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IS THE NORTH ATLANTIC OSCILLATION AFFECTING THE LONGSHORE DRIFT RATE IN SOUTH-EAST ENGLAND?

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Abstract

Coastal erosion at an artificially maintained headland on the Southeast of England continues to be a problem, one of the main concerns being that the outflanking of the seawall here would increase the chances of erosion or flooding of the hinterland. Over the years, it has been speculated the movements and changes of the offshore banks, the mobile ness on the beach nearby or the defences themselves have been accountable for this erosion. This paper shows the relationship between the longshore drifts in the area, caused by two main nearly-opposite wave directions, and the NAO (North Atlantic Oscillation) index, a measure for interannual variability in the atmospheric circulation. The NAO could intuitively be considered to affect the western coastline of the UK, although in principle it would have been less expected in Suffolk. The increased erosion observed in the area since 2013 is linked to two high positive NAO index years following a high negative NAO index in 2013.

Key words: coastal erosion, longshore drift, North Atlantic Oscillation, NAO index, coasts and climate

1. Introduction

A study to improve the general knowledge of the physical coastal processes off the Suffolk coast in the Southeast of U.K. has been carried out, its objective being to provide new baseline information for the stretch of coastline from the mouth of the river Deben, northwards to Shingle Street and thus including Bawdsey and East Lane. The headland in the middle of our study site, East Lane, has been maintained artificially for over a century with a variety of coastal management interventions. Coastal erosion however, at this point continues to be a problem.

Figure 1. Location map and aerial photograph of the area July 2016 (Courtesy of Mike Page).

To the north of East Lane, in particular, there is a concern that further erosion of the beach could lead to the

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risk of flooding of an extensive area of 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. There have been many papers and reports (SMP, Royal Haskoning, 2010; Halcrow, 1998) 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. The *ad-hoc* series of defences carried out to stop the erosion have also been suggested as being responsible for the continued erosion itself.

Within this study we have undertaken analysis of the coastal processes in the area, including the local waves. In addition, we have sought to understand the influence of larger scale climatic processes, more specifically the North Atlantic Oscillation (NAO), in order to aid understanding of the erosion processes and support development of improved mitigation measurements.

2. Background

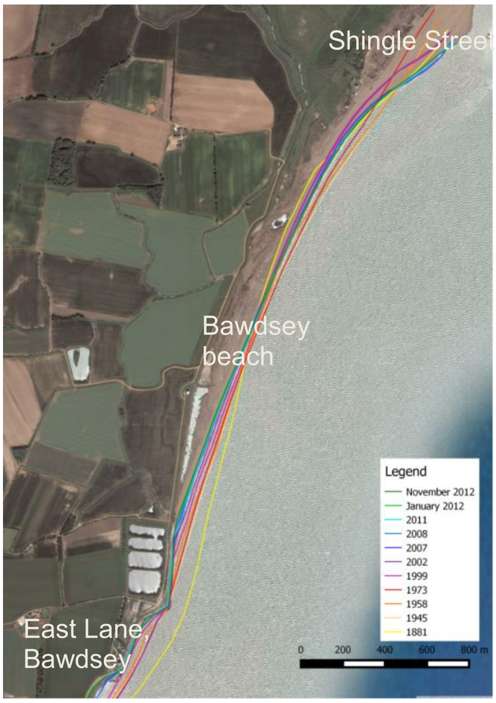
2.1 Historical view of coastal processes

The area of greatest interest in this study lies between Shingle Street and the Deben (Figure 2). At the center 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 ("shingle" being a British term referring to a mixture of gravel and sand largely derived from erosion of glacial cliffs), 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, which are the shingle banks across the mouth of the River Deben estuary.

Historically there have been, and to a certain extent, still are, conflicting views in terms of the coastal processes of the area including the sources of sediment, the rate and direction of the sediment transport (Onyett and Simmonds, 1983; Vincent, 1979) and the interaction with the nearshore banks (Burningham and French, 2006). 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 (TCE, 2008), all add to the complexities involved in understanding the evolution of the beaches. Moreover, the variations over time of the wave conditions, typically arriving from one of two very different directions and both at a substantial angle to the beach normal, contribute to the challenge of understanding and quantifying the coastal processes in this part of Suffolk.

