter of 2013/2014, resulting in at least one large tidal surges in the North Sea, can be expected to have had some effect on the beaches in the study area. But it is also important to look for any longer-term patterns of coastal change that could continue into the near future.

Figure 3.4 shows the changes in beach width in the northern part of our study area using just the rather widely-spaced SO profiles (see Figure 3.3). Travelling south, the following changes are observed:

- SO 59 – Just north of the 'ness' at Shingle Street – rather large variations in the beach width reaching a maximum in Spring 2002 and generally declining subsequently. Late in 2015 the width at this location was smaller than at any time since 1992.
- SO60 – Just south of the 'ness' at Shingle Street – steady increase until Spring 2002 and then eroding slowly.

- SO61 – middle of Hollesley Bay - remarkably stable, i.e. showing little long-term trend but with a reduction prior to and increase after Spring 1998.
- SO62 – just north of East Lane, Bawdsey – nearly stable prior to the Autumn of 1999 but the following stormy winter reduced the beach width here and was followed by a steady decline until the Spring of 2013. The width then decreased substantially to reach a minimum in early 2015, probably in part a result of the stormy winter of 2013/2014 which resulted in damage to beaches across much of southern England.
- SO64 – south of East Lane – stable until early 1998 but then decreasing steadily with a sudden reduction to a minimum in Autumn 2013. Since then the beach here has virtually disappeared so the distance to the 0 m OD contour is constant.
- SO65 – in front of the Bawdsey Manor Estate - a slight trend for erosion which has perhaps become slightly larger over the latter part of the period.
- SO66 – near Bawdsey Manor – reducing slowly but perhaps a little faster since Spring 2013.

South of East Lane, the information from survey profiles SO63 to SO65 suggests a southward transport of beach sediment which is maintaining beach widths in front of the Bawdsey Manor estate but at the expense of a reduction of beach width (and cliff recession at a consequence) south of the defences at East Lane.

North of East Lane, these profiles show the largest changes have been near Shingle Street, in and around the location of the ‘ness’ there, and just north of the promontory at East Lane, Bawdsey.

Extra beach profiles at closer spacing along the Hollesley Bay frontage, with HL prefixes, were introduced into the regular beach monitoring carried out in the Anglian Coastal Monitoring programme in 2009 and provide further information on recent changes near and between these two parts of the coastline. Interestingly, these cast doubt on some of the conclusions that could be drawn on the basis of the widely-spaced SO profiles on their own. Figure 3.6 to Figure 3.8 show the changes in beach width, divided for convenience to cover three parts of the study frontage. Travelling south, the following trends are observed:

<u>Near the Shingle Street ‘ness’ (Profiles HL001 to SO60) – see Figure 3.6</u>

- To the north of the Ore/Alde estuary, profile S058 shows a healthy accretion of nearly 1 m per year.
- To the north of Shingle Street, profiles HL001 and HL005 (only surveyed since 2011), show a mirrored behaviour of recent erosion and accretion respectively despite only being around 400 m apart.
- Profile S059 shows a trend for erosion between 2000 and 2005. Note that this recent trend for erosion contrasts with the accretion of the adjacent profiles HL005 and HL011 over the same time period.
- Profile HL011 shows the beach width here stable overall but accreting slightly since early 2014.
- Profile HL014 shows substantial accretion since 2009, more rapidly since the winter of 2013/2014.
- Overall there has been little net change in beach width at HL017 since 2009 but here too there has been accretion since the end of 2013.
- As with profile SO59, recent erosion at profile SO60 contrasts with accretion a little further north (HL017) and stability/ slow accretion a little further south (profiles HL024 and HL029).

It is likely that the changes recorded by these cross-sectional surveys are largely caused by localised variations in the beach plan-shape at or close to changes in the vicinity of the ness at Shingle Street. Such changes are accompanied by changes in the banks (the ebb shoal delta) across the mouth of the Ore/Alde estuary.

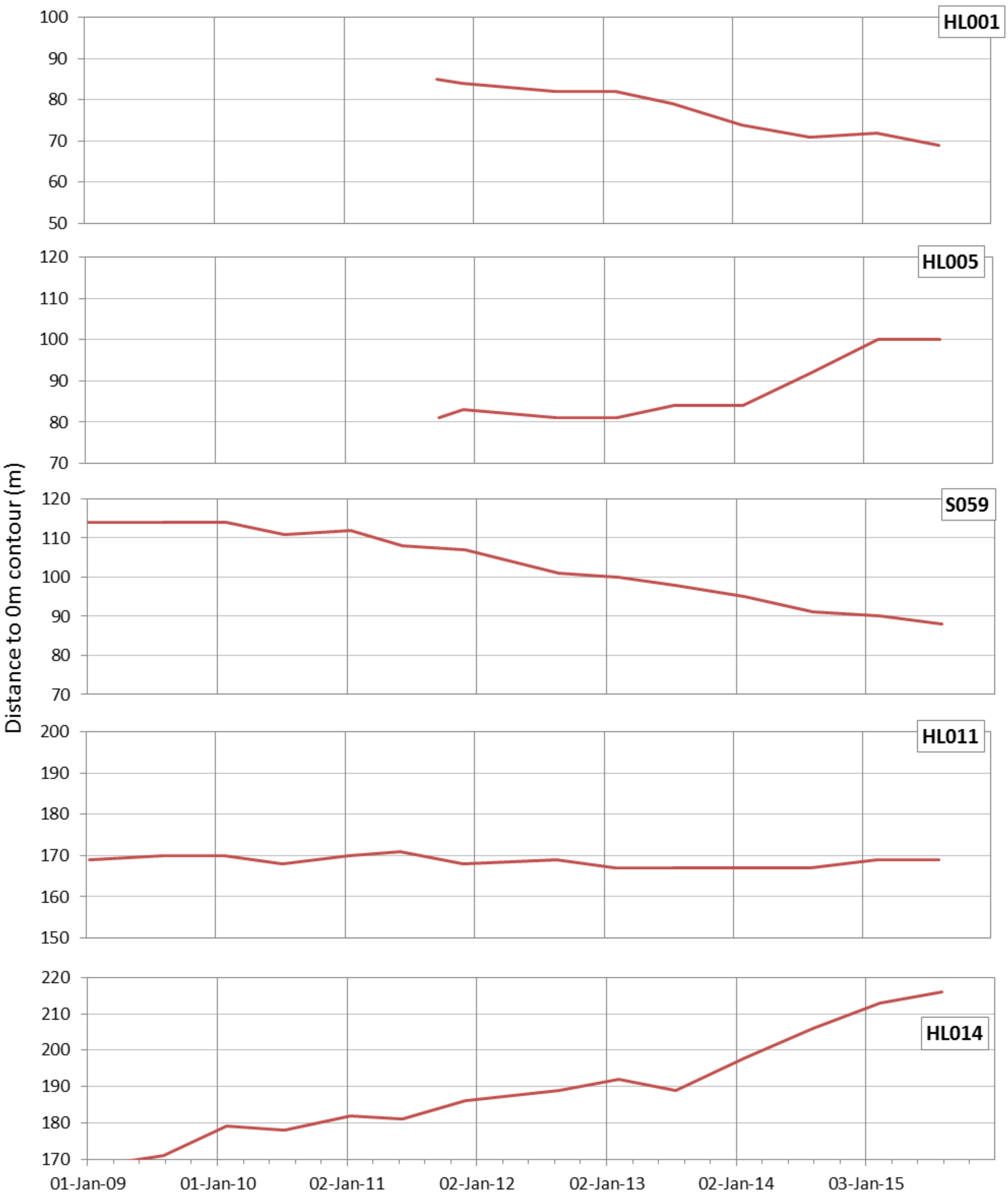

Figure 3.6: Beach width change (2009-2015): Shingle Street

Source: Anglian Coastal Monitoring programme

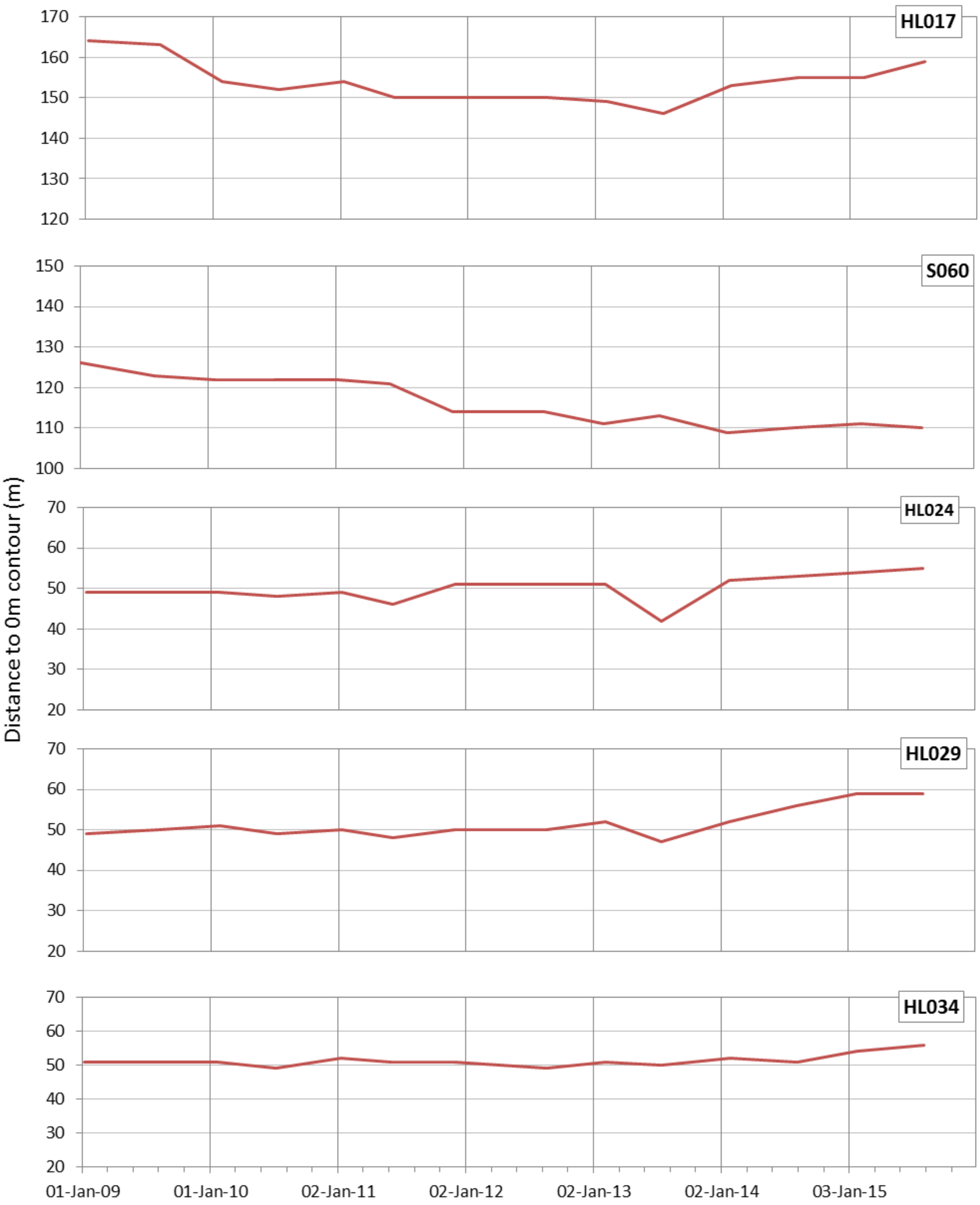

Figure 3.7: Beach width changes (2009-2015): Central Hollesley Bay

Source: Anglian Coastal Monitoring programme

In the centre of Hollesley Bay (Profiles HL024, HL029, HL034, SO61 and HL043) see Figure 3.7

- These profiles all indicate a stable or, since late 2013, a slowly accreting beach.

While these profiles indicate little change in beach width, this does not mean that sediment has not been able to move along this part of the coastline. Stability here indicates as much sediment has entered this part of the frontage as has left it.

Southern Hollesley Bay (Profiles H048, HL053, SO62 and HL061) see Figure 3.8

- At profile HL048 the beach width changed very little between 2009 and late 2013. Subsequently the beach has been narrowing slightly.
- There was little net change in the beach width at Profile HL053 between 2009 and early 2011 but subsequently there has been beach narrowing which appears faster since late 2013.
- Beach widths at Profile SO62 have behaved similarly to those at profile HL053 until early 2015, but there has been little change between then and autumn 2015.
- After reaching a maximum in early 2011, the beach width at Profile HL061, just to the north of East Lane, Bawdsey has been reducing rapidly with an increase in rate after the survey made in early 2014. Unlike Profile 61, there was a further reduction in the beach width here during 2015.

The combination of the above comments suggests that erosion of the beaches is greatest just north of East Lane and the trend for beach narrowing further north started rather later.

Taking these three sets of comments together suggests a recent movement of beach sediment northwards from the vicinity of East Lane, with that sediment moving along the coastline in the centre of Hollesley Bay and accumulating at or just south of Shingle Street. Changes in beach width close to Shingle Street village and from there north to the mouth of Ore/Alde estuary have been variable in both space and time suggesting more localised causes, probably related to changes in the morphology estuary entrance, particularly in the various mobile banks that form the ebb shoal delta which lies seaward and across the mouth of the estuary.

While these nearshore banks, often exposed at low tide, undoubtedly do affect the beaches to landward of them, it is less certain if and to what extent changes in banks and the seabed further offshore may also have affected the study frontage. This topic is discussed in Section 3.5.

3.4.4. Conclusions from the review of beach changes

Sections 3.4.2 and 3.4.3 have revealed how complicated the evolution of the beaches between the Ore/ Alde and the Deben estuaries have been in recent times. The main conclusions we have drawn from our review, starting with the hydrographic surveys discussed in Section 3.4.2 are as follows:

- The shingle beaches along this frontage rest on a wave-cut rock substrate. For the most part this rock is geologically recent, for example glacial till or clay, and will gradually continue to erode and lower as a result of currents, waves and the movement of sand and gravel particles over its surface.
- This underlying rock platform is substantially steeper in front of the cliffs between the Deben and East Lane, Bawdsey, reflecting the presence of coastal cliffs behind the beaches along this part of the study frontage. In contrast, between East Lane and the Ore/ Alde the shore platform is lower and slopes seaward more gently.

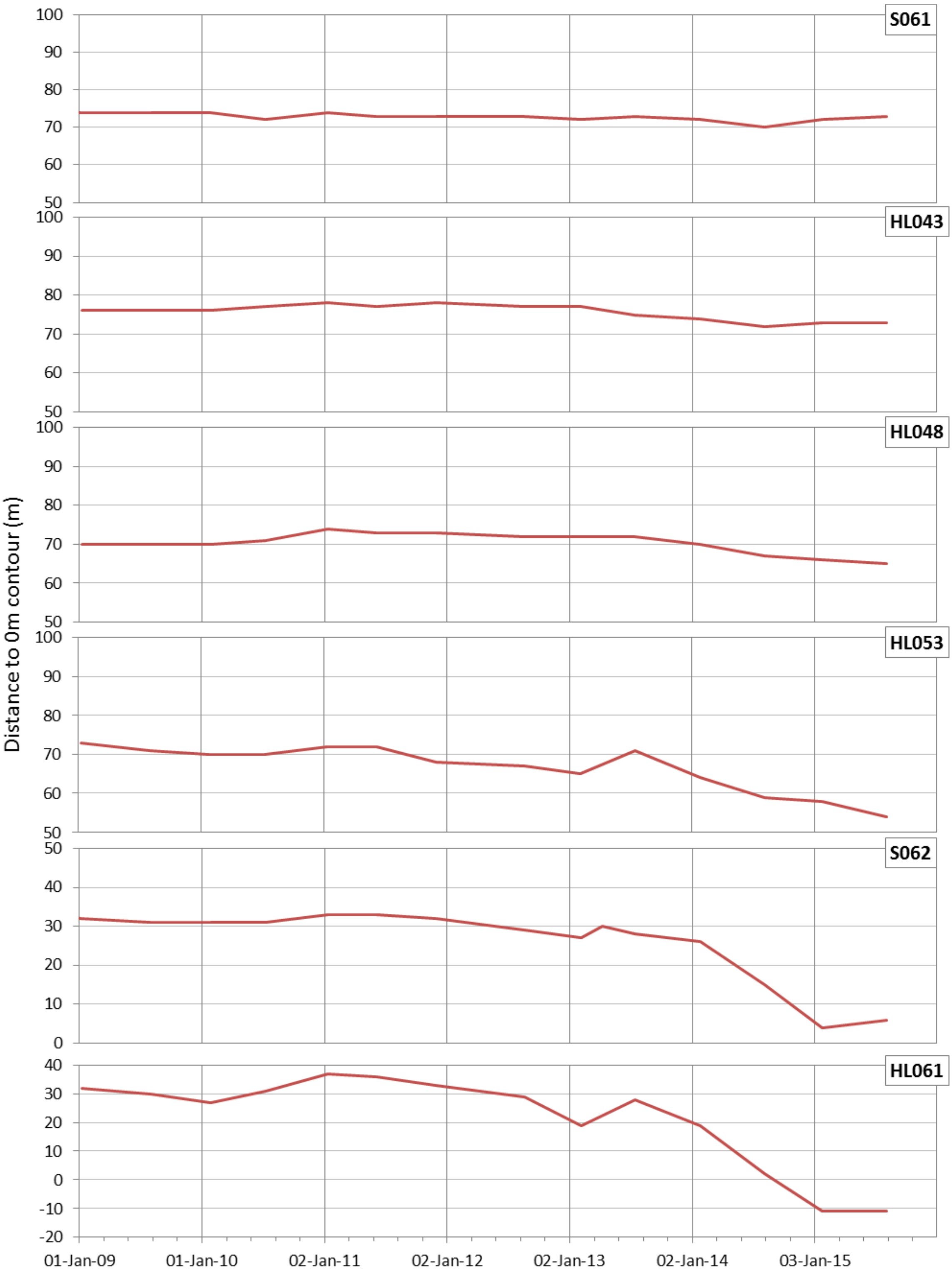

Figure 3.8: Beach width changes (2009-2015): Southern Hollesley Bay

Source: Anglian Coastal Monitoring programme

- The lower limit (toe) of the beach profiles, where the shingle finishes and the much more gently sloping shore-platform begins, varies considerably along this frontage both along the coast and over time. This latter variation is particularly noticeable just to the south of East Lane where the beach has become very narrow and its toe has recently been about the low tide mark. The steepness of this underlying platform close to the base of the cliffs, at about 1:50 (2%) contrasts with the gentler gradient further seawards, for example 1:150 (0.67%) at about -4 m OD (see Figure 3.5).
- Variability in the beach toe level over time is unusual and not included in computer models of beach plan-shape changes. As a consequence some difficulty in reproducing the beach erosion just south of East Lane can be anticipated.
- Along most of the study frontage, there is little evidence of changes in the nearshore seabed beyond the beach toe. This suggests that changes in the beach widths in the central part of Hollesley Bay, and at and to the south of East Lane, are not likely to be caused by changes in sandbanks close inshore, i.e. landward of the -10 m OD contour.
- However, near Shingle Street and from there north to the other side of the mouth of the Ore/ Alde estuary this situation changes. Here there is evidence (top four panes of Figure 3.4) of noticeable changes in bed levels seaward of the toe of the beaches. We have interpreted these as being caused by shingle being moving seaward from the beach face north of the entrance (Orfordness Spit) and then being transported southward via the various banks that constitute the ebb delta shoal of the Ore/ Alde estuary before reaching the beach near Shingle Street and then moving onshore to increase the beach width there (at least temporarily).

Turning to the topographic surveys, the main findings from Section 3.4.3 are:

- South of East Lane the pattern of stable beach widths along the Bawdsey Manor frontage while the beach widths further north have been decreasing (last three panes of Figure 3.4) strongly suggests a net southward movement of shingle along this frontage that has not been matched by the arrival of extra sediment from further north.
- The loss of beach sediment and the recent recession of the cliffs just south of the coastal defences at East Lane is a potential concern because of the danger of outflanking of the end of that seawall. More detailed evidence is available on beach width changes north of East Lane, where the introduction of extra profile surveys has improved understanding of beach processes within Hollesley Bay.
- The overall pattern of changes just north of East Lane show clear erosion in recent times (last four panes of Figure 3.8) particularly since the middle of 2013. Again the rather rapid and localised loss of beach sediment adjacent to the end of the seawall is a potential concern since outflanking the end of the seawall here would increase the chances of erosion or flooding of the hinterland.
- In the centre of Hollesley Bay, however, changes in beach width have been modest in the long-term but with a general trend for accretion and increasing beach width since the middle of 2013 (see Figure 3.7).
- Further north, along the coastline near Shingle Street and as far as the entrance to the Ore/ Alde, again the general trend is for a gain in beach width recently (Figure 3.6) but with local variations. These local variations are likely to be associated with longshore movements in the position and plan-shape of the shingle ‘ness’ near Shingle Street rather than reflecting a more complicated and time-varying pattern of longshore drift.
- Taking together, this pattern of changes in Hollesley Bay strongly suggests a net <u>northward</u> movement of shingle from East Lane towards Shingle Street, i.e. in the opposite direction to that suggested by Steers (1946) and others.

We therefore interpret the overall pattern of changes in beach widths along the coastline on either side of East Lane, Bawdsey as being caused by a recent change in the direction of longshore beach sediment transport in Hollesley Bay from southward to northward, particularly since summer 2013. As a consequence there appears to have been a 'drift divide' at East Lane with beach sediment moving away from both sides of that headland. In such a situation, the potential for the sea defences to prevent the transfer of beach sediment from one side of the headland to the other becomes largely irrelevant.

There is a potential for outflanking of one or even both of the ends of this seawall should the recent trends for coastal change continue.

While the very stormy winter of 2013/2014 with its storm surges was always likely to cause changes in beaches, it also appears that such changes have continued subsequently. What is not clear from the beach survey data is why there appears to have been a change in behaviour in the period 2013 to 2015, and this topic is returned to later in this study.

3.5. Historic bathymetric changes

In this section we present and comment on changes in the seabed offshore from the study coastline. Elsewhere along the coastline of Suffolk, changes in beaches and in drift rates have previously been attributed to changes in the nearshore seabed morphology, particularly the movements and changes in shape of nearshore sandbanks. So it is sensible to conclude this part of the review with a brief review of seabed changes offshore from East Lane and the coastline either side of that headland.

As with the historical shoreline mapping discussed in Sections 3.2 and 3.3, we have received information on historic changes in the seabed from Helene Burningham of University College, London (UCL).

Figure 3.9 to Figure 3.12 show differences in bed levels deduced from comparisons of Admiralty Charts based on surveys undertaken in 1840, 1880, 1940 and 1990.

Care needs to be taken in interpreting the differences in bed levels taken from such surveys since there will inevitably be errors both in recording the horizontal position of any depth sounding and in the conversion of that depth measurement to the bed level relative to Ordnance Datum. In these figures, the orange and red tones indicate a lowering of the seabed over the period of the comparison while the green and blue tones indicate an increase over that period of time. Changes smaller than ±0.5 m are regarded as too small to be reliable and such areas are shown in white; this range is probably rather an optimistic assessment of the errors in depth measurements especially when comparing surveys undertaken in Victorian times using a lead line and often from rowing boats (in shallow water) with more modern surveys using sonar and high-precision electronic position fixing.

What is clear from the four previous figures is that in their eastern parts there have been substantial movements in the positions of some of the main and generally north-south trending sandbanks (the Inner Gabbard and Galloper). In most instances the comparisons suggest an offshore movement of these banks but this conclusion does need to be treated with caution given the rather long time periods between the surveys. These banks, however, are so far offshore that their changes will have very little effect on wave conditions close inshore. In severe storms and particularly at low tide some wave energy will be lost due to depth-limited breaking over the crest of these banks, previous studies and similar modelling of waves in this study (see Section 4.4) shows that the continuing action of the wind over the sea between these banks and the shoreline compensates for the energy loss. This combined with wave diffraction results in these banks not providing any significant shelter to the coastline of Suffolk or Essex.

Closer to the coast, the changes in the Shipwash Bank (almost in the centre of Figure 3.9 to Figure 3.12) suggest it has undergone a slight reorientation since 1840 with its northern part moving landward and its southern part seawards but with little overall change in its height or length. Burningham and French (2009) concluded that the pattern of erosion and accretion around Shipwash suggest that different parts of the bank are shifting in different directions, but that in general it has narrowed, lengthened and shallowed over the last 180 years. While such changes are noticeable in the long-term, this bank is too far offshore for a shift in its position or orientation to have a noticeable effect along the coastline. This issue was considered in a regional environmental assessment commissioned in connection with past and planned future aggregate dredging offshore from this coastline (HR Wallingford, 2010).

In recent times, the most noticeable feature of the nearshore bed level changes shown in Figure 3.10 and Figure 3.11 is the deepening of the navigation channel into the Stour/ Orwell estuary allowing access by deeper draught vessels into the ports of Harwich and Felixstowe. The potential effects of this channel on wave conditions along the near parts of the coastline have been, and continue to be assessed as part of the environmental impact assessments carried out whenever permission is sought to increase its depth and length. Wave modelling carried out as part of such assessments, since 1990, has not indicated any cause for concern even close to the entrance to the Stour/Orwell estuary, for example along the southern part of Felixstowe's seafront. Neither, as far as we know, have any past increases in the depth of this channel been observed to affect the beaches and coastline nearest to the mouth of that estuary. This gives some useful guidance in regard to how natural changes in seabed levels might be expected to affect the beaches either side of East Lane, Bawdsey.

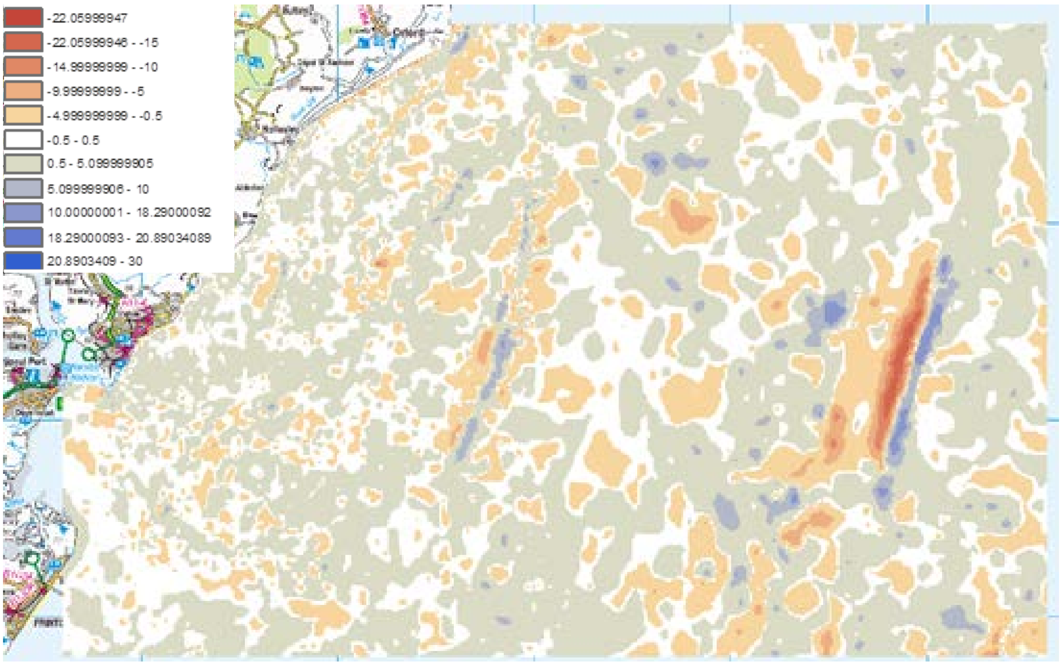

Figure 3.9: Seabed changes 1840-1980

Source: UCL

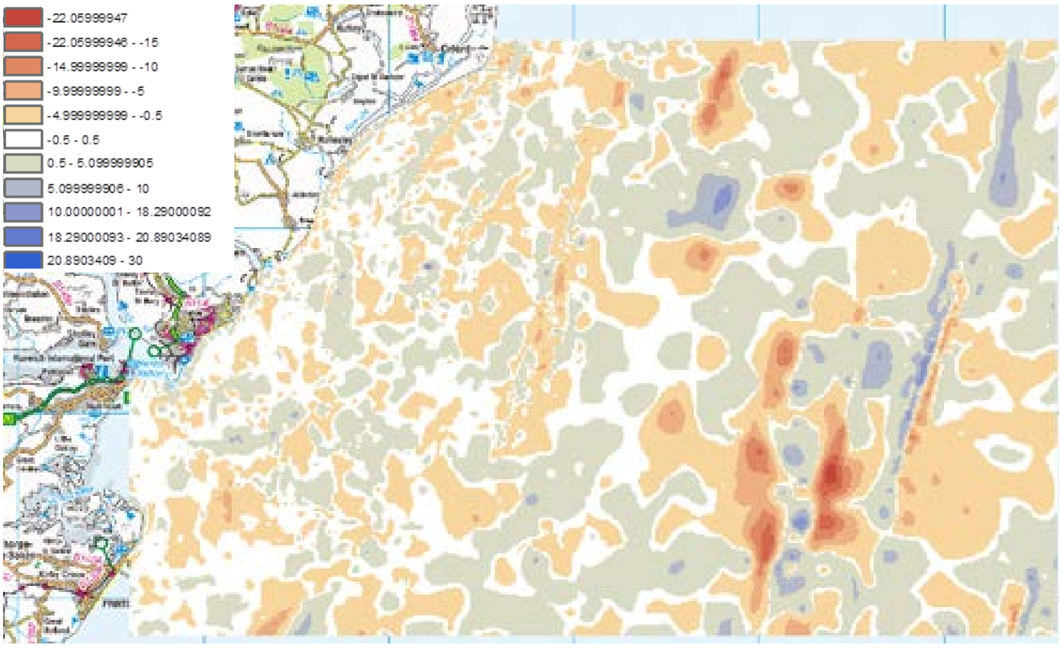

Figure 3.10: Bathymetric changes 1900-1940

Source: UCL

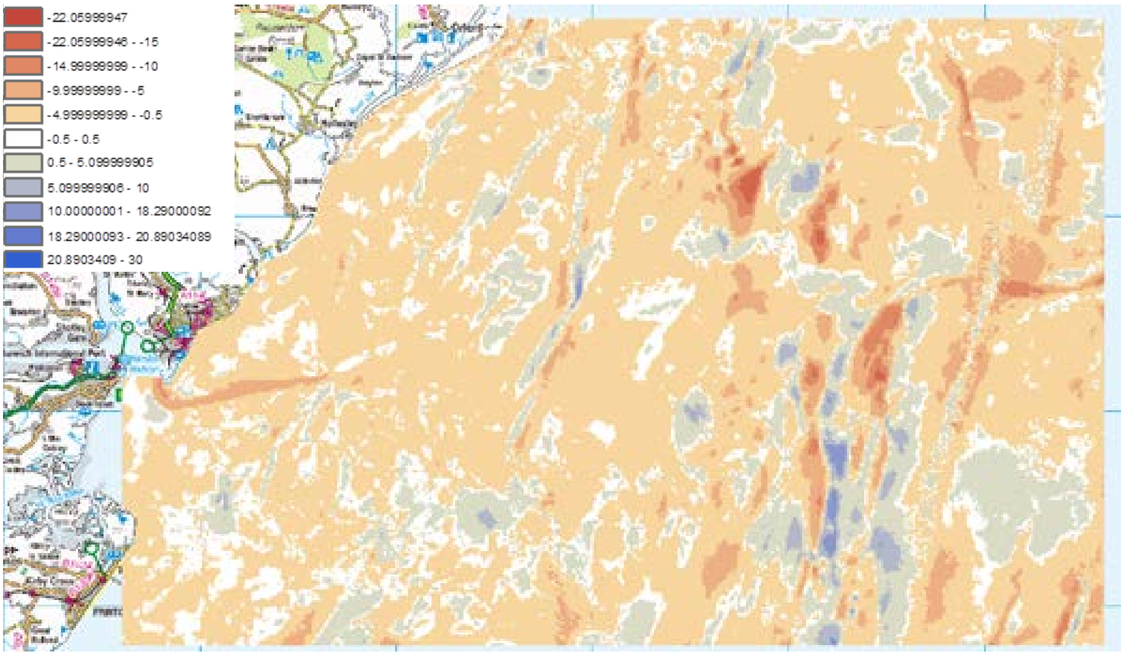

Figure 3.11: Bathymetric changes 1940-1990

Source: UCL

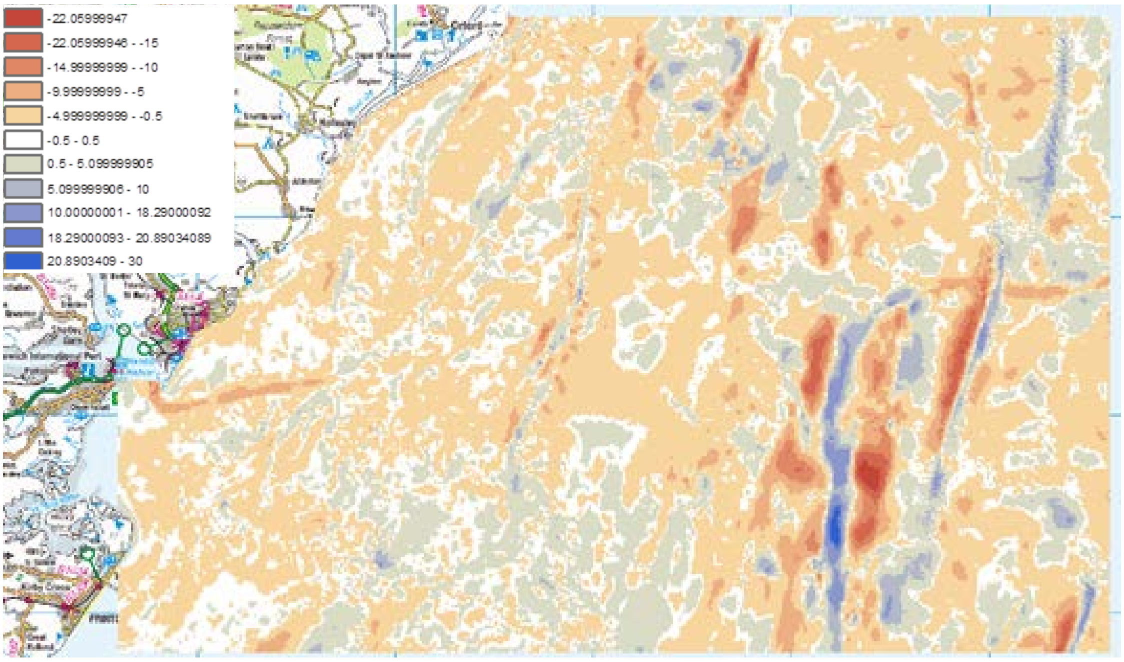

Figure 3.12: Bathymetric changes 1840-1990

Source: UCL

In that context, the bed level changes offshore from our study frontage, in the top left-hand corner of the panes, show apparently different trends in bed levels in the different epochs, sometimes suggesting lowering and sometimes becoming higher, in areas where we would expect the seabed to be rock (e.g. clay). While it is possible that the amount of sediment overlying some of these rocky areas has varied in the past, we think it more likely that the differences shown are often larger errors than ±0.5 m.

For convenience, part of Figure 3.12 has been enlarged and presented as Figure 3.13 showing changes close to East Lane. There is a suspicion of a slow offshore movement of Cutler Bank which lies seaward of the mouth of the Deben, an onshore movement of Whiting Bank and some large changes in bed levels rather closer to Orfordness than elsewhere between there and the Deben.

Burningham and French (2009) state that the offshore migration of Cutler Bank is clearly defined by associated areas of erosion (landward) and accretion (seaward) and in their 2008 study, they report that Cutler Bank has experienced a gradual lowering of about 1cm a year over the last 100 years. With respect to Whiting Bank, Burningham and French (2009) state that it has shown very little change in minimum depth over perhaps 400 years.

In Figure 3.13 we have not shown net changes in seabed level smaller in magnitude than ±0.50 m. In contrast Burningham and French (2008) only show changes in level greater than 2.0 m which is probably a better reflection of the likely accuracy of the original survey charts.

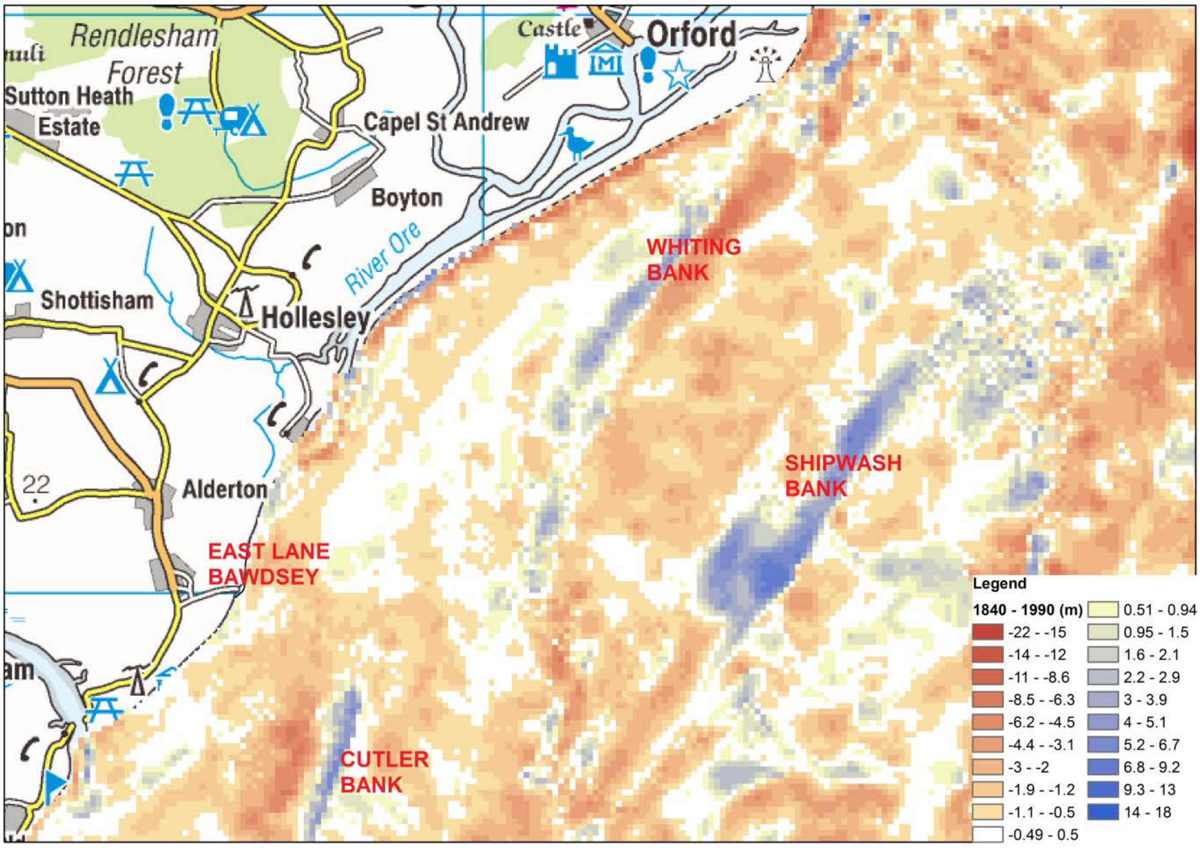

Figure 3.13: Bathymetric changes 1840-1990 (enlarged near study frontage)

Source: UCL

Bearing this in mind, the changes very close to the shoreline, showing as substantial bed lowering along Orfordness Spit and close to Shingle Street, need to be treated with great caution since surveys designed for safe navigation rarely extend so close inshore. There is rather stronger evidence of the seabed lowering a little further offshore, consistent with a gradual down-cutting of the shore-platform but unlikely to provide an accurate estimate of how quickly this is occurring.

Because these chart comparisons only cover the period prior to 1990, they cannot directly provide any indication of possible causes of changes near East Lane in the last 25 years. Our impression is that the historic changes prior to this date may have contributed to a very gradual increase in wave energy along the frontage each side of East Lane as the Cutler Bank moved offshore and the shore-platform gradually lowered. This would be expected to have led to a long-term tendency for the erosion of cliffs and landward retreat of the shingle barrier beach in Hollesley Bay. However, there is no evidence for rapid movements or changes in nearshore banks that might have caused different responses in the beaches over short stretches of the coastline near East Lane. This contrasts with the situation a little further north, particularly near Orfordness, where large changes in the nearshore seabed could well have caused localised changes in the beaches.

3.6. Recent bathymetric survey data

Toward the end of this study, The Crown Estate obtained a recent survey of the nearshore seabed undertaken in connection with a planned offshore windfarm. This data was provided by Scottish Power under the understanding that it was only to be used to inform our investigation of the changes in the coastline at and on either side of East Lane, Bawdsey.

The extent and data of the recent survey is depicted in Figure 3.14. Due to the limited extent of the survey, it did not add much value to the overall assessment of possible changes in the seabed that might have caused changes in the beach width.

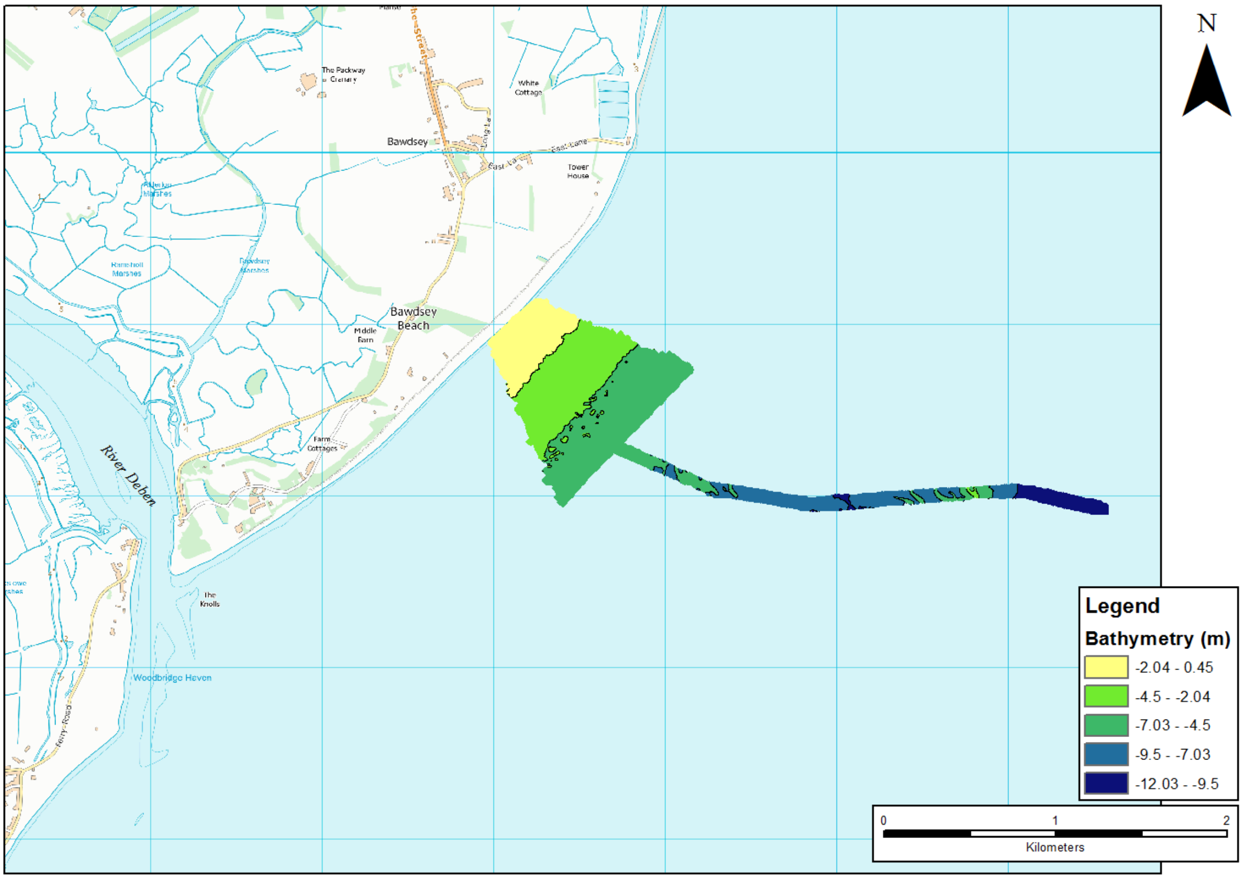

Figure 3.14: Recent bathymetric survey data

Source: Scottish Power

4. Derivation of nearshore wave conditions

4.1. Methodology

A long term time-series of nearshore wave conditions with corresponding water levels is required at a number of locations along the study coastline to help understand past changes and predict future changes. The seabed levels offshore of the area of interest are characterised by a number of sandbanks extending approximately 20km offshore, some of which have their crests above or only slightly beneath the lowest tidal level. Due to this, computational modelling was required to represent the propagation of waves between deep water and the coastline and in this study the spectral wave model SWAN was applied. SWAN is a phase averaged spectral wave model that represents the generation and propagation of waves and accounts for the processes of wave-growth, shoaling, refraction, depth limited wave breaking, bed friction and non-linear wave-wave interactions. More information on this model is provided in Appendix B.

For this project a long term time-series of offshore wave and wind conditions covering a period of 35 years was purchased from the Met Office. In order to efficiently derive a corresponding nearshore time-series, as required for the beach plan-shape modelling, a meta-modelling technique, as used in the recent EA National Flood Risk Assessment – State of the Nation (SoN) project, was applied (this methodology is described in Appendix C). Rather than run the complete long term time-series using SWAN, a SWAN Emulator was trained using a limited set of SWAN model runs. The training runs were carefully selected to cover the complete range in boundary conditions including: offshore wave height, period, and direction; wind speed and direction; and water level. SWAN emulators were then built that describe the nearshore conditions, in a mathematical form, relative to the corresponding boundary conditions and were used to derive wave conditions at nearshore points of interest, including at points collocated with historical observations to validate the model against measured data.

4.2. Model bathymetry and extent

The SWAN model bathymetry is based on Seazone TruDepth data. This data combines and de-conflicts survey and charted data and is mapped onto a regular grid with spatial resolution of approximately 30 m. A SWAN model was set up using a rectangular grid with spatial resolution of 200m as illustrated in Figure 4.1. The spatial coordinates are in metres OSGB and the vertical datum is mean sea level (MSL). The model grid was rotated counter clockwise by 3° to be approximately aligned with lines of equal latitude and longitude.

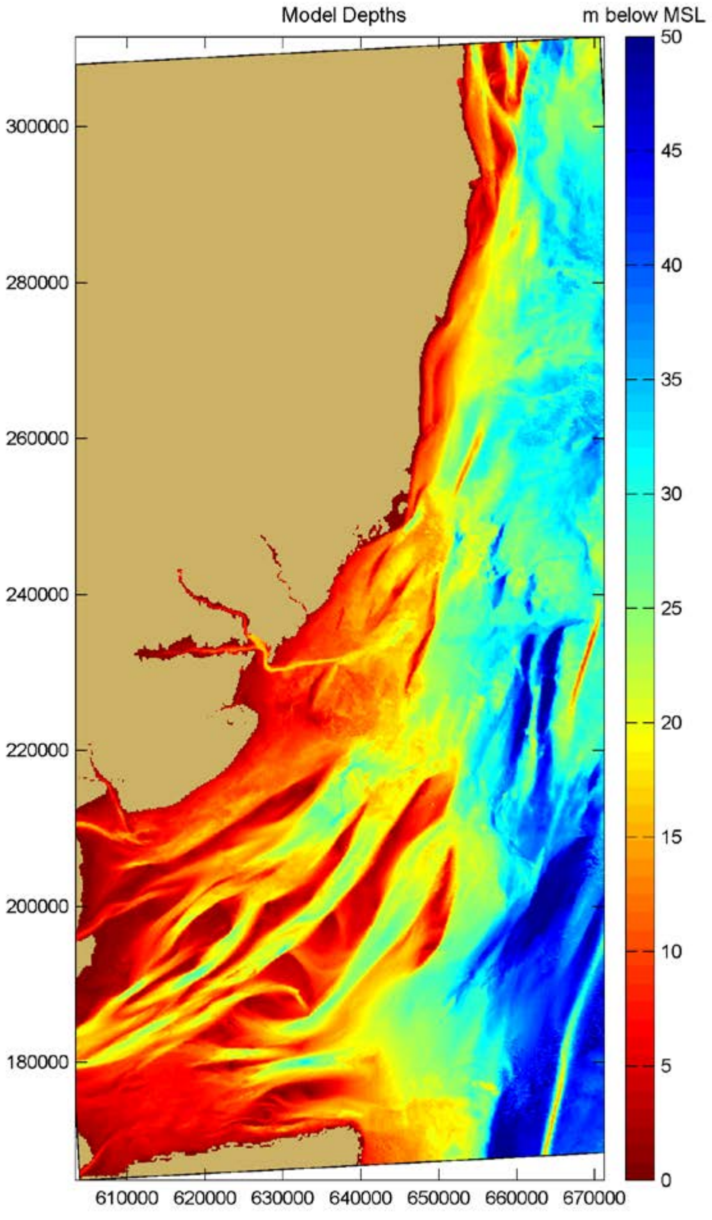

Figure 4.1: SWAN model extents and depths

Source: HR Wallingford/Seazone

4.3. Input data – offshore waves, winds and water levels

Offshore wave and wind conditions were the Met Office European WaveWatchIII ReMAP Hindcast purchased from the Met Office. This hindcast covers the 35 year period from 1980 to 2015, with 3 hourly time steps for the period 1980-2000 and hourly time steps from 2001 onwards. The ReMAP data was obtained for the offshore point: 51.86°N, 2.085°E, as the source of offshore waves and winds. The position of this point is shown in Figure 2.1.

A continuous 36 year time-series of predicted tide levels from CMAP at Felixstowe was used as the basis of the water levels in the study; note that no account was taken of tidal surges in our wave and beach modelling. For the SWAN emulator training runs the water levels at the corresponding time of the boundary wind and wave conditions were assumed spatially constant over the model area. As the tidal range varies by about 1m along the coast between Felixstowe to the south and Slaughden to the north of the area of interest, for the prediction at nearshore points, an estimate was made of the water at each nearshore point. This was done by application of an adjustment to the Felixstowe water levels that accounts for both the difference in tidal range and phase at points along the coast.

Figure 4.2 and Figure 4.3 show a wind and wave rose, respectively, of the offshore waves and winds for the 35 year period. Predominant winds are mainly from SSW, SW and SWW, whereas the waves show a more bidirectional composition, with two main directions from N and NE and SW.

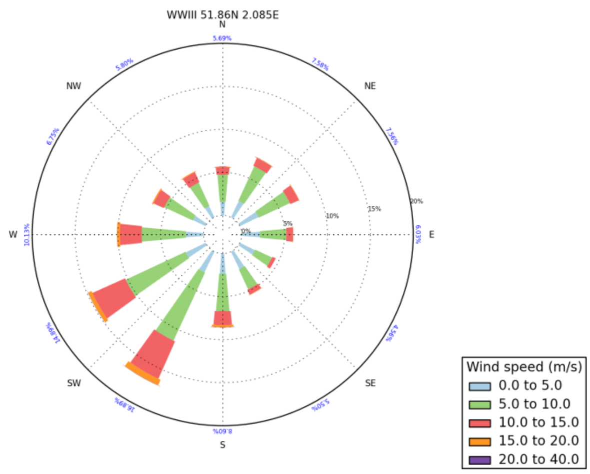

Figure 4.2: Offshore wind rose

Source: Met Office European WaveWatchIII ReMAP Hindcast

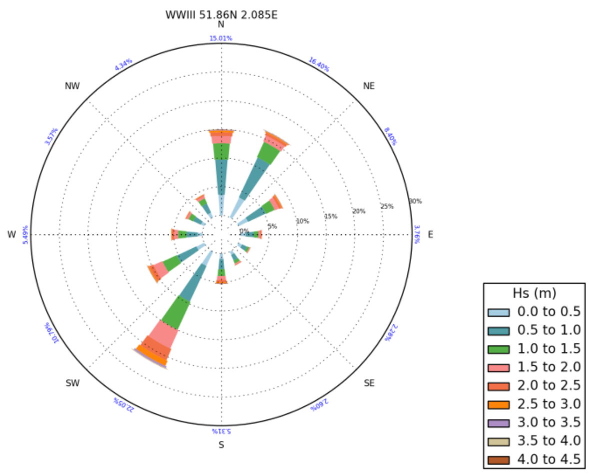

Figure 4.3: Offshore wave rose

Source: Met Office European WaveWatchIII ReMAP Hindcast

4.3.1. Offshore wave climate

The offshore wave conditions have been analysed in order to ascertain the trend in wave climate, if any, and to compare with the observed beach changes summarised in Section 3.4.4. For this analysis, the wave data has been separated in twelve months, from the start of June to the end of next year's May so that the winter season would not be split within the series. Hs (1%) and Hs(5%) have been calculated for each year, where Hs(1%) represents the 99th percentile of the wave heights within the year (or the 1% exceedance wave height) and Hs(5%) represents the 95th percentile of the wave heights within the year (or the 5% exceedance wave height). These exceedance wave heights have been presented in a graph in Figure 4.4. Although there is variability from year to year, no trend can be inferred from either of these exceedance heights. The average Hs(1%) over the 35 years is 3.04 m with a standard deviation of 0.18 m and the average Hs (1%) is 2.34 m with a standard deviation of 0.11m.

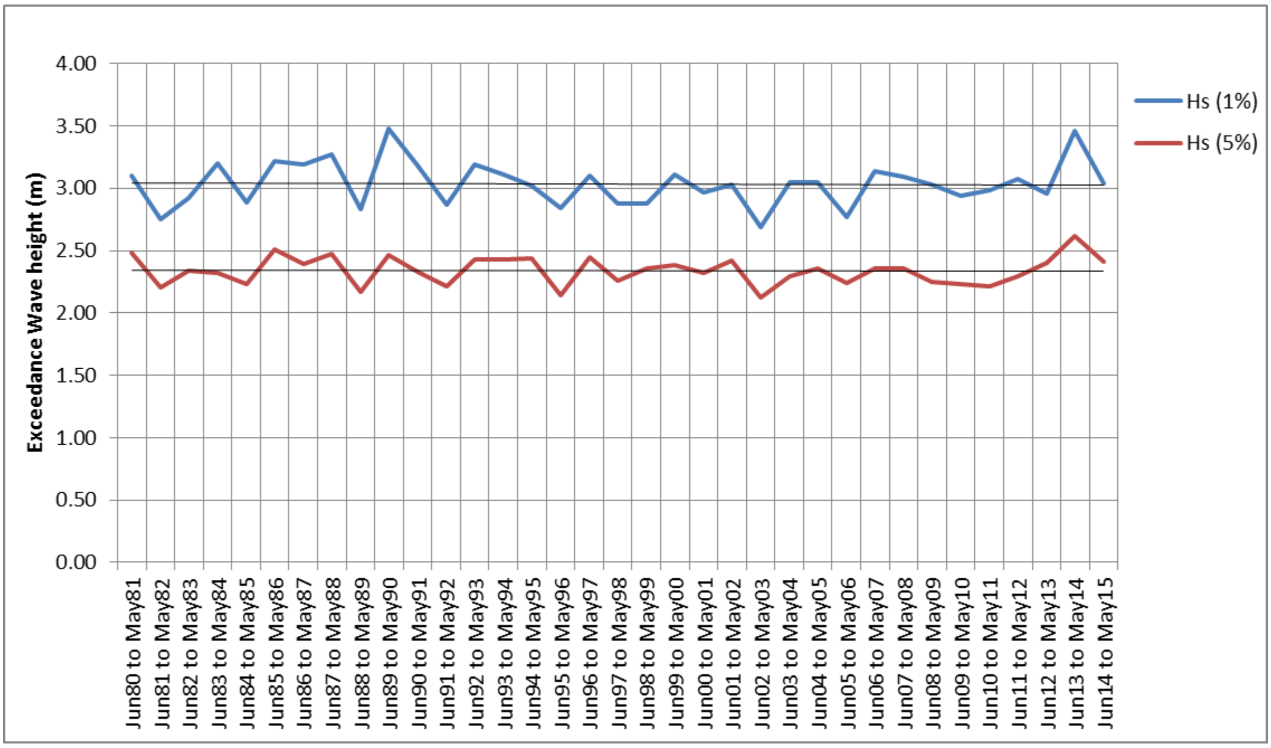

Figure 4.4: Time evolution of wave exceedance

Source: Data from Met Office European WaveWatchIII ReMAP Hindcast

It is worth noting the two distinct peaks in this history of the largest wave heights occurring in the winters of 1988/89 and 2013/14. These stormy winters seem to be linked to an increased value of the North Atlantic Oscillation (NAO) index which meteorologists use to characterize atmospheric pressure and wind patterns over that ocean (in the way that the El Niño / La Niña weather patterns occur over the Pacific Ocean).

The data is also presented in Figure 4.5 in terms of the percentage of time that a significant wave height threshold has been exceeded, namely from 2 m to 3.5 m in 0.5 m intervals. The average and standard deviation values are given in Table 4.1. The variability of these percentages is considerable, with the standard deviations being close to the averages for the two more extreme thresholds. It is also noted that the persistence of large waves has a peak in the last 3 years, where the values are quite high, the value for the year June 2013 to May 2014 being the highest of all years for all four thresholds considered.

Table 4.1: Annual percentage exceeding considerable threshold of wave heights

	%hours>3.5 m	%hours>3.0 m	%hours>2.5 m	%hours>2.0 m
Average value	0.3%	1.1%	3.5%	9.4%
Standard deviation	0.2%	0.5%	1.0%	1.6%

Source: Data from Met Office European WaveWatchIII ReMAP Hindcast

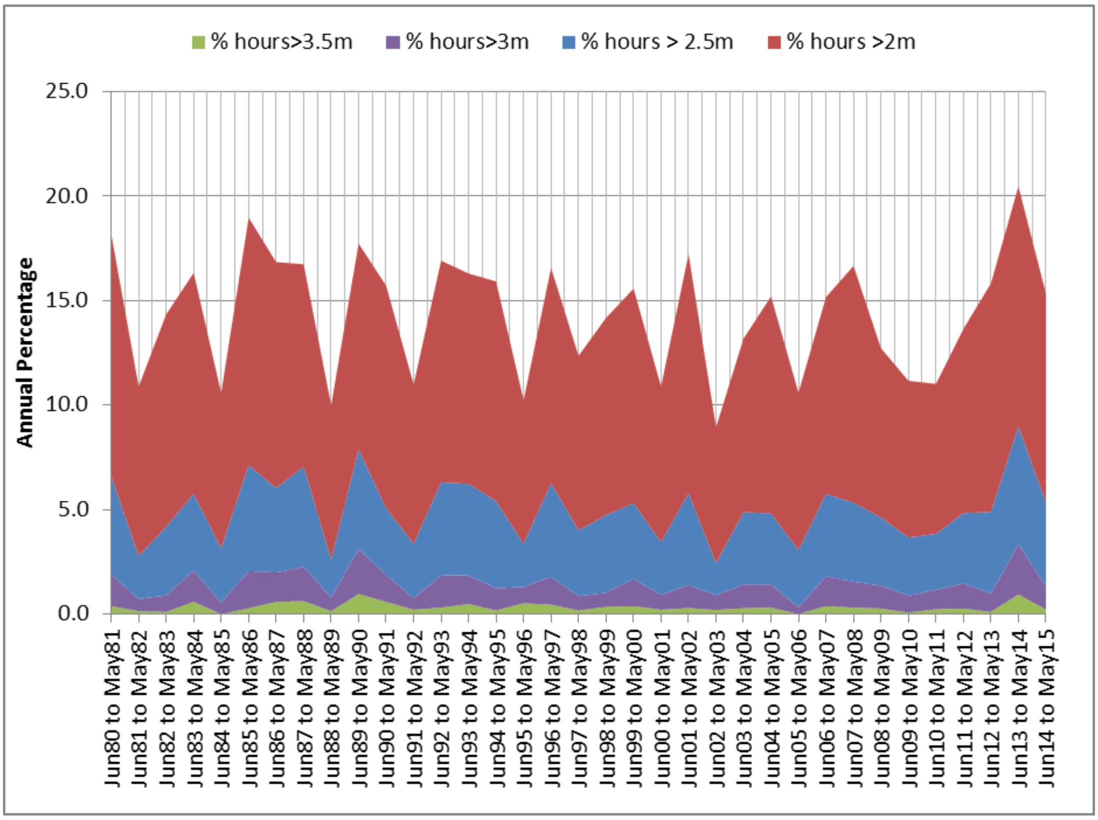

Figure 4.5: Annual percentage of hours exceeding considerable wave height thresholds

Source: Data from Met Office European WaveWatchIII ReMAP Hindcast

Note: Percentages are cumulative.

Variations in direction

A similar exercise has been carried out after separating the wave data into two directional sectors. Assuming a shore normal of 124º, waves have been separated into those coming from the left looking out to sea, predominantly N and NE waves, which would give a southerly drift and those coming from the right, predominantly SW waves, giving a northerly drift. It is important to note that this is a simplified approach as refraction inshore (where the longshore drift happens) has not been considered and only one shore normal has been taken into account. However, the point of the exercise was to see if there was any trend in the offshore wave direction and as such these limitations do not hinder the analysis.

The values in time for the 5% and 1% exceedance wave height for both sectors are quite variable, see Figure 4.6, but no significant trend can be deduced. Years seem to alternate between those with waves dominant from the N and NE and those coming from the SW with no real pattern. However, there are two periods with significant waves from the SW namely the years beginning June 1989 and 2013 and three years with more waves arriving from the N and NE starting in June 1980, 1985 and 1995.

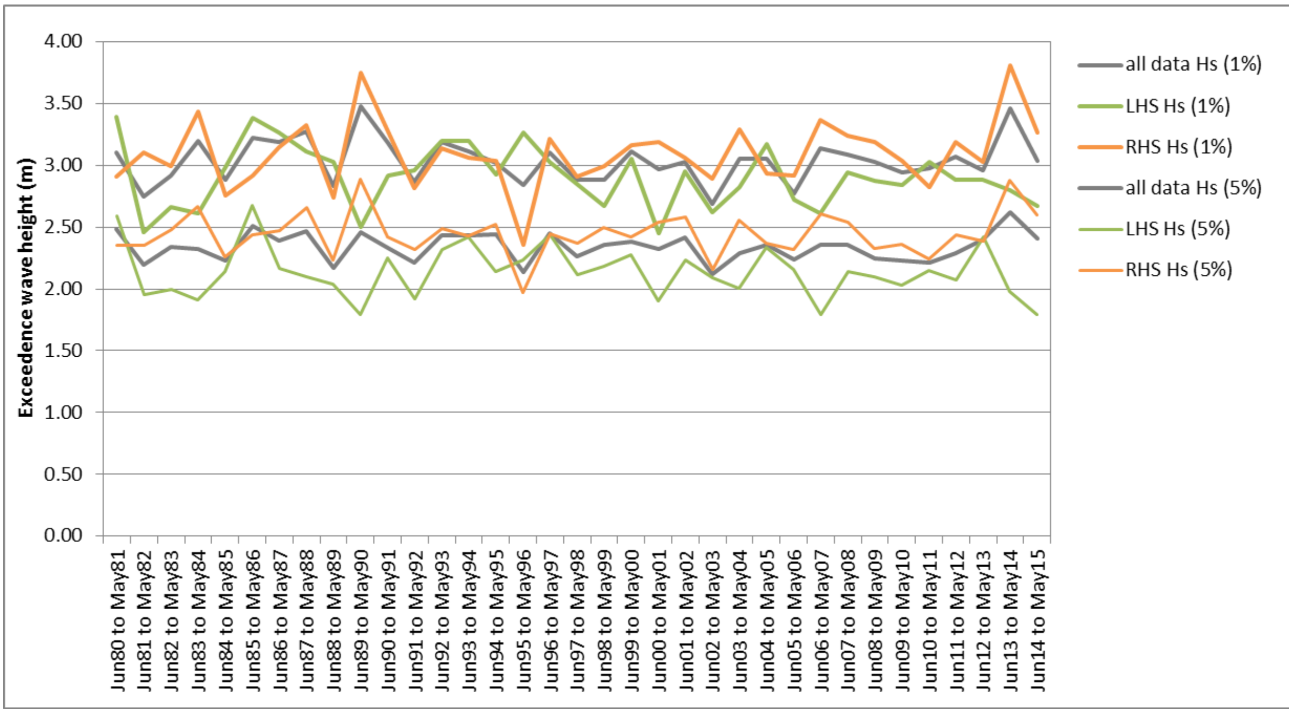

Figure 4.6: Time evolution of wave exceedance per sector

Source: Data from Met Office European WaveWatchIII ReMAP Hindcast
Note: LHS refers to waves from N or NE and RHS to waves from SW.

Similarly, as in the analysis done with the whole directional data, annual percentages for wave heights exceeding a considerable threshold (starting at 2 m and up to 3.5 m, in 0.5 m intervals) have been calculated for each sector. Figure 4.7 shows these percentages for waves from the two different sectors. The percentage of significant wave heights from the SW is usually bigger than those from the N and NE for the biggest waves (greater than 3.0 m), whereas for medium wave heights (greater than 2.0 m), the direction from the N and NE is more dominant.

This can also be appreciated in Table 4.3, where the average and standard deviation values for the annual percentages per sectors have been tabulated. The variability of the bigger waves is such that the standard deviation is of the same order of magnitude.

Table 4.2: Peak dates for each of the threshold wave height values

Percentage of time within a year exceeding the threshold value	Peak dates for waves from N and NE (or LHS waves)	Peak dates for waves from the SW (or RHS waves)
%>2.0 m	June80 to May81 June85 to May86	June13 to May14 June14 to May15
%>2.5 m	June80 to May81 June85 to May86	June13 to May14 June87 to May88
%>3.0 m	June85 to May86 June80 to May81	June89 to May90 June13 to May14
%>3.5 m	June95 to May96 June86 to May87	June89 to May90 June13 to May14

Percentage of time within a year exceeding the threshold value	Peak dates for waves from N and NE (or LHS waves)	Peak dates for waves from the SW (or RHS waves)
%>4.0 m	June95 to May96	June13 to May14
	June83 to May84	June89 to May90

Source: Data from Met Office European WaveWatchIII ReMAP Hindcast

Table 4.3: Annual percentage exceeding considerable threshold of wave heights per sector

	%hours>3.5 m		%hours>3.0 m		%hours>2.5 m		%hours>2.0 m	
	LHS	RHS	LHS	RHS	LHS	RHS	LHS	RHS
Average value (Contribution to whole value)	0.1 % (33%)	0.2% (67%)	0.4% (36%)	0.7% (64%)	2.2% (63%)	1.3% (37%)	6.1% (65%)	3.3% (35%)
Standard deviation	0.1%	0.2%	0.3%	0.5%	0.6%	1%	1.2%	1.6%

Source: Data from Met Office European WaveWatchIII ReMAP Hindcast
Note: LHS refers to waves from N or NE and RHS to waves from SW.

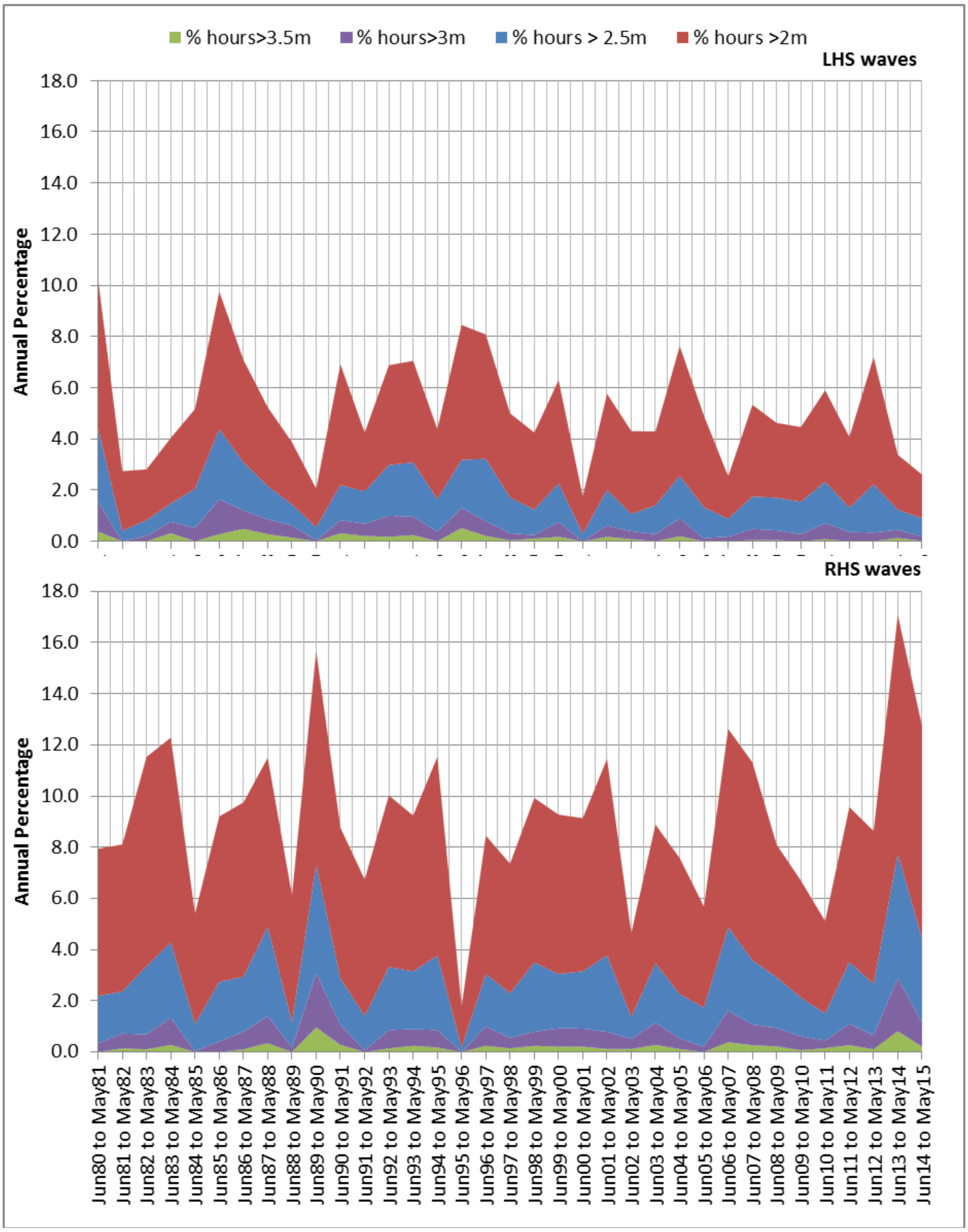

Figure 4.7: Annual percentage of hours exceeding considerable wave height thresholds per sector

Source: Data from Met Office European WaveWatchIII ReMAP Hindcast
Note: Percentages are cumulative.
Note: LHS refers to waves from N or NE and RHS to waves from SW.

4.4. Nearshore wave conditions

Nearshore wave conditions were predicted at a range of locations to provide input to the beach profile modelling (roughly along the -10 m MSL contour and -5 m MSL contour). The output locations are shown in Figure 4.8 and the corresponding coordinates of the points and levels relative to MSL are given in Appendix D.

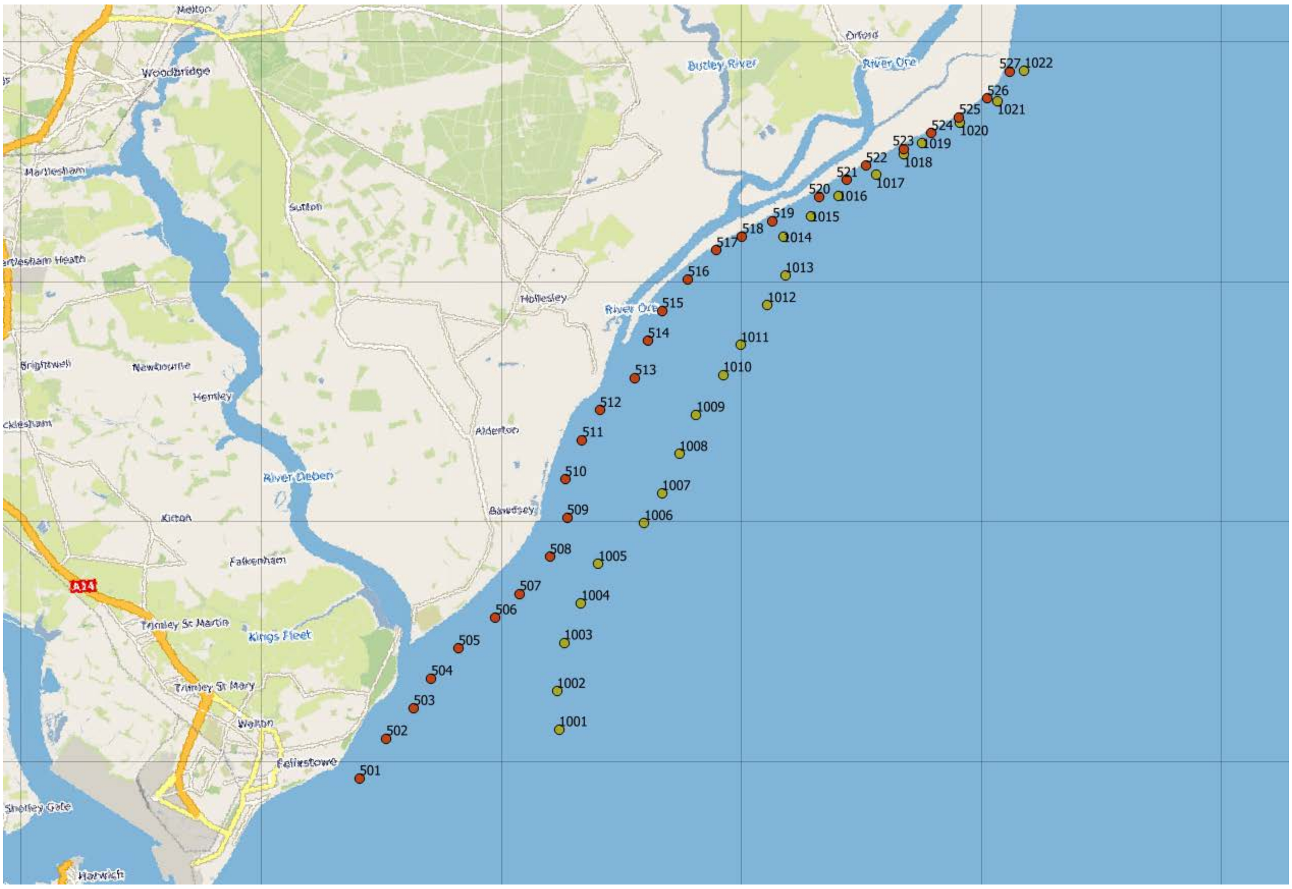

Figure 4.8: Wave model output locations

A 35 year time-series covering the period 1980-2015 was derived at each nearshore point for input to subsequent beach modelling studies. To illustrate the predicted wave conditions, wave roses and exceedence curves for a point along the -5 m MSL and -10 m MSL contour lines adjacent to Bawdsey are given Figure 4.9 to Figure 4.12. Results were also extracted at an intermediate point, at -25 m MSL, outside the influence of the main banks in the area. The wave rose and exceedance curve from predicted wave conditions at this location is given in Figure 4.13 and Figure 4.14 . Additional wave roses at selected nearshore points are presented in Appendix D.

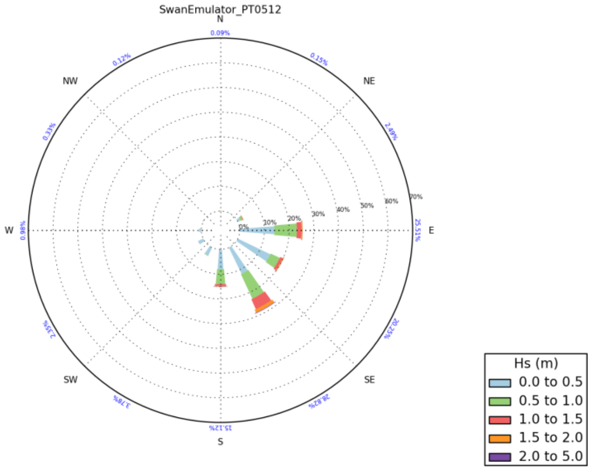

Figure 4.9: Wave Rose: PT512

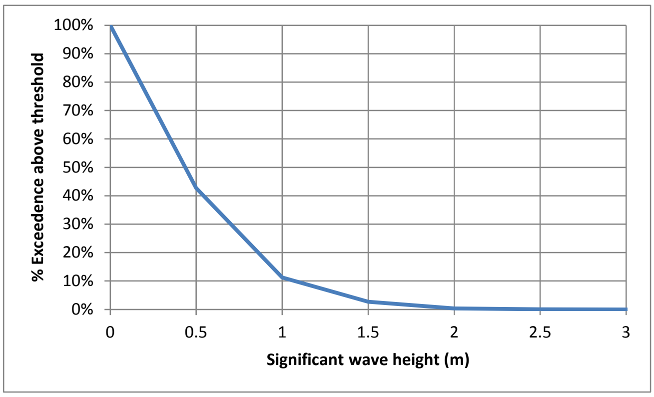

Figure 4.10: Exceedence Curve: PT512

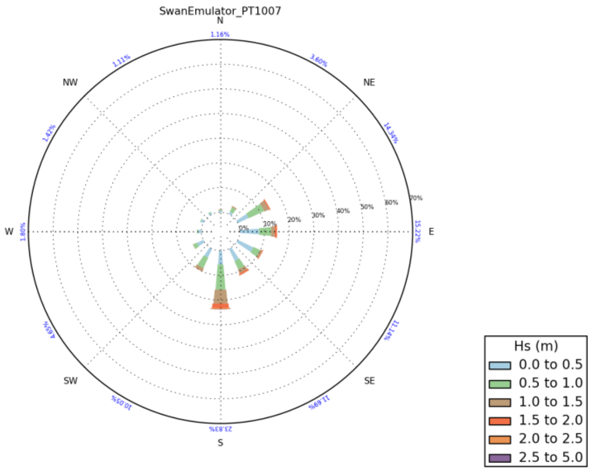

Figure 4.11: Wave Rose: PT1007

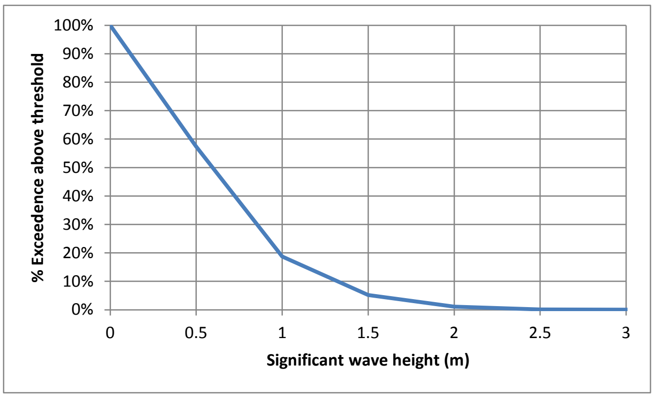

Figure 4.12: Exceedence Curve: PT1007

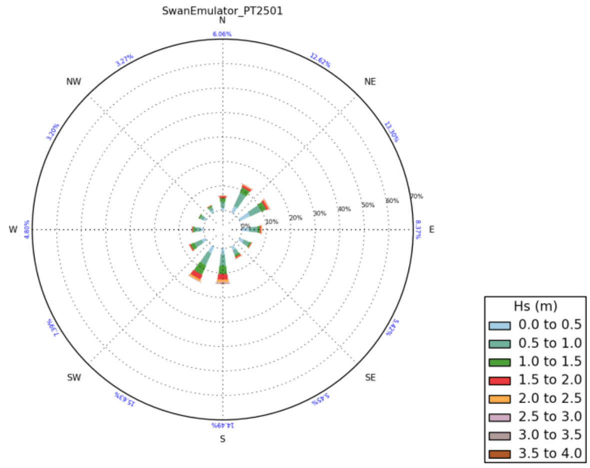

Figure 4.13: Wave Rose: PT2501

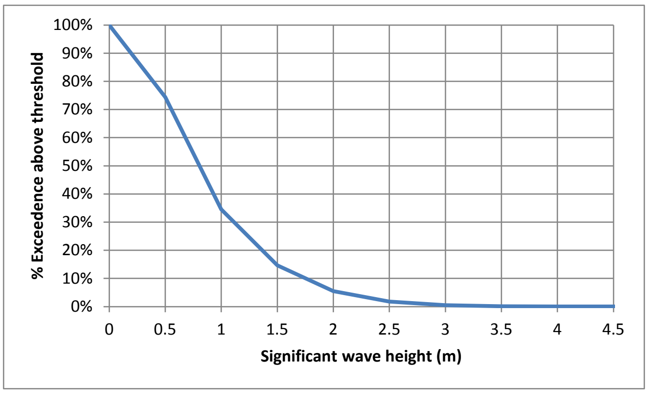

Figure 4.14: Exceedence Curve: PT2501

4.4.1. Inter-annual variation

Section 3.4 showed how some areas that had been subjected to small shoreline variations within the years had, in recent years, seen a significant change of behaviour with considerable shoreline variations. In order to see the influence of the wave climate on the shoreline behaviour, wave roses for a period of 2 years have been derived for the most recent wave data and for data from when the monitoring started. These wave roses are shown in Figure 4.15 for the period between June 2009 to May 2011 and Figure 4.16 for the period between June 2013 and May 2015. In both wave roses, the bulk of the energy (90%) happens between 75ºN and 195ºN; the difference between them being the shift of energy towards the south by about 7%, so that between June 2009 and May 2011 the E and ESE components total 50% whereas the SSE and S component total 40% compared to 43% for E and ESE and 47% for SSE and S for the period of June 2013 to May 2015.

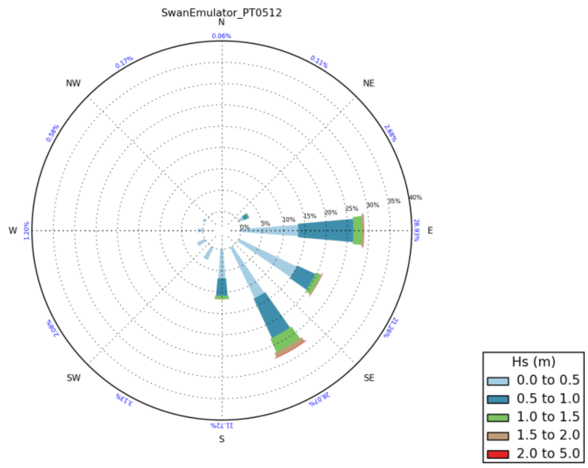

Figure 4.15: Wave rose, PT0512 June 2009 to May 2011

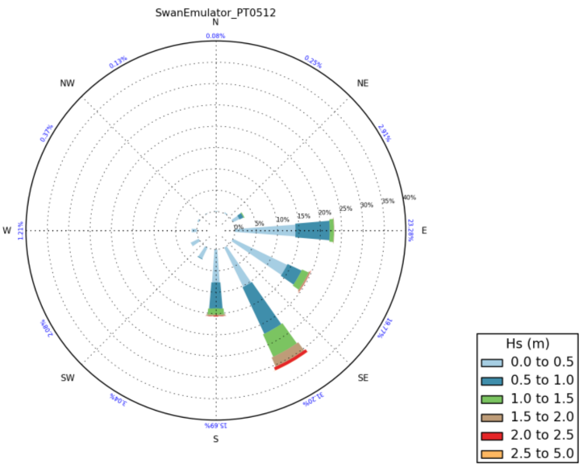

Figure 4.16: Wave rose, PT0512 June 2013 to May 2015

4.5. Model validation

An example of the SWAN model results is illustrated in Figure 4.17. This shows the model results for one of the SWAN Emulator training runs and is for an extreme event from South West. This figure shows a contour plot of the predicted significant wave height with vectors showing the mean wave directions (scaled by wave height), superimposed on contour lines showing the bed level relative to MSL. The strong influence of the offshore banks to the south west of the area of interest is clearly noticeable.

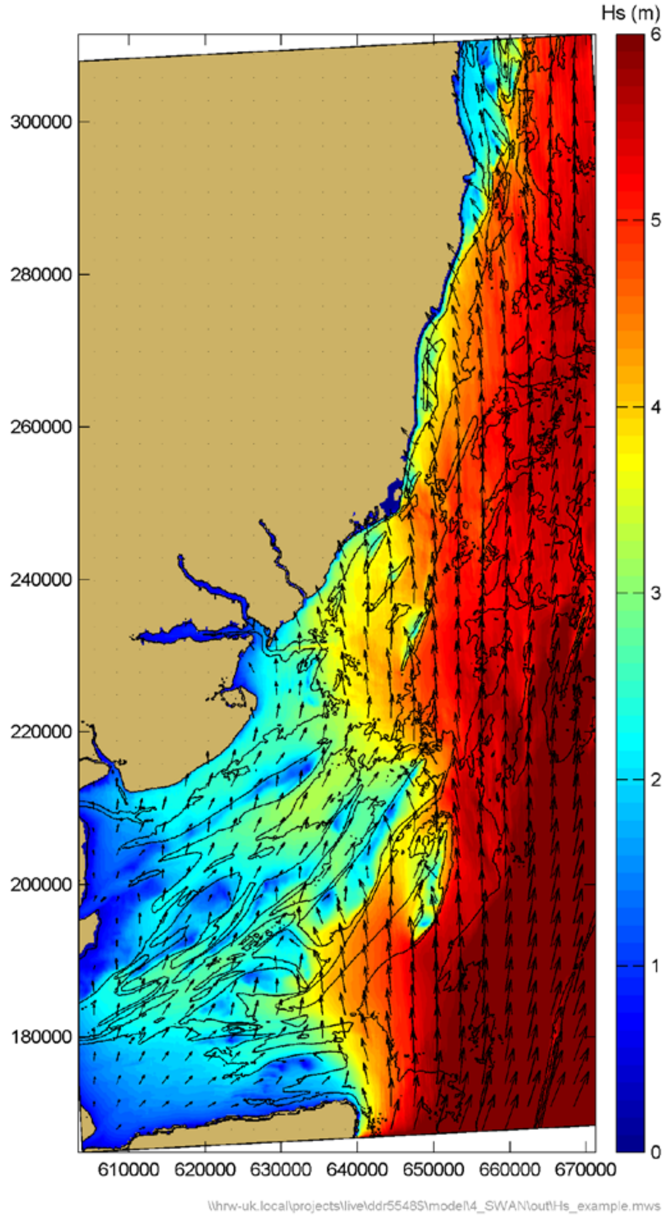

Figure 4.17: Predicted significant wave height

Source: HR Wallingford SWAN model

Two other conditions are shown within this report in order to see the propagation of large waves from offshore to inshore. The first condition, as depicted in Figure 4.18, is a wave from the NE with a NE wind. This figure shows the predicted significant wave height and mean wave direction with contour lines showing the bed levels 5, 10 and 15 m below MSL. The accompanying Figure 4.19 shows the same predicted conditions closer to the area of interest. These figures show the protection afforded by Orfordness along the coast to the south for waves from the NE and the strong refraction of waves from offshore to inshore, turning the waves from about 30°N to about 70°N, with an associated reduction in height.

The second condition is a SSW offshore wave with a SSW wind, which is shown in Figure 4.20 and, as a close up, in Figure 4.21. This illustrates how this offshore wave condition with a period of 6 seconds and direction of about 160°N transforms inshore to about 140°N The partial wave reflection off the Harwich approach channel is also noticeable in this figure, which gives confidence that the shallow water processes are being reasonably well resolved by the SWAN model.

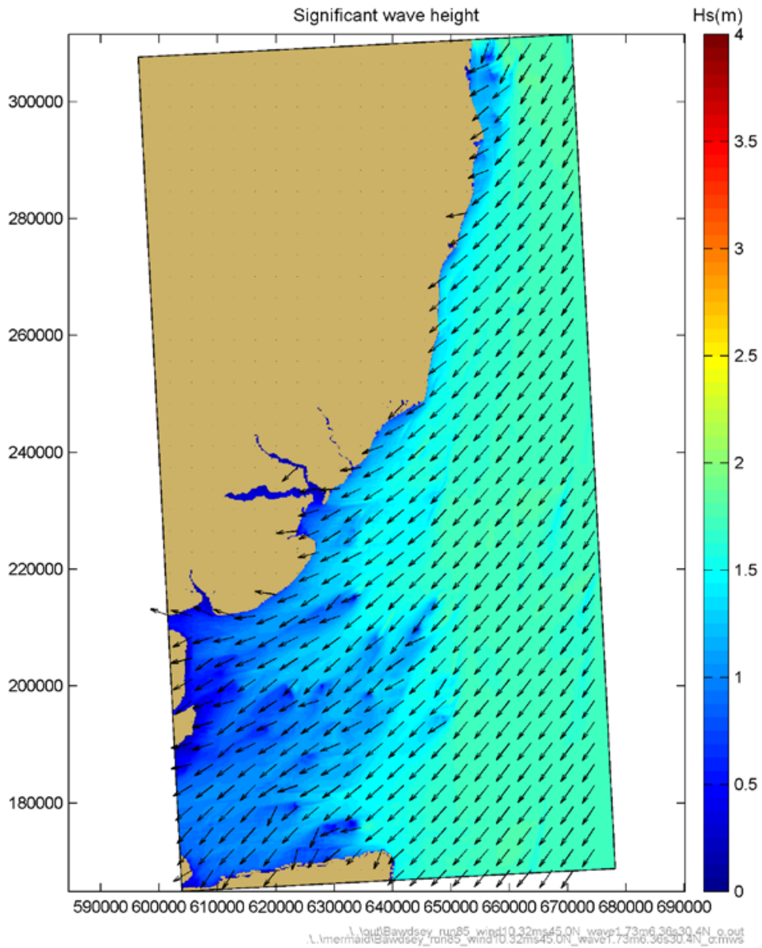

Figure 4.18: SWAN Training Run n#85 - Wave conditions Hs=1.73m, Tp=6.36s Dir=30.4N, Wind conditions U=10.32m/s Dir=45N

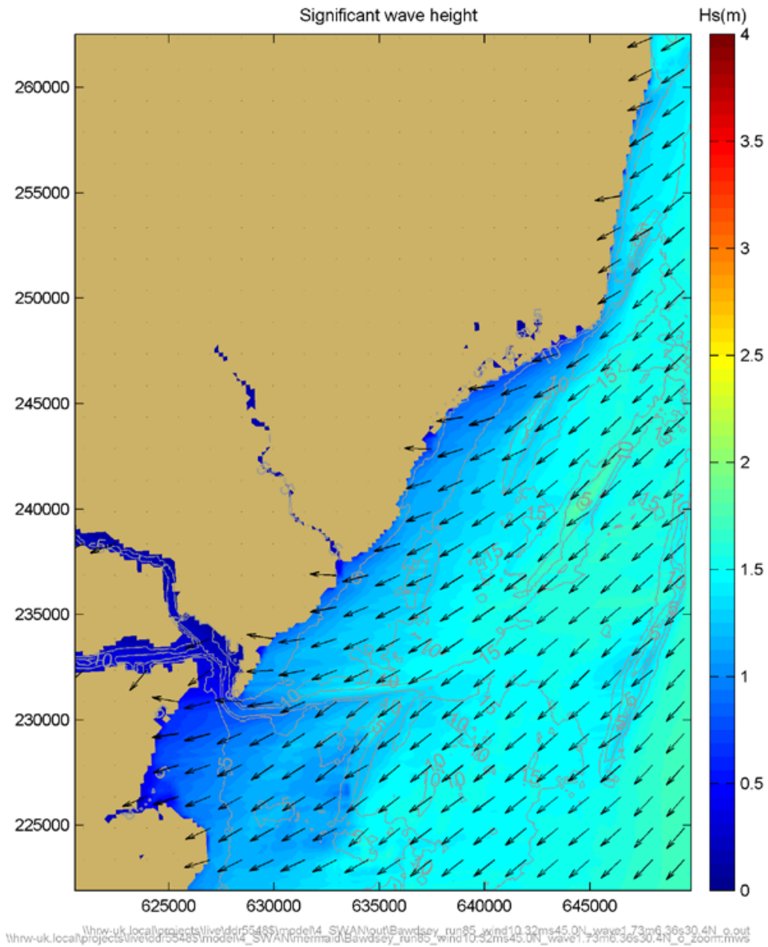

Figure 4.19: SWAN Training Run n#85 - Wave conditions Hs=1.73m, Tp=6.36s Dir=30.4N, Wind conditions U=10.32m/s Dir=45N. Close up

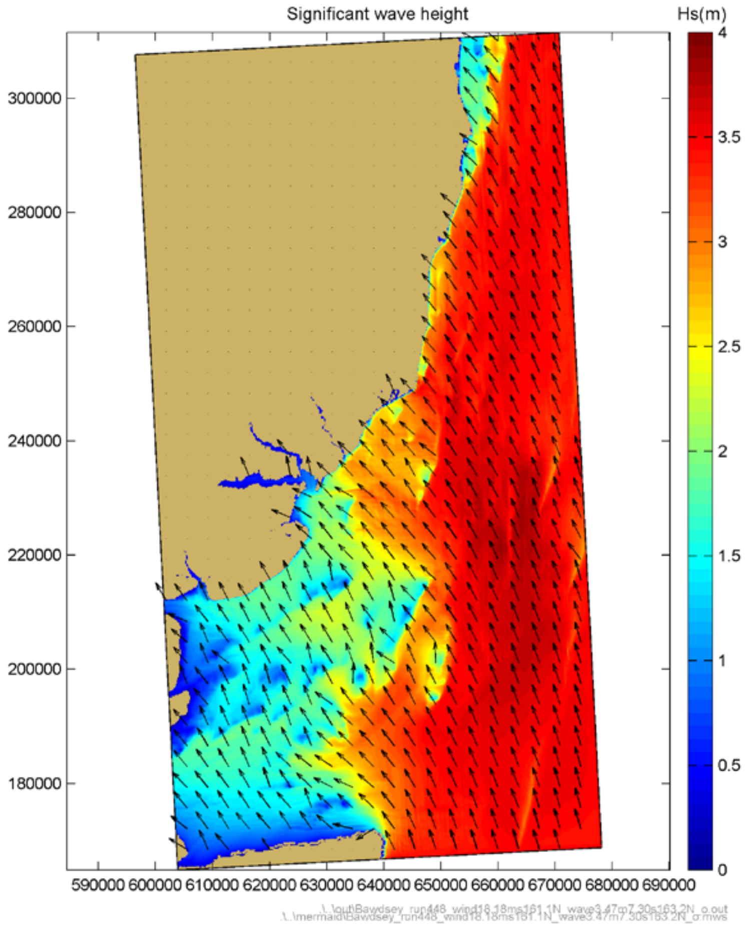

Figure 4.20: SWAN Training Run n#448 - Wave conditions Hs=3.47m, Te=6.34s Dir=163.2N, Wind conditions U=18.18m/s Dir=161N

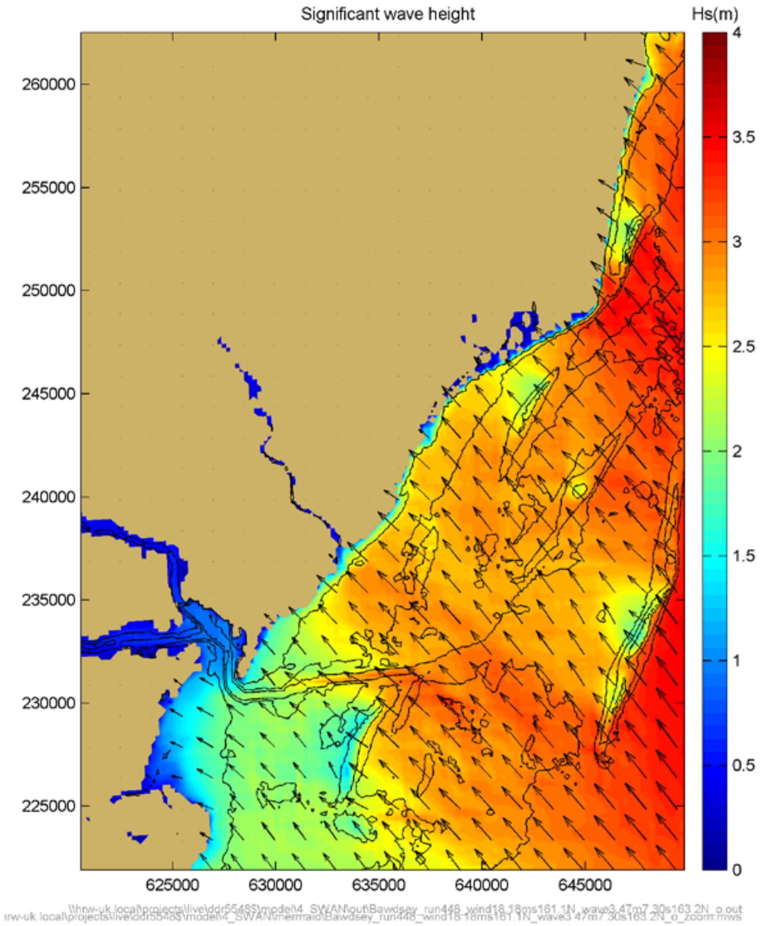

Figure 4.21: SWAN Training Run n#448 - Wave conditions Hs=3.47m, Te=6.34s Dir=163.2N, Wind conditions U=18.18m/s Dir=161N. Close up

4.5.1. Comparison with measured data

Measured wave conditions were available from WaveNet close to the area of interest as summarised in Table 4.4. The SWAN-Emulator was validated against the longest continuous periods of post-recovery data at Bawdsey (October 2006 - September 2009).