The most striking historical shoreline change north of East Lane is the substantial recession and straightening of the shoreline between 1881 and 1945 (see Figure 2), the great majority of the erosion is most likely to have taken place between 1881 and the 1920s when coastal defences were apparently first installed at East Lane.

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. In relation to this traditional view of the drift regime, it would 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.



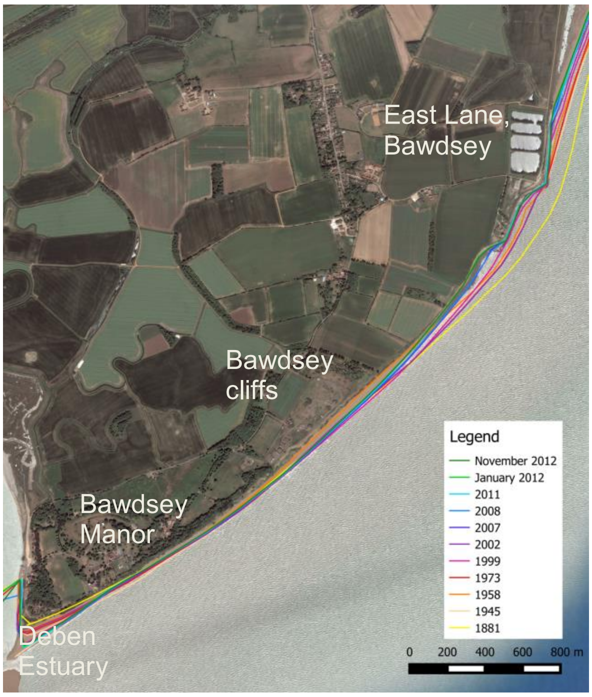


Figure 2. Historical shoreline positions – left pane: Shingle Street to East Lane, right pane: East Lane, Bawdsey to River Deben (Data from Burningham and French, 2017).

The headland is identified in the Shoreline Management Plan (SMP, Royal Haskoning, 2010) where it is considered to act as a control point on the coast providing some shelter from the dominant NE waves. It is thought also to regulate the net north to south alongshore transport of beach sediments between Aldeburgh and Felixstowe (Halcrow, 1998).

2.2 Large Scale Climatic Processes: NAO

To understand the influence of wider large-scale climatic processes on this part of the coastline analysis relating to the NAO was undertaken. According to NOAA Climate Prediction Center, the NAO is one of the principal climatic patterns in all seasons (Barnston and Livezey, 1987). The NAO comprises a surface atmospheric pressure differential, with one centre located over Greenland and the other centre of opposite sign spanning the central latitudes of the North Atlantic between 35°N and 40°N. The positive phase of the NAO reflects below-normal pressure across the high latitudes of the North Atlantic and above-normal pressure over the central North Atlantic, the eastern United States and western Europe. The negative phase reflects an opposite pattern of pressure anomalies over these regions. Both phases of the NAO are associated with basin-wide changes in the intensity and location of the North Atlantic Jet Stream and associated storm tracks, and in large-scale modulations of the normal patterns of zonal and meridional heat and moisture transport (Hurrell, 1995), which in turn results in changes in temperature and precipitation patterns often extending from eastern North America to western and central Europe. There are also relationships between both phases and temperatures and precipitation over the UK. The NAO exhibits considerable interseasonal and interannual variability, and prolonged periods (several months) of both positive and negative phases of the pattern are common. The wintertime NAO also exhibits significant multi-decadal variability.

3. Methodology

The study has involved the completion of four different but interrelated tasks, explained within this section.

3.1 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, followed by 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 had already been undertaken, so that where possible we have built on and used existing studies and findings. 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 obtained and analysed beach survey data from the Environment Agency's Anglian Monitoring System (EA, 2010, 2011 and 2014). Past research has suggested that changes in the bathymetry of the seabed beyond the low tide mark might also be influential and therefore a review of such changes, based on published papers and survey data, was also completed (Burningham and French, 2009).

3.2 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 (35 years from 1980) of offshore wave and wind conditions obtained from the Met Office European WaveWatchIII ReMAP Hindcast. A SWAN model was set up using a rectangular grid with spatial resolution of 200m. The SWAN model bathymetry was based on Seazone TruDepth data. In order to efficiently derive the nearshore time series, a meta-modelling technique using an emulator (Camus, et al 2011a,b and Gouldby et al. 2014)), as used in the recent EA National Flood Risk Assessment – State of the Nation project (HR Wallingford, 2015), was applied to obtain sea conditions at a series of nearshore points (Figure 5). The inter-annual variation of the nearshore wave conditions was studied in order to relate it to the erosion problems seen in the area.

3.3 Task 3- Longshore transport study

Potential longshore transport rates were calculated at numerous points along the frontage based on the predicted nearshore wave conditions for the past 35 years. The longshore drift rate was calculated using the CERC formulation (Komar and Inman, 1970) modified for shingle beaches, for a fixed point along the beach and a constant orientation of such point along the beach. Although simplistic, the calculations of these drift rates provide a useful way of assessing how the drift rates vary spatially along the frontage. It also enables temporal variations to be examined, e.g. how the gross and net drift may vary between different years and seasons.

These calculated drift rates 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 into its breaking point assuming locally parallel contours. The model 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.

3.4 Task 4- NAO

The NAO index, standarised seasonal mean during the cold season (January , February, March), was downloaded from the NOAA National weather service webpage (***http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/JFM_season_nao_index.shtml***) in order to analyse its variation. These variations were compared with the drift rates calculated in Task 3.

4. Results

4.1 Desktop review of past shoreline and seabed changes

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.

4.1.1 Shoreline changes

The shoreline recession from 1945 (shown in left panel of Figure 2) 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. 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.

Since 1945, the overall impression of shoreline changes between East Lane 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

In Figure 2 (right panel) the substantial recession of the shoreline at and just to the south of East Lane 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. 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.

4.1.2 Beach profile changes

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). Beach topographic profiles have been undertaken at 1km intervals, twice yearly in summer and in winter, along the coast since 1991, the main aim being to obtain the average rate of beach erosion or accretion along the coast. 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. These surveys 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.

Seasonal changes in the position of the 0 m OD contour (roughly mean tide level) provide a good indication of how the amount of sediment (i.e. the beach cross-sectional area) is changing over time. Figure 3 uses information from 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. Along the coastline near Shingle Street and as far as the entrance to the Ore/ Alde (HL011 and HL014), the general trend is for a gain in beach width recently 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. In the centre of Hollesley Bay (HL24 and HL29) 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. The overall pattern of changes just North of east Lane show clear erosion in recent times (SO62 and HL061), particularly since the middle of 2013. The rapid and localized loss of beach close to the seawall is a potential concern.

This pattern of changes in Hollesley Bay strongly suggests a net northward 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 therefore 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.