Table 4.4: Available nearshore measured wave conditions

Location	Start Date	End Date	Latitude	Longitude	Easting	Northing	Depth
"Bawdsey Cliff AWAC"	03/10/2006	25/09/2009	52.00483	1.440667	636244.9	239634	6 m
"Off Bawdsey Cliff"	21/08/2003	21/08/2004	52.00483	1.440667	636244.9	239634	4.2 m

Source: WaveNet

SWAN Emulator predictions were generated at the location of the 2006-2009 Bawdsey measurements. Figure 4.22 to Figure 4.24 show the time series of peak direction, significant wave height and mean wave period for the measurement period. Figure 4.25 to Figure 4.26 show the corresponding wave roses (based on the measured and predicted data, respectively) and corresponding exceedence curves at Bawdsey. The wave rose plots illustrate the directional distribution of waves whereas the exceedence curves show the percentage of time wave heights are above a given threshold.

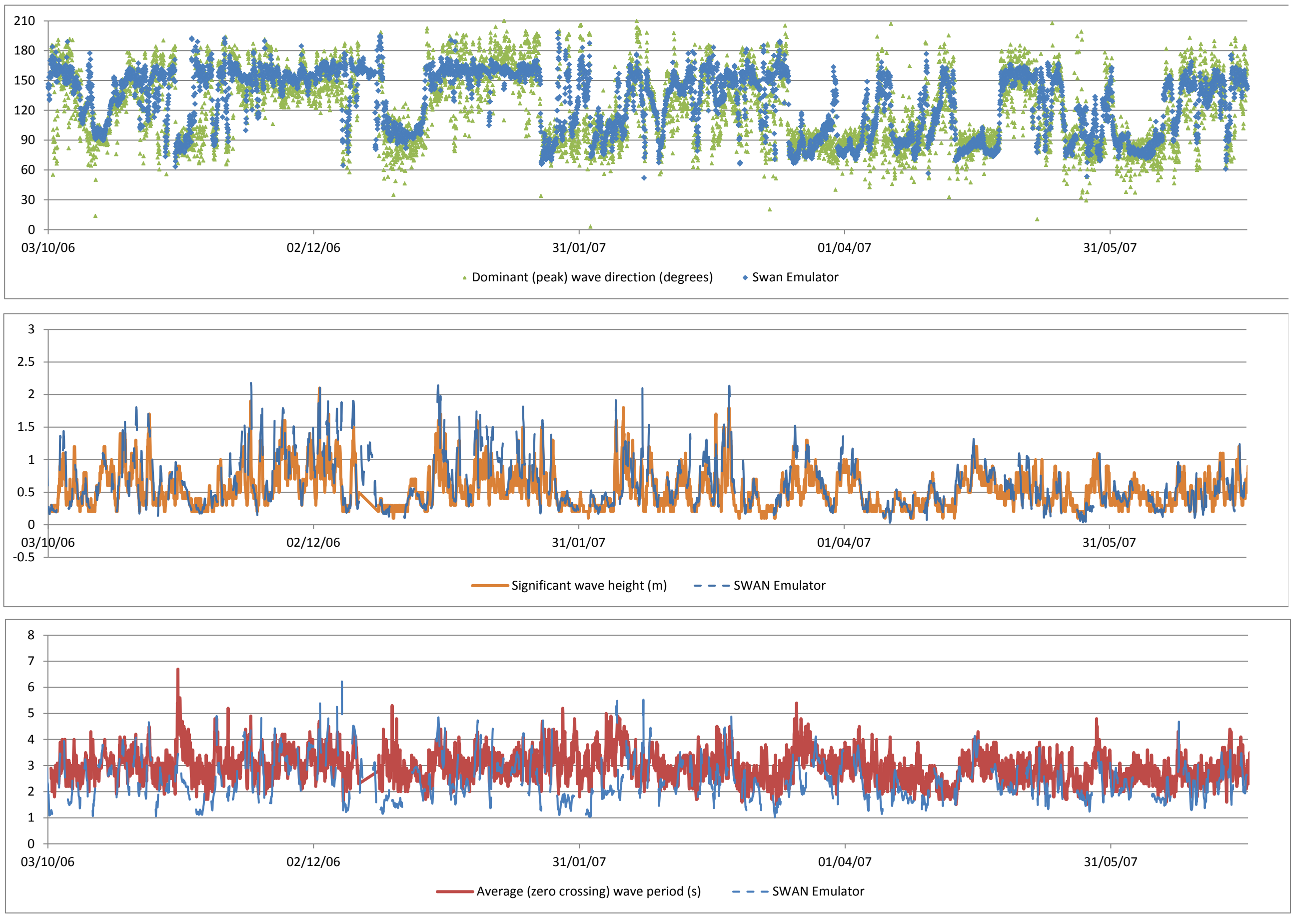

Figure 4.22: Time series of measured and predicted wave conditions at Bawdsey (October 2006-June2007)

Source: WaveNet and HR Wallingford

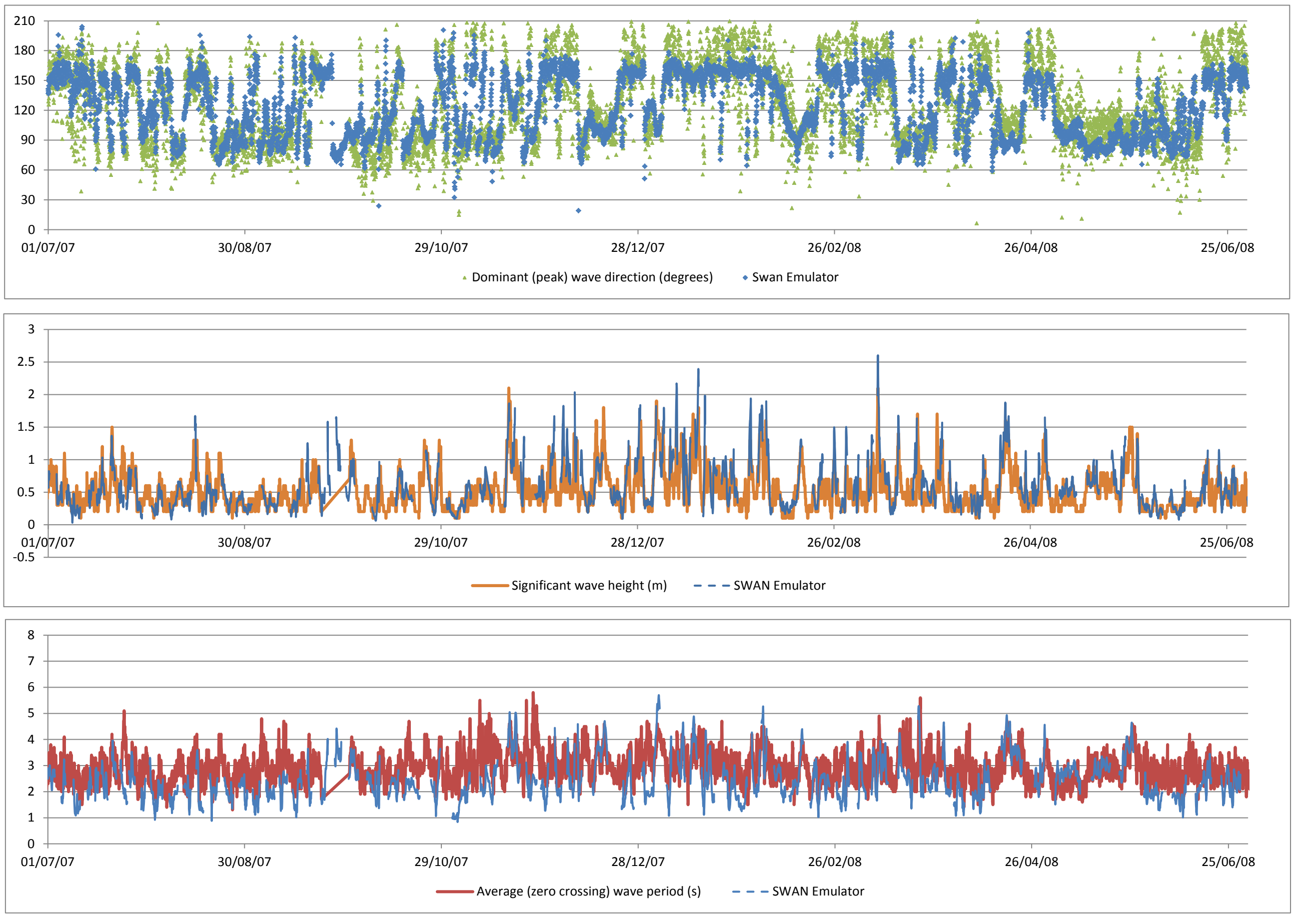

Figure 4.23: Time series of measured and predicted wave conditions at Bawdsey (July 2007-June2008)

Source: WaveNet and HR Wallingford

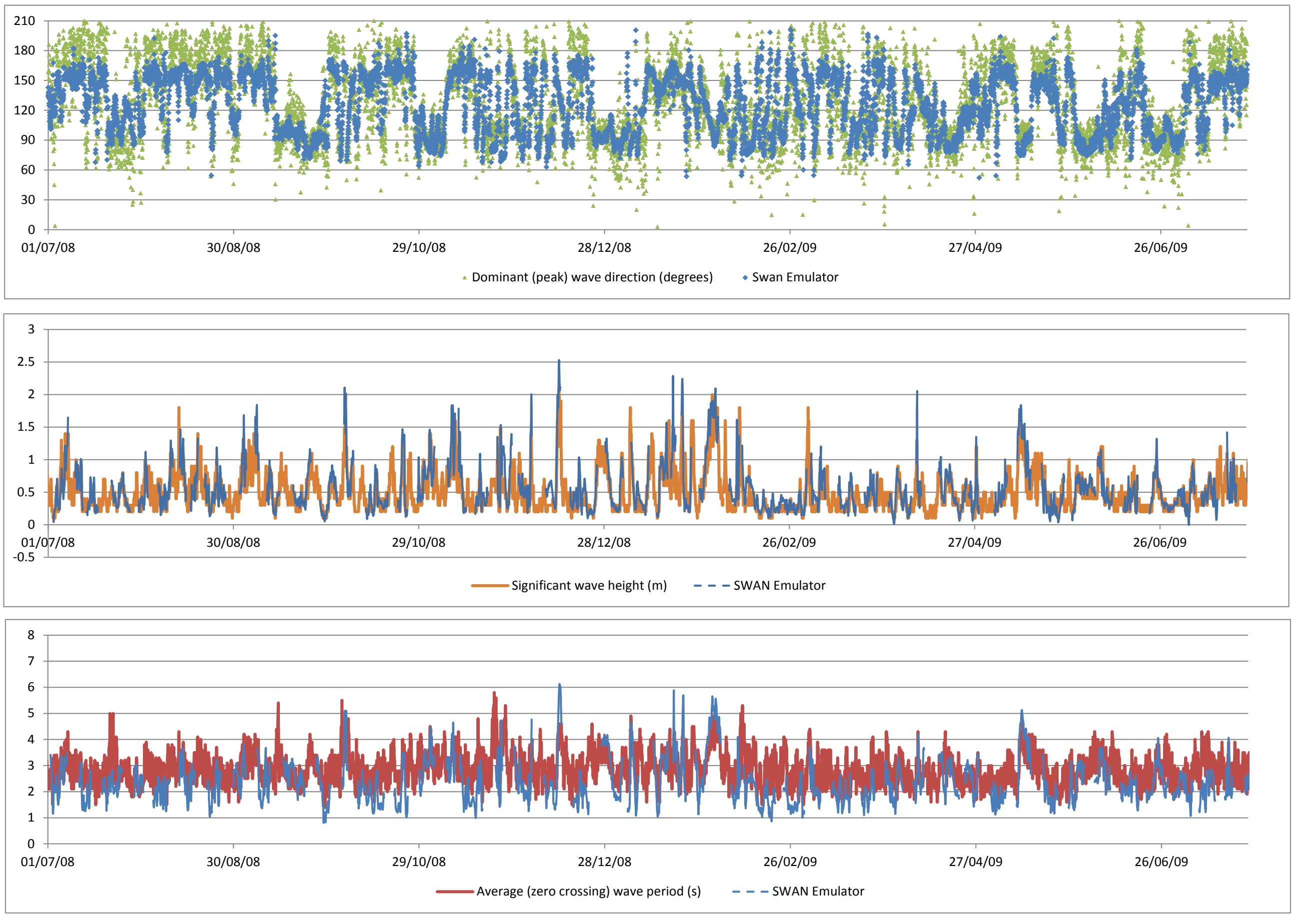

Figure 4.24: Time series of measured and predicted wave conditions at Bawdsey (July 2008-June2009)

Source: WaveNet and HR Wallingford

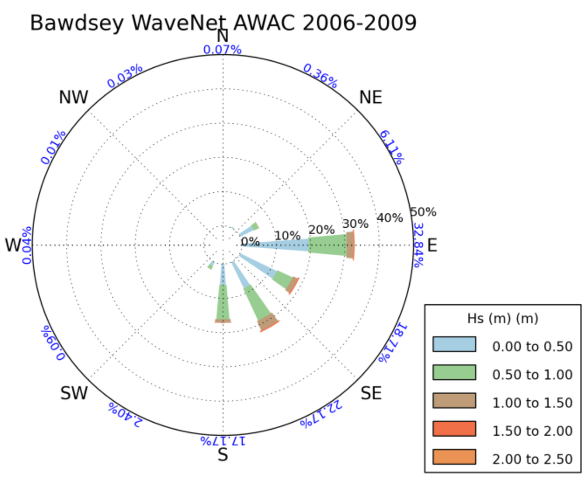

Figure 4.25: Wave Rose: Measured at Bawdsey

Source: WaveNet

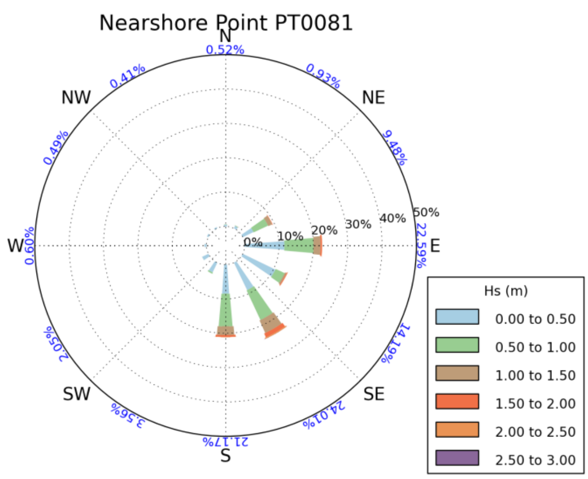

Figure 4.26: Wave Rose: Predicted at Bawdsey

Source: SWAN-Emulator

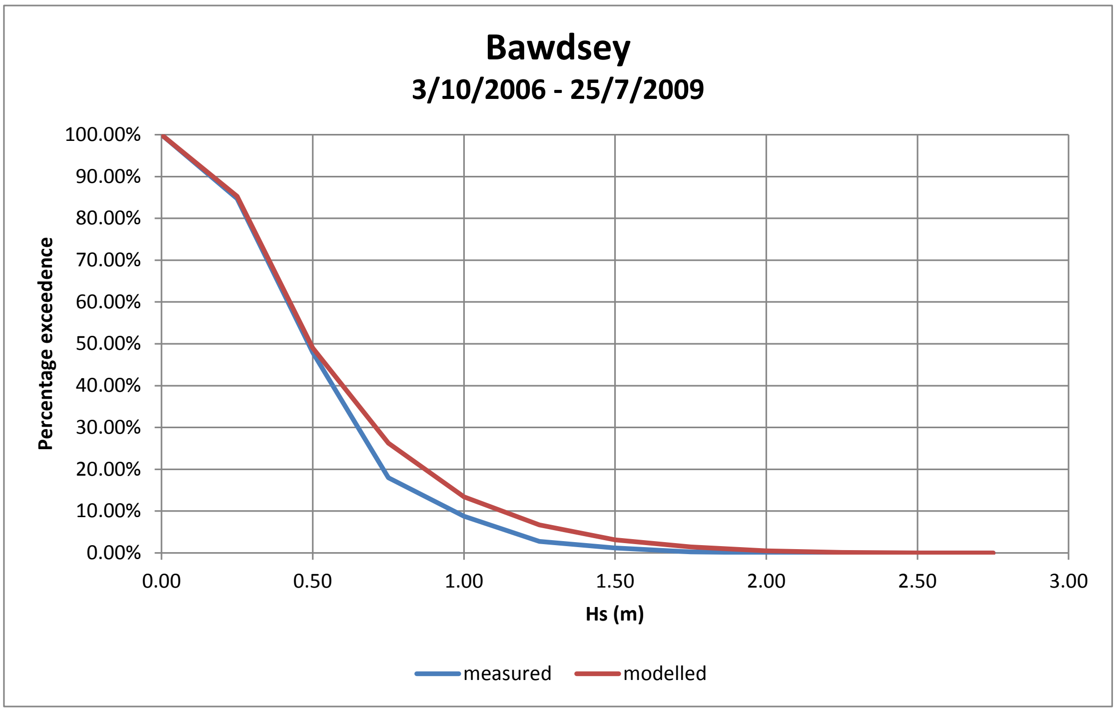

Figure 4.27: Significant wave height exceedence curve at Bawdsey

Source: HR Wallingford SWAN model

The time-series plots show that the general characteristics of the wave directions are reproduced by the model, but that the measurements have a wider range of directions than those predicted. These plots also show that the predicted significant wave heights are in reasonable agreement with the measurements, but the mean periods predicted by the model are, in general, lower than the measured mean periods.

The wave exceedence curves show that SWAN-Emulator predictions are in reasonably good agreement with the corresponding curves from the measured data, with the model wave heights (Hs) slightly higher than the measured wave heights. The wave rose plots shows that the general directional distribution in wave conditions is represented reasonably well, but both the measurements and predictions show a wide spread of directions.

Although the validation results are considered acceptable, this validation has proved difficult. Looking at the time-series of model vs measured wave heights show that there is good agreement in the sequencing of events, but that the model tends to overestimate the wave height and underestimates the periods.

Although the general methodology used for deriving the inshore wave conditions is well established, there are several reasons expected to contribute to the observed discrepancies between the predictions and measurements. Most of these reasons relate to the input conditions to the SWAN model but some of them are related to the measurements. A summary of these reasons follows:

- Possible errors in the offshore waves derived from the Met Office, which are used as input conditions to our methodology. In the previous State of the Nation study for the Environment Agency, a comparison made between the full measured time-series at West Gabbard the closest point to our offshore point, and the offshore point, showed a scatter index of 0.24.
- Wave conditions at a single offshore Met Office point have been applied along the eastern boundary of the model, i.e. no account has been taken of spatial variability in wave conditions along the offshore

boundary of the SWAN model. Just a single wave point is normally used in our wave studies and usually gives acceptable results. Because of the character of the wave conditions offshore from this coastline, a possible improvement to the wave modelling might have been to use predicted wave conditions than one offshore location to simulate how these vary along the boundary of the SWAN model. However, as explained later, this possible expensive and time-consuming extension would not have improved the prediction of future beach changes which will depend on unpredictable weather conditions.

- Discrepancies in the bathymetry between the survey dates and the measurement campaigns. While the model is based on the most up to date bathymetry available, this may still differ from the actual seabed bathymetry at the time of the wave measurements.
- Errors in the measurements e.g. due to attenuation or sampling rates.
- Errors in the location of the predicted values. The wave buoy location is given both in terms of the coordinates and the water depth at which they are deployed. Several points in the model around the coordinates and the depth have been extracted for the comparison with the results, as no one point in our model matches both.

There are several other phenomena that we do not think have an influence in the validation, such as:

- Although the bathymetry in the area is quite variable because of the banks and only one bathymetry has been used for the derivation of the 35 years of inshore data, we do not think this is a major issue as it has been seen that the effect of the refraction is more important than the attenuation by the banks themselves, see examples of results in Figure 4.19 and Figure 4.21. The outer banks have only a localised effect on the waves. Banks and shoals close to the coast might have a more important role, but as was seen in Section 3.5, the uncertainty regarding these changes is very high. Wave refraction processes offshore of this part of the coastline are a very important as offshore waves approach the coastline very obliquely (see Figure 4.3) the main waves being from the N or NE or from the SW.
- Although in places like the south of England, it has been proven that the wave bimodality (separation of the incoming wave spectra into wind sea and swell) can play a very important role in the propagation of the waves inshore and its interpretation, this area has little swell as the fetches are not that long.

In the light of these reasons, the validation was considered acceptable. Some of these deficiencies can be mitigated during the calibration the beach plan-shape modelling. For example although the wave model seemed to overestimate the nearshore wave heights, there is a parameter in the longshore transport formulation that during the calibration of the plan-shape model that can compensate for this discrepancy.

5. Beach plan-shape modelling

5.1. Methodology

In order to assess the potential long term evolution of the beach plan-shape, the shoreline has been numerically modelled with the one-line model Beachplan.

Beachplan is a state-of-the art model which simulates the evolution of the plan-shape of a beach due to variations in longshore drift rates, which are evaluated using a modified CERC formula. The model has been designed as a tool for understanding the behaviour of a coast and the impact of engineering works upon it and is ideally suited to assessing the shoreline response to beach control structures and other management activities such as recycling, renourishment or by-passing.

Beachplan was developed at HR Wallingford over 40 years ago and, as a result of its regular use around the world, numerous developments and improvements to the model have been made during this period. Further details of Beachplan are provided in Appendix E.

Before using a model to predict the future evolution of a beach, and in order to ensure the correct model parameters have been used, it is important to first demonstrate that the model can reproduce how that beach has evolved previously, a process known as model calibration. This calibration requires the model to predict the shoreline orientation correctly and reproduce the observed temporal variations of the shoreline. This calibration procedure is explained in Section 5.3.

Having calibrated the baseline condition, the model is then used to examine the possible long term development of the beach without any further intervention using one of the long term synthetic nearshore wave climates. The derivation of these wave time series and future predictions are covered in Section 5.4 and 5.5, respectively.

There is an intermediate step, between the derivation of the inshore waves and the beach plan-shape model, usually done in conjunction with the calibration of the shoreline model, which is the derivation of the longshore drifts along the frontage, reported in Section 5.2. Although this derivation of the longshore drifts does not feed the shoreline evolution model directly, it helps interpret the drift patterns in the area, as well as the variability, seasonal and annual, of such longshore drifts, especially as it is done for the whole nearshore wave time series. Calculating the net longshore transport rate and how it varies from year to year is also an important first step in assessing possible intervention measures such as shingle recycling or beach recharge to counter problems caused by beach erosion.

5.2. Potential net and gross drift rates along the study frontage

To support the beach plan-shape modelling, annual longshore drift rates along the shoreline have been quantified using a simple model named DRCALC (capability statement given in Appendix F), for the nearshore wave points described in Section 4.4 and given in Figure 5.1. DRCALC calculates the longshore drift rate using the CERC formulation, the same formulation used in Beachplan, but undertakes if for a fixed point along the beach and a constant orientation of such point along the beach (so that the changes in the shoreline are not updated). Although simplistic, the calculations of these drift rates provide a useful way of assessing how the drift rates vary spatially along the frontage, due solely to the nearshore wave climate at that location and a fixed local shoreline orientation. It also enables temporal variations to be examined, e.g. how the gross and net drift may vary between different years and seasons. The drift rates calculated by

DRCALC are considered as potential drift rates, in so far as these are the rates expected to occur on an open beach where there is no limit to the sediment available for transport. In calculating this upper-bound 'potential' drift rate, the model first refracts and shoals each wave condition the short distance from the wave prediction point in to its breaking point using locally parallel contours. The CERC formula is then used to predict the potential drift from the breaking wave height and direction. These individual values of drift are summed to give both gross and net annual drift rates. In the present case, we have used the CERC formulation using coefficients suitable for the shingle beaches near East Lane, Bawdsey. The value for the sediment transport calibration parameter, K1, is 0.07, which is the same as has been used in the beach plan-shape modelling described later. For the same wave condition, a shingle beach will have a substantially lower transport rate than that along a sandy beach.

Table 5.1 presents the results of the DRCALC model giving both the net and gross potential drift over the 35 years from 1981 to 2015 at various locations along the study frontage. The positions of these locations, superimposed on the bathymetry used within this study are shown in Figure 5.1.

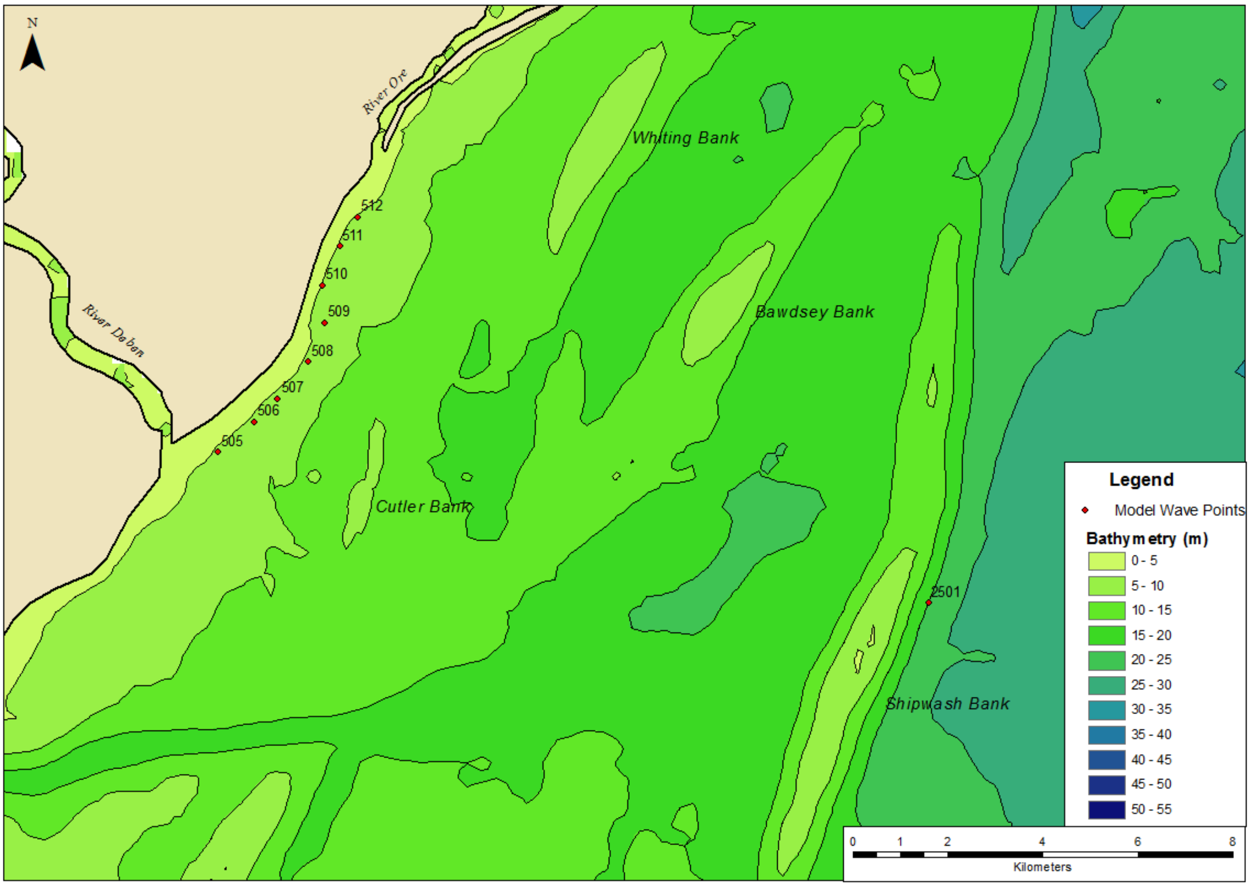

Figure 5.1: Location of the nearshore points with the bathymetry contours superimposed

Source: HR Wallingford/Seazone

The main characteristic of this site is that the gross drifts are very high, of the order of 86,000 to 133,000 m^3/year, mainly due to the strong bimodality (i.e. having two main and widely separated wave directions offshore) of the wave climate. In contrast, the net drift rate is modest, of the order of 10,000 to 45,000 m^3/year. At all but the Bawdsey Manor location (Point 506), the net drift is predicted to be to the North.

Table 5.1: Average annual drifts at each nearshore point

Point	Shore normal (°N)	Drift to North (m^3/yr)	Drift to South (m^3/yr)	Net drift (m^3/yr)	Gross drift (m^3/yr)
Point 512 (S of Shingle Street)	128	66,200 (16,400)	-39,900 (17,200)	26,300 (27,600)	106,100 (19,200)
Point 511	110	78,000 (18,800)	-32,900 (14,400)	45,000 (27,400)	110,900 (19,400)
Point 510	109	65,100 (15,300)	-35,900 (14,800)	29,200 (24,900)	100,900 (17,000)
Point 509 (East Lane)	108	79,700 (18,700)	-45,700 (18,000)	34,000 (30,600)	125,500 (20,300)
Point 508	128	76,100 (18,200)	-57,500 (22,700)	18,700 (35,200)	133,600 (24,300)
Point 507	133	76,700 (18,400)	-53,500 (24,200)	23,200 (34,000)	130,100 (23,500)
Point 506	138	65,500 (15,900	-48,900 (20,600)	16,600 (30,200)	114,400 (21,100)
Point 505 (Bawdsey Manor)	150	37,600 (8,900)	-48,300 (18,100)	-10,700 (22,900)	86,000 (17,200)

Note Values in parenthesis give the standard deviation of the annual drifts.

It is important to note that the standard deviations of the annual drift rates are very high, of the order of 20,000 m^3/year. This reflects how variable the drift rates are from year to year. This is clearly seen when plotting the variation of the annual net drift in time, as shown in Figure 5.2 for Point 507. (Similar graphs have been provided for all of the points in Appendix G). In this figure the drift to the North is shown in blue and the drift to the South in red; the resulting net drift is shown by the black line. The average and standard deviation of the values are shown in the last two columns, i.e. following the values for year 2015.

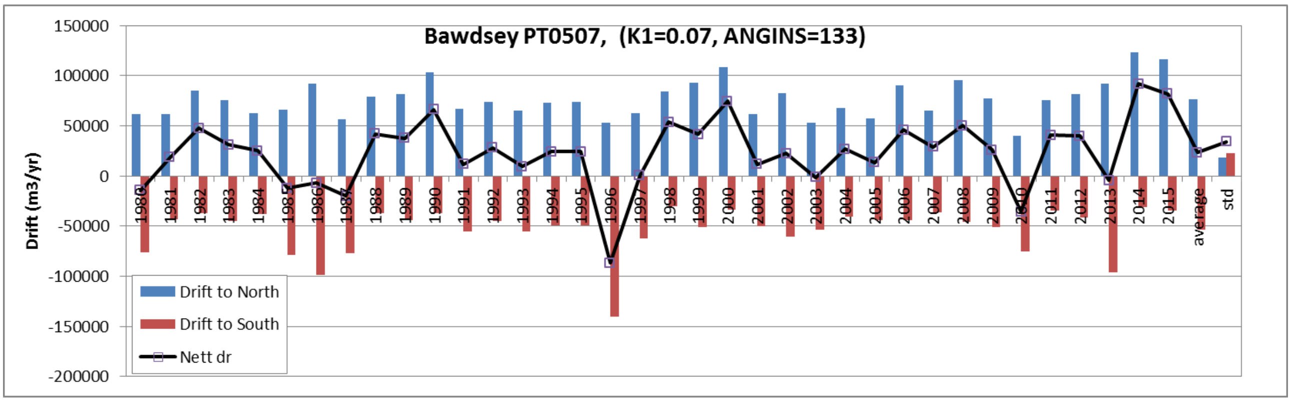

Figure 5.2: Potential longshore drift from 1980 to 2015. Point 507

The high annual variability can be easily appreciated in this graph. Note that for this point, in particular, the southerly drift seems to be smaller and generally more consistent than that to the north, with a mode around the 40,000 m^3/year. However, in six years of the time series, the southerly drift is considerably bigger, about 75,000 to 100,000 m^3/year and in one year it goes up to 140,000 m^3/year. The northerly drift at this position seems to have more of a highly variable pattern, where the values oscillate between about 50,000 to 100,000 m^3/year. As a result, the annual net drift is very variable and mainly to the north, although on those seven years with exceptionally high southerly drifts, the drift is reversed and the net drift is to the South.

An example of the seasonal variability of the longshore drift is given in Figure 5.3. In this plot, the monthly contributions to the annual drift are plotted per year. Unsurprisingly, the most important months in terms of longshore drift are January to March and November to December, although it is seen how some months in some years in April or even June sometimes make a considerable contribution to the drift.

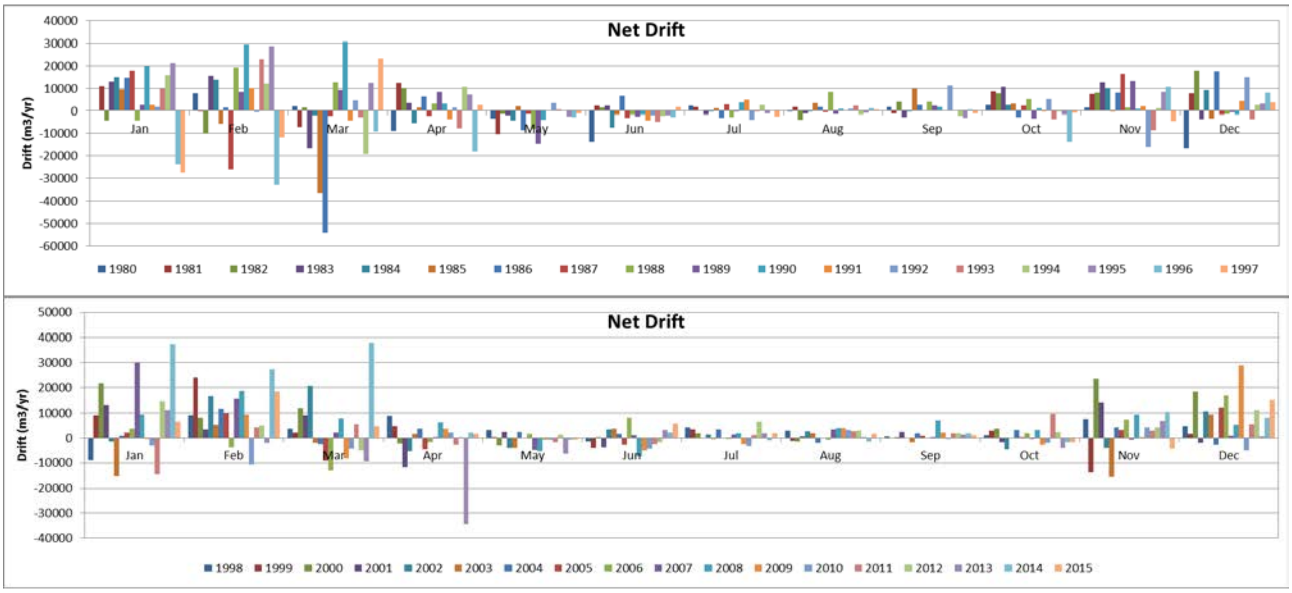

Figure 5.3: Monthly variation in gross and net drift at Point PT0507 (+ve = northwards, -ve = southwards)

The variability alongshore of the net drift and its scatter is easily seen in Figure 5.4. The net drift seems to reduce slightly going southwards from Hollesley Bay towards Bawdsey Manor. To the North of East Lane the net drift is mostly to the North.

For about half of the years between 1981 and 2015, the DRCALC results indicate a ‘drift divide’, i.e. where the beach sediment moves away in both directions (northwards to the north of it and southward to the south). Such locations are often where beach erosion occurs most quickly. Along this frontage, this drift divide is predicted to be at different locations from year to year but it generally is predicted to be somewhere to the south of East Lane, but north of Bawdsey Manor, where the net drift changes to being mostly to the South. This drift divide seems to have been located at the North of East Lane (close to Point 510) in two years (1980, 1987).

For the other half of the years between 1981 and 2015, the DRCALC results indicate no drift divide, generally because the net drift is to the North along the whole frontage. This behaviour is seen in the most extreme years, in term of net drifts, 2014 and 2015, where the drift is very high, in the case of 2014 about double the average value. There have been only two years (1996, 2010) during which the net drift was predicted to be to the South the along the whole frontage. These admittedly simple calculations therefore tend to support the view of Professor Ken Pye regarding beach sediment north of East Lane being supplied by erosion of the cliffs further south and to oppose the view of Professor Steers who believed the net drift from Shingle Street to the mouth of the Deben was generally southwards (see the discussion in Section 2.2.4 above). Note however that the latter view would have been based on both a rather different coastline and potentially a different wave climate to that considered in this study.

Figure 5.5 and Figure 5.6 show similar graphs to Figure 5.4 but for the southerly and northerly drifts, respectively. The southerly drifts, Figure 5.5, seem to vary with no particular trend alongshore up until the last point (505 at Bawdsey Manor), where the drift always seem to get smaller, due mainly to the change of shoreline angle. The northerly drifts, Figure 5.6, follow a different pattern, reducing value from Point 511 to Point 508 (just South of East Lane) and from there on until Bawdsey Manor, increasing slightly, but never to the values a Point 512 or 511.

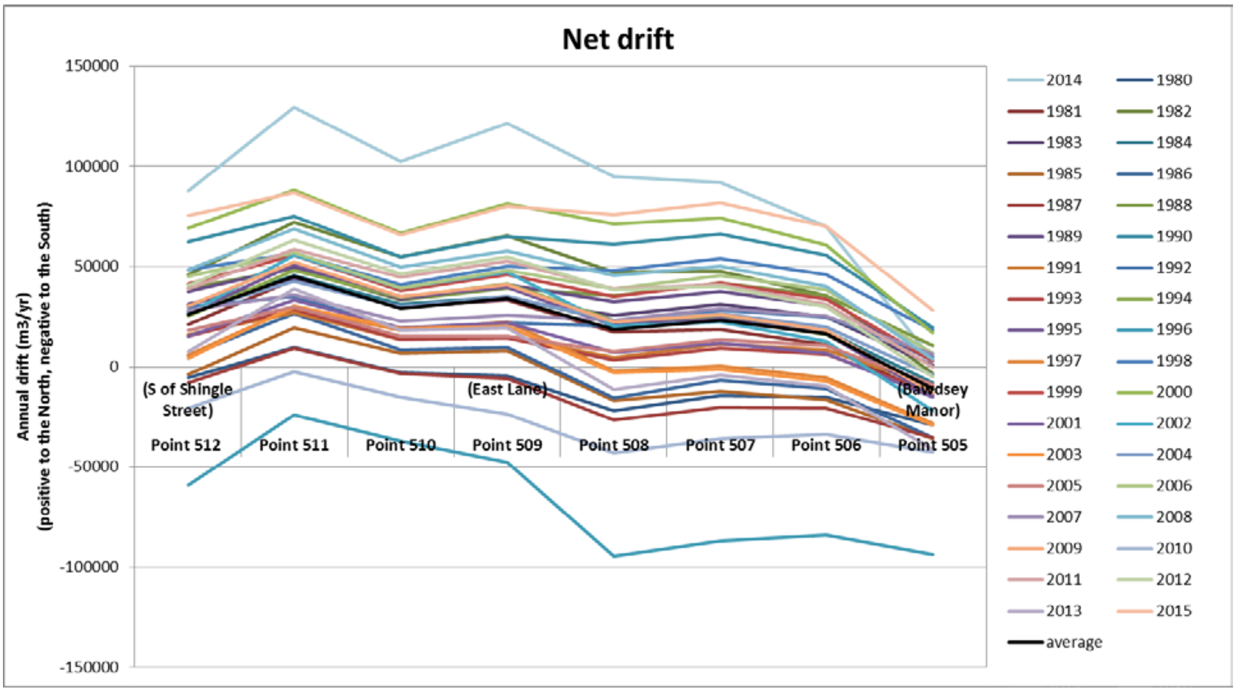

Figure 5.4: Variability alongshore of the yearly net drifts

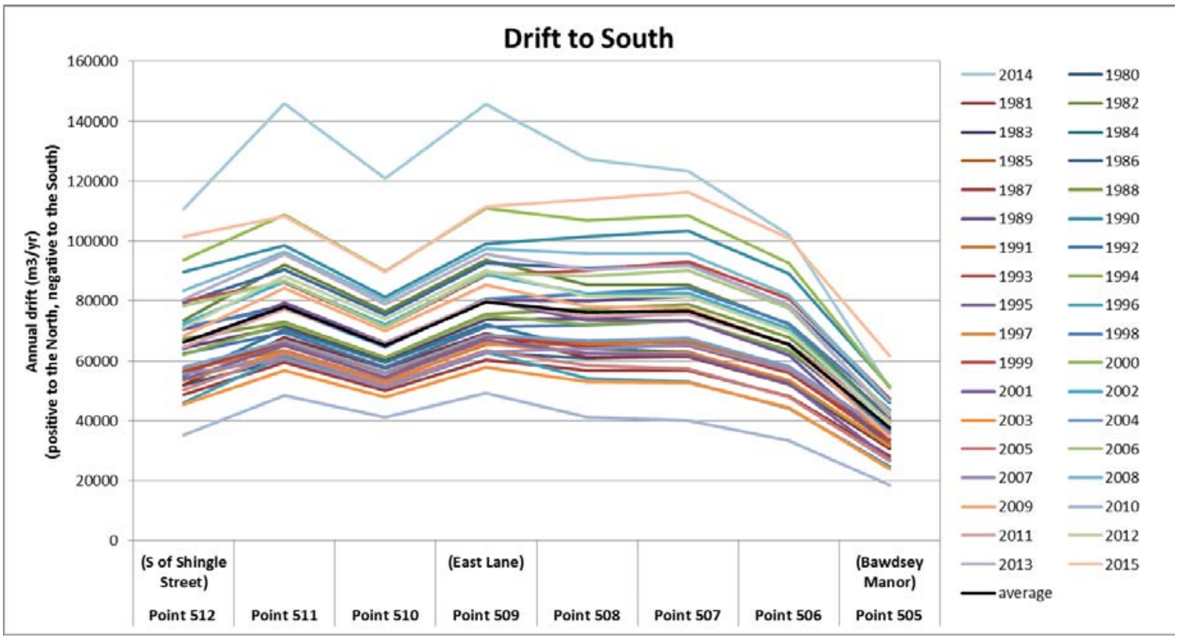

Figure 5.5: Variability alongshore of the yearly drift to the South

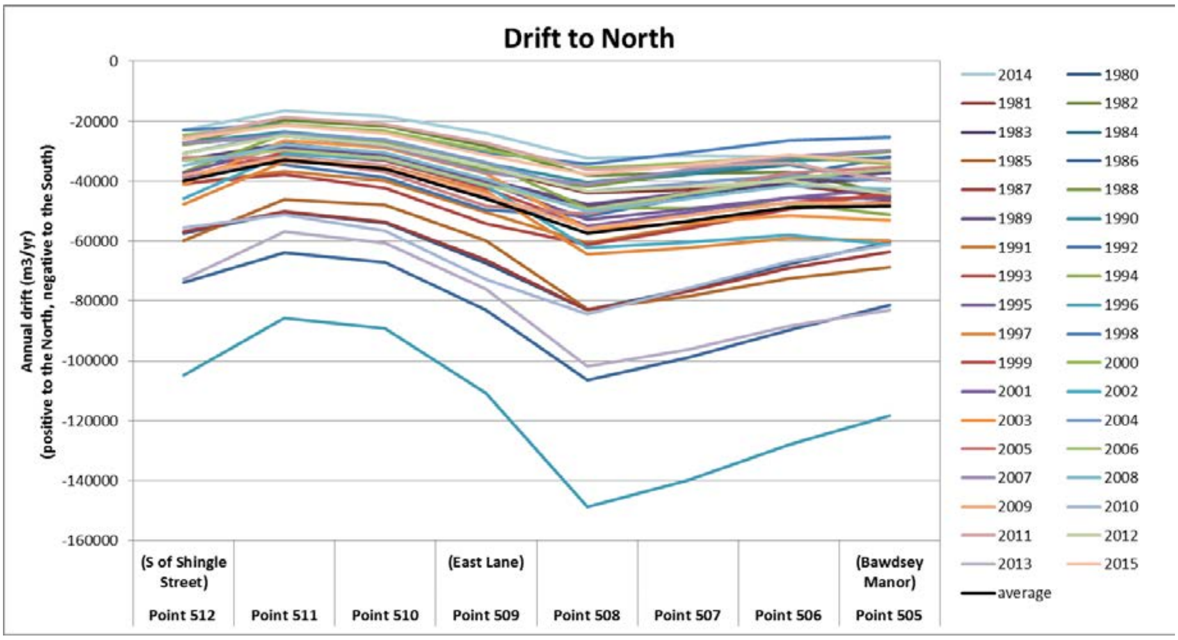

Figure 5.6: Variability alongshore of the yearly drift to the North

5.2.1. Comparison between drift rates and the North Atlantic oscillation

Previous studies have linked events around the UK during the most severe winters with the North Athlantic Oscillation (NAO). The NAO is a measure on how the atmospheric pressure changes between the northern and central latitudes[1] (frequently measured at Iceland and Azores) and would intuitively affect the waves on the western side of the UK although perhaps it would be less expected in Suffolk. However, we have found that there seems to be a correlation between the net drift at a given point, in this case PT0507, and the NAO, as depicted in Figure 5.7.

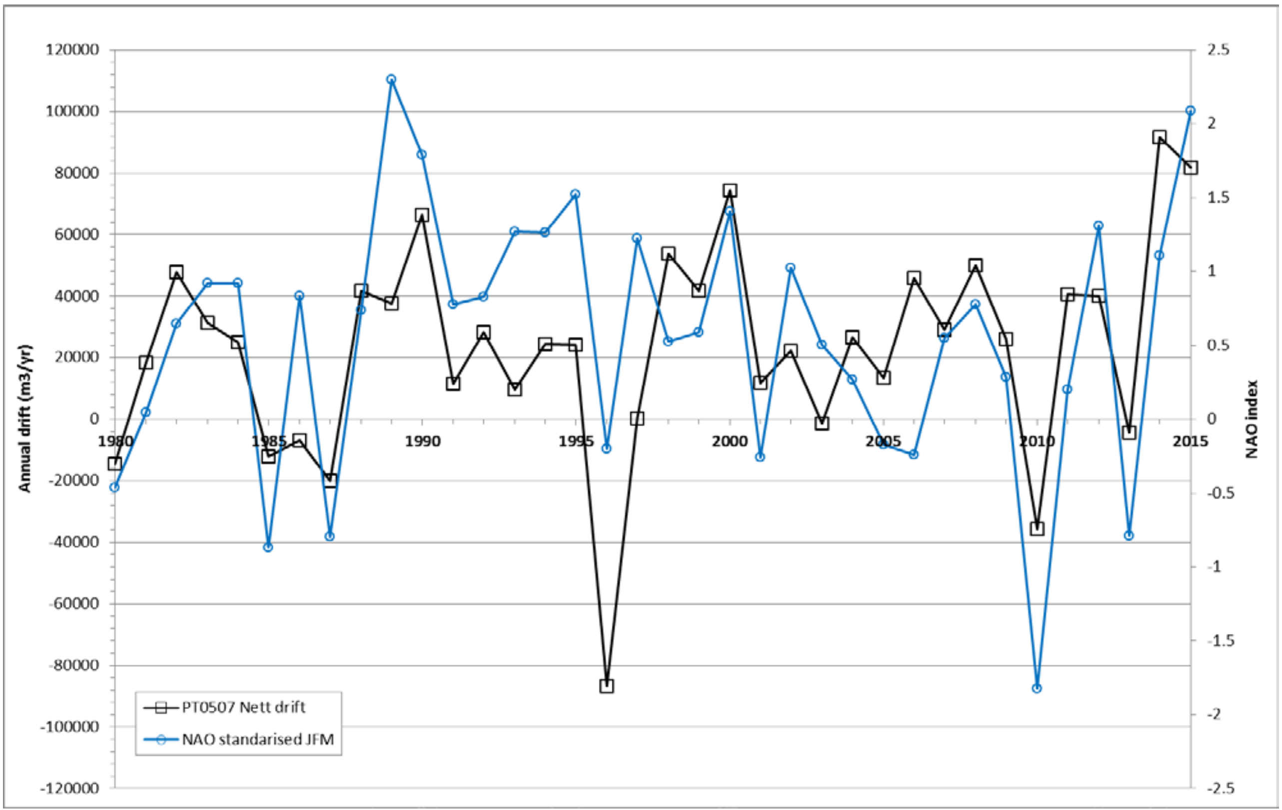

Figure 5.7: Comparison between net drift and NAO index

Source: NAO standardised JFM index: from NOAA (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/JFM_season_nao_index.shtml)

This graph shows how years where the NAO index is negative coincide with years with a southerly net drift (as the waves from the NE seem to prevail over the S and SE waves), and years where the NAO index is positive coincide with years with a northerly net drift (where the waves from the S and SE prevail over those from the NE).

[1] More information about NAO can be found on the Met Office webpage: http://www.metoffice.gov.uk/learning/learn-about-the-weather/north-atlantic-oscillation.

5.3. Calibration of the beach plan-shape numerical model

While the calculations of drift rates using DRCALC are interesting, they can be criticised for a number of reasons. Firstly they assume that there has always been sufficient shingle available to be transported by the waves, and in many cases especially below the low tide mark, this has not always been the case. Secondly, no account is taken in DRCALC of changes in the orientation of the beach during the 35 years for which the calculations were carried out; this too as patently not been the case especially near East Lane, Bawdsey.

A better understanding of how and why changes in beach widths have occurred along this stretch of coastline can be obtained by using a more sophisticated computer model that takes into account how the drift rates at any location and time are influenced by changes in the beach width (and hence the amount of shingle available to be transported along the coast). This is the reason for using our Beachplan model to try to reproduce past changes in the beaches either side of East Lane and then to predict how these beaches might evolve in the future.

For the calibration of this beach plan-shape numerical model, several parameters of the model, together with input conditions such as which waves are chosen to be representative of the area, are modified in an orderly manner in order to tune the model to represent measured shoreline changes.

Calibration period

The calibration period should cover a time period of the same order of magnitude as the time period of the required predictions, in our case decades. Also, such calibration period should comprise of a time in which there is concurrent shoreline change data and historical inshore wave data. The available shoreline positions available are given in Figure 3.1 and Figure 3.2 whereas the inshore wave data available, as described in Section 4.4, covers the period between 1980 and 2015. It was therefore concluded that the best calibration period would be from 1999 to 2012, covering 13 years.

Model extent

The Beachplan model was set up to represent the beach either side of East Lane extending from the mouth of the Deben past Bawdsey Manor and the headland at East Lane and on northwards into Hollesley Bay but stopping short of the very complex frontage just south of the mouth of the Ore/Alde. Beachplan uses a local Cartesian coordinate system, using a baseline which reflects the main orientation of the shoreline. Figure 5.8 shows the measured shorelines used in the calibration together with the chosen model baseline and the model chainages. Although the baseline starts at 0 at the apex of Shingle Street 'ness', Beachplan is not able to reproduce this beach feature which results from movements of nearshore sandbanks caused by changes in the estuary entrance channel. Such changes are largely the result of tidal flows rather than just by the wave-driven longshore transport represented in Beachplan. Because of this, the northern end of the model was chosen to be to the south of the 'ness' at Shingle Street where the effects of these nearshore banks and the tidal currents are less noticeable, i.e. at about the 850m chainage point along the baseline shown in Figure 5.8. Similarly, at the southern end of the model, shoreline changes to the south of Bawdsey Manor are influenced by the sandbanks and tidal flows in the mouth of the Deben; therefore the southern end of the Beachplan model was set at a chainage of about 6100m (see Figure 5.8).

Both boundaries to the north and south are treated as open boundaries in the model, allowing sediment to freely enter or leave the model at both ends of the frontage modelled. The coastline shore-normal angle varies significantly from Shingle Street to East Lane to Bawdsey Manor, ranging from 155º in Hollesley Bay to 175º at East Lane and 130º at the southern end of the model domain, near Bawdsey Manor. The orientation of the model baseline was varied as part of the calibration, the optimum choice being 208.5ºN.

Figure 5.8: Model baseline and measured shoreline positions used in the calibration

Source: UCL (Burningham, pers. com. 2016)

Observed shoreline behaviour in the calibration period

During the calibration phase, the different variables of the model are changed in order to derive the optimum set of variables that would best represent the measured shoreline changes. The box below summarises the changes in the shoreline during the calibration period as revealed by changes in the measured shorelines.

Observed shoreline behaviour in the calibration period (1999 to 2012)

During these thirteen years, the shoreline around Bawdsey has undergone several changes. At the North of Hollesley Bay, Shingle Street seems to have undergone some accretion, whereas at the southern end of the Bay, near East Lane, there has been erosion of up to 45m.

The revetment in East Lane has been extended since 2000 and four different lengths of the seawall are present within this calibration period. At East Lane, beach levels have been falling in front of this structure.

Immediately south of East Lane, there has been a very strong erosion, of up to 80m, decreasing further southward, so at Bawdsey Manor the erosion has been modest, about 5 to 10 m during those 13 years.

Figure 5.9 shows the amount of shoreline retreat between 1999 and 2012, which is what the calibrated Beachplan model should seek to reproduce.

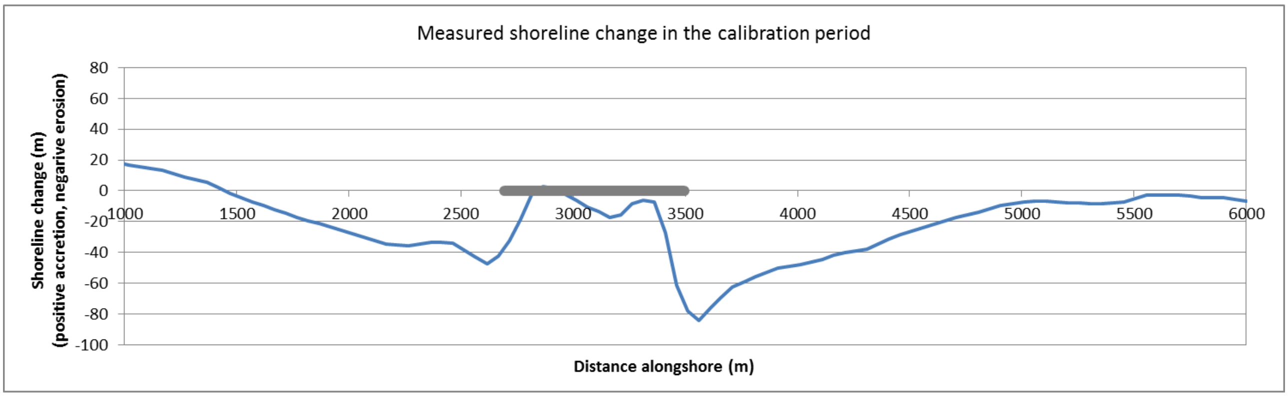

Figure 5.9: Measured shoreline change in the calibration period (1999 to 2012)

Source: Grey area shows approximate extent of the seawall

During the period over which we chose to calibrate our plan-shape model, the length of that seawall was extended, apparently more than once. We did not have information on when this happened or on changes in the seawall profile/ character so our approach was to investigate whether altering the assumed length of the seawall would substantially improve the model calibration; it didn't. The model results close to the ends of the seawall altered as we altered the length of the seawall as expected, but these were only very localised changes that did not affect the overall performance of the model on the evolution of the shoreline.

It is worth pointing out here that our plan-shape modelling indicates the tendency for faster and larger changes in beach width at the end of a seawall, as is often the case. What is unusual at East Lane, and shown well in Figure 5.9 has been the erosion adjacent to both ends of the seawall rather than at just one as normally experienced. This indicates the possible risk of outflanking of the seawall, a problem that cannot be solved, in general, by extending it along the coast although it can be re-located.

Calibration Results

A great amount of time and effort was spent in the model calibration. After a great number of models runs in which the input conditions were varied slightly, the best results obtained are shown in Figure 5.10. Using this calibration we have demonstrated the main features in the beach changes and related to the wave conditions predicted during that period as described in Section 3.6 of this report. Figure 5.10 shows the initial measured position in 1999 in orange, as well as the final measured shoreline position in November 2012 in grey which can be compared to the final shoreline position predicted by the Beachplan model, shown in blue. The model is able to reproduce both the erosion south of East Lane extending towards to Bawdsey Manor and the erosion north of East Lane reasonably well. However, changes within Hollesley Bay area have not been reproduced as well. The model was unable to replicate the amount of erosion towards the southern end of Hollesley Bay while overestimating it within further north within this bay.

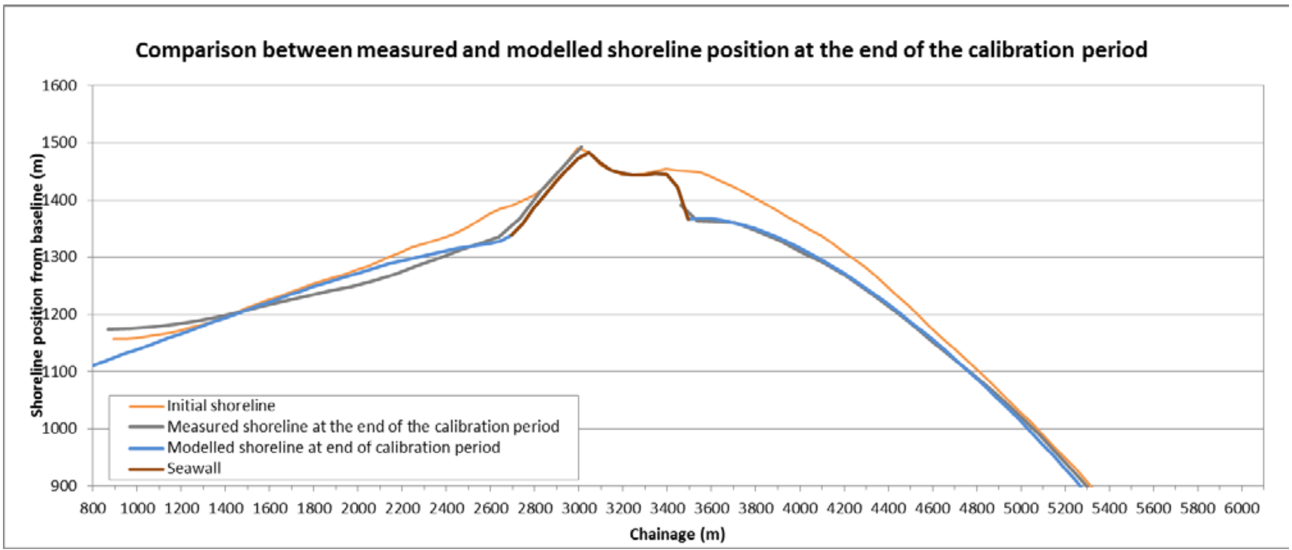

Figure 5.10: Comparison between measured and modelled shoreline positions at the end of the calibration period

The modelled annual drifts during the calibration period are shown in Figure 5.11. This plot shows how the drift at the north of East Lane, in Hollesley Bay, is mostly to the North (except in one year, 2010, where it is to the South), whereas to the south of East Lane, the drift is mostly to the South, increasing further south. In some instances, a drift divide location occurs to the south of East Lane and not close to East Lane itself. (Drift divide locations points tend to be erosion ‘hot-spots’). The Beachplan model therefore has indicated the likely cause of erosion close to East Lane in recent times and the variability in both the location and the timing of where erosion has been worst.

The comparison between Figure 5.11 and Figure 5.4 represent, to a certain degree, the adjustments made to the nearshore wave sequence as part of the calibration in order to improve how the model reproduce the measured changes in the shoreline. Such adjustments are normal in such modelling, reflecting the uncertainties in predicting even offshore wave directions which are only likely to be within ± 10˚ of actual values. It is worth noting that the changes to the nearshore waves carried out for the calibration are in line with the possible bias encountered in the nearshore wave validation discussed in Section 4.5 of this report.

The reason why the changes in Hollesley Bay are not as well reproduced within the model could be due to the variability alongshore of the wave conditions and therefore of the associated drifts (as seen in Figure 5.4), which is not seen in the model (Figure 5.11) where the drift at that end seems to be quite constant. The year-to-year variability is quite high in these modelled drift rates, with northerly drifts ranging from 10,000 to 50,000 m^3/yr and the southerly drifts from about 10,000 to 75,000 m^3/yr.

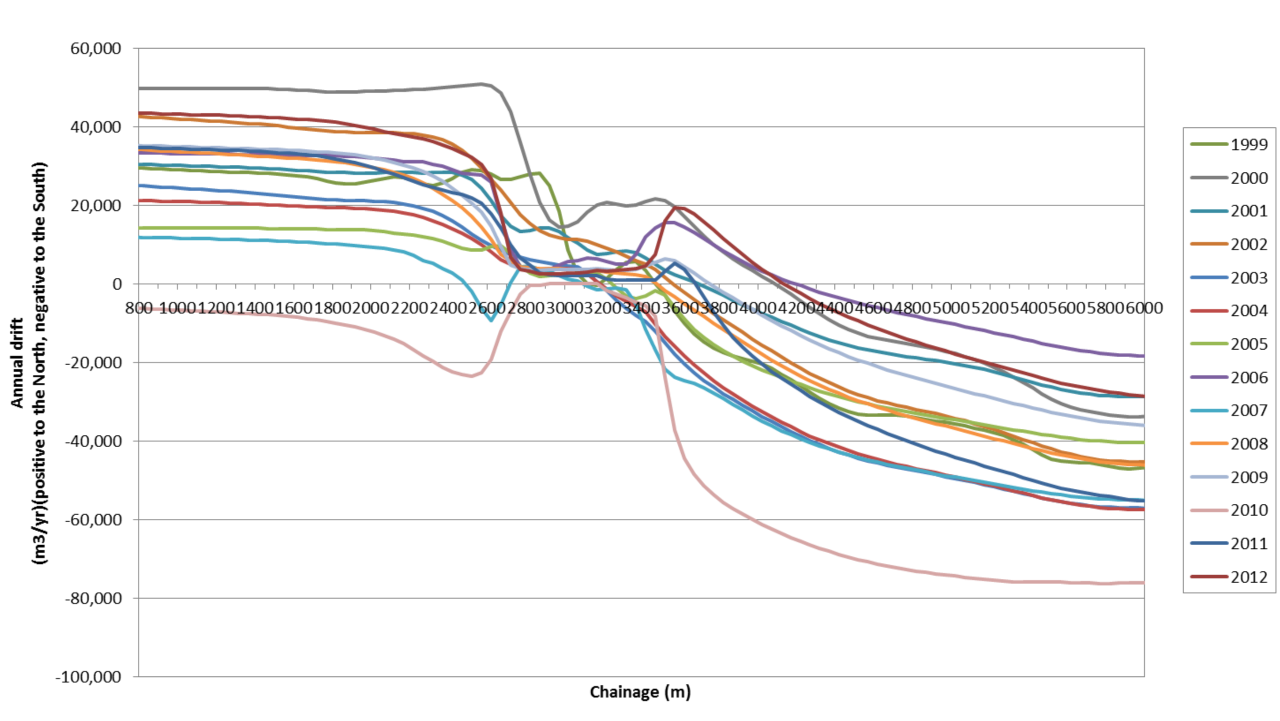

Figure 5.11: Modelled annual drifts during the calibration period

5.4. Development of future wave climates

Shoreline changes are sensitive to the variation of the nearshore climate and how this climate may change in time. As future nearshore wave conditions are impossible to predict, a series of plausible and possible long-term nearshore wave climates have been developed in order to obtain a range of possible shoreline positions for the next 50 years. For the present study, we have developed 40 synthetic nearshore wave time-series of 50 years duration. These have been created from the nearshore wave time-series derived from the baseline nearshore wave modelling but also considering the following:

- Climate Change, both in terms of Sea level Rise (SLR) and change in wave direction; and
- Chronology of the wave conditions, i.e. the sequence in which they occur.

5.4.1. Climate change

Early this year, the Environment Agency issued an update on their recommended allowances for climate change (EA, 2012 now complemented by EA, 2016) that should be demonstrated to have been considered in flood risk analysis studies. This gives higher allowances for sea level rise and therefore it will be the advice used herein together with UKCP09 (Lowe et al, 2009) for the future change predictions in respect to Sea Level Rise (SLR), and in surge, wind and wind climates.

Sea Level Rise

Table 5.2 from EA (2016) gives the yearly sea level allowance for each epoch for the east and south regions. Applying it to our 50 years, it gives about 444mm from 2015 to 2065. Consequently, for our modelling we have considered a SLR of 0.45 m.

Table 5.2: Sea level allowance for each epoch in millimetres (mm) per year

	1990 to 2025	2026 to 2055	2056 to 2085	2086 to 2115
East and south east	4mm/yr	8.5mm/yr	12mm/yr	15mm/yr

Source: EA (2016)

Surge Level

The EA (2012) provides estimates of future storm surge allowances, and UKCP09 gives site specific estimates as illustrated in Figure 5.12.

This shows that for the area of interest for the medium emission rate scenario the 50% percentile skew surge trend is predicted to be negative. For the 95% percentile there a small increase of 1mm/year, but for all intense and purpose it can be considered that there will be no increase in surge level at the site over the next 50 years.

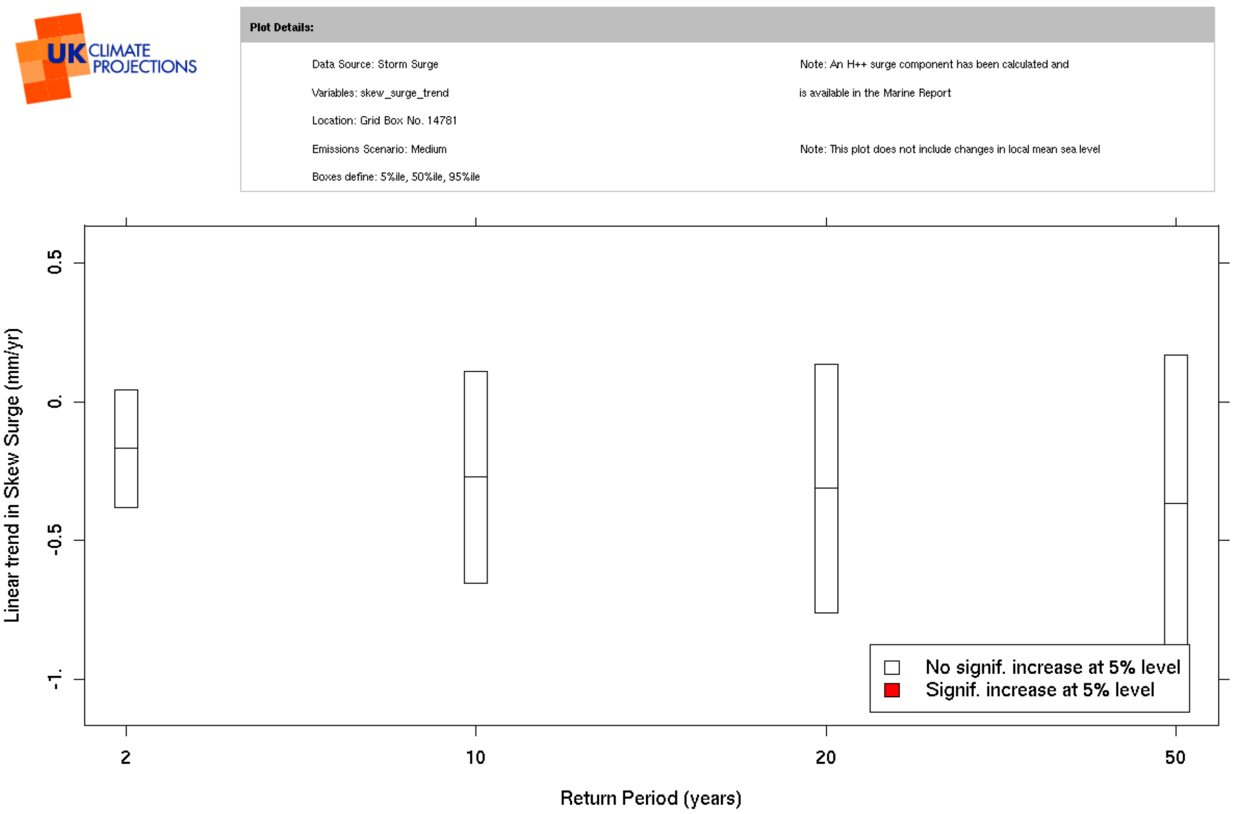

Figure 5.12: Predicted change in surge level

Source: UKCP09

Wind and heights

The EA (2016) updated the allowances of wind and wave heights, recommending a 10% increased offshore wind speed and extreme wave height, with a further increase of 10% in offshore wind speed and extreme wave height for sensitivity testing. However, this was outside the scope of the work carried out within this study, especially as the recommendation came half way through the study.

To incorporate possible effects of climate change, in particular its influence in changing future wave direction, climate change scenarios with SLR have been be applied through the SWAN emulator to derive alternative nearshore wave time-series from which the wave chronology can be constructed. Also, nearshore wave directions have been modified in order to introduce more extreme cases, Section 5.4.3.

5.4.2. Chronology of the wave climate

Along the frontage, the gross and net drift rates vary very substantially, both annually and seasonally, as discussed in Section 5.2. Given that we are looking at the possible long term evolution of the shoreline, the typical seasonal variations within a year are of less concern, and therefore we created 50 year time series by randomly selecting years from the available 35-year inshore time series. In order to examine the influence of the years with more southerly or more northerly wave conditions, the years within the predicted long-term wave sequence were ranked in order, from those resulting in the greatest net transport to the south to those creating the greatest transport to the north (Figure 5.13).

When developing the synthetic time-series, different biases have been applied to the random selection of the annual years that make up the climate. The three bias scenarios chosen are:

- No bias - there is equal chance that any year is selected
- Northerly bias - chances that a northerly net transport year is selected at point PT0507 increased by 3
- Southerly bias - chances that a southerly net transport year is selected at point PT0507 increased by 3.

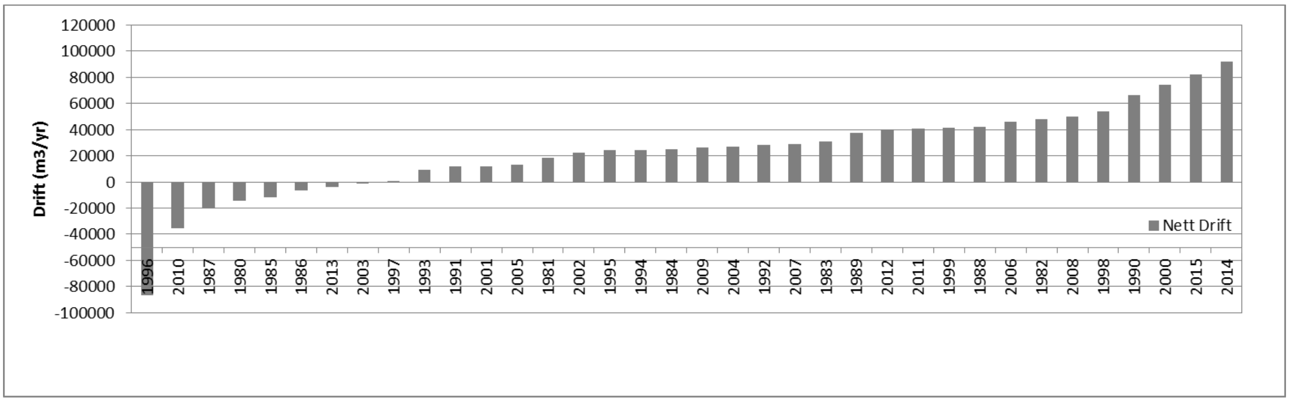

Figure 5.13: Variation in annual net drift arranged from peak southerly to peak northerly

5.4.3. Change in Wave direction

For selected synthetic wave time series, the nearshore wave direction, at each of the wave points used in the modelling, was rotated by a given quantity, 3, 5 or 10 degrees in order to introduce more extreme cases.

5.4.4. Synthetic wave time series

The synthetic times series have been generated using the criteria identified above, namely: an increase of sea level affecting the offshore waves, rotation of the inshore waves and inshore wave sequencing (for each synthetic time-series the individual selected years are chosen at random; where a bias to northerly and southerly transport is applied, the bias has been included by examining and ranking the net transport at wave point PT0507).

For each wave point the nearshore sequencing are constructed using the same annual sequencing of years.

A summary of synthetic wave time series derived in provided in Table 5.3. Where more than one time series is shown in the first column, for example 7-10, the difference between the time series is the randomised selection of each of year from the 35 available years in order to create the 50-year long time series.

Table 5.3: Summary of synthetic wave climates

Time-series	Wave model run	Rotation of the inshore waves	Wave Chronology	Bias of net transport
1	Present Day	+3 degrees	None	None
2	Present Day	+5 degrees	None	None
3	Present Day	+7degrees	None	None
4	Present Day	-3 degrees	None	None
5	Present Day	-5 degrees	None	None
6	Present Day	-7degrees	None	None
7-10 (*)	Present Day	None	Random selection and reordering	None
11-15	Present Day	None	Random selection and reordering	To North
16-20	Present Day	None	Random selection and reordering	To South
21	Present Day + S.L.R of 0.45m	+3 degrees	None	None
22	Present Day + S.L.R of 0.45m	+5 degrees	None	None
23	Present Day + S.L.R of 0.45m	+7degrees	None	None
24	Present Day + S.L.R of 0.45m	-3 degrees	None	None
25	Present Day + S.L.R of 0.45m	-5 degrees	None	None
26	Present Day + S.L.R of 0.45m	-7degrees	None	None
27-30	Present Day + S.L.R of 0.45m	None	Random selection and reordering	None
31-35	Present Day + S.L.R of 0.45m	None	Random selection and reordering	To North
36-40	Present Day + S.L.R of 0.45m	None	Random selection and reordering	To South

Note: Present day – refers to climates using climate with no added SLR.
**The first of these time series, Time series 7, has been named Baseline.*

5.5. Modelling of future beach changes

With the model calibrated for the specific study area, it was then applied to predict possible future changes in shoreline position. This exercise was aimed at identifying what potential changes in the current situation might result from changes in the mean offshore wave direction, changes in the sequencing of wave events or an increase in sea level (relative to the land), all of which could be a consequence of climate change. Our modelling of the future change to the beaches was simplified by assuming there was a sufficient width of beach landward of the 2012 shoreline that it could erode to any extent predicted but retain its character. (This of course is unrealistic but does allow the use of Beachplan to compare and contrast different climatic scenarios and hence assess the possible challenges faced by any proposed beach management scheme).

5.6. Model results

The model has been run for the do-nothing scenario or 'Baseline' case for a total of 50 years. For this modelling, the initial shoreline position has been taken as that of November 2012, as it is the latest one available. All of the other variables remained the same as in the calibration runs.

Each of the time series in Table 5.3 were then used to run the Beachplan model. Results from one of the 'Present Day' wave sequences (Time series 7 in Table 5.3) was selected as the reference baseline for comparing how changes in wave conditions would affect the Beachplan model predictions of shoreline change over 50 years. This wave sequence had no wave rotation and no bias in the sequencing; it was constructed by randomly selecting year by year from the available 35 years of inshore wave climate. The results of this baseline reference are reported in Section 5.6.1.

The model was also run for the rest of the synthetic time series in Table 5.3, the results being presented in Section 5.6.2.

5.6.1. Baseline reference results

A do-nothing scenario was considered, where the initial shoreline of 2012 was left to develop over 50-years (using time series 7 in Table 5.3) with the existing seawall with no other intervention. The results are shown in Figure 5.14 in terms of shoreline position and changes to the initial shoreline. The results show how the beach goes back about 10-20m in 50 years in Hollesley Bay and about 50-100m in the 50 years along Bawdsey cliffs.

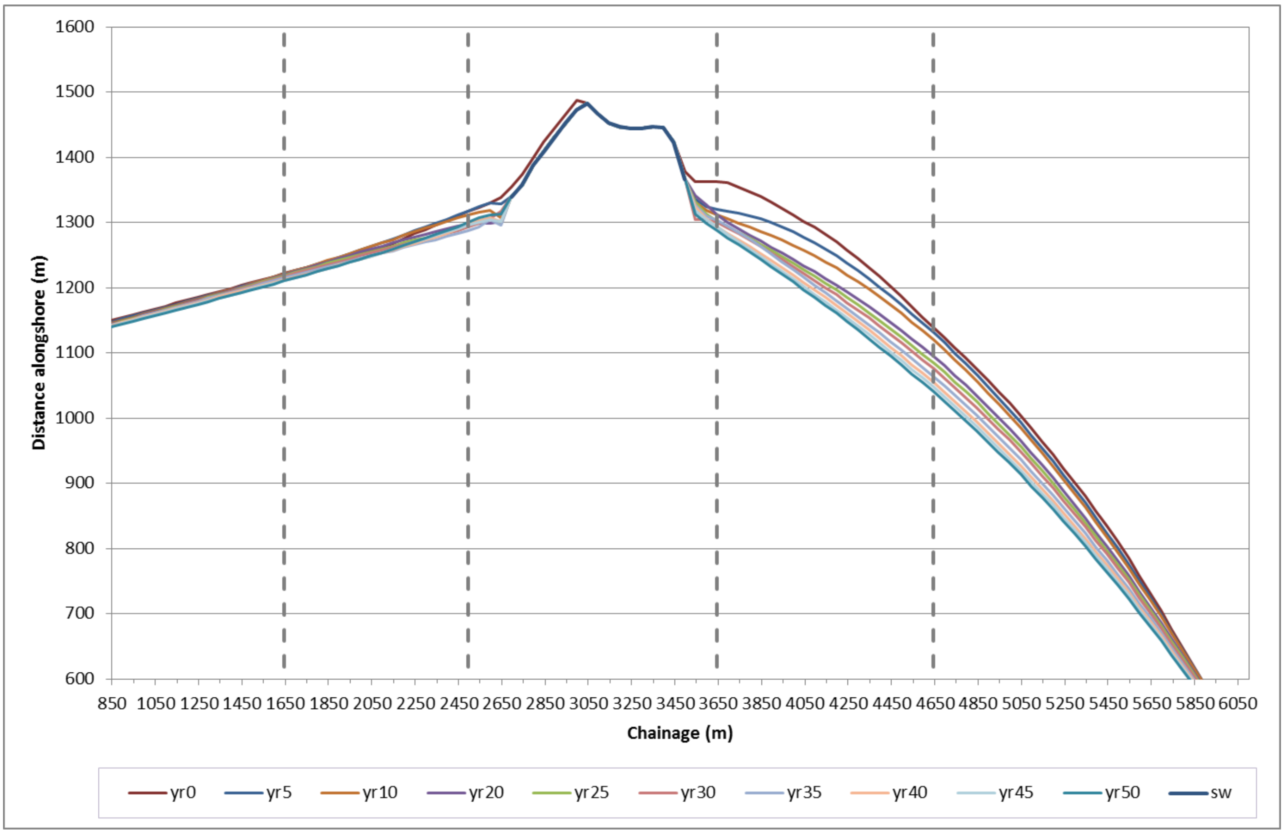

Figure 5.14: Baseline reference case – shoreline evolution

Dashed lines show the location of the transects used in Figure 5.15.

Figure 5.15 shows the evolution in time of four transects, so that the trend at those chainages is easily inferred as well as the variability within the years. This figure shows:

- In Hollesley Bay (Chainage 1645), the modelling results show an erosion of about 10 m in 50 years (0.2 m/yr).
- Just to the north of East Lane (Chainage 2495). This transect seems to be very variable, probably due to the interaction with the nearby seawall, with periods of accretion and erosion with an underlying erosion trend of up to 30 m in 49 years (0.6 m/yr). Surprisingly, in the last year about 30 m of erosion occurred, although this should be considered with caution as could be a spurious result due to an instability of the model or a very extreme year at the end of the sequence.
- To the south of East Lane (Chainage 3645), where there is still an influence of the structures in East Lane, the transect seems to vary with erosion and accretion periods, although the results show an underlying erosion trend of about 70 m in 50 years (1.4 m/yr).
- Along Bawdsey cliffs (Chainage 4645), towards Bawdsey Manor, the erosion seems quite steady with the largest trend of about 100 m in 50 years (2 m/yr).

Different sequencing of the waves will produce a graph similar to this one with regards to the trends, but with different variability within it. The trends will not be exactly the same, as the sequencing will have an impact on the shoreline evolution to a certain degree.

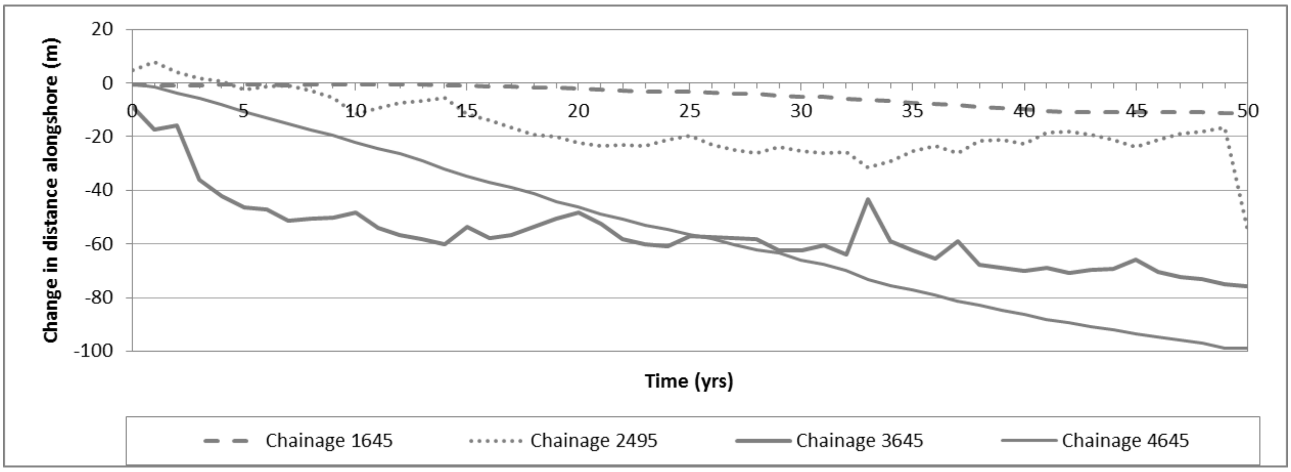

Figure 5.15: Baseline reference case - Time evolution at different transects

The position of the transects is shown in Figure 5.14 as vertical dashed lines.

These future recession rates can be put into context comparing them with the recession rates derived from the topographic beach surveys described in Section 3.4.3 as changes in beach widths. As such, each of our modelling transects has been assigned to a nearby profile and the past measured rates have been compared with the future predicted rates in the table below, Table 5.4. The comparison shows that the predicted trends are within the measured changes, giving confidence in the modelled predictions.

Table 5.4: Comparison between measured historical trends and predicted future trends

Topographic beach survey	Measured trend (1991 to 2015)	Modelling transect	Predicted future trend
SO61	Remarkably stable, i.e. showing little long-term trend but with a reduction prior to and increase after Spring 1998	Chainage 1645 m	Erosion of about 10 m in 50 years (0.2 m/yr)
SO62	Nearly stable prior to the Autumn of 1999 but followed by a steady decline until the Spring of 2013, about 65 m in 17 years (3.8 m/yr)	Chainage 2495 m	Periods of accretion and erosion with an underlying erosion trend of up to 30m in 49 years (0.6 m/yr)
SO64	Stable until early 1998 but then decreasing steadily with a sudden reduction to a minimum in Autumn 2013 of about 70 m in 19 years (4.15 m/yr)	Chainage 3645 m (*This transect is 600 m to the north of the topographic survey*)	Erosion and accretion periods, although an underlying erosion trend of about 70 m in 50 years (1.4 m/yr)
SO65	A slight trend for erosion which has perhaps become slightly larger over the latter part of the period, of about 10 m in 5 years (2 m/yr)	Chainage 4645m	Erosion seems quite steady with the largest trend of about 100 m in 50 years (2 m/yr)

5.6.2. Sensitivity to climate change and wave chronology

The results of the shoreline modelling using the 40 different synthetic time-series described in Section 5.4.4 are presented within Appendix H, the main influence on the beach plan-shape results discussed within this section.

With regards to the three changes in the input time series and their effects in the beach plan-shape evolution results, the main findings are:

Influence of the sea level rise

On its own, the sea level rise does not have much of an effect on shoreline changes. Sea level rise might of course change the vulnerability of the defence structures, but this is outside the remit of this study.

Wave chronology

The main influence of the randomised selection of the years and its sequencing is mainly short term, without affecting the long term evolution substantially. In broad terms, the chronology does not affect the long-term behaviour of the shoreline but it is likely that the beach response immediately north and south of the structures at Bawdsey is more sensitive to this sequencing. Periods of intense drifts will have more impact in these areas than in others, potentially defining them as hot-spots. As such, intervention measures will need to concentrate on these hot-spots.

Influence of wave direction

The effect of the wave direction on the predicted beach changes has been carried out in two ways, which main findings are described herein.

- Firstly, we assumed a uniform change in all wave directions applied to all the points alongshore the model, to represent a substantial shift in the balance between north-easterly and southerly/ south-westerly waves offshore from the Suffolk coastline. Although this is not extremely realistic, these simplified runs show that the change in wave direction rotates the resultant shoreline position, so that those runs where the wave directions have been increased (rotated clockwise) result in less erosion (even accretion sometimes) to the North of East Lane and faster beach erosion along Bawdsey cliffs and towards Bawdsey Manor. For those runs where the wave directions have been decreased (rotated anti-clockwise) the erosion at the North of East Lane increases whereas the erosion along Bawdsey cliffs and towards Bawdsey Manor decreases. Less expected, however, is the result on the drifts: the result of this rotation is greatest along the Bawdsey cliffs frontage, where the drift rates increase by about 50-100%, than along Hollesley Bay where the rotation produced much less variation in the yearly drift rates.
- However, these rotations in the wave climate are not likely to happen, at least not under any prolonged amount of time, and that is why a more realistic way of examining the influence of the wave direction was carried out. This was done by producing a 50-year long synthetic time series by randomly selecting from the available 35 years of inshore data, but introducing a bias towards the selection of the years producing a more northerly drift or a more southerly drift. This way preserves the balance between the northerly and southerly years, which is what has been observed in the past. The prediction of the shoreline changes with these biased wave time series show that the area at the north of East Lane is less strongly affected by variations of the waves towards more N/NE or more SW than the area of the Bawdsey cliffs.

In general, it was found to changes in wave direction have the greatest influence on the predicted beach changes. However, there is no way of predicting with any confidence which way such changes in wave directions may go in the future.

6. Discussion and conclusions

The work completed within this study involved three interrelated tasks, namely a desktop review of past shoreline, profile and seabed changes, a wave assessment to derive a set of nearshore time-series and numerical modelling of shoreline evolution to investigate how the longshore shingle transport and the plan-shape of the beaches are likely to change in the future.

6.1.1. Introduction

These three tasks have proven to be more challenging than usual, reflecting the fact that the waves, coastal processes and longshore drift regime along this frontage are very complex. This has not been helped by the fact that historically and presently there have been and still are, conflicting views in terms of the coastal processes of the area including the sources of sediment, the direction of the sediment transport and the interaction with the nearshore banks. Features such as the mobile 'ness' on the beach at Shingle Street, the movements and changes in the banks and tidal flows in the entrances to the estuaries of the Deben and the Ore/ Alde, the possible effects of offshore banks and changes in the nearshore seabed levels all add to the difficulties in understanding the evolution of the beaches. Moreover, the variations over time in wave conditions, typically arriving from one of two very different directions and both at a substantial angle to the beach normal, contribute in making the understanding and quantifying of coastal processes in this part of Suffolk particularly challenging.

However difficult and lengthy this project has been, it has highlighted several conclusions which that should help inform coastal defence/ management options appraisals for this frontage.

6.1.2. Sources of beach sediments

The local source of beach sediment from the coastal cliffs between East Lane and the Deben has not been emphasised in previous studies. It is concluded in this study that these cliffs and longshore drift from the north past Orford Ness have both provided shingle to the beaches between Shingle Street and the Deben, and could do so again in certain circumstances.

Although some southward transfer of beach sediment from the mobile banks across the mouths of these estuaries does occur episodically, its transport is influenced by tidal flows in and out of the estuaries as well by wave action. These transfers are likely to be strongly influenced by the occasional meandering of the main entrance channels to the Deben and Ore/Alde estuaries and are hence impossible to predict. As a consequence the balance between the gain of shingle from the north and the loss to the south is highly variable and difficult even to measure let alone predict.

The available evidence from surveys of the nearshore seabed does not suggest to us any significant offshore losses of gravel from these beaches, where it would presumably have otherwise resulted in a noticeable accumulation.

6.1.3. Historical coastline changes near East Lane

The most striking shoreline change north of East Lane (Figure 3.1) is the substantial recession and straightening of the shoreline near between 1881 and 1945, the great majority of the erosion most likely to have taken place between 1881 and the 1920s when coastal defences were apparently first installed at East Lane. Since 1945, the overall impression of shoreline changes between East Land and Shingle Street is a 'seesawing' of the coastline around a hinge point in the centre of Hollesley Bay between those two locations, with beach sediment transferring from one end of the frontage to the other. Just north of East Lane, there is little or no evidence of periods of beach volumes increasing. Instead there has been a gradual landwards recession of the coastline over this same period. However both here and at Shingle Street, there seems to be evidence of periods during which very little changed followed by more active times when the beach plan-shape altered more noticeably.

It is also clear that the maximum beach widths at Shingle Street shown on this figure occur in 2011 and 2012 at the same time as the narrowest beach widths just north of East Lane. This immediately raises the suspicion that there has been a transport of beach sediment northwards from one end of this frontage to the other in the preceding years, i.e. a net northward longshore drift along the beaches of Hollesley Bay.

To the south of East Lane, substantial recession of the shoreline at and just to the south of East Lane is the most striking difference between recent shoreline and that of 1881. The much smaller recession of the coastline further south is also noteworthy. As for the beaches further north, those just to the south of the coastal defences at East Lane have gone through phases of both advance and retreat. Recession has dominated with the latest surveys showing the most landward shoreline position over the last 130 years.