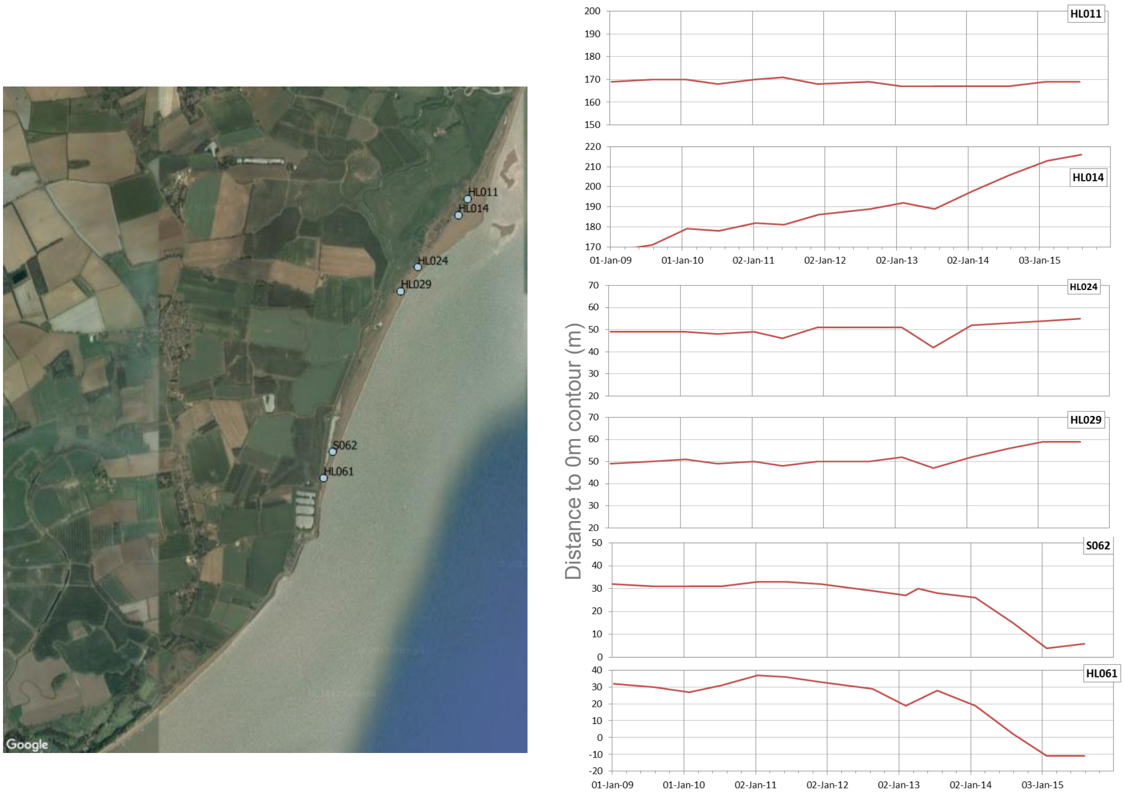


Figure 3. Beach width changes (2009-2015) (Data source: Anglian Coastal Monitoring programme and GooglePro)

4.1.3 Historic bathymetric changes

In this section we present and comment on changes in the seabed offshore from the study coastline, the information on historic changes from Burningham and French, 201. Figure 4 shows 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.

For convenience, part of Figure 4a has been enlarged and presented as Figure 4b 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.

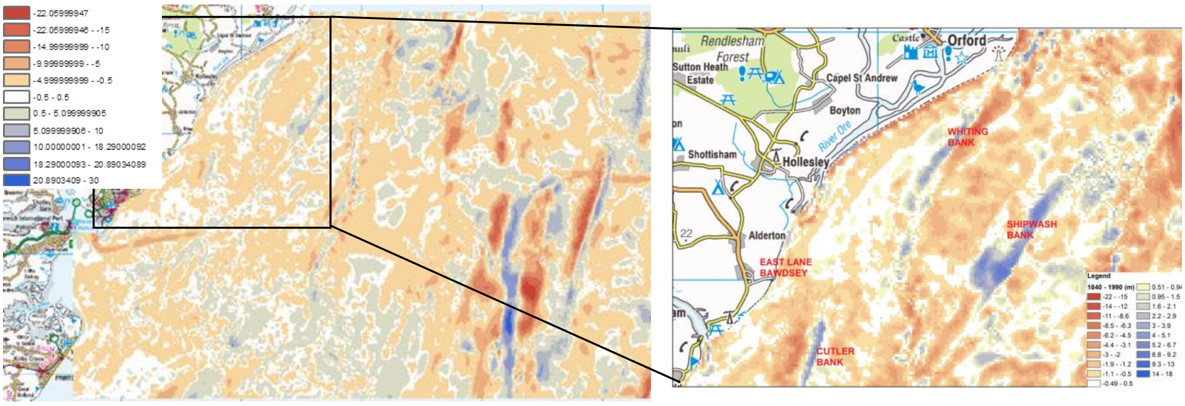


Figure 4. Bathymetric changes near study frontage (1840-1990) (Data source: UCL)

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.

4.2 Derivation of nearshore wave conditions

Figure 5 (left pane) show a wave rose 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. Nearshore wave conditions in the form of a 35 year time series, were predicted at a range of locations to provide input to the beach modelling (roughly along the -10 m MSL contour and -5 m MSL contour). To illustrate the predicted wave conditions, a wave rose at one of the nearshore points, PT 507 (which position is shown in Figure 6) is given in Figure 5 (right pane).