Examining the topographic beach surveys provided by the Environment Agency's Anglian Coastal Monitoring project the suggests that since 2012 there has been a continuing movement of beach sediment northwards from the vicinity of East Lane, with that sediment moving along the coastline in the centre of Hollesley Bay and accumulating at or just south of Shingle Street. Changes in beach width close to Shingle Street village and from there north to the mouth of Ore/Alde estuary have been variable in both space and time suggesting more localised causes, probably related to changes in the morphology estuary entrance, particularly in the various mobile banks that form the ebb shoal delta which lies seaward and across the mouth of the estuary.

We therefore interpret the overall pattern of changes in beach widths along the coastline on either side of East Lane, Bawdsey as being caused by a recent change in the direction of longshore beach sediment transport in Hollesley Bay from southward to northward, particularly since summer 2013. As a consequence there appears to have been a 'drift divide' at (or near) East Lane with beach sediment moving away from both sides of that headland. In such a situation, the potential for the sea defences to prevent the transfer of beach sediment from one side of the headland to the other becomes largely irrelevant. While the stormy winter of 2013/2014 with its storm surges was always likely to cause changes in beaches, it also appears that such changes have continued subsequently. This change in beaches between 2013 and 2015 is due to an increased northerly drift rate as explained later.

6.1.4. Changes in the seabed bathymetry

The chart comparisons carried out in order to examine the bathymetric changes (Section 3.5) only cover the period prior to 1990, and so they cannot directly provide any indication of possible causes of changes near East Lane in the last 25 years. Our impression is that the historic changes prior to this date may have contributed to a gradual increase in wave energy along the frontage each side of East Lane as the Cutler Bank moved offshore and the shore-platform gradually lowered. This would be expected to have led to a long-term tendency for the erosion of cliffs and landward retreat of the shingle barrier beach in Hollesley Bay. However, there is no evidence for rapid movements or changes in nearshore banks that might have caused different responses in the beaches over short stretches of the coastline near East Lane.

Comparison of more recent cross-sectional surveys of the beaches and the nearshore seabed undertaken as part of the Environment Agency's Anglian Coastal Monitoring programme have shown, in contrast, that a little further north, particularly near Orfordness, large changes in the nearshore seabed have occurred at the same time as localised changes in beach widths.

6.1.5. Wave conditions

Wave conditions approaching this part of the East Anglian coast are characterised by directional bimodality. Along the study coastline, the predominant winds are mainly from SSW, SW and SWW, whereas the waves show a more bidirectional composition, with two main directions, i.e. from N and NE and from the SW sector. This bimodality complicates the behaviour of the shoreline: in general, and given long enough, shorelines either evolve to face the average wave direction so reducing the rate of longshore transport of beach sediment to zero or to an orientation that results in an average net rate that is (roughly) constant along the coastline. However, when the wave conditions approach so obliquely as at East Lane and from very different directions, the shoreline cannot evolve towards an equilibrium facing some average wave direction. In these cases, the difference in persistence and strength of each of the wave directions will govern the response of the shoreline to the wave climate.

The offshore wave data has been analysed and shows two years since 1981 where the offshore wave height exceeded for more than 1% of the year was substantially higher than the average. These years were from June 1989 to May 1990 and June 2013 to May 2014, and very strong winds during the winters of 1989/90 and 2014/15 resulted in considerable damage over much of the UK. Not surprisingly substantial changes in the study shoreline were observed and measured during these winters.

Further analysis revealed that during these winters, the normal ratio of waves approaching from the north-east and south-west sectors also altered. The proportion approaching from the south-west almost doubled and many fewer waves arrived from the north-east sector. Both the increased intensity of large waves and the change in their direction seem to be linked to an increased value of the North Atlantic Oscillation (NAO) index which meteorologists use to characterize (high-altitude) atmospheric pressure and wind patterns over that ocean (in the way that the El Niño / La Niña weather patterns occur over the Pacific Ocean).

6.1.6. The longshore drift regime

The ‘traditional’ view of the longshore drift regime, based on studies going back some 70 years, is that the net drift direction along this part of the Suffolk coastline is southwards. It has also been recognised that this net long-term transport rate alters from time to time, with most past reports indicating periods of a reverse drift both along the spit that extends south from Orfordness as well as along almost the whole frontage between the Ore/Alde and the Deben.

As a consequence of this traditional view of the drift regime, it is to be expected that the beach just north of the artificially-maintained headland at East Lane would remain well-stocked with sediment but there would likely be a problem of erosion to the south of it since the projection of the seawall and the lack of beach sediment in front of it would greatly reduce the longshore drift rate at that point.

However, beach changes in recent years strongly suggest a net northwards transport of shingle from East Lane towards Shingle Street, in line with the views of Pye (2016) that *‘long-term (at least 200 years) net littoral drift has been northwards to the north of East Lane’*.

Longshore drift rates in Hollesley Bay and along Bawdsey cliffs are very variable. In general, in most years, there seems to be a drift divide point somewhere in between East Lane and Bawdsey Cliffs (the position of this point varying throughout the years). From the winter of 2013 there has been an increased northerly drift at all the points studied except one close to Bawdsey Manor. In the last two years, the northerly drift increased to about double its average value and the southerly drift has been less than its average value. The result has been a large net northerly drift which would be responsible for the changes seen in the beach survey data. It is worth pointing that the increase in northerly drift causing the erosion at the north of East Lane is mainly due to natural but unpredictable causes i.e. an increase of the waves from the SW and reduced waves from N and NE.

6.1.7. Predicted future shoreline evolution

A beach plan-shape model of the area from just south of Shingle Street and extending almost to Bawdsey Manor has been set up and calibrated. A great amount of time and effort was spent in the model calibration, especially in trying to find the final best nearshore wave sequence that produced beach changes as observed. Even so, the final calibrated model is not as good as we would have hoped. It reproduces the erosion from just south of East Lane to Bawdsey Manor quite well, as well as the erosion just north of East Lane. However, changes further north are not so well matched with the model unable to replicate the erosion towards the south of Hollesley Bay and overestimating it within the north of the Bay. The reason why the changes in Hollesley Bay are not as well reproduced within the model could be due to the alongshore variability of wave conditions and therefore of the associated drift rates. The year-to-year variability in these modelled drift rates is large, with northerly drifts ranging from 10,000 to 50,000 m^3/yr and the southerly drifts from about 10,000 to 75,000 m^3/yr.

With the model calibrated for the specific study area, it was then applied to predict possible future changes in shoreline position. This exercise was aimed at identifying what potential changes in the current situation might result from changes in the mean offshore wave direction, from changes in the sequencing of wave events or from an increase in sea level (relative to the land), all of which could be a consequence of climate change. Our modelling of the future change to the beaches was simplified by assuming there was a sufficient width of beach landward of the 2012 shoreline that it could erode to any extent predicted but retain its character. (This of course is unrealistic but does allow the use of Beachplan to compare and contrast different climatic scenarios and hence assess the possible challenges faced by any proposed beach management scheme).

Of course it is impossible to predict the future nearshore wave climate for the next 50 years let alone predict the sequencing of the individual wave events that will occur under any climate. Because of this our approach was to produce a series of 40 plausible long-term time-series of nearshore wave conditions and use these to predict a range of possible shoreline positions over the next 50 years.

With regards to the three changes in the input time series and their effects in the beach plan-shape evolution results, the main findings are:

- On its own, the sea level rise does not have much of an effect on shoreline changes. Sea level rise might of course change the vulnerability of the defence structures, but this is outside the remit of this study.
- The main influence of the randomised selection of the years and its sequencing is mainly short term, without affecting the long term evolution substantially. In broad terms, the chronology does not affect the long-term behaviour of the shoreline but it is likely that the beach response immediately north and south of the structures at Bawdsey is more sensitive to this sequencing. Periods of intense drifts will have more impact in these areas than in others, potentially defining them as hot-spots. As such, intervention measures will need to concentrate on these hot-spots.
- The effect of the wave direction on the predicted beach changes has been carried out in two ways:

- Firstly, we assumed a uniform change in all wave directions applied to all the points along the coastline in the model. Although this is necessarily realistic, these simplified runs show, as one might expect, that the change in wave direction rotates the resultant shoreline position, so that those runs where the wave directions have been increased (rotated clockwise) result in less erosion (even accretion sometimes) at the North of East Lane and faster beach erosion along Bawdsey cliffs and towards Bawdsey Manor. Less expected, however, is the result on the drifts: the result of this rotation is greatest along the Bawdsey cliffs frontage, where the drift rates increase by about 50-100%, than along Hollesley Bay where the rotation produced much less variation in the yearly drift rates. Similar but opposite changes in the predicted patterns and rates of beach width change were predicted by rotating the nearshore wave directions in the opposite direction.
- A more realistic way of examining the influence of the wave direction was carried out: by producing a 50 year long synthetic time series by randomly selecting from the available 35 years of inshore data, but introducing a bias towards the selection of the years producing a more northerly drift or a more southerly drift. The prediction of the shoreline changes with these biased wave time series show that the area at the north of East Lane is less strongly affected by variations in the wave conditions, whether to more towards the N/NE or towards the SW, than the beaches in front of Bawdsey cliffs. Here the changes in the beach plan-shape were found to be more sensitive to the biasing of the wave conditions.

In general, it was found that changes in wave direction have the greatest influence on the predicted beach changes. However, there is no way of predicting with any confidence how such changes in wave directions will occur in the future. Because of this, there will be a continuing danger of outflanking one end of the seawall at East Lane and perhaps both. Further loss of beach sediment north of this seawall would add to the dangers of flooding of the low-lying hinterland while beach erosion to the south of the East Lane defences would increase the rates of cliff top recession and erosion of the nearshore seabed there.

6.2. Recommendations

The substantial historical changes discussed throughout this report make a strong case for continuing the monitoring of the beaches in the area (currently undertaken by the Anglian Monitoring System), and possibly increasing the frequency of the surveys which involve bathymetric surveying of the nearshore seabed designed to record the levels of the nearshore seabed approximately as far out as the -10m OD contour. These bathymetric surveys were intended to provide extra information on how and why the beaches were changing and have provided a very good insight. However, the latest of these surveys was in July 2007 and it would be very desirable to have a recent one in order to draw comparisons and conclusions on the lower limit of the beach profiles, where the shingle finishes.

Throughout the study it has been emphasised how natural changes in the winds and therefore waves have a great impact in the development of this area. At the beginning of the report, four areas in East Anglia were mentioned where changes thorough the years have been extreme and opposite (Gorleston, near Great Yarmouth, Pakefield, near Lowestoft, Dunwich and The Dip at Felixstowe). Bawdsey should be added to the list. The main changes in the behaviour of the beaches near East Lane in recent times seem to be the result of changes in offshore wave conditions that have altered the direction of the alongshore sediment transport. These changes could be exacerbated or alleviated by changes in the seabed contours, changes in the amount of beach sediment crossing the mouths of the Deben and Ore/Alde estuaries and by anthropogenic causes, such as altering or removing coastal defences.

Turning now to possible intervention options, it should first be pointed out that the drift rate in Hollesley Bay may reverse naturally, leading to a return of at least some of the shingle that has moved away to the north in recent times. This study has shown that the drift rates towards and either side of the East Lane headland are variable in both magnitude and direction. In this context it is not straightforward to assess the possible advantages or disadvantages of installing groynes to help reduce the changes in beach width to the north of the East Lane headland. In general, groynes can help spread a localised and intense erosion problem over a greater length of a frontage allowing more time to intervene and remedy a loss of beach sediment. Given the extent to which the seawall at East Lane already projects seaward, and the lack of beach sediment in front of it, this structure reducing the transfer of shingle from one side of the headland to the other. Further modelling of beach changes between and on each side of any proposed groyne system would be needed to clarify their likely effectiveness.

7. References

British Geological Survey, 1996. ‘Sediment Input from Coastal Cliff Erosion: Operational Investigation 577’, Technical Report 557/4/A, August 1996, 67+vi pp.

Burningham, H., & J. French. 2006. ‘Morphodynamic behaviour of a mixed sand-gravel ebb-tidal delta: Deben Estuary, Suffolk, UK’, Marine Geology, **225**, pp23–44.

Burningham, H., & J. French. 2008. ‘Historical changes in the seabed of the greater Thames Estuary’, The Crown Estate – Caird Fellowship Research Project Final Report. July 2008. See http://www.thecrownestate.co.uk/media/5746/historical_changes_in_thames_estuary_seabed.pdf.

Burningham, H., & J. French. 2009. ‘Seabed mobility in the greater Thames Estuary’, The Crown Estate – Caird Fellowship Research Project Final Report. January 2009. See http://www.thecrownestate.co.uk/media/5773/thames_seabed_mobility_report.pdf.

Burningham, pers. com., 2016.

Carr, AP, 1972. ‘Aspects of spit development and decay: the estuary of the River Ore’, Suffolk. Field Studies, **4**, pp633-653.

Clayton, KM, McCave, IN, and Vincent CE, 1983. ‘The establishment of a sand budget for the East Anglian coast and its implications for coastal stability’. In ‘Shoreline Protection, proceedings of a conference organised by the ICE’. Thomas Telford, London. pp 91–96.

Environment Agency, 2011. ‘Coastal Trends Report: Suffolk (Lowestoft to Landguard Point, Felixstowe), Report RP022/S/2011,February 2011.

Environment Agency, 2012. ‘Adapting to Climate Change: Advice for Flood and Coastal Erosion Risk Management Authorities’.

Environment Agency, 2016. ‘Flood risk assessments: Climate change allowances’, https://www.gov.uk/guidance/flood-risk-assessments-climate-change-allowances.

HR Wallingford, 1997. ‘Harwich Channel Deepening: wave climate monitoring studies for 1996’. Report for Harwich Harbour Commissioners, EX 3612.

HR Wallingford *et al.*, 2002. ‘Southern North Sea Sediment Transport Study, Phase 2 : Sediment Transport Report’. Report produced for Great Yarmouth Borough Council by HR Wallingford, CEFAS/UEA, Posford Haskoning and Dr Brian D’Olier, Report EX 4526, August 2002. (See also www.SNS2.org).

HR Wallingford, 2010. 'Thames Estuary Dredging Association. MAREA Summary Report', Report EX6213, April 2010.

HR Wallingford, 2016. 'Sandscaping Feasibility Assessment: Suffolk Shingle Engine, Slaughden site.', HR Wallingford Report DDR543-RT001-R03-00, January 2016. (Confidential report for The Crown Estate).

Komar P D and Inman D L, 1970. 'Longshore sand transport on beaches', Journal of Geophysical Research, **75** (30), pp 5914 - 5927.

Lowe, J. A., Howard, T. P., Pardaens, A., Tinker, J., Holt, J., Wakelin, S., Milne, G., Leake, J., Wolf, J., Horsburgh, K., Reeder, T., Jenkins, G., Ridley, J.,Dye, S., Bradley, S. (2009), 'UK Climate Projections science report: Marine and coastal projections', Met Office Hadley Centre, Exeter, UK.

Mott MacDonald, 2015. 'Coastal Processes Study: East Lane, Bawdsey, Suffolk: Final Report', Report to the Environment Agency, September 2015, 115+iv pp.

Onyett, D. and Simmonds, A., 1983. 'East Anglian Coastal Research Programme Final Report 8: beach transport and longshore transport'.

Posford Duvivier. 2000. 'Hollesley to Bawdsey Sea Defences: Coastal Processes Final Report'. Report for the Environment Agency.

Royal Haskoning, 2010. 'Bawdsey Policy Options', Report for Suffolk Coastal DC.

UKCP09 website http://ukclimateprojections.metoffice.gov.uk/

U.S. Army Coastal Engineering Research Center, 1984. 'Shore Protection Manual', U.S. Government Printing Office, Washington, DC.

Vincent, CE, 1979. 'Longshore sand transport rates – a simple model for the East Anglian coastline'. Coastal Engineering, **3**, pp113–136.

Walkden M and van Baanen B, 2013. 'iCOAAST Deben Composition: Site Observations'.

8. Acknowledgements

HR Wallingford gratefully acknowledges the provision of survey data by the Anglian Coastal Monitoring project, from University College, London and a recent bathymetric survey by Scottish Power. The prompt advice and assistance given by Philip Staley of the Environment Agency and of Helene Burningham of University College in making this information available to us is greatly appreciated.

HR Wallingford appreciates the support from Mike Cowling throughout the difficulties in this project as well as the comments from Bawdsey Coastal Partnership (Gerry Matthews and Tim Green in particular), Gary Watson and Mark Johnson from the Environment Agency, Bill Parker from Suffolk Coastal and Waveney District Councils and Jane Burch from Suffolk County Council.

HR Wallingford gratefully acknowledges the provision of the aerial photograph in the front cover by Mike Page.

Appendices

A. Profiles

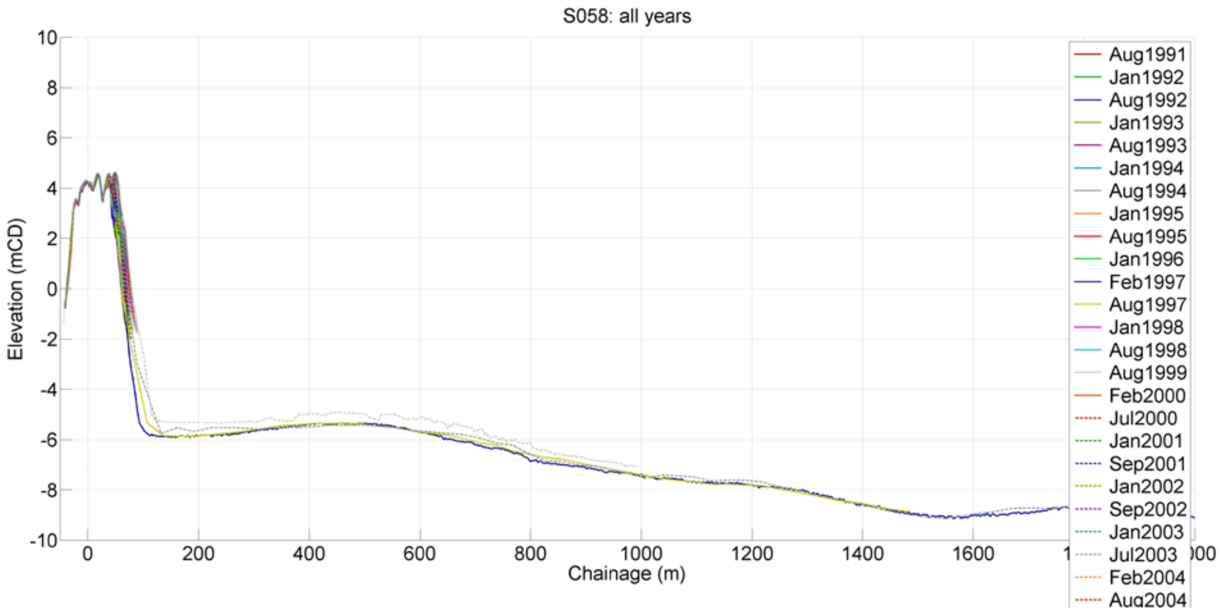

Figure A.1: Profile S058

Source: Anglian Monitoring System

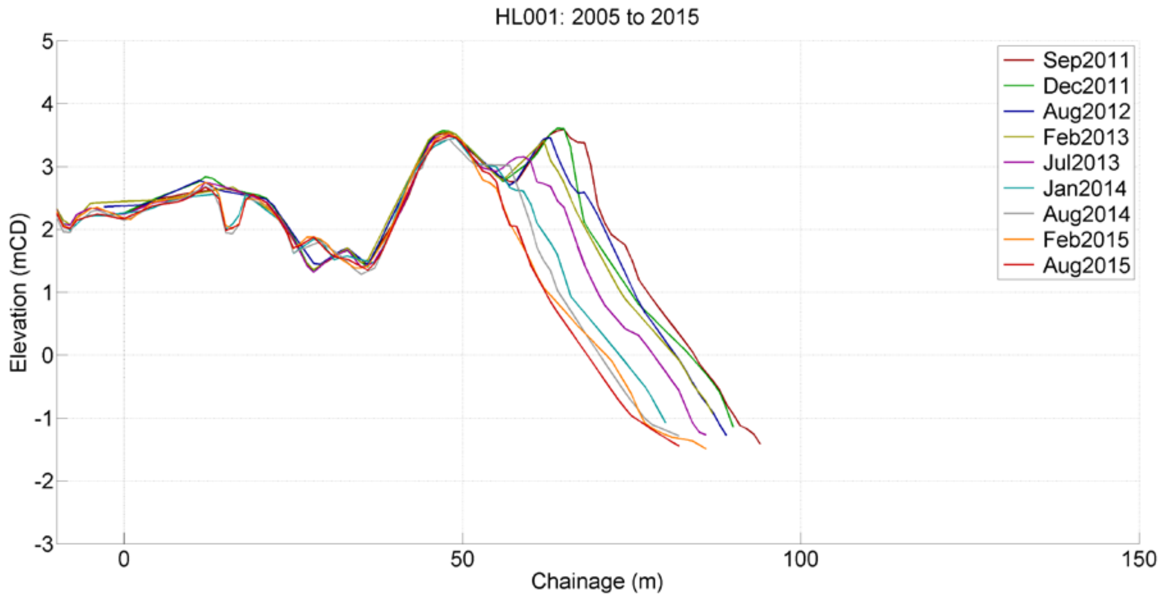

Figure A.2: Profile HL001

Source: Anglian Monitoring System

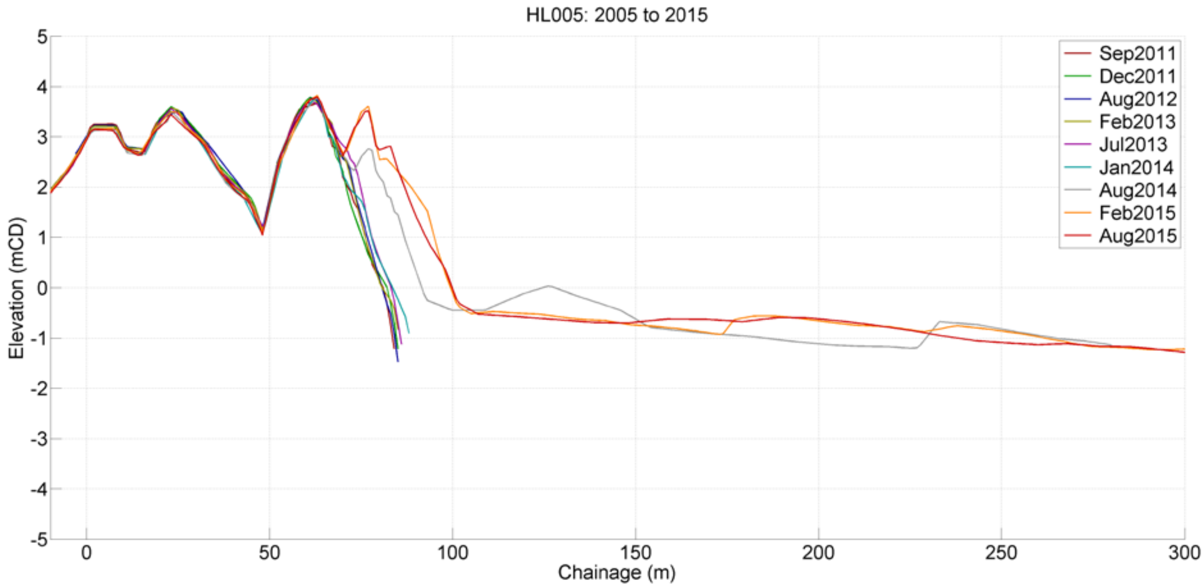

Figure A.3: Profile HL005

Source: Anglian Monitoring System

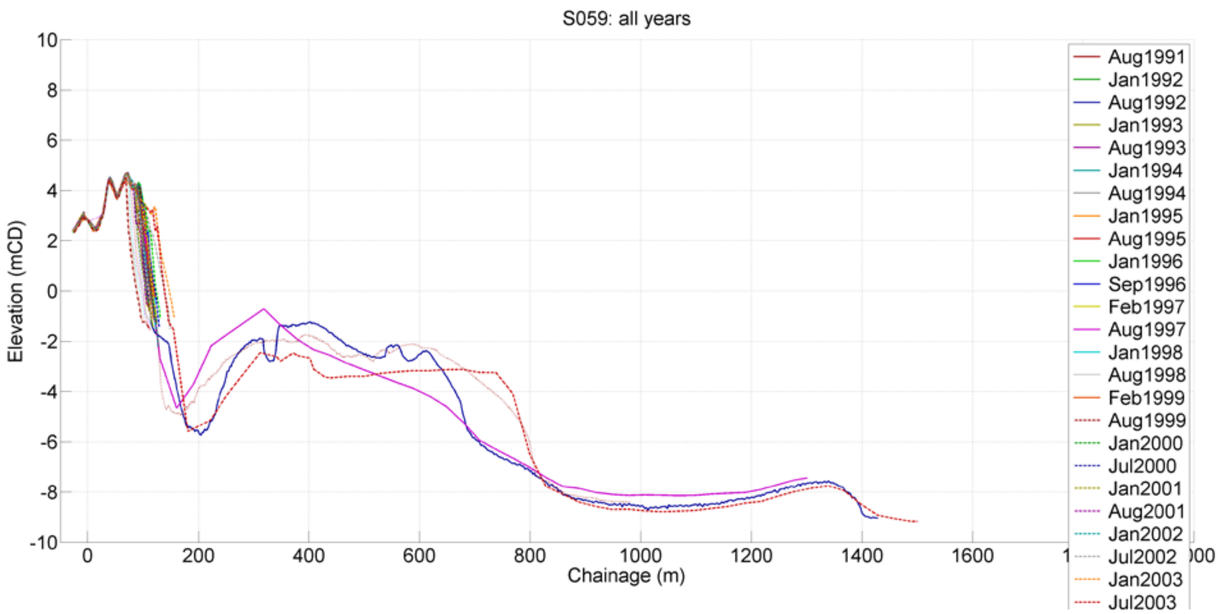

Figure A.4: Profile S059

Source: Anglian Monitoring System

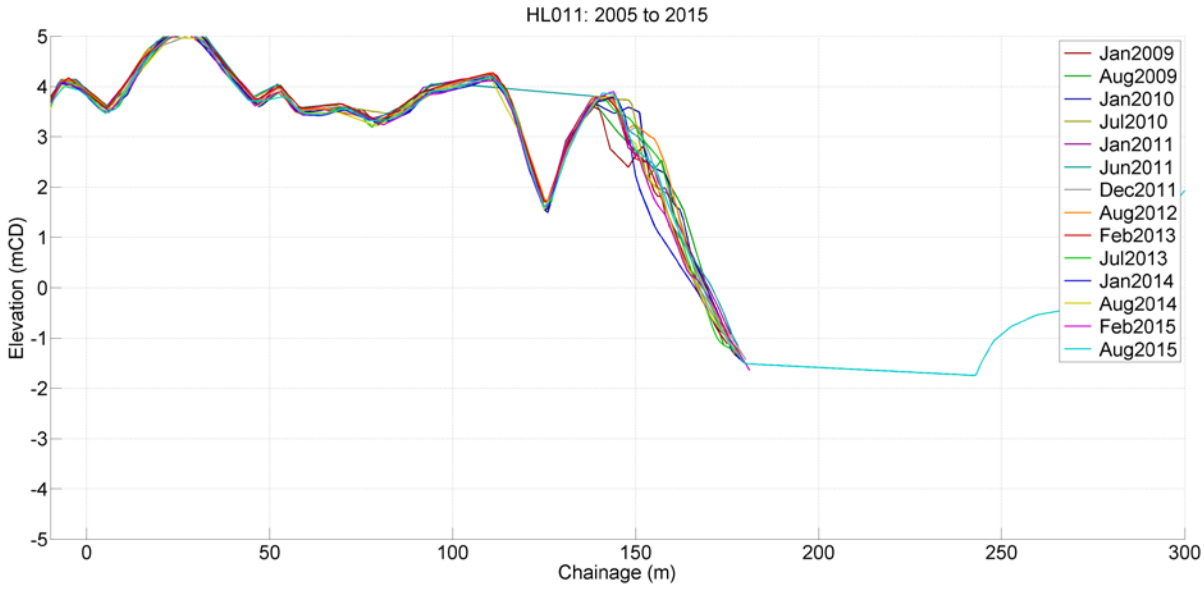

Figure A.5: Profile HL011

Source: Anglian Monitoring System

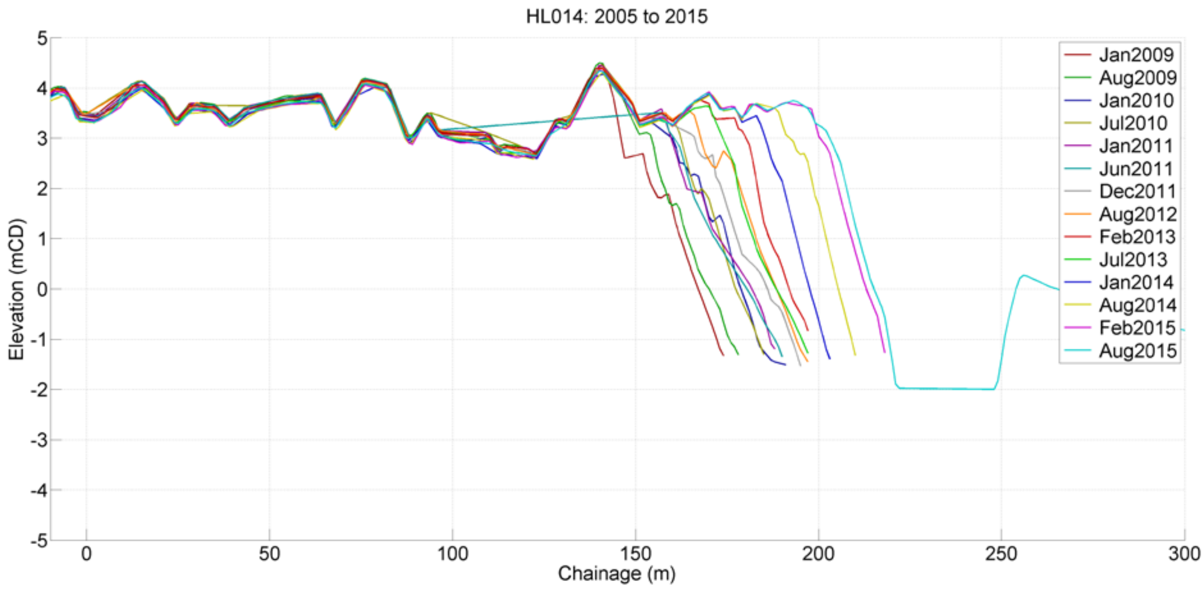

Figure A.6: Profile HL014

Source: Anglian Monitoring System

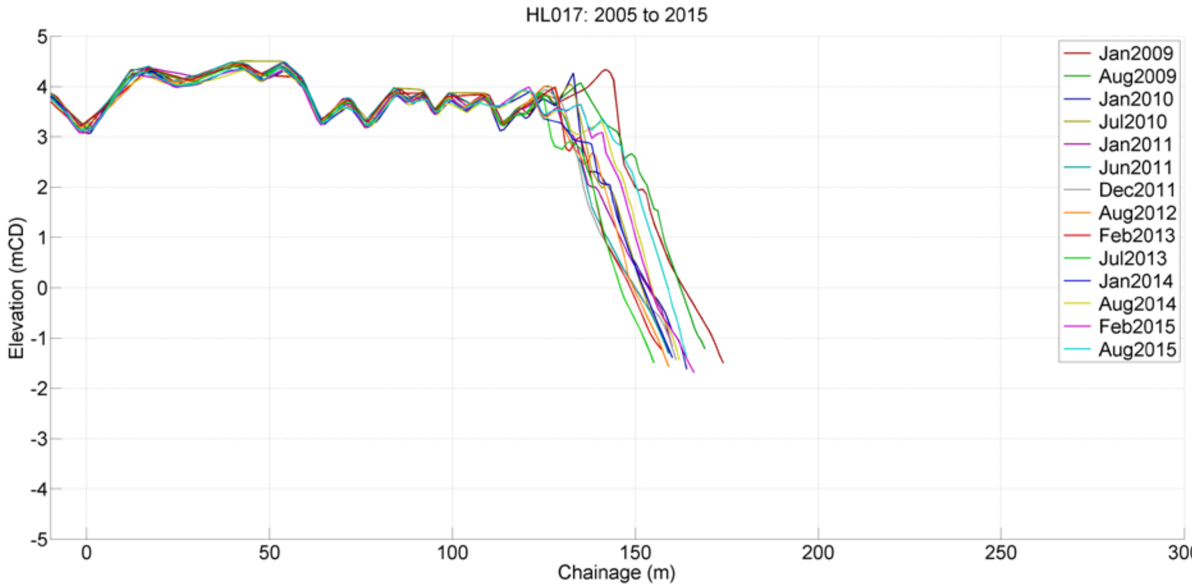

Figure A.7: Profile HL017

Source: Anglian Monitoring System

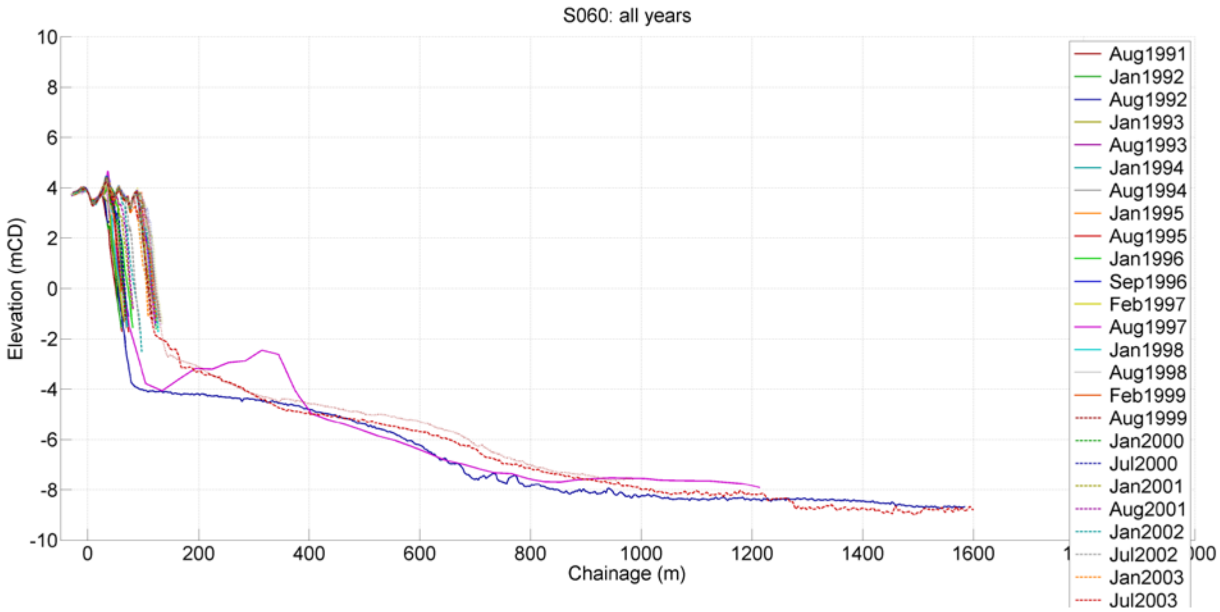

Figure A.8: Profile S060

Source: Anglian Monitoring System

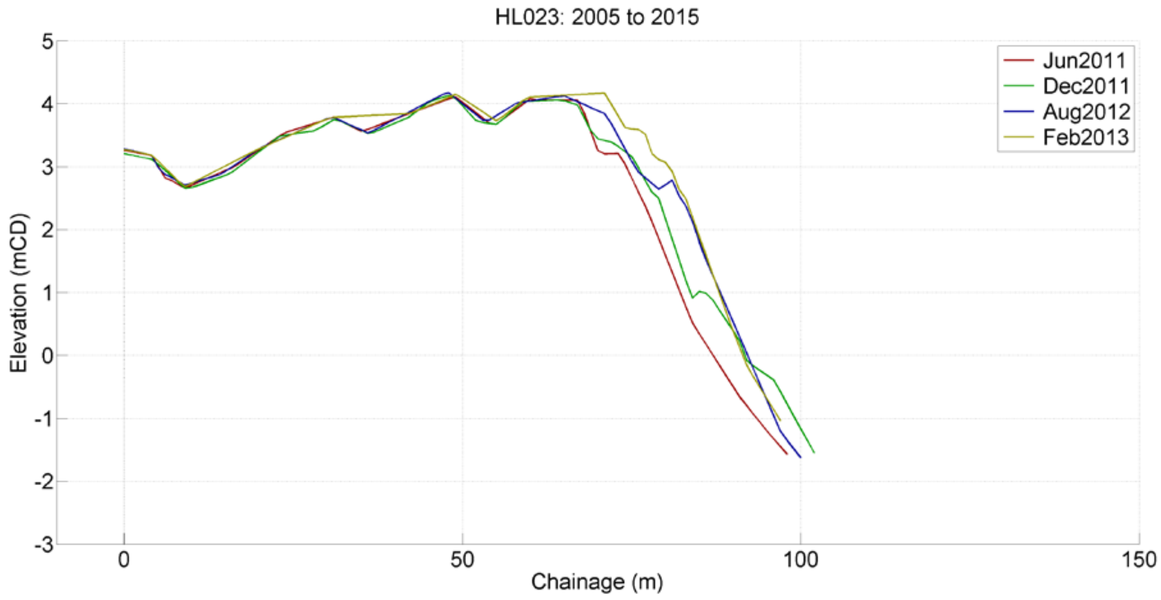

Figure A.9: Profile HL023

Source: Anglian Monitoring System

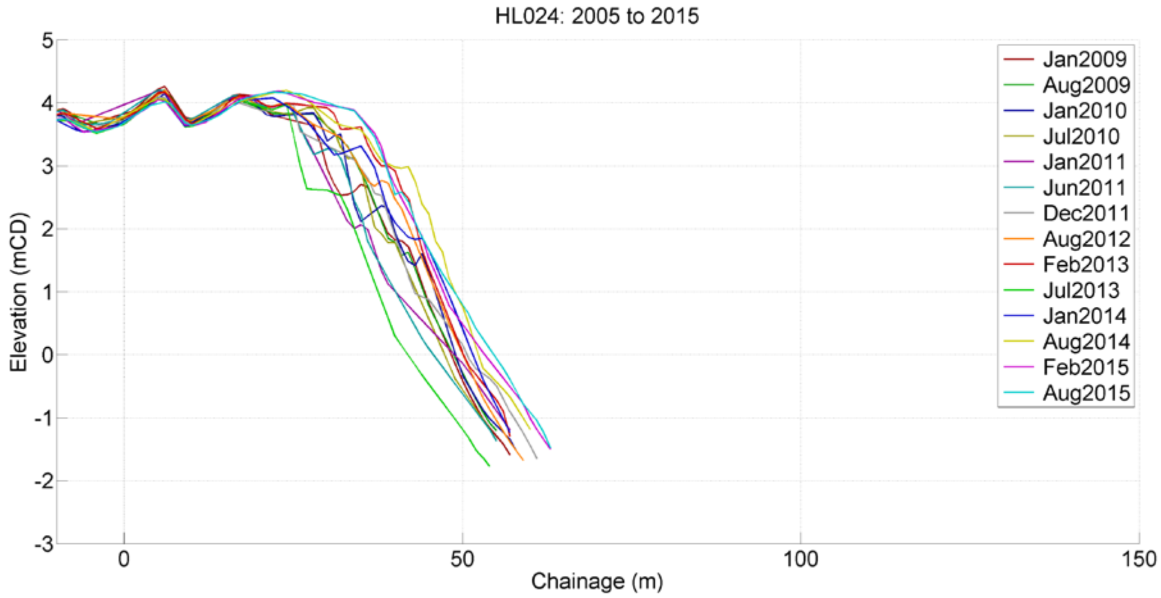

Figure A.10: Profile HL024

Source: Anglian Monitoring System

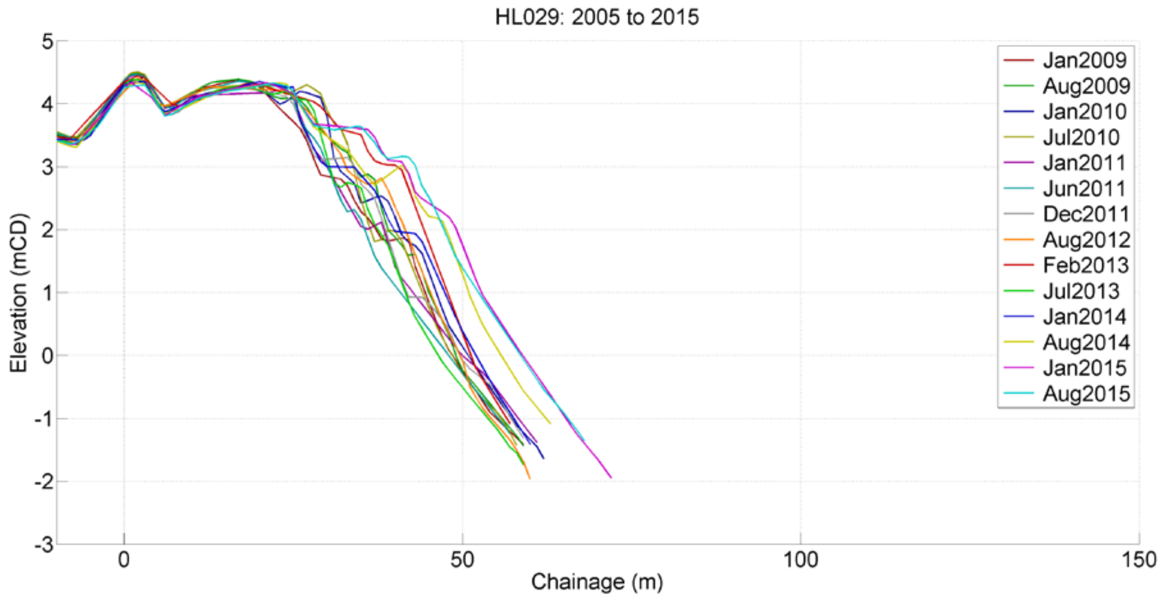

Figure A.11: Profile HL029

Source: Anglian Monitoring System

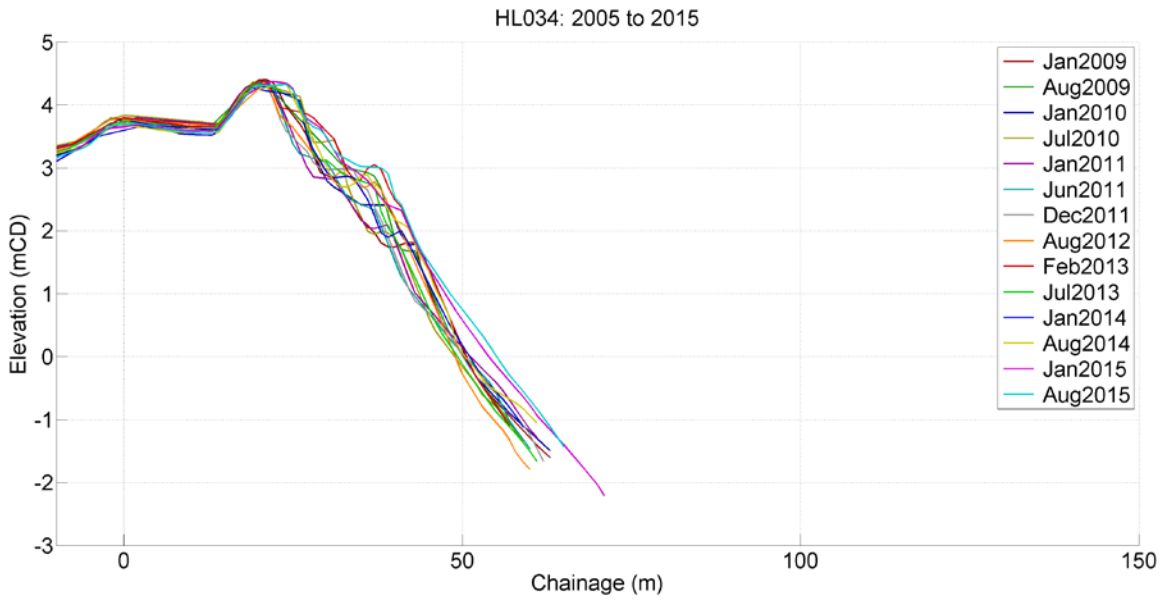

Figure A.12: Profile HL034

Source: Anglian Monitoring System

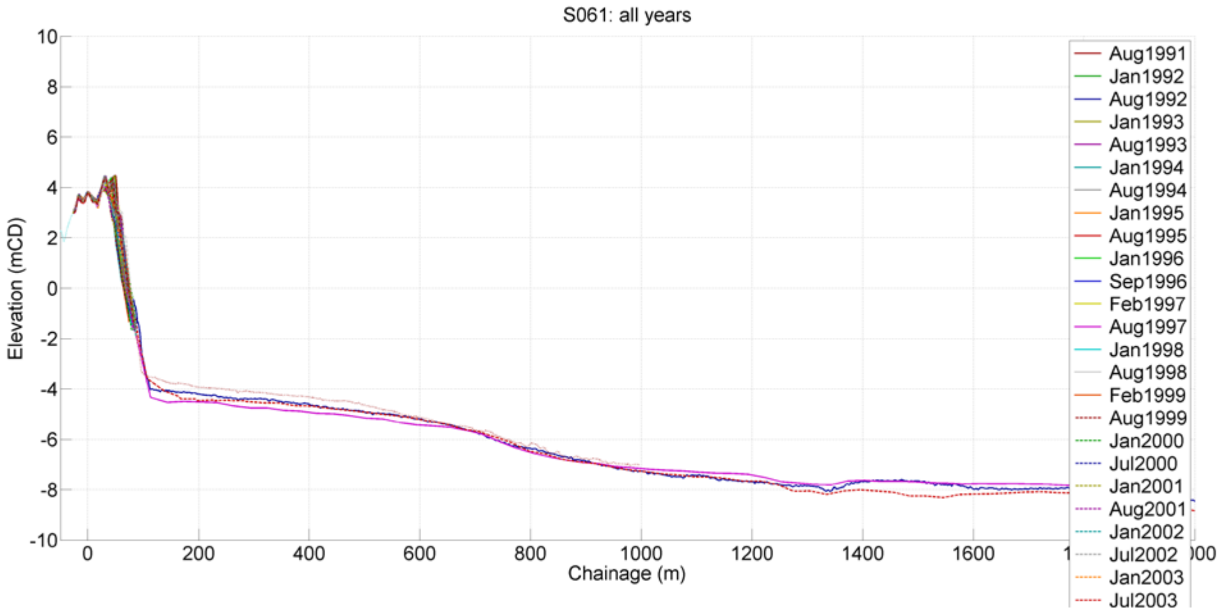

Figure A.13: Profile S061

Source: Anglian Monitoring System

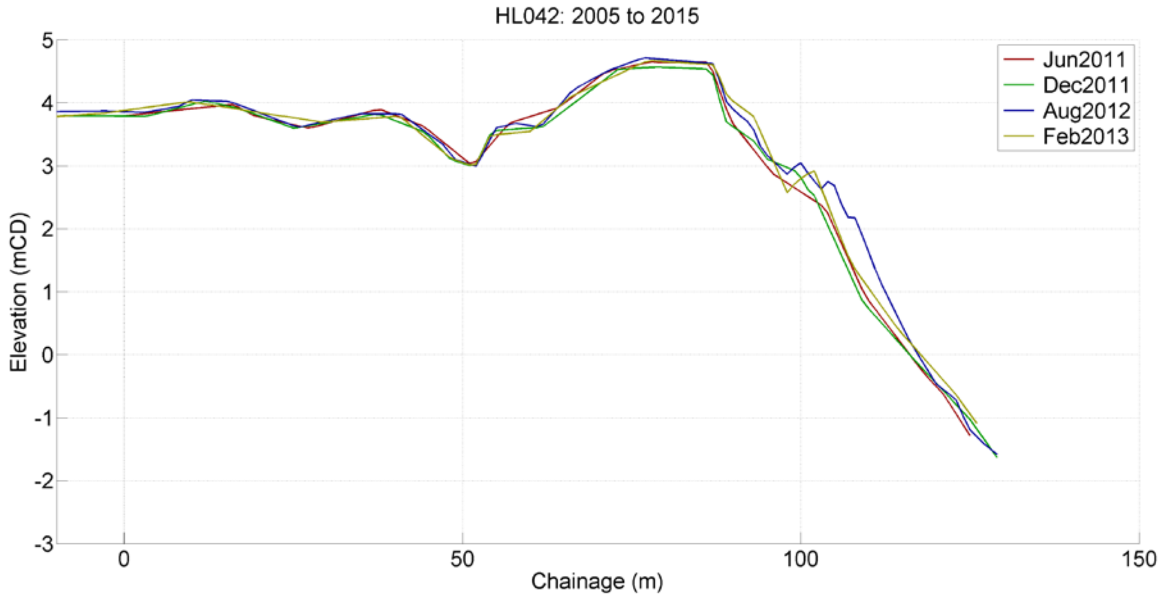

Figure A.14: Profile HL042

Source: Anglian Monitoring System

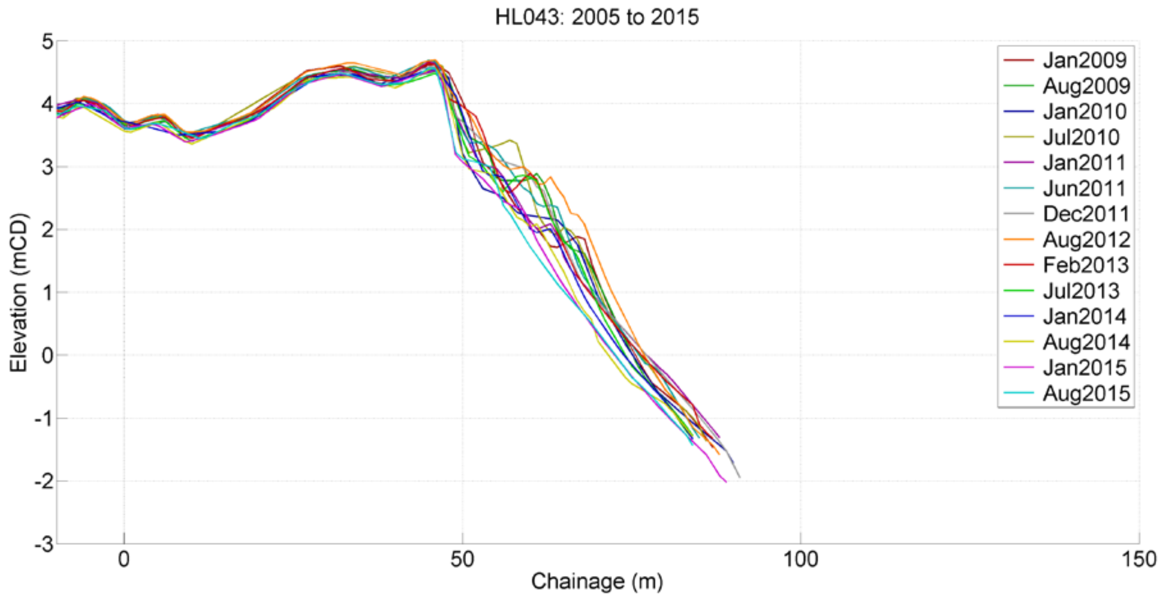

Figure A.15: Profile HL043

Source: Anglian Monitoring System

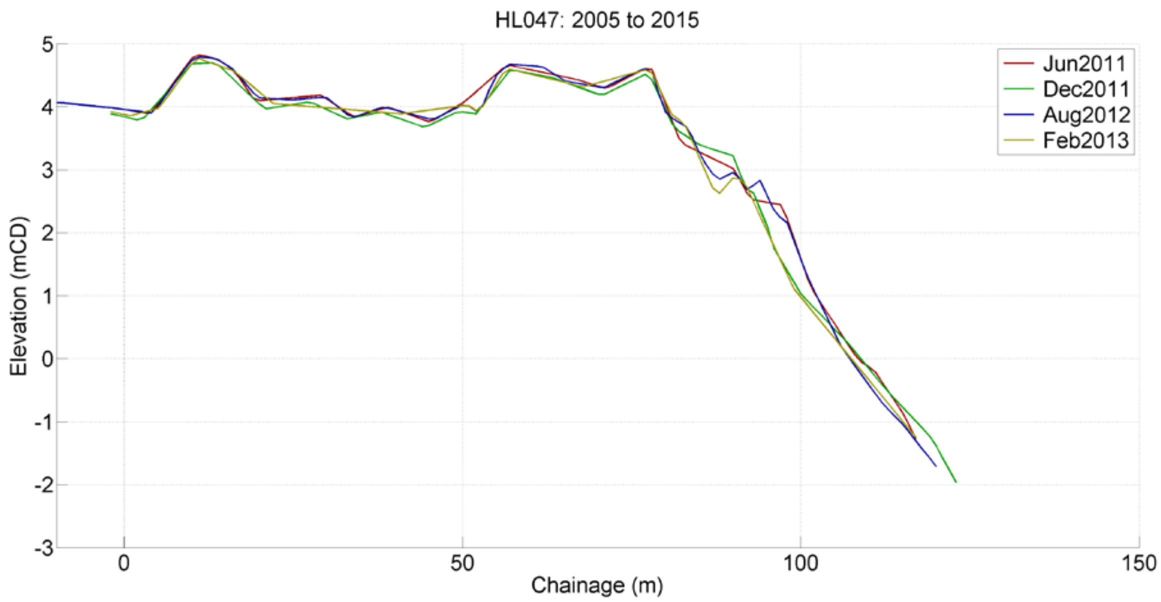

Figure A.16: Profile HL47

Source: Anglian Monitoring System

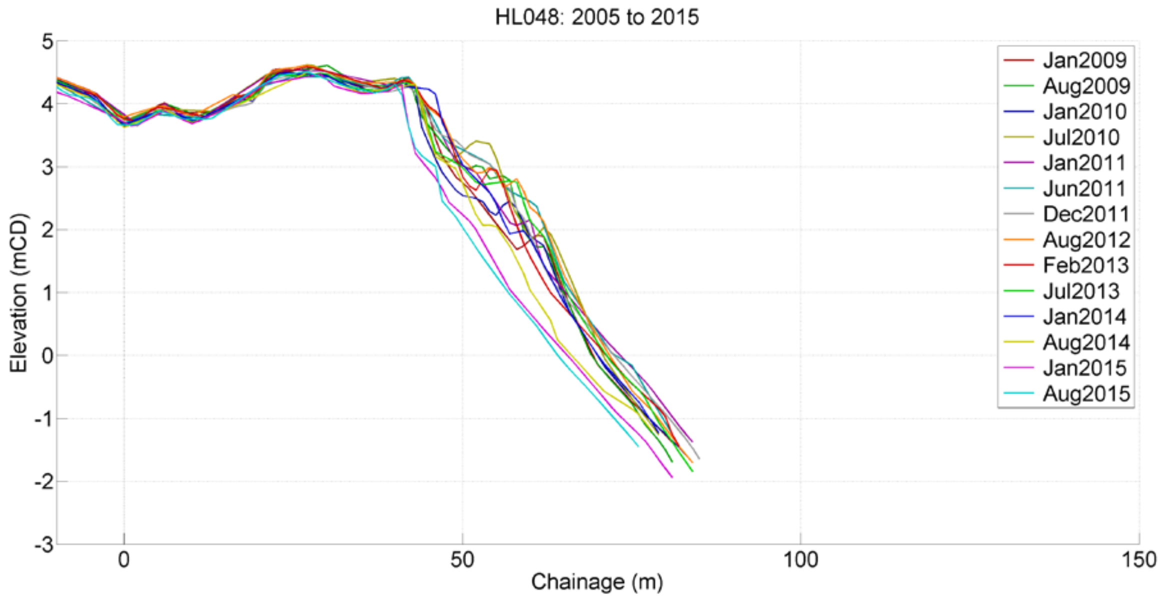

Figure A.17: Profile HL048

Source: Anglian Monitoring System

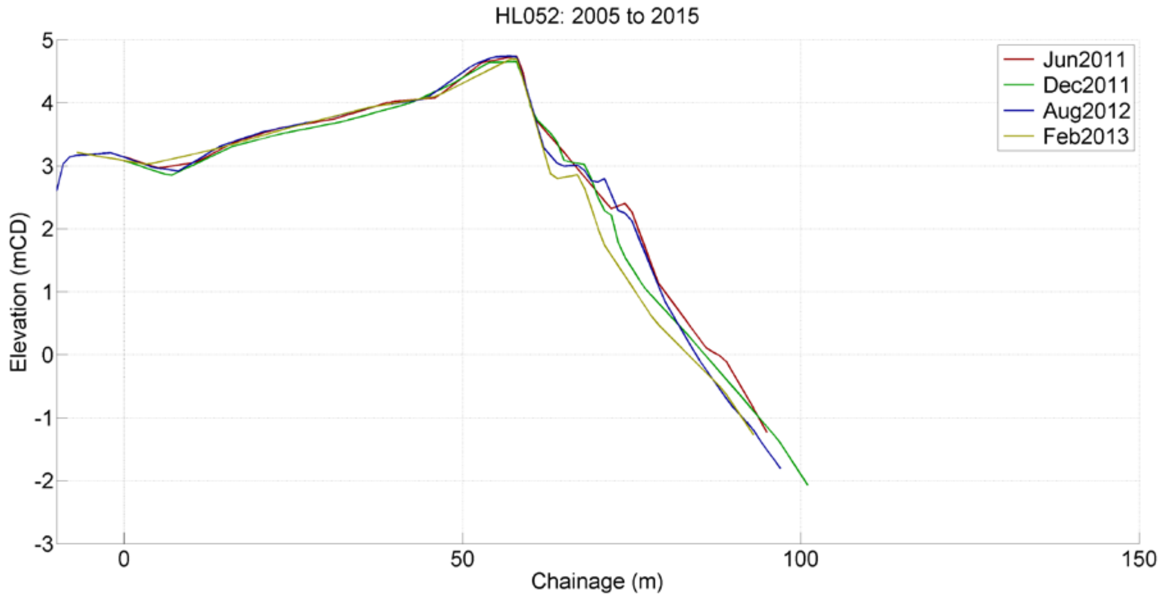

Figure A.18: Profile HL052

Source: Anglian Monitoring System

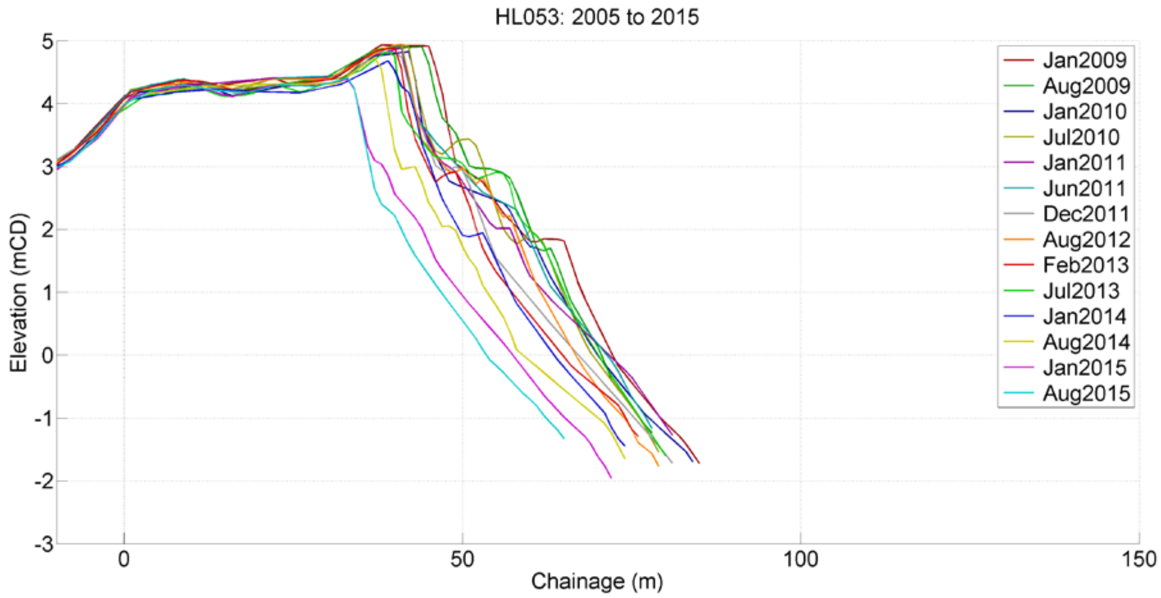

Figure A.19: Profile HL053

Source: Anglian Monitoring System

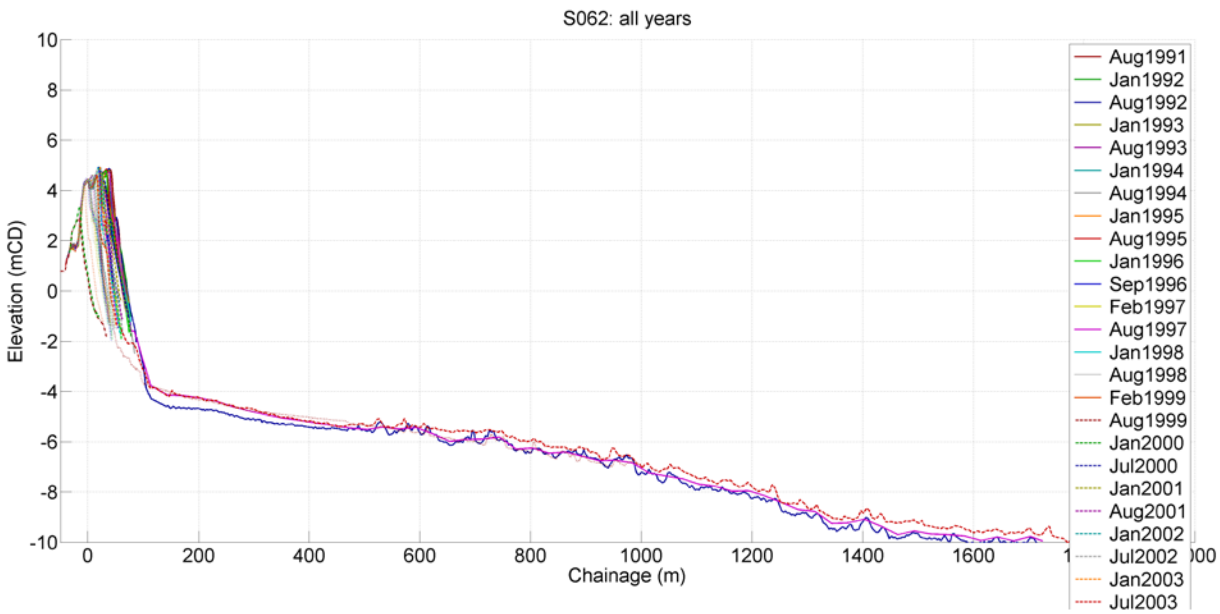

Figure A.20: Profile S062

Source: Anglian Monitoring System

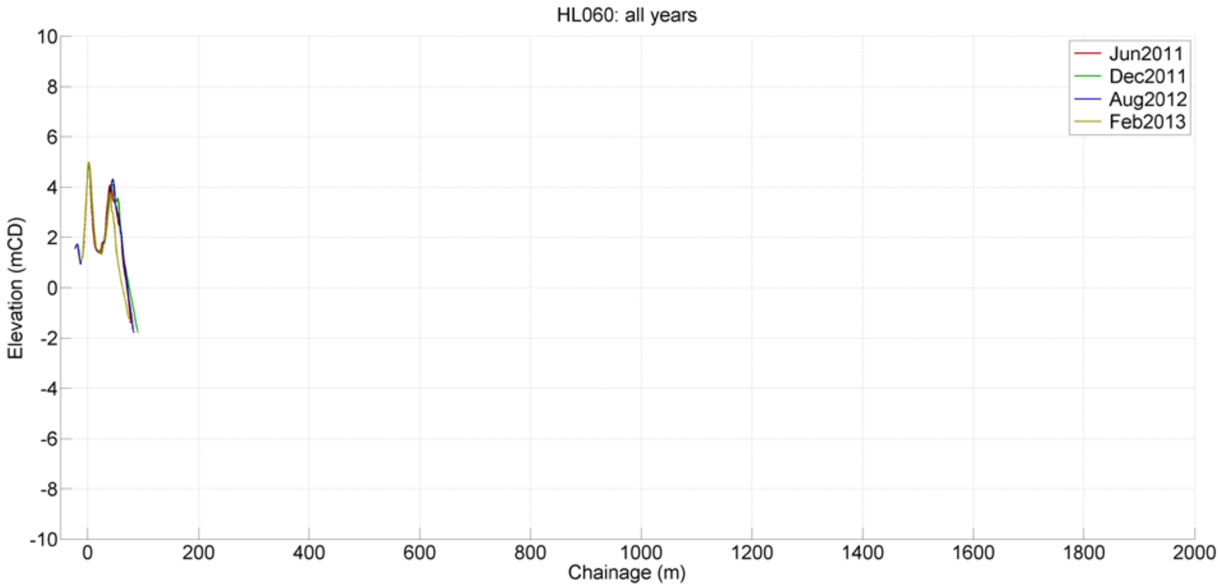

Figure A.21: Profile HL060

Source: Anglian Monitoring System

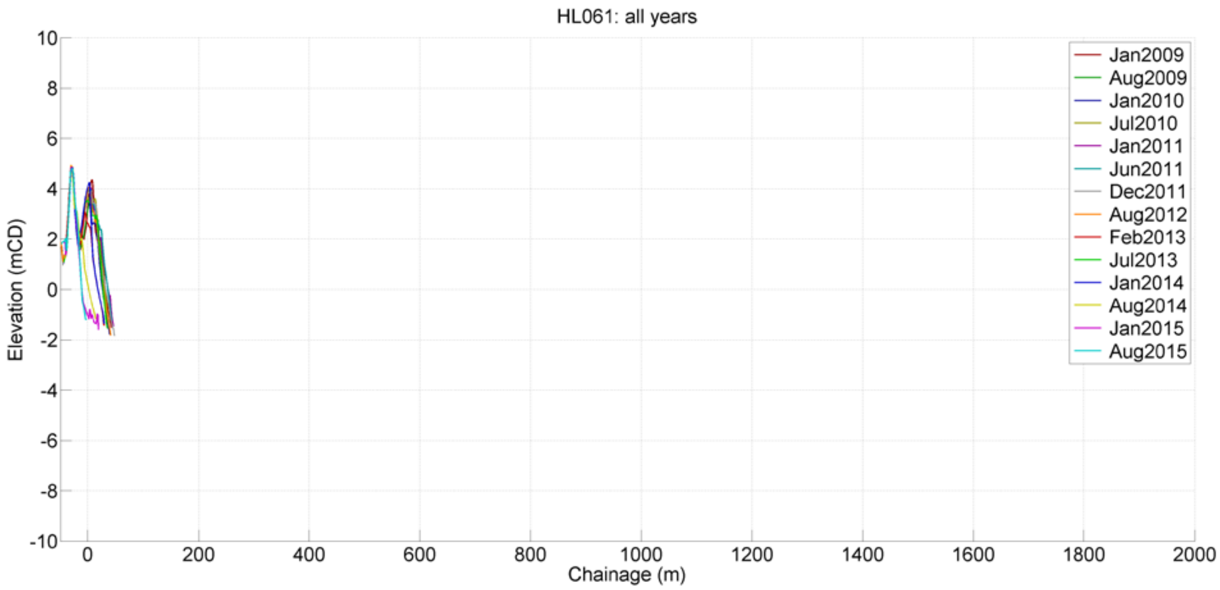

Figure A.22: Profile HL61

Source: Anglian Monitoring System

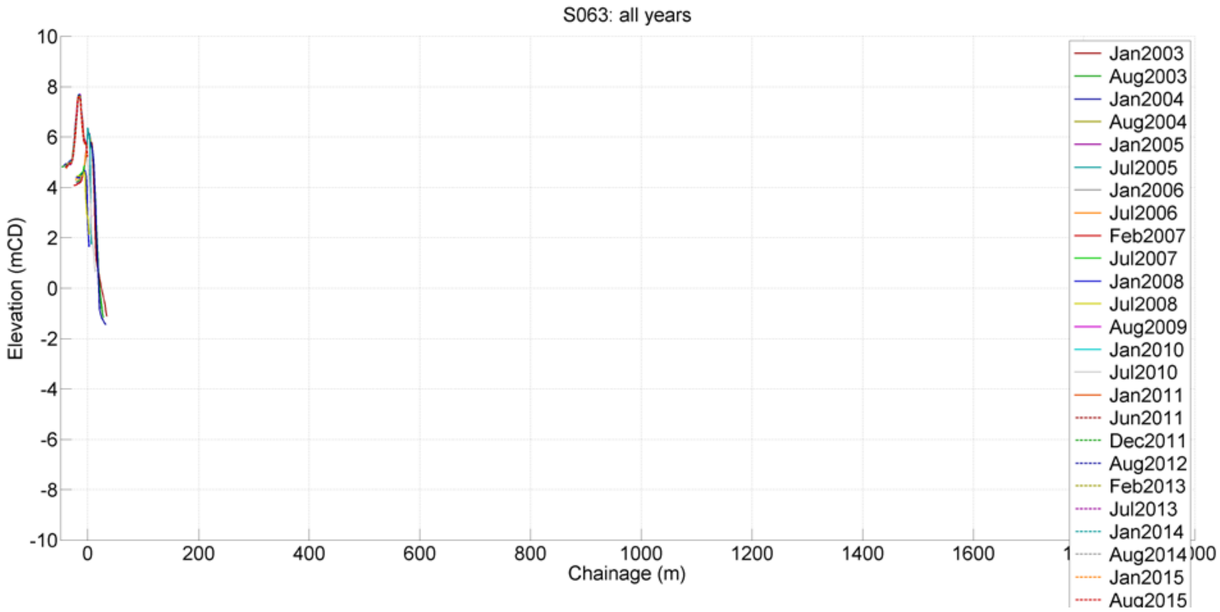

Figure A.23: Profile S063

Source: Anglian Monitoring System

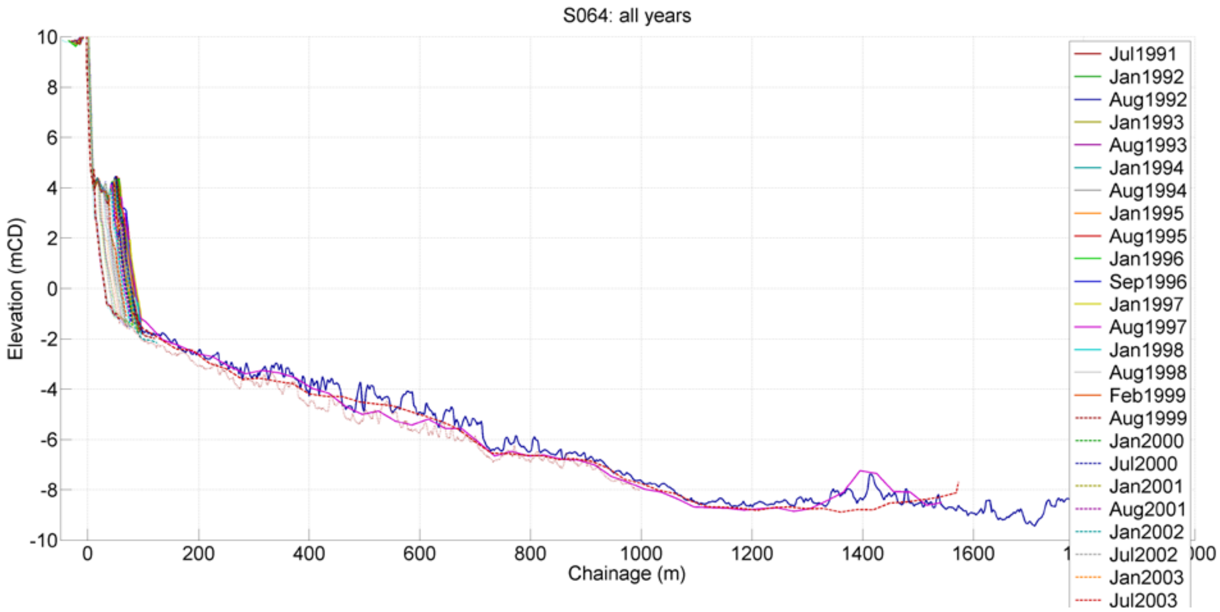

Figure A.24: Profile S064

Source: Anglian Monitoring System

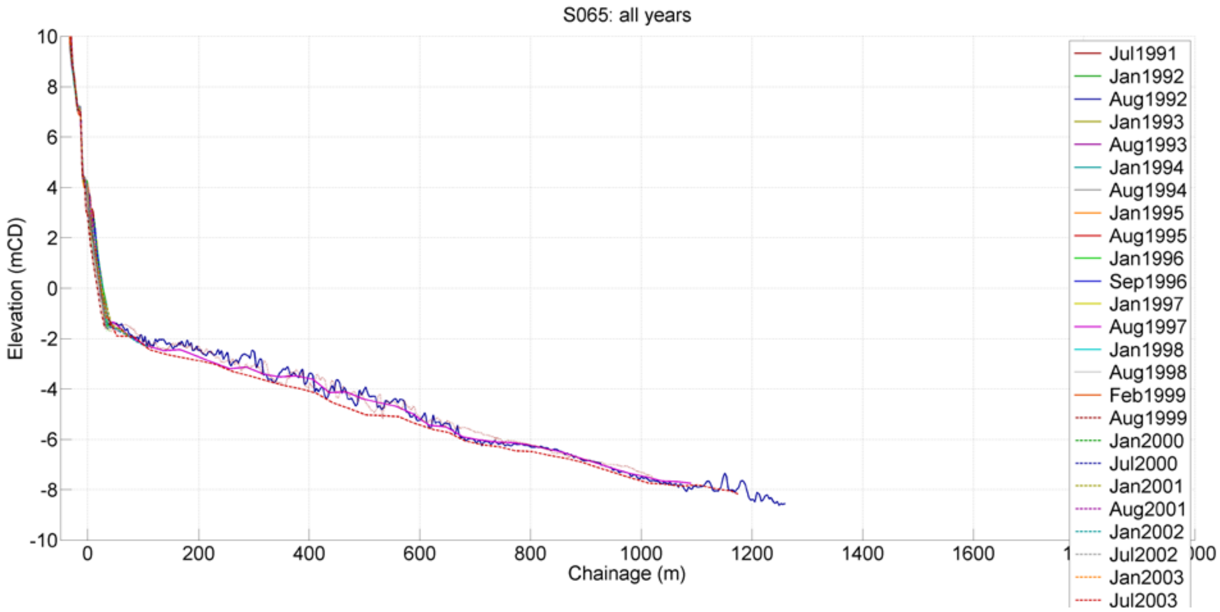

Figure A.25: Profile S065

Source: Anglian Monitoring System

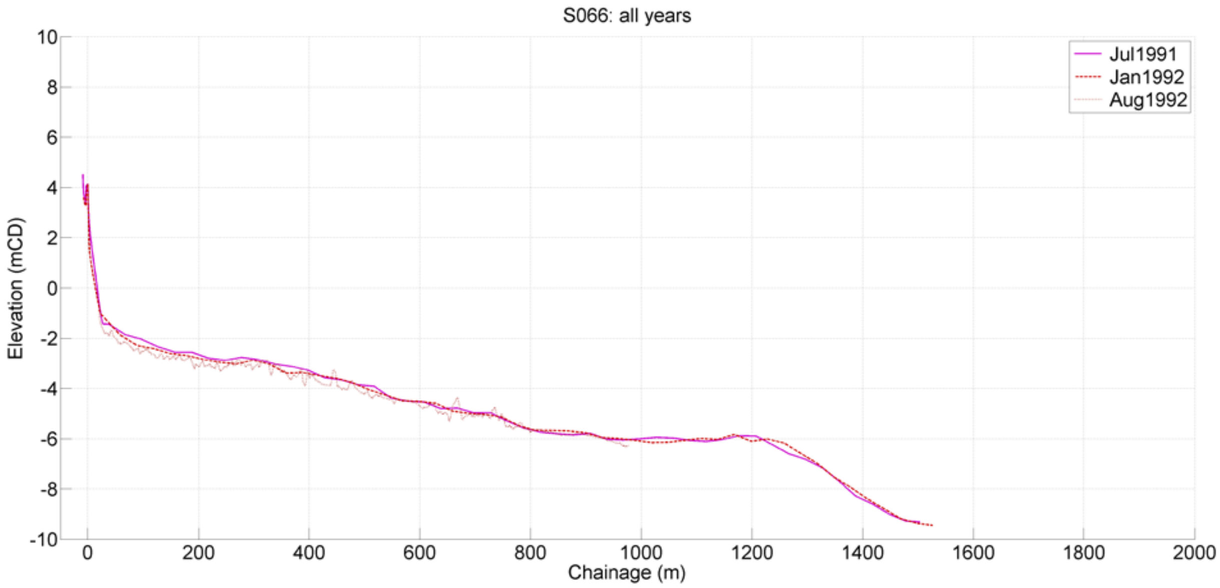

Figure A.26: Profile S066

Source: Anglian Monitoring System

B. SWAN capability statement

B.1. Introduction

SWAN is a computational spectral wave transformation model. It can be used to obtain realistic estimates of wave parameters in coastal areas, lakes and estuaries from given wind, seabed, and current conditions. The model has been developed by the Technical University of Delft (TU Delft).

SWAN is based on a fully spectral representation of the wave action balance equation (or energy balance in the absence of currents) with all physical processes modelled explicitly. No a priori limitations are imposed on the spectral evolution. This makes SWAN (Simulating WAves Nearshore) a third-generation wave model.

The model has been used successfully at numerous sites around the UK and in other parts of the world. It is designed to represent the following wave propagation processes:

- refraction due to spatial variations in seabed and current;
- shoaling due to spatial variations in seabed and current;
- blocking and reflections by opposing currents;
- transmission through, blockage by or reflection from obstacles (such as coastlines or breakwaters).

The following wave generation and dissipation processes are also represented in SWAN:

- generation by wind;
- dissipation by whitecapping;
- dissipation by depth-induced wave breaking;
- dissipation by seabed friction;
- wave-wave interactions (quadruplets and triads);
- obstacles.

Diffraction is not represented in SWAN, so the model should not be used in areas where variations in wave height are large within a horizontal scale of a few wavelengths. Because of this, the wave field computed by SWAN will generally not be accurate in the immediate vicinity of obstacles.

The SWAN wave model has been conceived to be a computationally feasible third-generation spectral wave model for waves in shallow water (including the surf zone) with ambient currents.

B.2. The SWAN wave model

The SWAN model represents the waves in terms of the two-dimensional wave action density spectrum $N(\sigma,\vartheta)$, even when nonlinear phenomena dominate (e.g., in the surf zone). The independent variables are the relative frequency σ (as observed in a frame of reference moving with the action propagation velocity) and the wave direction ϑ (the direction normal to the wave crest of each spectral component). The action density is equal to the energy density divided by the relative frequency: $N(\sigma,\vartheta) = E(\sigma,\vartheta)/\sigma$.

In SWAN the two-dimensional wave action density spectrum may vary in time and space. Its evolution is described by the spectral action balance equation, which for Cartesian coordinates is (e.g. Hasselmann et al., 1973):

$$\frac{\partial}{\partial t}N + \frac{\partial}{\partial x}C_x N + \frac{\partial}{\partial y}C_y N + \frac{\partial}{\partial \sigma}C_\sigma N + \frac{\partial}{\partial \vartheta}C_\vartheta N = \frac{S(\sigma,\vartheta)}{\sigma} \quad (1)$$

The first term in the left-hand side represents the local rate of change of action density in time. The second and third term represent propagation of action in geographical $x-$ and $y-$space (with propagation velocities C_x and C_y respectively). The fourth term represents shifting of the relative frequency due to variations in depths and currents in time (with propagation velocity C_σ in $\sigma-$space). The fifth term represents propagation of action in $\vartheta-$space (depth-induced and current-induced refraction) with propagation velocity C_ϑ. The expressions for these propagation speeds are taken from linear wave theory. The term $S(\sigma,\vartheta)$ at the right hand side of the action balance equation is the source term representing the effects of generation, dissipation and non-linear wave-wave interactions.

The formulations for the generation, the dissipation and the quadruplet wave-wave interactions are taken from the WAM model (WAM Cycle3, WAMDI group, 1988, and optionally WAM Cycle4, Komen et al., 1994). These are supplemented with a spectral version of the dissipation model for depth-induced breaking of Battjes and Janssen (1978) and a more recently formulated discrete interaction approximation for the triad wave-wave interactions (Eldeberky and Battjes, 1995).

B.3. Transfer of wind energy to the waves

The transfer of wind energy to the waves is described in SWAN with a resonance mechanism (Phillips, 1957) and a feed-back mechanism (Miles, 1957). The corresponding source term for these mechanisms is commonly described as the sum of linear and exponential growth:

$$S_{in}(\sigma,\vartheta) = A + B \times E(\sigma,\vartheta) \quad (2)$$

in which A and B depend on wave frequency and direction, and wind speed and direction. The effects of currents are accounted for in SWAN by using the apparent local wind speed and direction. The expression for the term A is due to Cavaleri and Malanotte-Rizzoli (1981, revised by Tolman, 1992). Two optional expressions for the coefficient B are used in the model. The first is due to Snyder et al. (1981), re-scaled in terms of friction velocity by Komen et al. (1984). The second expression is due to Janssen (1991) and accounts explicitly for the interaction between the wind and the waves by considering atmospheric boundary layer effects and the roughness length of the sea surface.

B.4. Whitecapping

Whitecapping is primarily controlled by the steepness of the waves. In presently operating third-generation wave models (including SWAN) the whitecapping formulations are based on a pulse-based model (Hasselmann, 1974), as adapted by the WAMDI group (1988):

$$S_{ds,w}(\sigma,\vartheta) = -\Gamma\tilde{\sigma}\frac{k}{\tilde{k}}E(\sigma,\vartheta) \quad (3)$$

where Γ is a steepness dependent coefficient, k is wave number and $\tilde{\sigma}$ and $\tilde{k}$ denote a mean frequency and a mean wave number, respectively (cf. the WAMDI group, 1988). The value of Γ depends on the wind input formulation that is used. Since two expressions are used for the wind input in SWAN, two values for Γ are used. The first is due to Komen et al. (1984), and is used in SWAN when the wind input coefficient of

Komen et al. (1984) is used. The second expression is an adaptation of this expression based on Janssen (1991). It is used when the wind input term of Janssen (1991) is used.

B.5. Depth-induced dissipation

Depth induced-dissipation may be caused by seabed friction, by seabed motion, by percolation or by back-scattering on seabed irregularities. For continental shelf seas with sandy seabeds, the dominant mechanism appears to be seabed friction, which can generally be represented as:

$$S_{ds,b}(\sigma,\vartheta) = -c_{bed}\frac{\sigma^2}{g^2\sinh^2(kd)}E(\sigma,\vartheta) \qquad (4)$$

in which c_{bed} is a seabed friction coefficient. A large number of models has been proposed. Hasselmann et al. (JONSWAP, 1973) suggested use of an empirically obtained constant. This seems to perform well in many different conditions as long as a suitable value is chosen (typically different for swell and wind sea; Bouws and Komen, 1983). A nonlinear formulation based on drag has been proposed by Hasselmann and Collins (1968), which was later simplified by Collins (1972), and is also implemented in SWAN. More complicated, eddy viscosity models have been developed by Madsen et al. (1988). The effect of a mean current on the wave energy dissipation due to seabed friction is not taken into account in SWAN.

B.6. Depth-induced wave breaking

Although the process of depth-induced wave breaking is still poorly understood and little is known about its spectral modelling, the total dissipation (i.e. integrated over the spectrum) can be well modelled with the dissipation of a bore applied to the breaking waves in a random field. And laboratory observations show that the shape of initially uni-modal spectra propagating across simple (barred) beach profiles is fairly insensitive to depth-induced breaking. This has led Eldeberky and Battjes (1995) to formulate a spectral version of the bore model of Battjes and Janssen (1978) which conserves the spectral shape. Their expression has been expanded in the SWAN model to include direction:

$$S_{ds,br}(\sigma,\vartheta) = \frac{D_{tot}}{E_{tot}}E(\sigma,\vartheta) \qquad (5)$$

in which E_{tot} is the total wave energy and D_{tot} (which is negative) is the rate of dissipation of the total energy due to wave breaking according to Battjes and Janssen (1978). The value of D_{tot} depends critically on the breaking parameter $\gamma = H_{\max}/d$ (in which $H_{\max}$ is the maximum possible individual wave height in the local water depth d). In SWAN γ has a constant value (default is 0.73 corresponding to the mean value of the data set of Battjes and Stive, 1985).

B.7. Wave transmission

SWAN can estimate wave transmission through a structure such as a breakwater. Since obstacles usually have a plan area that is too small to be resolved by the bathymetric grid, in SWAN, an obstacle is modelled as a line. The transmission coefficient is defined as the ratio of the (significant) wave height at the downwave side of the breakwater over the (significant) wave height at the upwave side. If the crest of the breakwater is such that waves can pass over, the transmission coefficient is taken from Goda et al. (1967) and is expressed as a function of wave height and freeboard (difference in crest level and water level).

Note that a change in wave frequency is to be expected as well as a change in wave height, since often the process above the breakwater is highly non-linear. But given the little information available, SWAN assumes that the frequencies remain unchanged over an obstacle (only the energy scale of the spectrum is affected and not the spectral shape).

B.8. Nonlinear wave-wave interactions

In deep water, quadruplet wave-wave interactions dominate the evolution of the spectrum. They transfer wave energy from the spectral peak to lower frequencies (thus moving the peak frequency to lower values) and to higher frequencies (where the energy is dissipated by whitecapping). In very shallow water, triad wave-wave interactions transfer energy from lower frequencies to higher frequencies often resulting in higher harmonics (Beji and Battjes, 1993; low-frequency energy generation by triad wave-wave interactions is not considered here).

A full computation of the **quadruplet wave-wave interactions** is extremely time consuming and not convenient in any operational wave model. A number of techniques, based on parametric methods or other types of approximations have been proposed to improve computational speed. In SWAN the computations are carried out with the Discrete Interaction Approximation (DIA) of Hasselmann et al. (1985). Eldeberky and Battjes (1995) introduced a discrete triad approximation (DTA) for co-linear waves, obtained by considering only the dominant self-self **triad interactions**. Their model has been verified with flume observations of long-crested, random waves breaking over a submerged bar (Beji and Battjes, 1993) and over a barred beach (Arcilla et al., 1994). A slightly different version, the Lumped Triad Approximation (LTA) was later derived by Eldeberky (1996) and is used in SWAN.

Cycle III of SWAN is stationary and optionally non-stationary, formulated in Cartesian (recommended only for small scales) or spherical (small scales and large scales) coordinates. The stationary mode should be used only for waves with a relatively short residence time in the computational area under consideration (i.e. small travel time of the waves through the region compared to the time scale of the geophysical conditions: wave boundary conditions, wind, tides and storm surge). A quasi-stationary approach can be taken with stationary SWAN computations in a time-varying sequence of stationary conditions.

The current version of SWAN can be used on any scale relevant for wind generated surface gravity waves, as the model now uses more accurate numerical propagation schemes and can compute on spherical co-ordinates (longitude, latitude), allowing calculations in laboratory situations, coastal regions, shelf seas and oceans. However, SWAN is specifically developed for coastal applications, which would usually not require such flexibility in scale. And it must be emphasized that on oceanic scales SWAN is certainly less efficient on oceanic scales than WAVEWATCH III and probably also less efficient than WAM.

Fully implicit numerical schemes are used in the SWAN model for propagation in both geographic and spectral spaces (an iterative, forward-marching, four-sweep technique due to Ris et al., 1994). This scheme is unconditionally stable in contrast with the explicit schemes of conventional spectral wave models.

B.9. Typical results

i. Colour contour plots of significant wave height, H_s, and vector plots of mean wave direction over the model area.
ii. Tables of H_s, T_z, T_p and mean direction at a selection of inshore locations. For example the model can be used to investigate which offshore wave conditions lead to the worst inshore wave

heights at a particular site.

iii. SWAN also calculates fields of wave-induced forces per unit surface area, wave orbital velocities, and a variety of other parameters. Such results can be used directly as input into a sediment transport model.

iv. 2D (frequency and direction) spectrum at a selection of inshore location. Information of this type would normally be required as input to a numerical harbour model or a mathematical model of beach processes. In addition this information would also be needed at the wave paddle positions in a physical model in order to generate the correct random wave sequence for design studies.

B.10. References

Battjes, J.A. and J.P.F.M. Janssen, 1978: Energy loss and set-up due to breaking of random waves, *Proc. 16 th Int. Conf. Coastal Engineerin*g, ASCE, 569-587.

Booij, N., L.H. Holthuijsen and R.C. Ris, 1996, The "SWAN" wave model for shallow water, *Proc. 25th Int. Conf. Coastal Engineering.,* Orlando, pp. 668-676.

Collins, J.I., 1972: Prediction of shallow water spectra, *J. Geophys. Re*s., 77, No. 15, 2693-2707.

Eldeberky, Y., 1996: Nonlinear transformation of wave spectra in the nearshore zone, *Ph.D. thesi*s, Delft University of Technology, Department of Civil Engineering, The Netherlands.

Eldeberky, Y. and J.A. Battjes, 1995: Parameterization of triad interactions in wave energy models, *Proc. Coastal Dynamics Conf. '9*5, Gdansk, Poland, 140-148.

Goda, Y, H. Takeda and Y. Moriya, 1967: Laboratory investigation of wave transmission over breakwaters*, Rep. port and Harbour Res. Ins*t., 13 (from Seelig, 1979).

Hasselmann, K., T.P. Barnet, E. Bouws, H. Carlson, D.E. Cartwright, K. Enke, J.A. Ewing, H. Gienapp, D.E. Hasselmann, P. Kruseman, A. Meerburg, P. Müller, D.J. Olbers, K. Richter, W. Sell and H. Walden, 1973: Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP), *Dtsch. Hydrogr.* Z. Suppl., 12, A8.

Hasselmann, S., K. Hasselmann, J.H. Allender and T.P. Barnet, 1985: Computations and parameterizations of the nonlinear energy transfer in a gravity wave spectrum. Part II: Parameterizations of the nonlinear transfer for application in wave models, *J. Phys. Oceanog*r., 15, 11, 1378-1391.

Janssen, P.A.E.M., 1991: Quasi-linear theory of wind-wave generation applied to wave forecasting, *J. Phys. Oceanog*r., 21, 1631-1642.

Komen, G.J., S. Hasselmann, and K. Hasselmann, 1984: On the existence of a fully developed wind-sea spectrum, *J. Phys. Oceanog*r., 14, 1271-1285.

Komen, G.J., Cavaleri, L., Donelan, M., Hasselmann, K., Hasselmann, S. and P.A.E.M. Janssen, 1994: *Dynamics and Modelling of Ocean Wave*s, Cambridge University Press, 532 p.

Madsen, O.S., Y.-K. Poon and H.C. Graber, 1988: Spectral wave attenuation by seabed friction: Theory, *Proc. 21 th Int. Conf. Coastal Engineerin*g, ASCE, 492-504.

Ris, R.C., N. Booij and L.H. Holthuijsen, 1999, A third-generation wave model for coastal regions, Part II: Verification, *J.Geoph.Research,* 104, C4, 7667-7681.

Tolman, H.J., 1992: Effects of numerics on the physics in a third-generation wind-wave model, *J. Phys. Oceanogr*., 22, 10, 1095-1111.

WAMDI group, 1988: The WAM model - a third generation ocean wave prediction model, *J. Phys. Oceanogr*., 18, 1775-1810.

C. State of the Nation Coastal Boundaries Methodology

To derive the present day and future climate change coastal boundary conditions, the methodology currently being applied by HR Wallingford for the Environment Agency's State of the Nation (SotN) flood risk analysis has been applied. The methodology is captured in Figure C.1 below and comprises two main components:

- Stage 1: Offshore multivariate extreme value analysis;
- Stage 2: Wave transformation modelling.

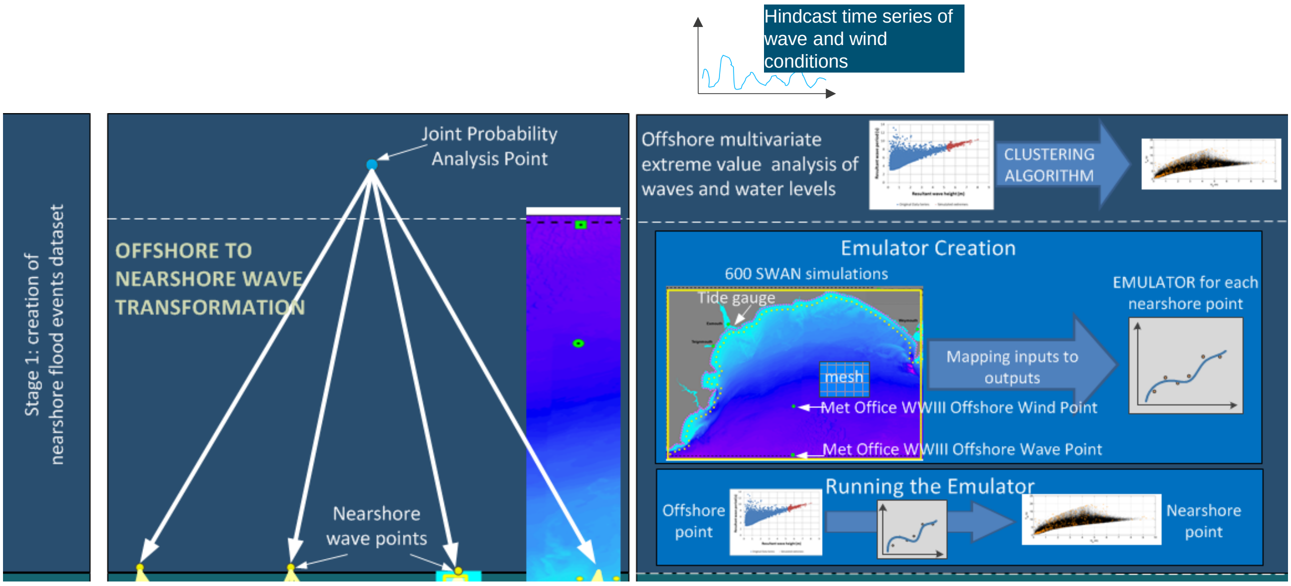

Figure C.1: Conceptual diagram showing the components of the analysis methodology

C.1. Stage 1: Offshore multivariate extreme value analysis

The requirement to undertake joint probability analysis of wave and water level information, for coastal flood risk analysis is well-established. Previous simplified approaches that make use of joint probability contours (joint exceedence contours) are known to underestimate return period overtopping rates and it is known that the magnitude of the error varies depending on structure type and exposure to extreme conditions. To overcome these limitations a state-of-the-art multivariate extreme value models is used as proposed by Heffernan and Tawn (2004). The method requires data in the form of concurrent observations of waves, winds and water levels.