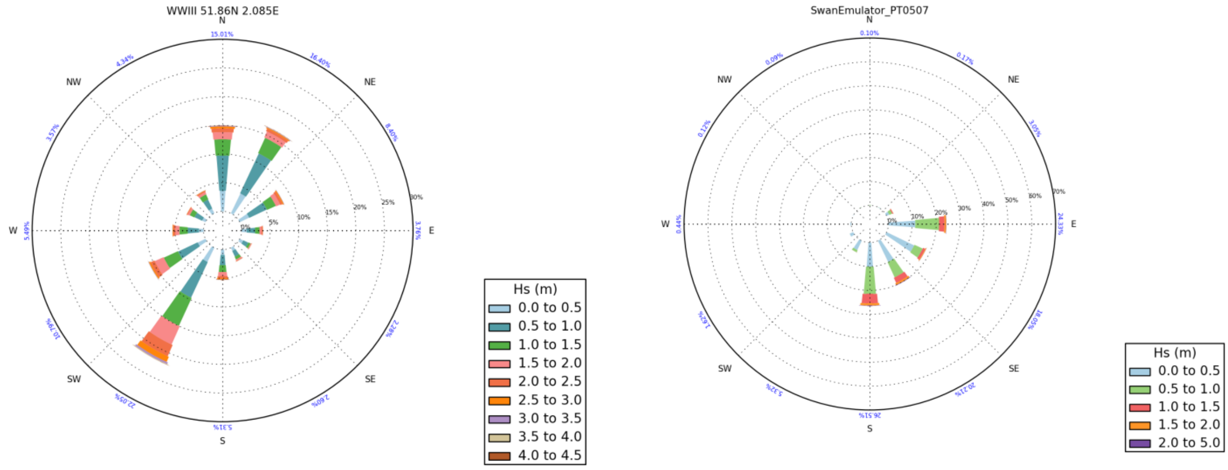


Figure 5. Offshore wave rose and nearshore wave rose at PT 507 (Data source: Met Office European WaveWatchIII ReMAP Hindcast)

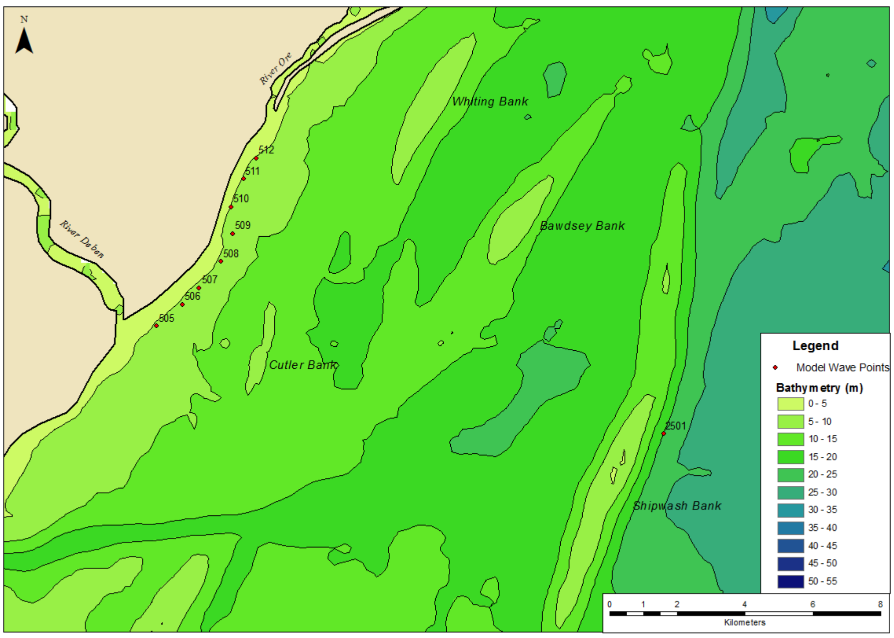


Figure 6. Location of the nearshore points with the bathymetry contours superimposed

4.3 Potential net and gross drift rates along the study frontage

Figure 7 shows the results of the average annual longshore drifts giving both the net and gross potential drift over the 35 years from 1981 to 2015 at various locations along the study frontage. The main characteristic of this site is that the average annual gross drifts are high, of the order of 86,000 to 133,000 m3/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 average annual net drift rate is modest, of the order of 10,000 to 45,000 m3/year. At all but the Bawdsey Manor location (Point 506), the net drift is predicted to be to the North. This is opposite to the widely held view that the long-term drift between the Alde and the Deben is southwards.