The wave and wind information is provided from an extensive hindcast from the well-established Wavewatch III model run by the Met. Office from 1980 to 2013. Water levels from the existing Environment Agency gauges are also used. Statistical models are fitted to these data to enable extrapolation to extreme coastal events.

The sources of data to be used for the study area are summarised in Figure C.2 below. This figure shows the location of observed data including: the Lowestoft tide gauge (central red pentagon),and; the Met Office

WaveWatchIII EUHC model points PT978 (offshore wave) (orange square) and PT1069 (wind) (green triangle), respectively.

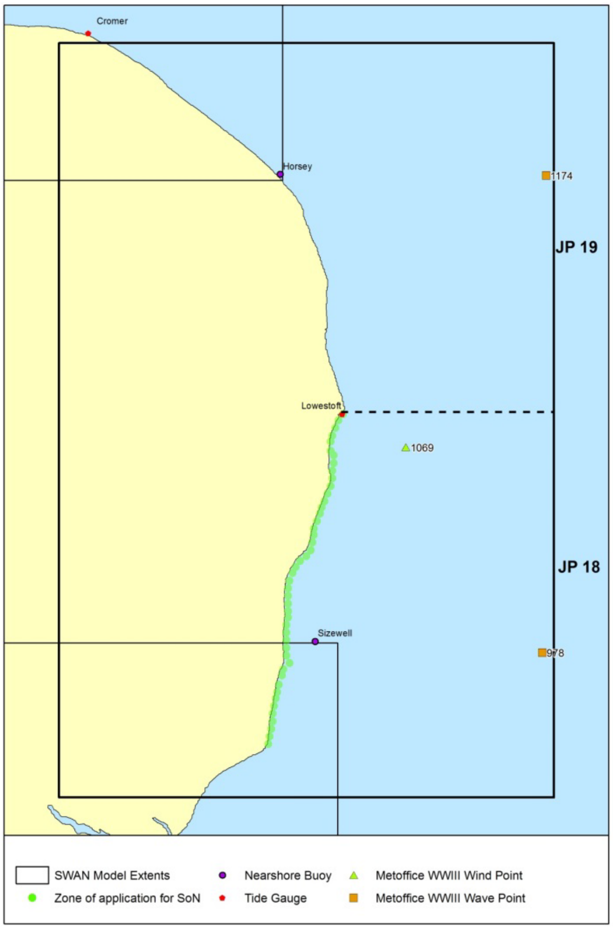

Figure C.2: Sources of data for study area

Note this is not the real extend of the SWAN grid, as it was further extended southwards.

The output of the analysis is a simulation of numerous scenarios (800) of extreme waves, wind and water level information that includes appropriate levels of dependence between the variables.

C.2. Stage 2: Wave transformation modelling

There was a SWAN grid already set up from the Coastal Boundaries State of the Nation project JP18. However, following closer examination of the area, the original SWAN 2D model was extended further south and rerun. The model was set up to transfer the offshore time series of wave conditions through to the nearshore at the study area. Ten nearshore points were selected pacing near the -10m (ODN) contour.

The model has been set-up on a 200m regular grid based on SeaZone TruDepth gridded, (approximately 30x30m resolution), bathymetry data. The data have been transformed from chart datum to Ordnance Datum using the UK Hydrographic Office's (UKHO) Vertical Offshore Reference Frame (VORF) data and methodology.

C.3. Model results

Figure C.3 is provided as a sample to illustrate the results of the SWAN model for one of theruns. This figure shows the significant wave height and mean wave direction predicted by SWAN for an North Easterly wave condition.

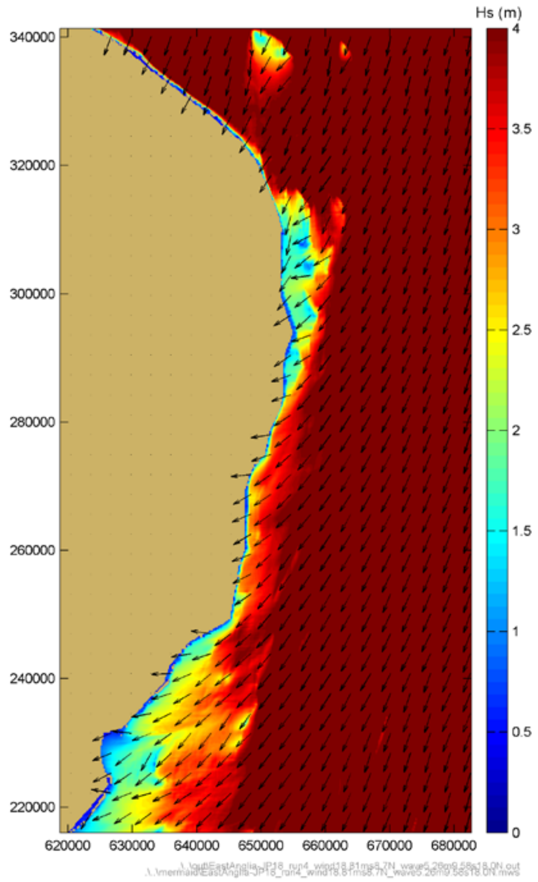

Figure C.3: Sample SWAN model output – predicted significant wave height and mean wave direction

Offshore Condition: Hs= 5.3m, Tp= 9.6s, Mean Wave Direction= 18°N, Wind Speed= 18.9ms^{-1}, Wind Direction= 8.7°N

D. Nearshore wave conditions

Nearshore wave conditions were predicted at a range of locations to provide input to the beach profile modelling (roughly along the -10m MSL contour and -5m MSL contour). The output locations are shown in Figure 4.8 and the corresponding coordinates of the points and levels relative to MSL are given within this appendix. Figure D.1 to Figure D.19 give the wave roses at the locations of the nearshore points.

Table 8.1: SWAN model nearshore point locations and levels along the -5m MSL contour

Point Label	Easting (m OSGB)	Northing (m OSGB)	Level (m below MSL)
501	632057	234641	4.94
502	632614	235471	5.02
503	633182	236102	5.14
504	633550	236722	4.98
505	634118	237352	5.11
506	634886	237993	4.8
507	635390.5	238488	4.98
508	636021	239255	4.69
509	636379	240074	4.61
510	636337	240873	5.09
511	636694	241693	5.21
512	637062	242313	4.86
513	637791.3	242987.8	4.92
514	638061.6	243756.4	5
515	638356	244384	5.07
516	638893.5	245041.1	4.75
517	639491	245645	5.94
518	640023.7	245932.6	4.9
519	640662.5	246255.5	4.96
520	641636	246759	5.91
521	642213.9	247108.5	4.82
522	642603	247410	4.63
523	643382.7	247761.3	4.78
524	643970	248083	4.53
525	644544.5	248417.7	4.64
526	645130.7	248807.3	4.74
527	645604.5	249372.4	4.84

Table 8.2: SWAN model nearshore point locations and levels along the -10m MSL contour

Point Label	Easting (m OSGB)	Northing (m OSGB)	Level (m below MSL)
1001	636210	235660	9.75
1002	636168	236458	9.95
1003	636315	237468	10.63
1004	636673	238287	10.07
1005	637030	239107	10.13
1006	637987	239958	10.24
1007	638355	240579	10.17
1008	638713	241398	9.87
1009	639070	242218	10.18
1010	639627	243049	10.29
1011	639996	243669	10.19
1012	640553	244499	10.16
1013	640921	245119	9.81
1014	640879	245918	9.83
1015	641457	246349	9.78
1016	642035	246780	10.16
1017	642813	247221	11.04
1018	643392	247652	9.9
1019	643781	247873	10.15
1020	644559	248314	9.58
1021	645337	248755	9.7
1022	645904	249386	10.33

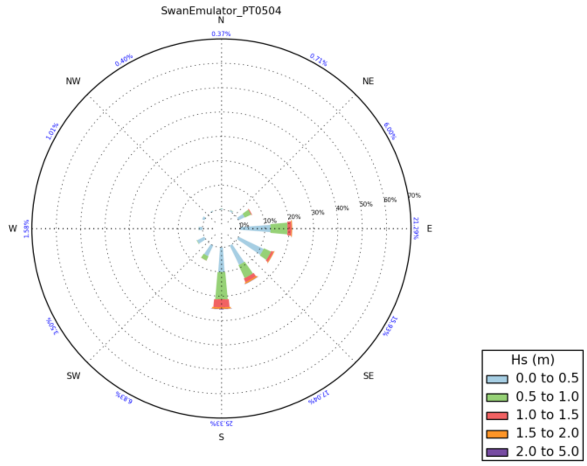

Figure D.1: Wave Rose: PT504

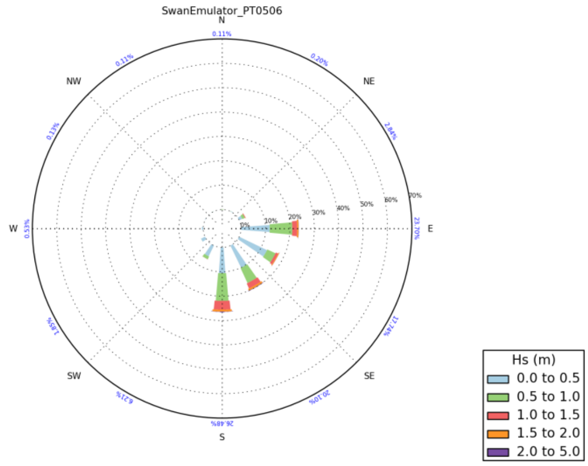

Figure D.2: Wave Rose: PT506

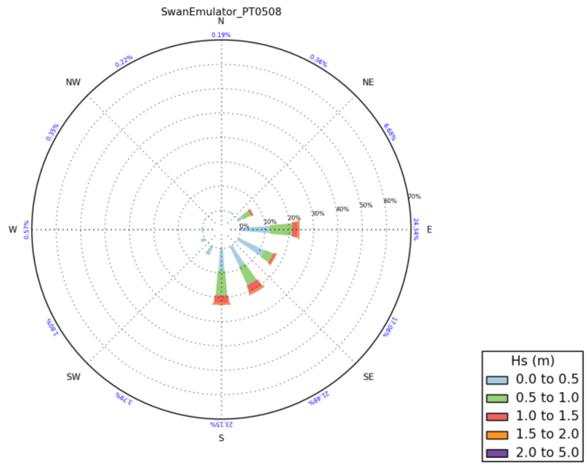

Figure D.3: Wave Rose: PT508

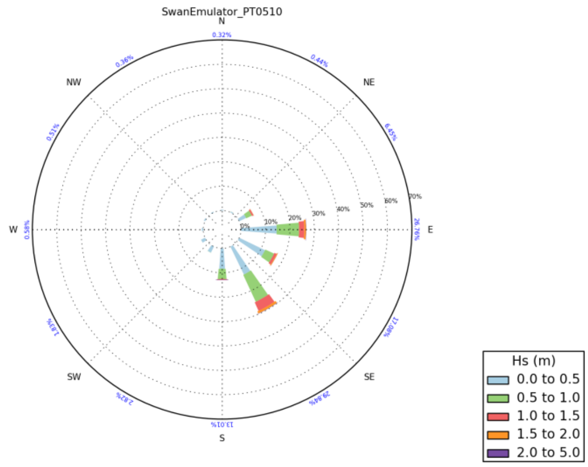

Figure D.4: Wave Rose: PT510

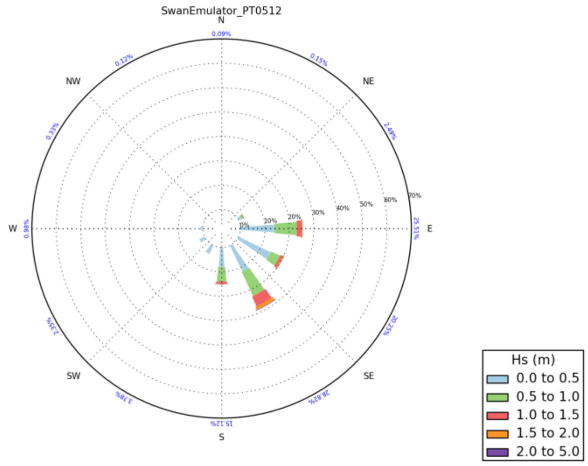

Figure D.5: Wave Rose: PT512

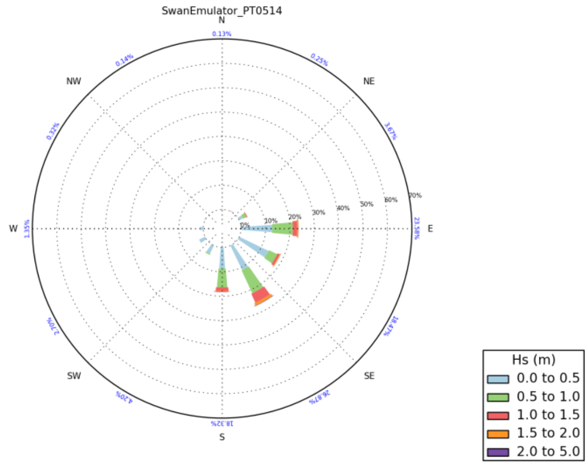

Figure D.6: Wave Rose: PT514

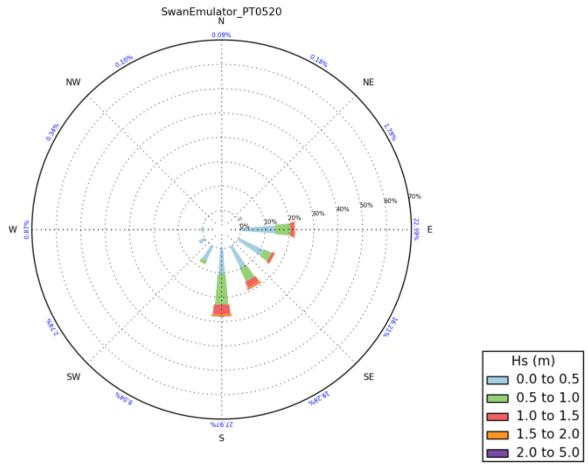

Figure D.7: Wave Rose: PT520

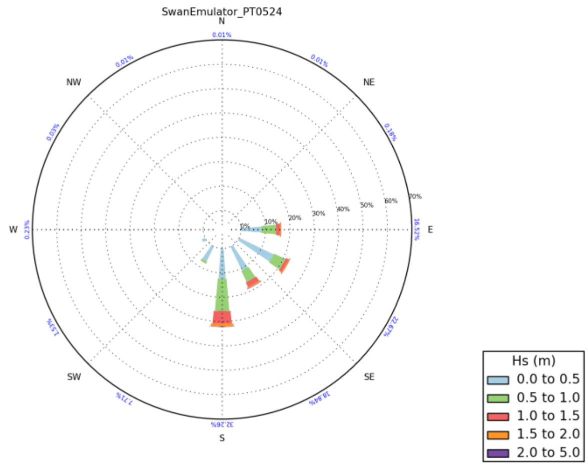

Figure D.8: Wave Rose: PT524

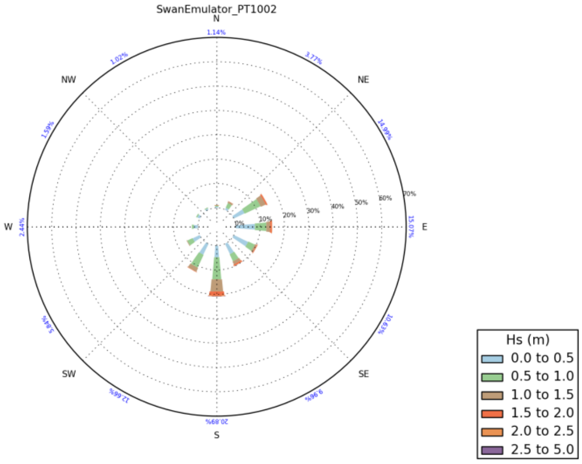

Figure D.9: Wave Rose: PT1002

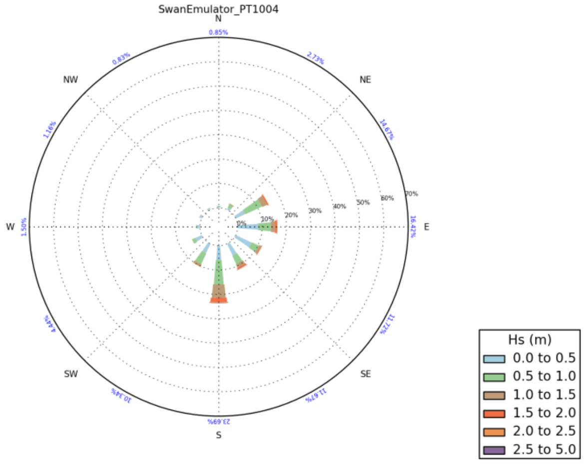

Figure D.10: Wave Rose: PT1004

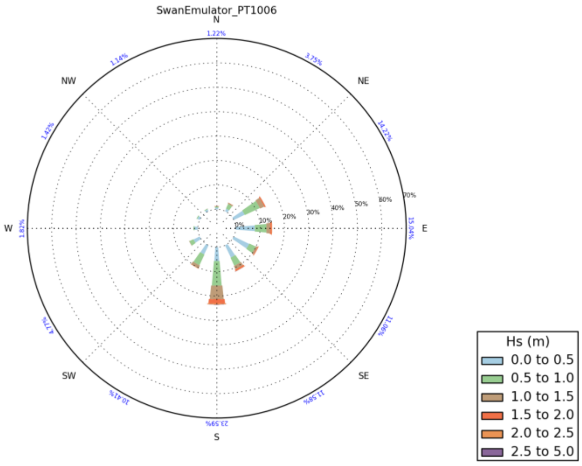

Figure D.11: Wave Rose: PT1006

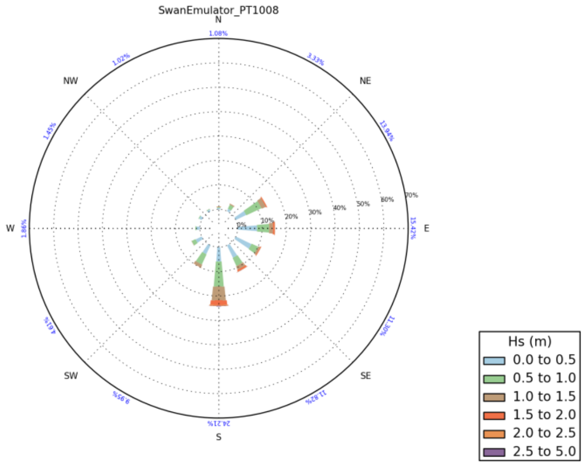

Figure D.12: Wave Rose: PT1008

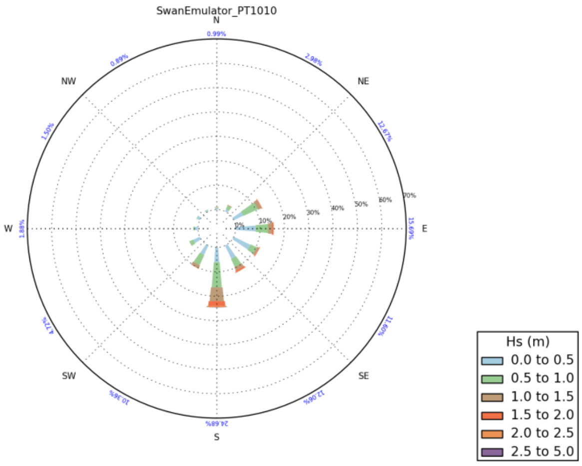

Figure D.13: Wave Rose: PT1010

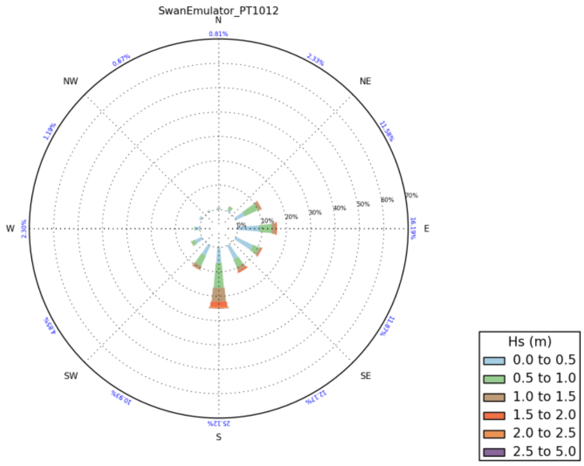

Figure D.14: Wave Rose: PT1012

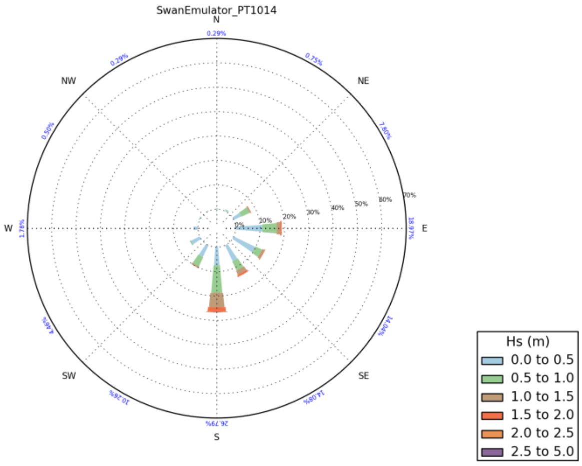

Figure D.15: Wave Rose: PT1014

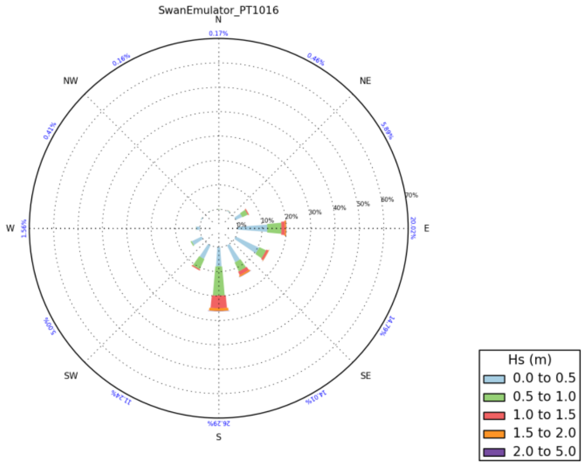

Figure D.16: Wave Rose: PT1016

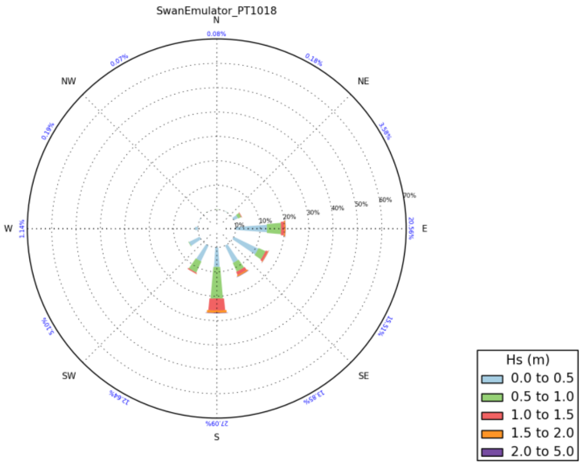

Figure D.17: Wave Rose: PT1018

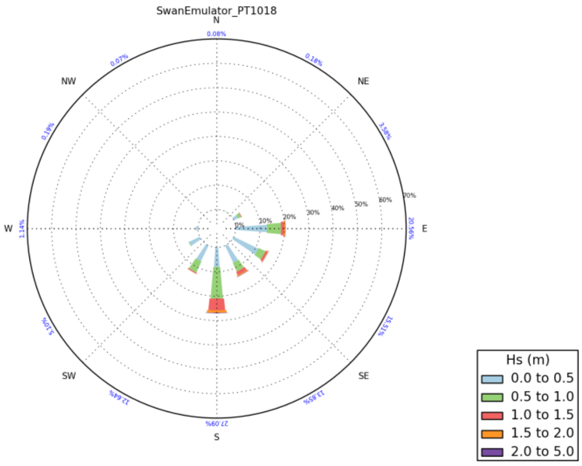

Figure D.18: Wave Rose: PT1020

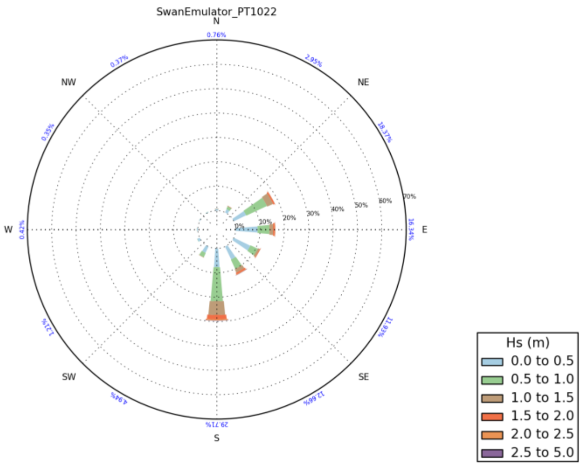

Figure D.19: Wave Rose: PT1022

E. Beachplan capability statement

E.1. Introduction

BEACHPLAN is a state-of-the-art model that simulates the evolution of the plan-shape of a beach. It was first developed at HR Wallingford around 40 years ago and has been in continuous development since, to become one of our most important tools on beach protection studies. BEACHPLAN uses a formulation of total longshore transport rate based on the widely used CERC formula. The model changes the coastline every time step, allowing for the correct simulation of the changing drift rates with time. BEACHPLAN models the following processes:

- Wave transformation:

  refraction,

  shoaling,

  diffraction.
- Structures:

  wave transmission through structures,

  bypassing of groynes and breakwaters,

  effect of seawalls on the sediment transport.
- Sediment transport:

  CERC formula,

  longshore drift due to alongshore variation of breaking wave height,

  cross-shore distribution of the longshore drift,

  limited toe of the beach.
- Active beach management techniques:

  beach renourishment,

  beach mining.

The beach plan-shape is specified by the position of a single contour, usually either Mean Water Level or a particular high tide level. The model assumes an average beach slope and does not consider short term changes in the beach profile. Offshore wave conditions are refracted into the position of breaking at each point along the beach. These breaking wave conditions are used to calculate the longshore drift at each of these points. The change in position of the specified contour is calculated from differences in the wave induced longshore transport.

In the presence of groynes, the process of diffraction has to be added to bypassing of the structure to accurately assess the evolution of the coastline either side of the groyne. BEACHPLAN models the change in bypassing of groynes by varying the rate of bypassing depending on the distance between wave breaking and the tip of the groyne. Hence, the bypassing will change for different wave heights and different locations of the beach profile.

In the presence of detached breakwaters, the processes of diffraction and wave transmission through the structure will create a rapid change in wave height and direction. In such cases, the second term of the CERC formulae, introduced by Ozase & Brampton (1980), gains increasing importance, as the gradient of wave height will introduce a substantial change in the longshore drift. The simulation of these processes in BEACHPLAN allows an accurate representation of the beach behaviour behind detached structures. The detached structures can have any shape which allows features such as artificial or natural islands to be represented.

The BEACHPLAN model has been designed as a first-stage tool in understanding the behaviour of a coast and the impact of engineering works upon it. Its relative simplicity and ease of use allow the model to be used by non-specialist engineers with a minimum of data, as well as allowing more detailed investigations by more experienced users.

E.2. The beach plan-shape mathematical model

The model is essentially a finite difference solution of the following equation which expresses the continuity of the volume of sediment moving along the shoreline,

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \qquad (1)$$

where:

Q is the volume rate of alongshore sediment transport,

x is the distance along the shore,

A is the beach cross-sectional area,

and t is time

The basic equation can be modified to

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} + q = 0 \qquad (2)$$

where q is used to express the volume of material brought onshore by wave action, added to the beach by artificial nourishment or removed from the beach by mining. By denoting the co-ordinate perpendicular to the beach by y, the beach cross-sectional area, A, can then be expressed by the product of y and a depth D. If D is assumed not to vary with time, then equation (2) can be written

$$\frac{\partial Q}{\partial x} + D\frac{\partial y}{\partial t} + q = 0 \qquad (3)$$

Starting from some initial position, y = y (x), the model evaluates successive beach positions at time intervals Δt, at points along the shore separated by Δx. So for each ordinate x_i (separated from its neighbour $x_{i+1}$by Δx) we have $y_i(0)$, $y_i(\Delta t)$, $y_i(2\Delta t)$ and so on. The model used is of a type known as 'one line', that is to say that the beach position is given by the location of a single contour which represents, say, the high water line. An important factor in the accuracy of the model is the representation of the alongshore rate of sediment transport, Q, which is dominated by the breaking waves. For waves of small unevenness in height along a beach with nearly straight contours, Q can be well approximated by

$$Q = K_1(\gamma_s)^{-1} E_b (nC)_b \left(\sin 2\alpha_b - 2K_2 \frac{\partial H_b}{\partial x} \cot \beta \cos \alpha_b \right) \quad (4)$$

where

K_1, K_2	are non-dimensional coefficients
E	is the wave energy density = 0.125 ρ gH^2
H	is the significant wave height
g	is the acceleration due to gravity
ρ	is the water density
γ_s	is the submerged weight of beach material in place
nC	is the group velocity of the waves
α	is the angle between their crests and the local depth contours
tanβ	is the mean slope of the beach face, and
b	denotes breaking wave conditions (where used as a subscript).

The first term in equation 4 is the well known CERC (Scripps) formula and describes the alongshore sediment transport due to obliquely breaking waves. Other well known formulae can be substituted for this in the model. The second term takes into account the transport created by any alongshore variation in breaking wave height, which becomes important for beaches in the lee of headlands or breakwaters where diffraction effects are significant. Very little practical work has been carried out into the assessment of K_2. Purely theoretical calculations can produce a value of 3.2 (Ozasa and Brampton 1980), but work by Kraus & Harikai (1983) has suggested a lower figure may be more correct, in the range from 0.3 to 0.7. For sand beaches a value of K_2 = 0.5 is normally used.

The height, period and direction of the breaking waves, however, are more difficult to prescribe. Although it is occasionally possible to represent the mean annual wave activity at a site by a single breaking wave condition, typically several or many such conditions are required. Often, it is necessary to supplement such wave data, either with results from the analysis of previous beach plan-shape changes in the study area, or by using offshore wave conditions and predicting the resulting conditions at wave breaking by means of wave refraction analysis.

E.3. Results

Output from the model is in the form of tables (displayed on the screen or listed to the line-printer), or as plots showing beach plan-shape ranges. Files are also created allowing easy continuation of model runs if required. In addition, the results are also stored in a file compatible with spreadsheets, so that further analysis can be carried out by the user.

E.4. References

Ozasa H and Brampton A H. Mathematical Modelling of Beaches Backed by Seawalls. Coastal Eng. 1980.

Kraus N C and Harikai S. Numerical model of the shoreline change at Oarai Beach. Coastal Eng No 1, 1983.

F. DRCALC capability statement

Longshore drift on a beach is caused primarily by waves breaking at an angle to the coast. The rate of transport depends both on the wave height at breaking and the angle that the waves make to the beach normal. The DRCALC model calculates the total potential longshore drift produced by a given wave climate using the widely used CERC formula.

The potential drift rate is the drift that would occur on an open beach covered with sufficient beach material such that all the wave energy is employed moving the beach. In calculating this upper bound 'potential' drift rate the model first refracts each wave condition the short distance from the wave prediction point in to its breaking point using locally parallel contoured refraction. The CERC formula is then used to predict the potential drift from the breaking wave height and direction. These individual values of drift are summed according to the frequency of occurrence of the wave conditions that produced them to give both gross and net annual drift rates.

An important feature of the DRCALC model is to predict the cross-shore distribution of the total potential longshore drift. This takes into account both the distribution of tidal heights and balance between waves of different heights and direction. For any given wave condition at a given tidal level the cross-shore distribution of longshore drift can be related to the position of the breaker point using an empirical formula based on field and physical model tests. Larger waves break further offshore so cause their peak drift in deeper water. The DRCALC model calculates the overall cross-shore distribution of the net and gross longshore drift.

G. Potential longshore drifts

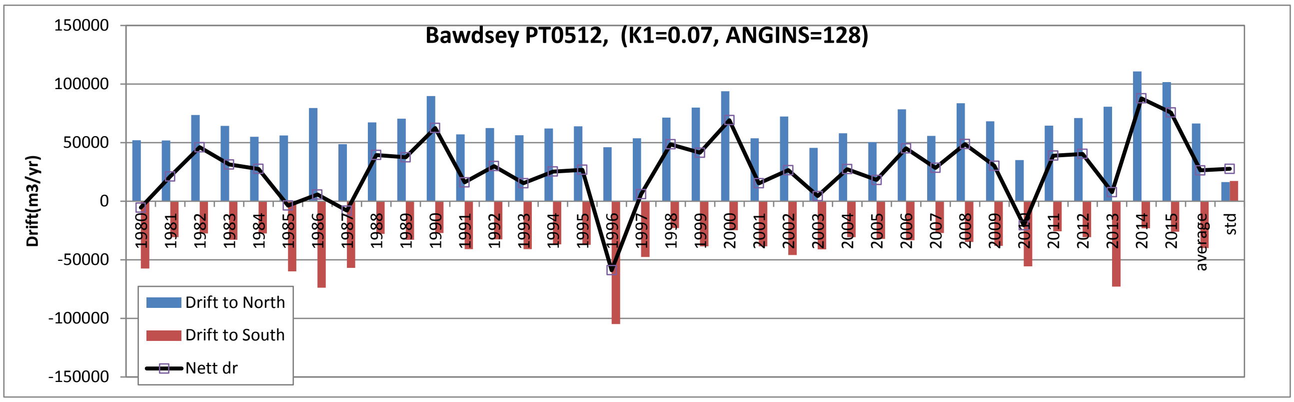

Figure G.1: Potential longshore drift from 1980 to 2015. Point PT0512 (S of Shingle Street)

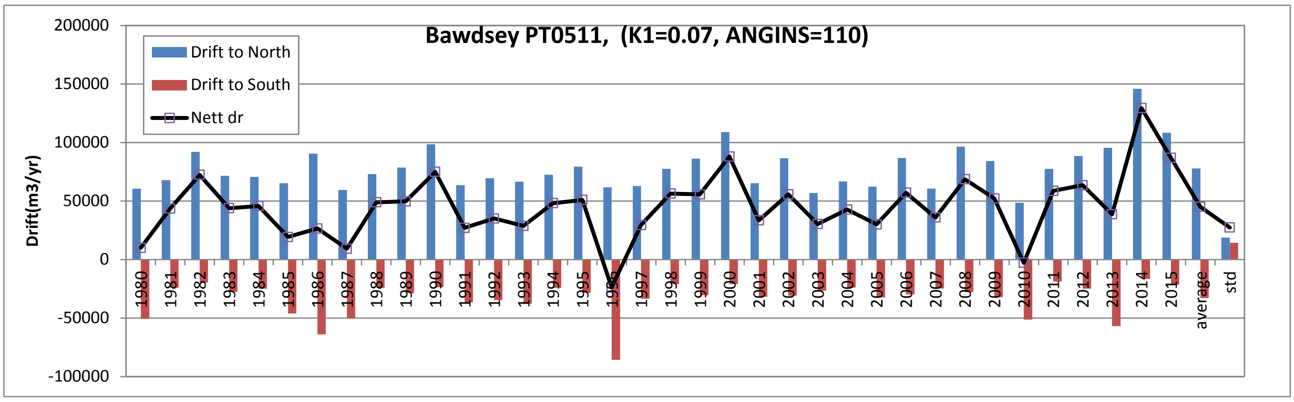

Figure G.2: Potential longshore drift from 1980 to 2015. Point PT0511

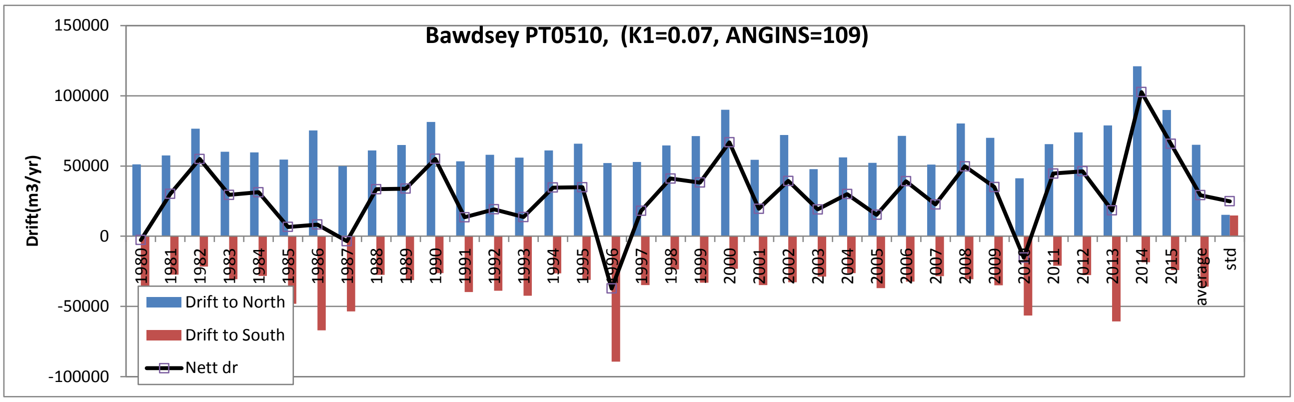

Figure G.3: Potential longshore drift from 1980 to 2015. Point PT0510

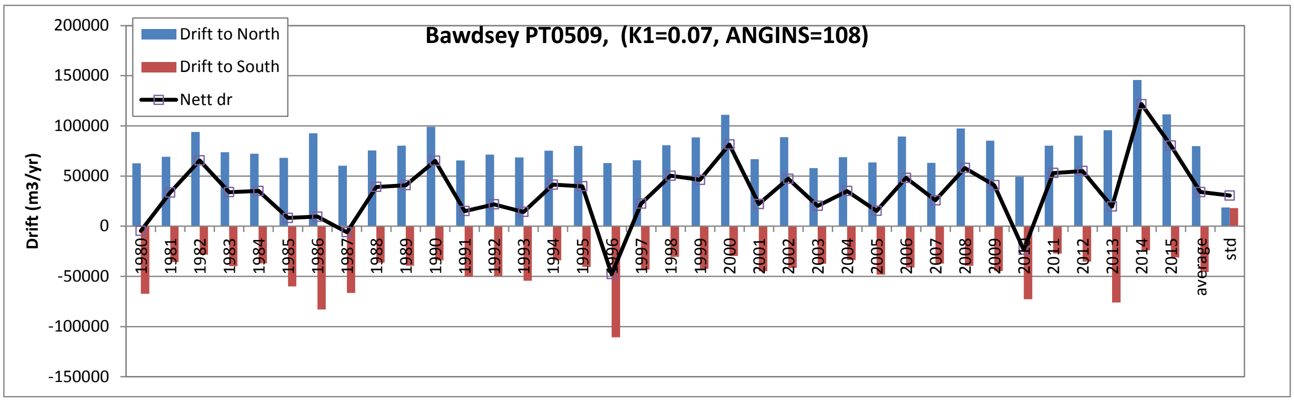

Figure G.4: Potential longshore drift from 1980 to 2015. Point PT0509 (East Lane)

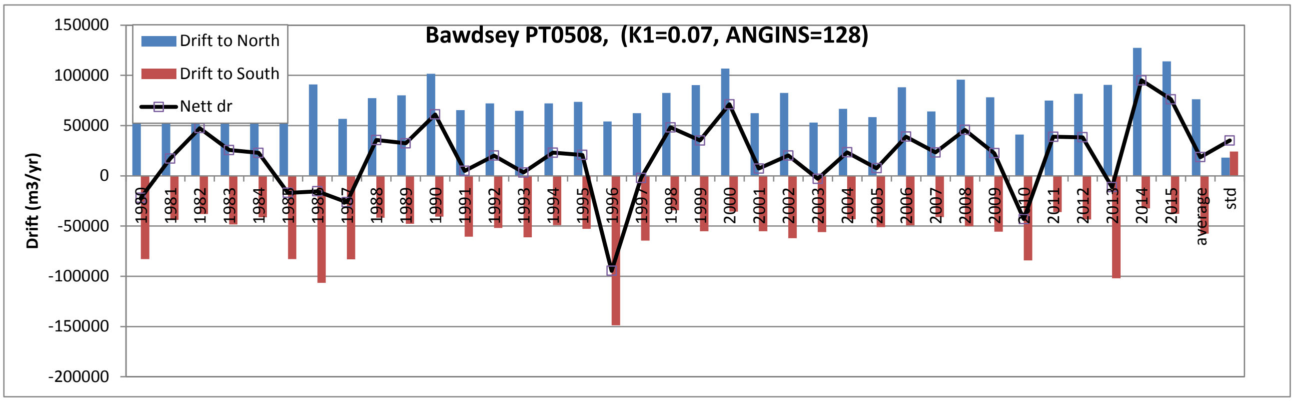

Figure G.5: Potential longshore drift from 1980 to 2015. Point PT0508

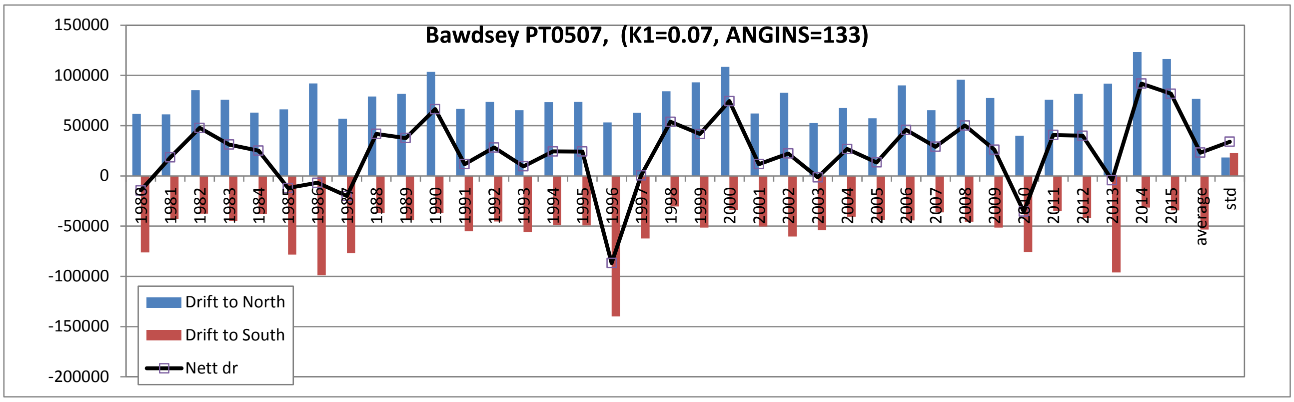

Figure G.6: Potential longshore drift from 1980 to 2015. Point PT0507

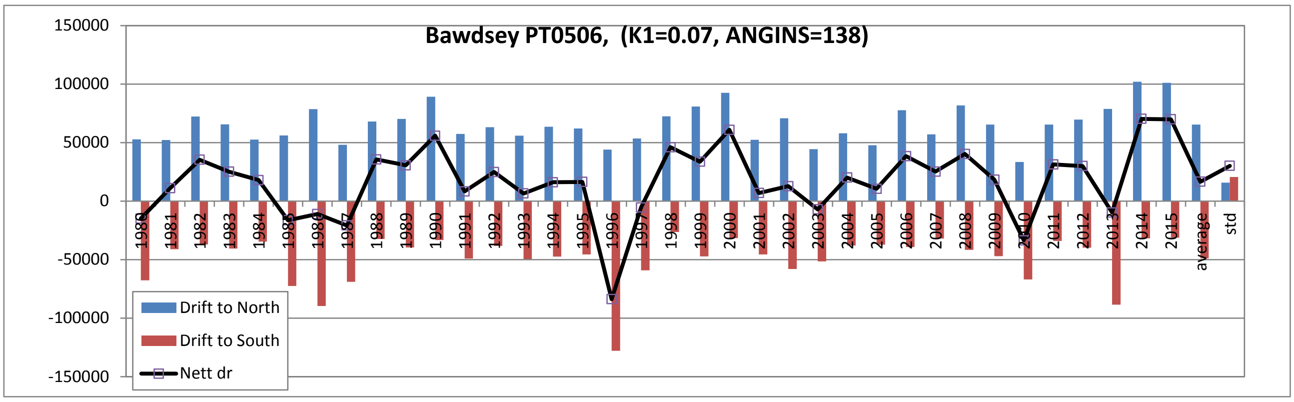

Figure G.7: Potential longshore drift from 1980 to 2015. Point PT0506

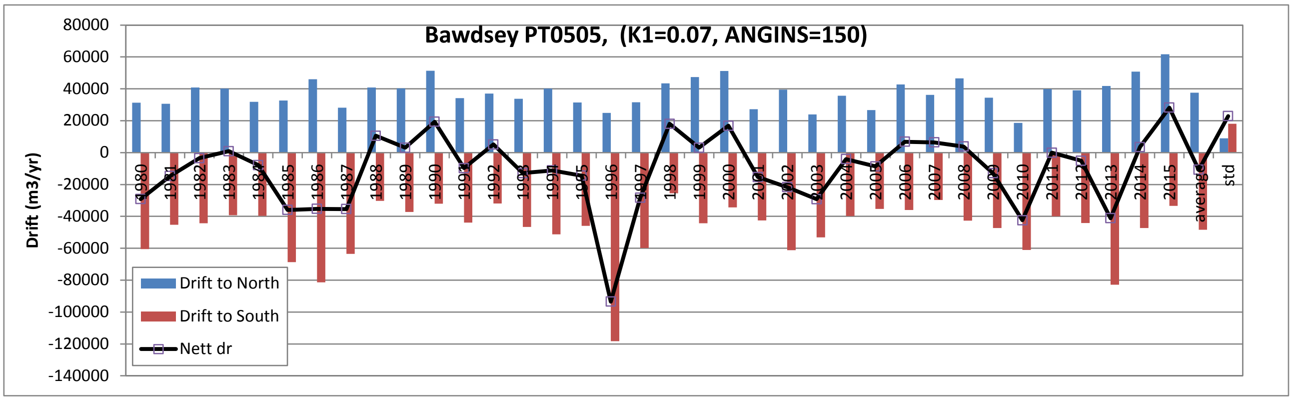

Figure G.8: Potential longshore drift from 1980 to 2015. Point PT0505 (Bawdsey Manor)