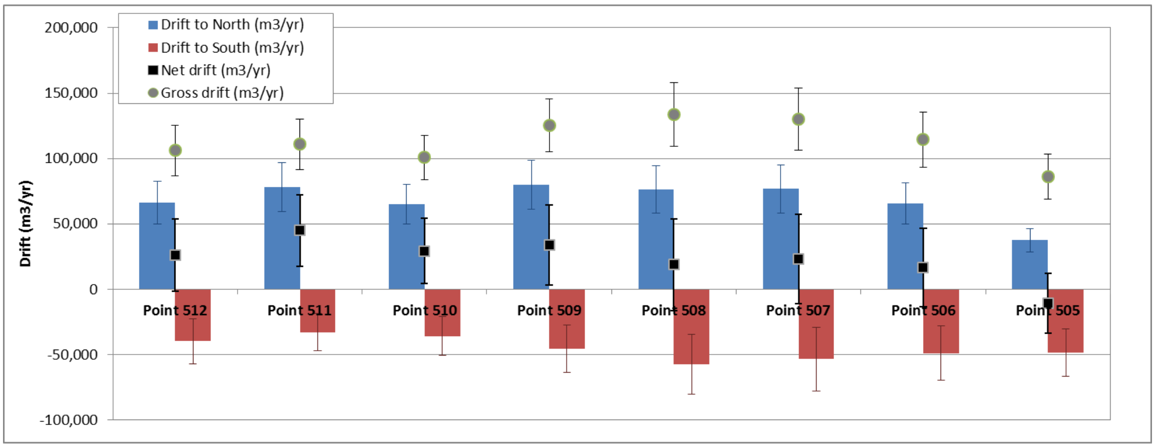


Figure 7. Average annual drifts at each nearshore point (error bars show the standard deviation)

It is important to note that the standard deviations of the annual drift rates are high, of the order of 20,000 m3/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 8 for Point 507. 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.

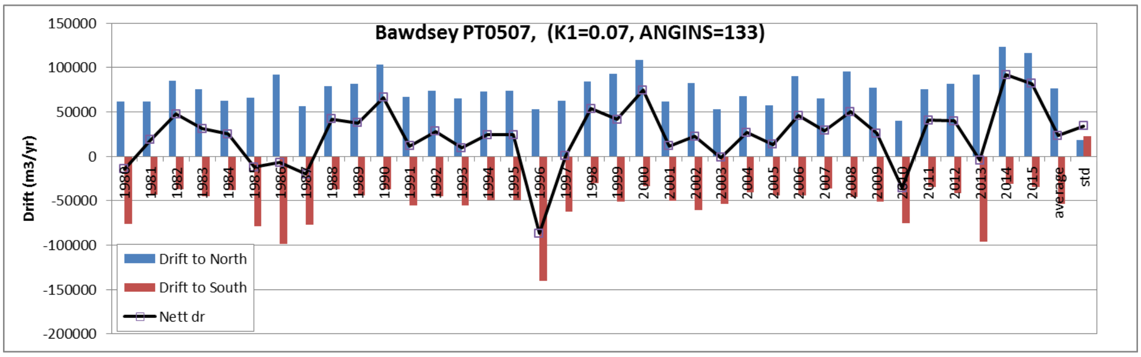


Figure 8. Potential longshore drift from 1980 to 2015. Point 507

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.

4.4 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. The NAO could intuitively be considered to affect western UK coastline although perhaps it would be less expected in Suffolk. We have compared the NAO index to the potential drift rates calculated within this study. The initial analysis undertaken here, does however, indicate a significant degree of correlation between the net drift at a given point (Point 507), and the NAO, as depicted in Figure 9 and Figure 10.

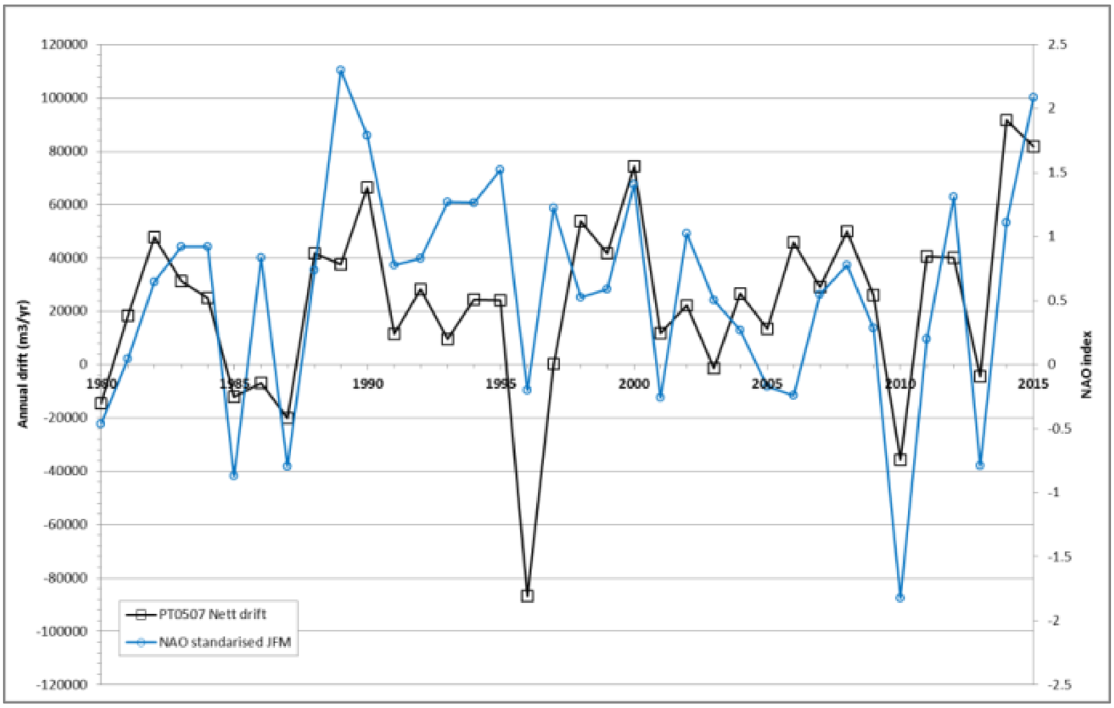


Figure 9. Comparison between average annual net drift and NAO index

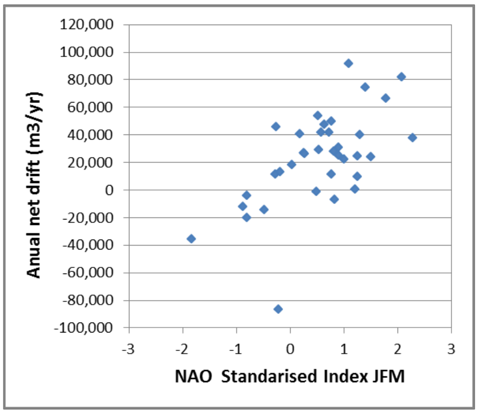


Figure 10. Scatter plot comparing the average annual net drift and NAO index

These figures show 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).

5. Discussion and Conclusions

A study of the coastal processes of an area in the Southeast of England has been carried out in order to aid understanding of the erosion processes and support development of improved mitigation measurements.

Potential longshore drift rates in Hollesley Bay and along Bawdsey cliffs have been found to be variable. At all but the Bawdsey Manor location (Point 506), the net drift is predicted to be to the North. This is opposite to the widely held view that the long-term drift between the Alde and the Deben is southwards. This shows that, 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 recent beach survey data. It is worth noting 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. This is observed in the relationship between southerly net drifts and negative NAO index (and *vice versa*) seen within this paper, indicating that the increased erosion observed in the area from 2013 is due to a year with a strong negative NAO index followed by two years of high NAO index. This result is perhaps not expected, as intuitively the climatic changes in the Atlantic would have been assumed to have an effect predominantly on the western coastline in the UK.

Changes in the bathymetry of the nearby banks have also been considered as a potential cause of the increased recent erosion, but within this paper these changes have been shown too small to have an effect on the beaches nearby.

Future research in this area could explore storm tracking and its influence on the longshore drift rates, as well as investigating other locations along the South and Southwest of the UK.

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