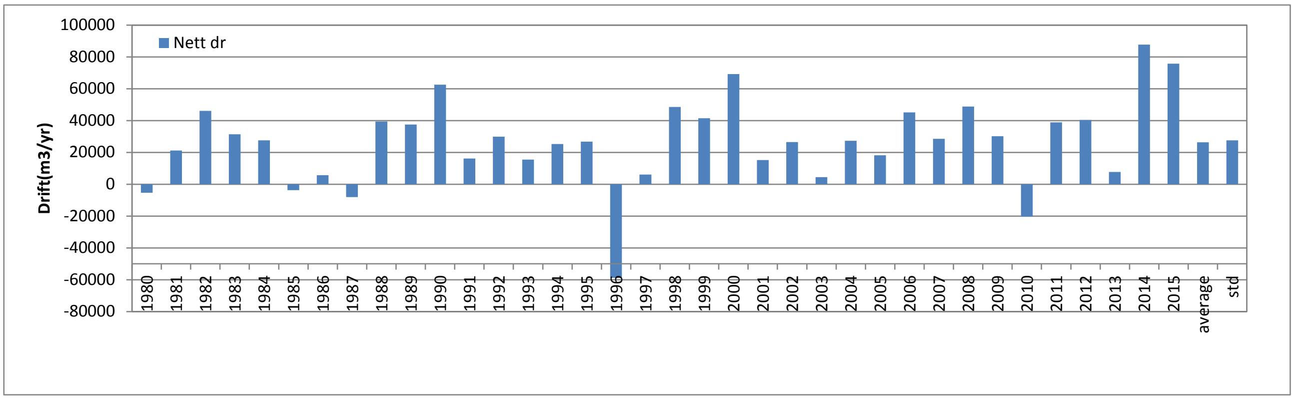

Figure G.9: Potential net longshore drift from 1980 to 2015. Point PT0512 (S of Shingle Street)

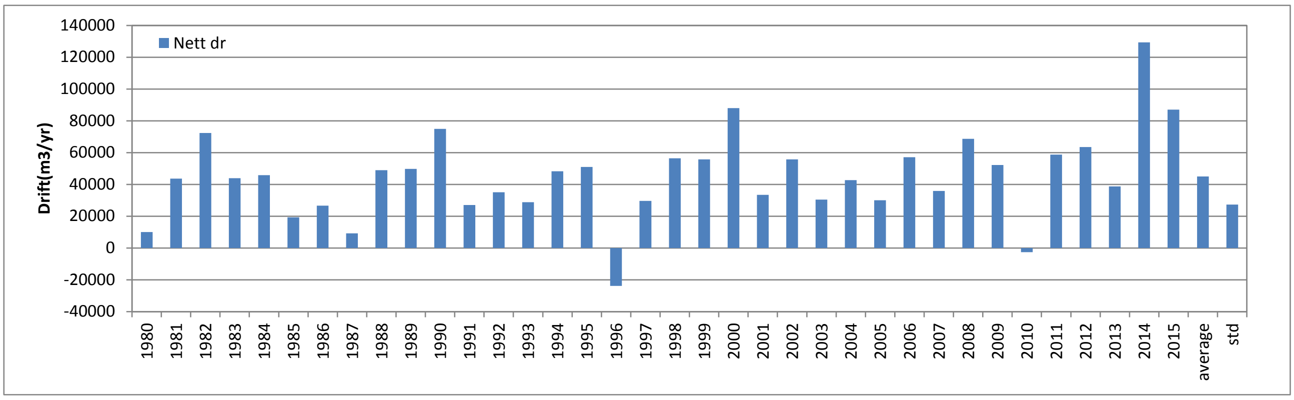

Figure G.10: Potential net longshore drift from 1980 to 2015. Point PT0511

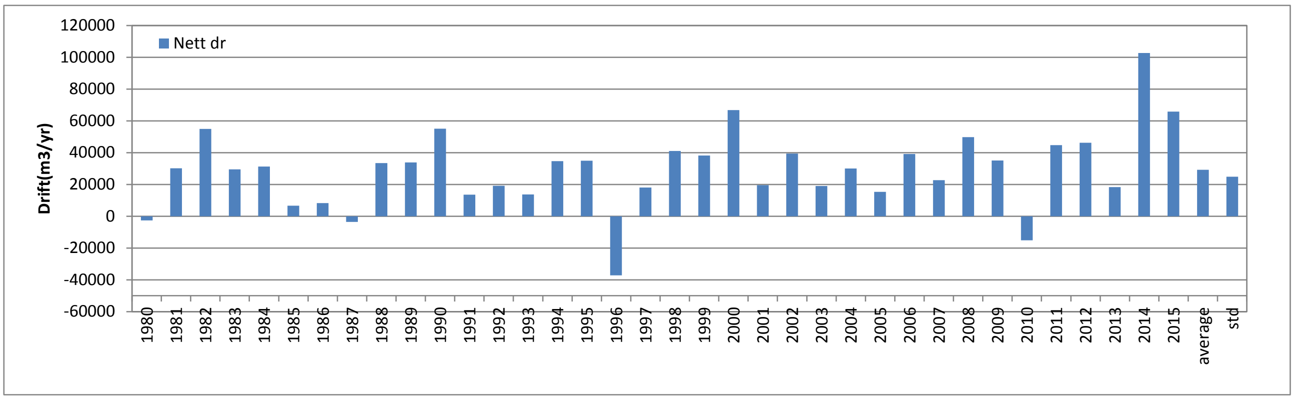

Figure G.11: Potential net longshore drift from 1980 to 2015. Point PT0510

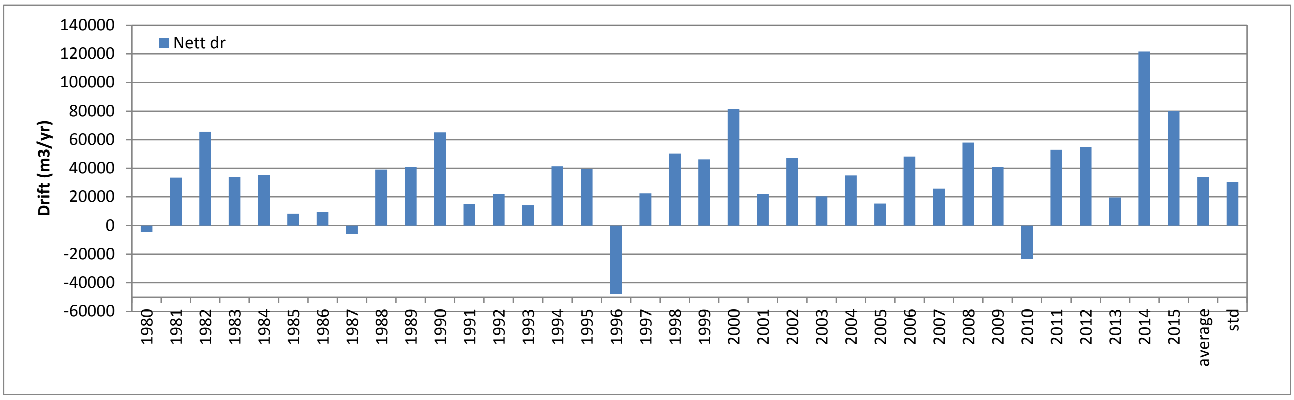

Figure G.12: Potential net longshore drift from 1980 to 2015. Point PT0509 (East Lane)

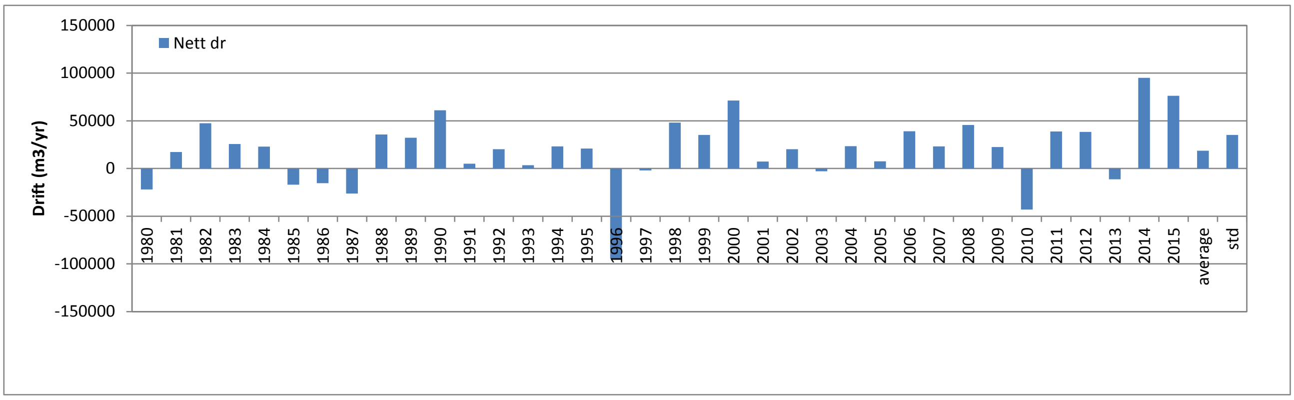

Figure G.13: Potential net longshore drift from 1980 to 2015. Point PT0508

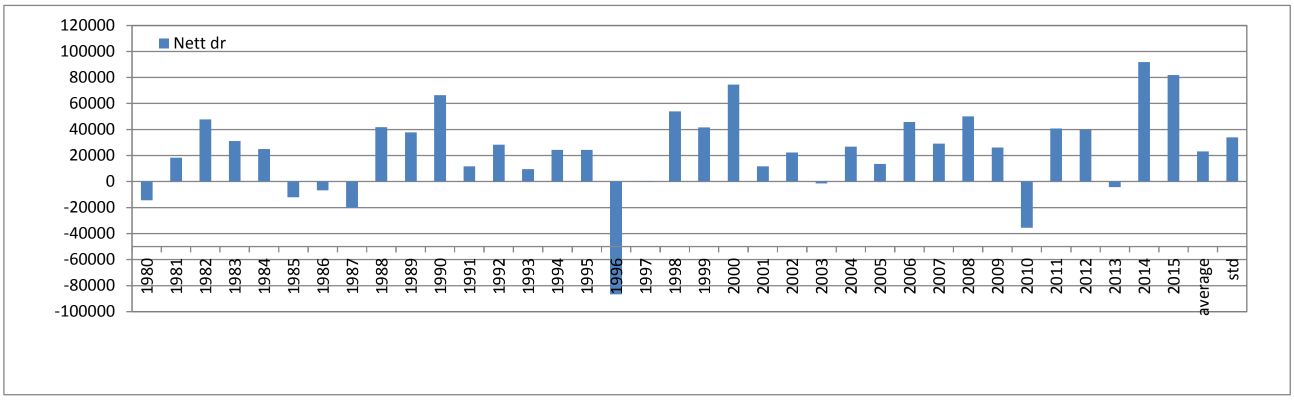

Figure G.14: Potential net longshore drift from 1980 to 2015. Point PT0507

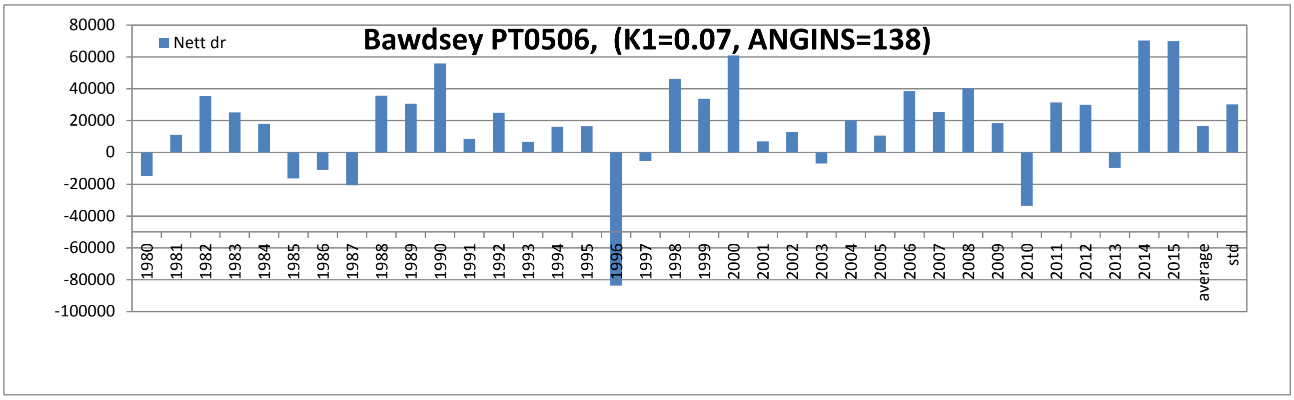

Figure G.15: Potential net longshore drift from 1980 to 2015. Point PT0506

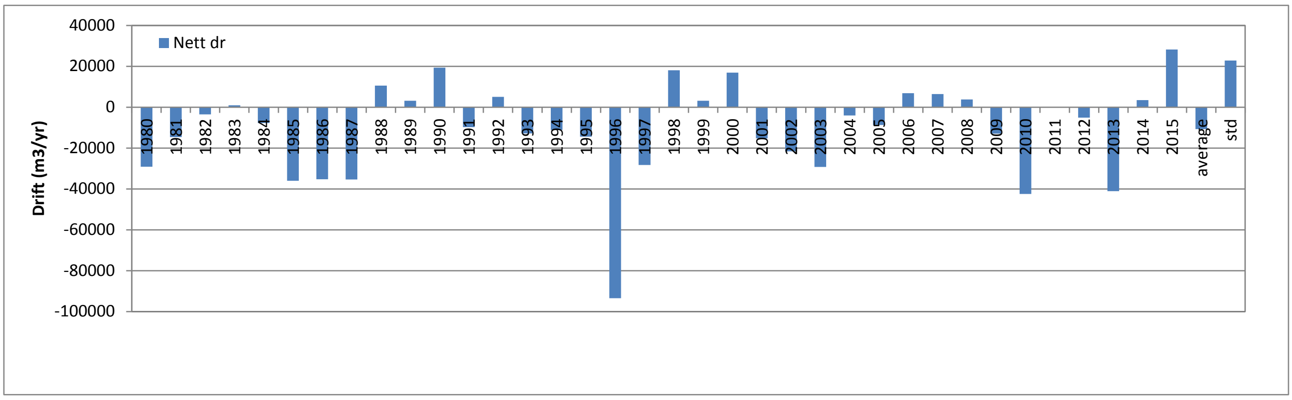

Figure G.16: Potential net longshore drift from 1980 to 2015. Point PT0505 (Bawdsey Manor)

H. Sensitivity to climate change and wave chronology

The results of the shoreline modelling using the 40 different synthetic timeseries described in Section 5.4.4 are presented within this appendix. They have been separated into Present day results, presented in Section H.1, where no sea level rise was applied to the offshore wave conditions and SLR results, presented in Section H.2, where a sea level rise of 0.45m was applied to the offshore wave conditions.

It is worth reminding the reader that the modelling of the future change to the beaches was simplified by assuming there was a sufficient width of beach landward of the 2012 shoreline that it could erode to any extent predicted but retain its character. (This of course is unrealistic but does allow the use of Beachplan to compare and contrast different climatic scenarios and hence assess the possible challenges faced by any proposed beach management scheme).

H.1. Present day results

Present day wave conditions, i.e. not applying any sea level rise, using time series 1 to 20 in Table 5.3, are discussed in this section. These results show the influence of the sequencing of the nearshore waves as well as that of the rotation of the wave directions.

The shoreline position at the end of the 50 years for each of these runs is shown in Figure H.1, so that the general envelope of movement is appreciated. The final shoreline position varies of the order of a maximum of 100m with the different runs, which is quite important. In the next set of plots, we have separated the different contributions to this variability.

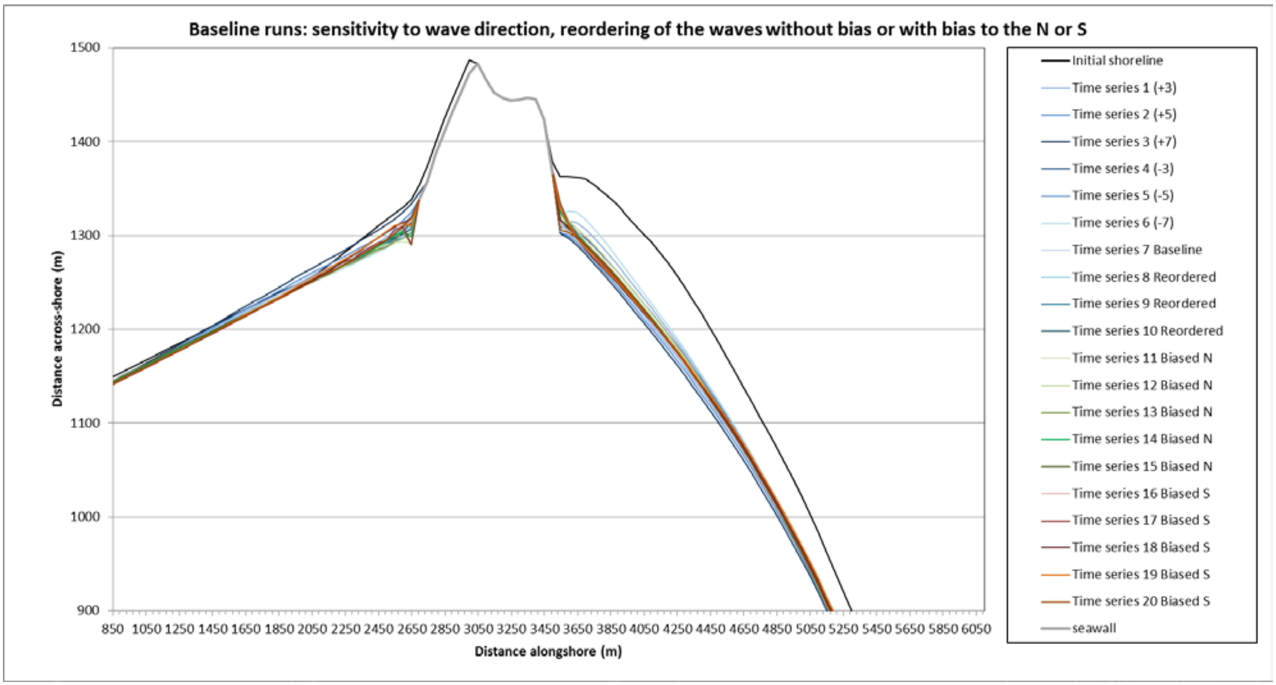

Figure H.1: Present day wave conditions results: all runs

Sensitivity to inshore wave direction

It is customary to do sensitive tests to the change in wave direction inshore and its effect in shoreline evolution although it is not in the climate change recommendations. Normally, variations of up to ± 5º are applied. In this case, and due to the high obliquity of the waves in this region, we have also applied a more extreme ± 10º. The results of these runs are shown in Figure H.2 in terms of shoreline change (with respect to the initial shoreline of 2012). These figure shows the shoreline change at the end of the 50 years for each of the wave direction change runs, together with the baseline. As expected, the change in wave direction rotates the resultant shoreline position, so that those runs where the wave directions have been increased (rotated clockwise, in blue in the graph) result in less erosion (even accretion sometimes) at the North of East Lane and more erosion along Bawdsey cliffs and towards Bawdsey Manor. For those runs where the wave directions have been decreased (rotated anti-clockwise, in orange in the graph) the erosion at the North of East Lane increases whereas the erosion along Bawdsey cliffs and towards Bawdsey Manor decreases. It is worth remarking here that the rotation of the wave direction has been applied to all the points alongshore the model, to represent a substantial shift in the balance between north-easterly and southerly/ south-westerly waves offshore from the Suffolk coastline.

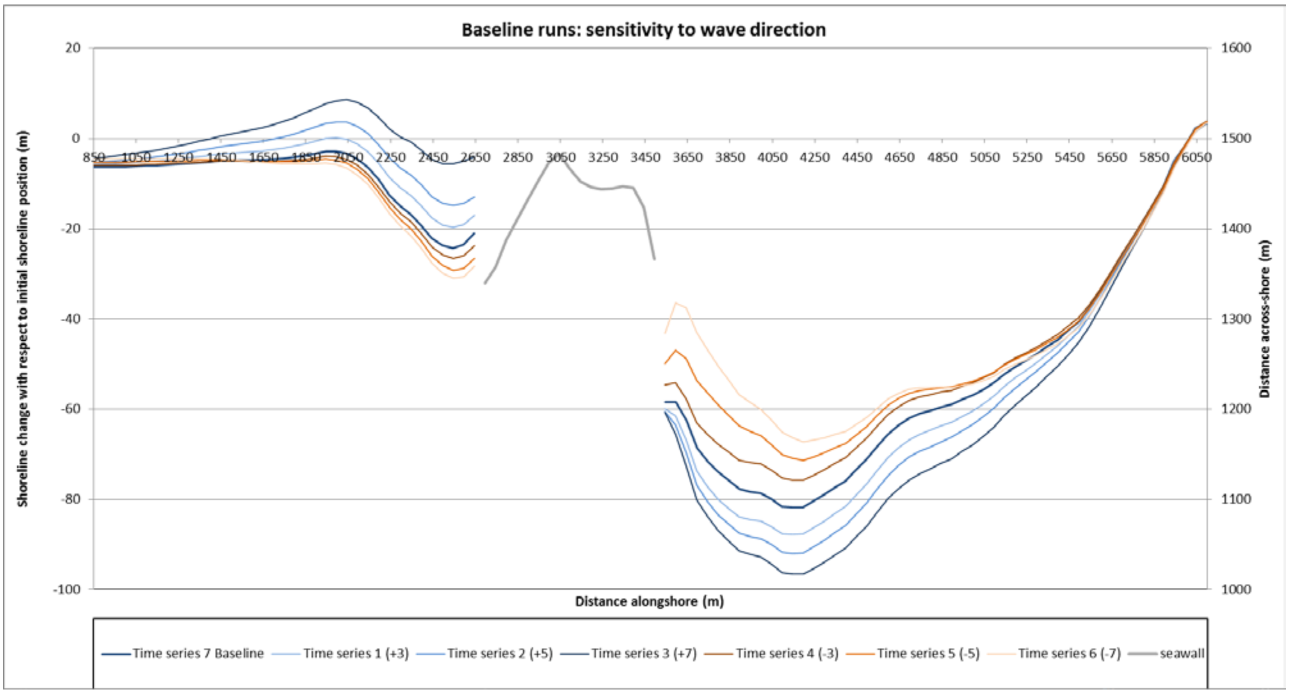

Figure H.2: Present day wave conditions results: influence of rotating the wave direction

The seawall is shown for reference purposes, its distance alongshore measured with respect to the secondary y-axis.

In order to see the difference this rotation of the waves has on longshore drift rates, Figure H.3 has been created. The annual drifts for the 50 years for the one of the most extreme conditions (+10 degrees) has been compared to those in the baseline in this figure. The result of this rotation is greatest along the Bawdsey cliffs frontage, where the drift rates increase by about 50-100%, whereas in the Hollesley Bay this rotation produced much less variation in the yearly drift rates.

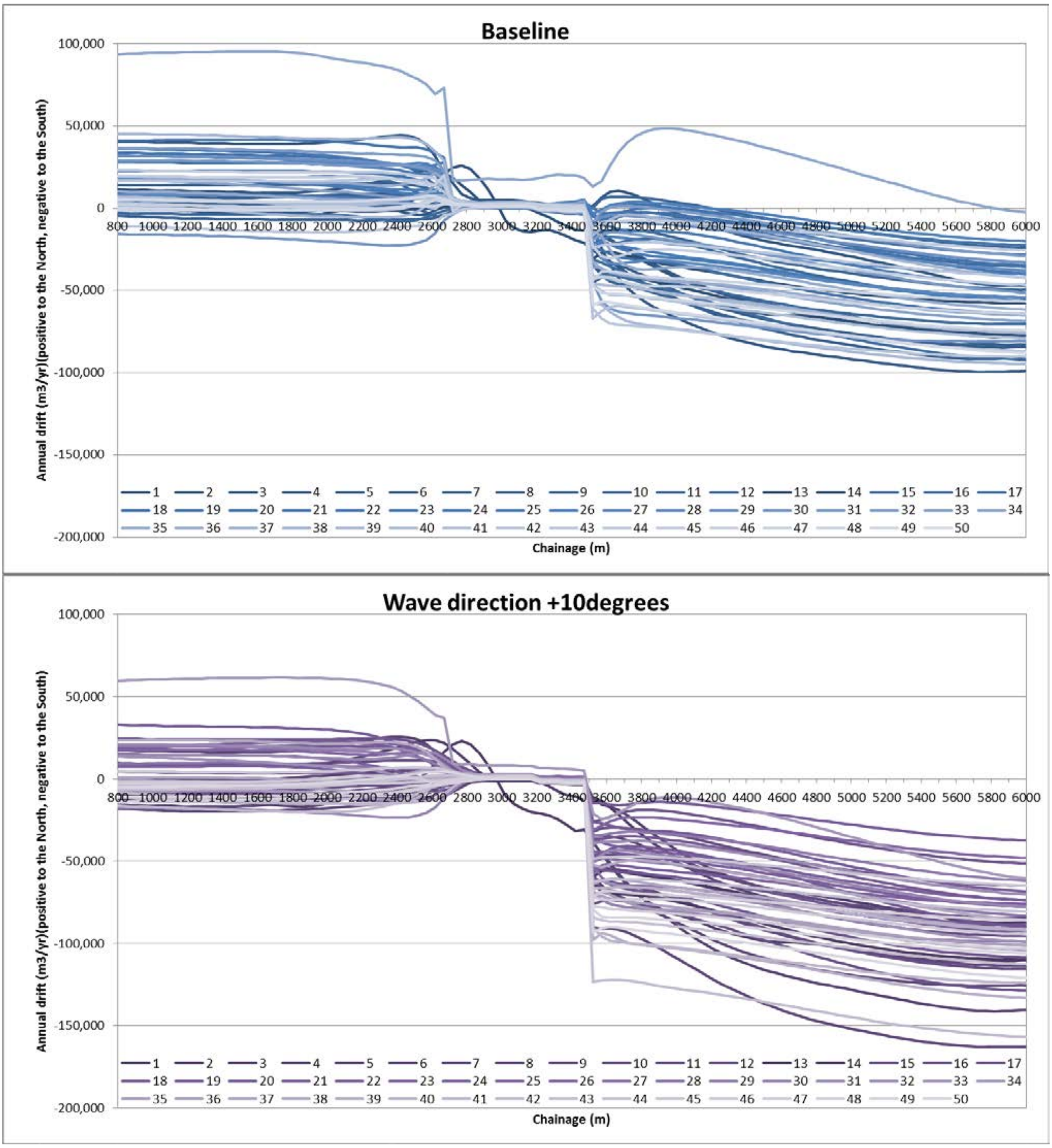

Figure H.3: Annual drifts for baseline case and for wave direction $+10^0$

Wave Sequencing sensitivity

Sensitivity to wave sequencing has been carried out using the wave time series 7-20 listed in Table 5.3. The results have been presented in Figure H.4 as envelopes of shoreline change, presenting the mean and standard deviation of the shoreline positions at the end of the simulations. The envelope of shoreline change is greater just to the north of East Lane and just to the south of it, both locations where the interactions with the seawall occur. (We have assumed in our Beachplan modelling that the beaches extend sufficiently far landwards at all points along the study frontage to allow the amount of erosion predicted).

The changes in shoreline change with biased sequencing show that the area at the north of East lane is less strongly affected to variations of the waves towards more N/NE or more SW than the area of the Bawdsey cliffs.

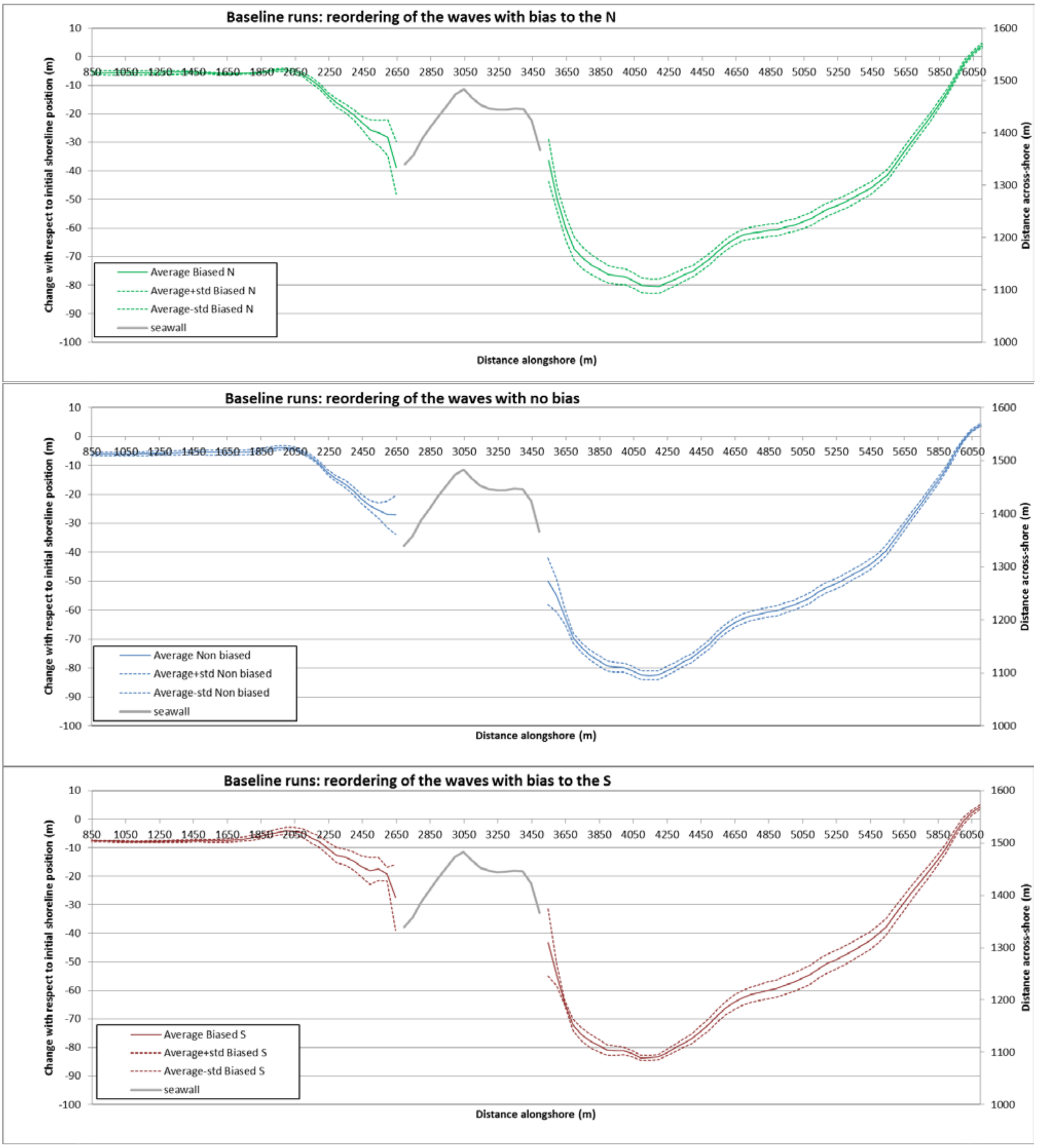

Figure H.4: Baseline runs: sensitivity to reordering of the waves, with or without bias

The seawall is shown for reference purposes, its distance alongshore measured with respect to the secondary y-axis.

The time evolution along the four transects shown in Figure 5.14 has been plotted in Figure H.5 for one of the non-biased wave reordered sequences, in order to compare it to the reference baseline transect evolution presented in Figure 5.15. This gives an idea of the importance of the sequencing in shoreline evolution. The variability of the transects is similar to the one in Figure H.5 but the evolution is very different, in special close to East Lane. This figure shows:

- In Hollesley Bay (Chainage 1645), the modelling results show quite an steady erosion of about 10m in 50 years (0.2m/yr).
- Right at the north of East Lane (Chainage 2495). This transect seems to be very variable, with periods of accretion and erosion with an underlying erosion trend of up to 38m in 50 years (0.8m/yr).
- To the south of East Lane (Chainage 3645), where there is still influence of the structures in East Lane, the transect and the transect seems to vary with erosion and accretion periods, although an underlying erosion trend of about 75m in 50 years (1.3m/yr).
- Along Bawdsey cliffs (Chainage 4645), towards Bawdsey Manor, the erosion seems quite steady with the largest trend of about 87m in 50 years (1.7m/yr).

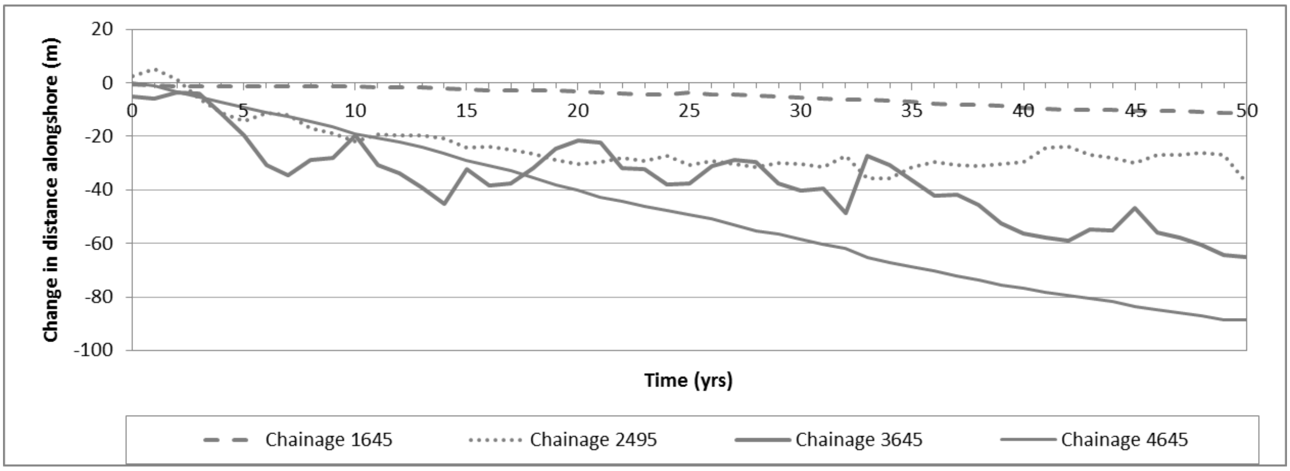

Figure H.5: Re-ordered with no bias case - Time evolution at different transects

H.2. S.L.R Results

A total of 20 runs were carried out with climates where an increase of sea level had been applied to the offshore waves. Similarly to the present day runs, sensitivity to wave direction inshore and sequencing of the waves with or without bias was carried out, using time series 21 to 40 in Table 5.3.

The shoreline position at the end of the 50 years for each of these runs is shown in Figure H.6, so that the general envelope of movement is appreciated. The final shoreline position varies of the order of a maximum of 100m with the different runs, the same order of magnitude as with the present day wave conditions seen in Figure H.1. In the next set of plots, we have separated the different contributions of this variability.

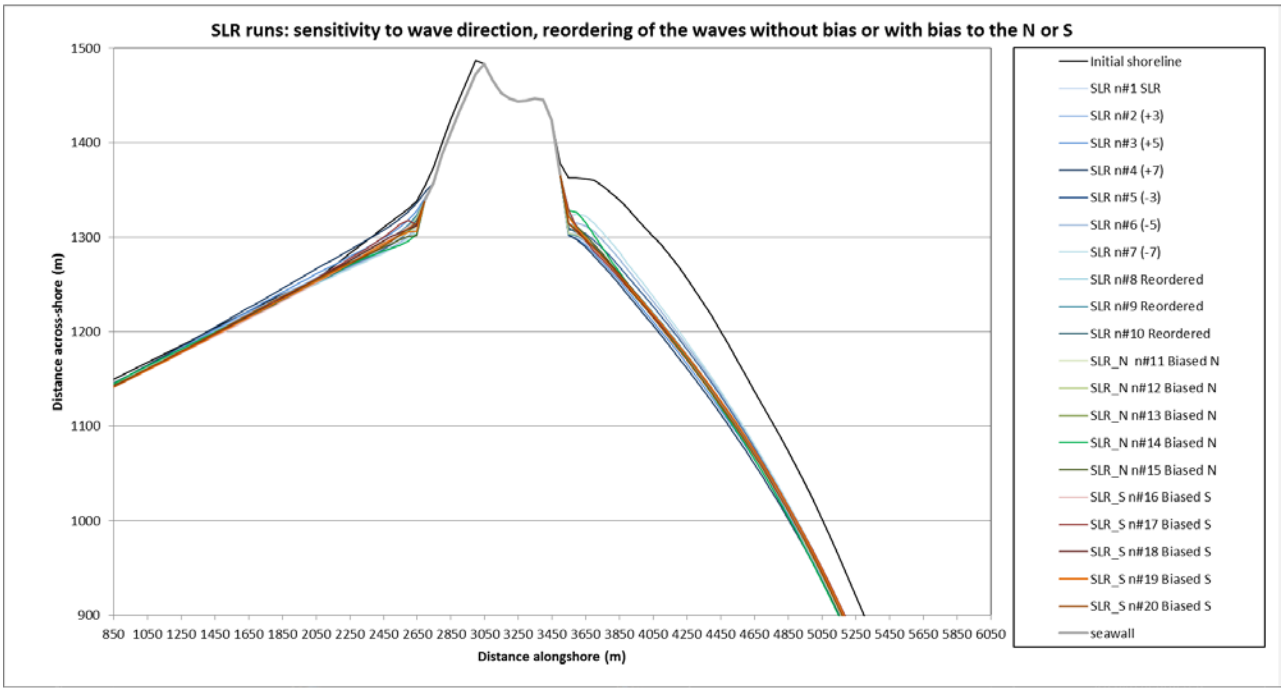

Figure H.6: S.L.R. wave conditions results: all runs

Sensitivity to inshore wave direction

Sensitivity to the inshore wave direction is presented in Figure H.7 in terms of shoreline change (with respect to the initial shoreline of 2012). These figure shows the shoreline change at the end of the 50 years for each of the wave direction change runs, and is comparable to Figure H.2 where the same analysis was done for the present day wave conditions. The results are very similar with differences in the shoreline positions only of the order of 2-4m between the present day and the equivalent SLR run, therefore concluding the same: those runs where the wave directions have been increased (rotated clockwise, in blue in the graph) result in less erosion (even accretion sometimes) at the North of East Lane and more erosion along Bawdsey cliffs and towards Bawdsey Manor. Equally, in those runs where the wave directions have been decreased (rotated anti-clockwise, in orange in the graph, the erosion at the North of East Lane aggravates whereas the erosion along Bawdsey cliffs and towards Bawdsey Manor becomes less. The other conclusion from this comparison is that the effects of rotating the inshore waves are much more important than those by imposing an increased sea level in the offshore wave conditions.

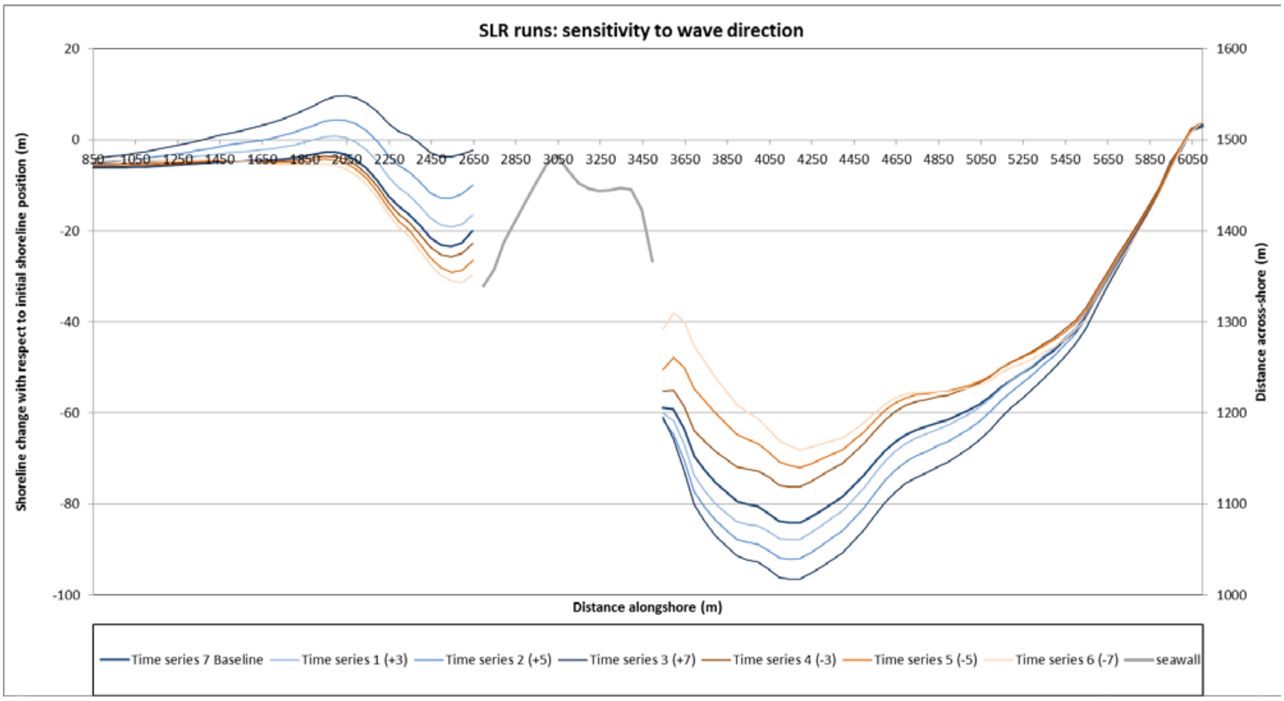

Figure H.7: S.L.R. wave conditions results: influence of rotating the wave direction

The seawall is shown for reference purposes, its distance alongshore measured with respect to the secondary y-axis.

Effects of S.L.R

Sensitivity to wave sequencing has been carried out with time series 27-40 in Table 5.3. The results have been presented in Figure H.8 as envelopes of shoreline change, presenting the mean and standard deviation of the shoreline positions at the end of the simulations. This figure is comparable to Figure H.4 which was done for the present day wave conditions without the added sea level. The differences between both figures are mainly in the biased sequencing, especially in the northerly-biased ones. The average position seems to retreat about 5m less in the south of Hollesley Bay for the SLR but retreat about 5m along the centre part of Bawdsey cliffs area in comparison with the present day wave climates. The differences between the SLR runs and the present day results for the non-biased sequencing and the south biased sequencing is much more subtle. Therefore, one can conclude that the influence of the SLR on the wave conditions that produce a northerly drift (SW mainly) is important. In the future, if SLR was to happen to the extent predicted and there were more southerly waves, the erosion around the Bawdsey cliffs area would accelerate and the erosion at the south of Hollesley Bay would reduce.

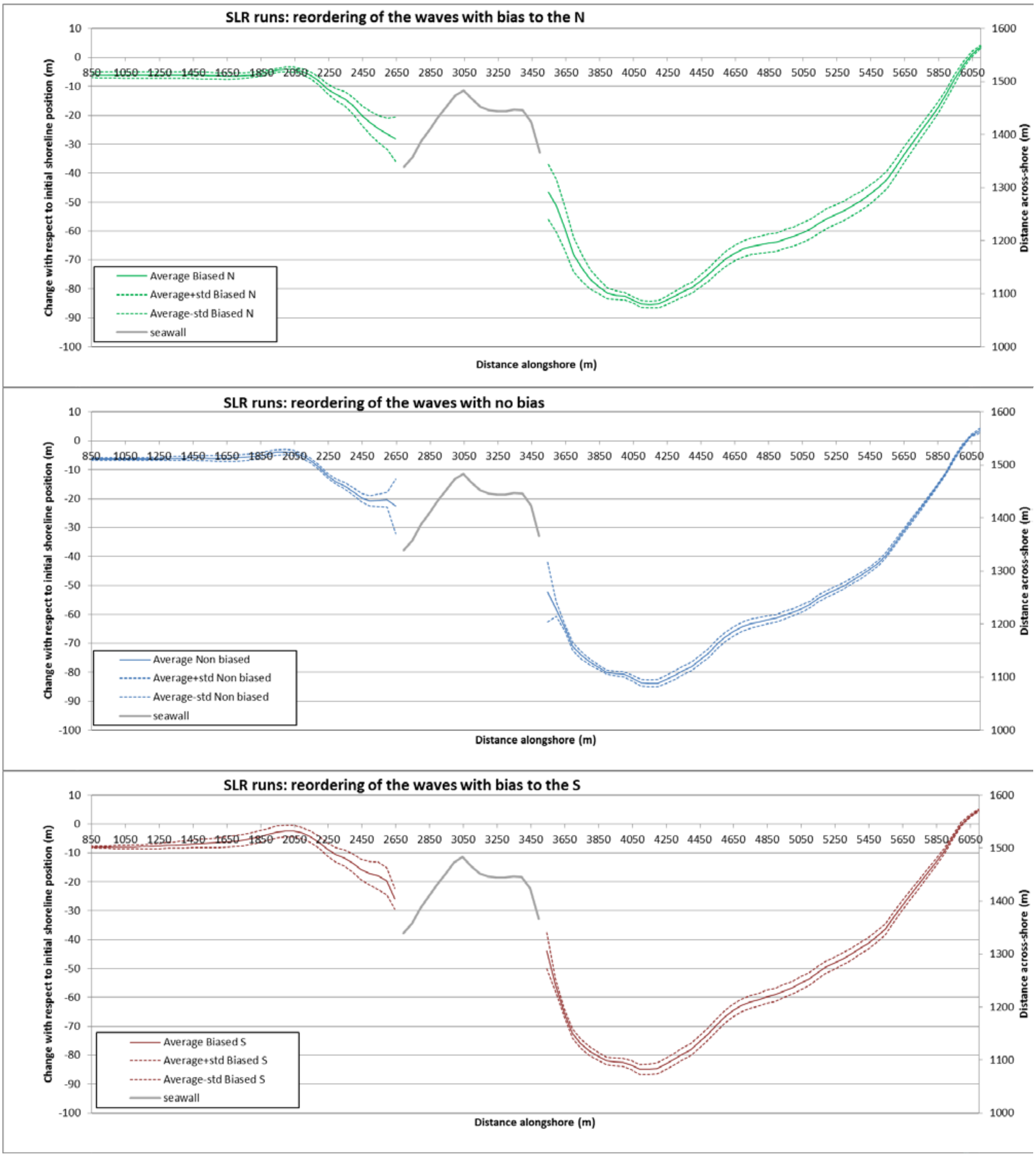

Figure H.8: S.L.R. runs: sensitivity to reordering of the waves, with or without bias

The seawall is shown for reference purposes, its distance alongshore measured with respect to the secondary y-axis.

HR Wallingford
Working with water

HR Wallingford is an independent engineering and environmental hydraulics organisation. We deliver practical solutions to the complex water-related challenges faced by our international clients. A dynamic research programme underpins all that we do and keeps us at the leading edge. Our unique mix of know-how, assets and facilities includes state of the art physical modelling laboratories, a full range of numerical modelling tools and, above all, enthusiastic people with world-renowned skills and expertise.

FS 516431
EMS 558310
OHS 595357

HR Wallingford, Howbery Park, Wallingford, Oxfordshire OX10 8BA, United Kingdom
tel +44 (0)1491 835381 fax +44 (0)1491 832233 email info@hrwallingford.com
www.hrwallingford.com