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Flooding-Erosion Interactions: Implications for Coastal Risk Management

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Abstract

As routinely experienced coastal hazards, flooding and erosion are key considerations within coastal management plans and policy. Flooding and erosion hazards are often analysed separately, without due attention to their interaction. Low lying barrier islands exemplify coastal environments particularly affected by erosion-flooding interactions. Such environments often support substantial human populations, critical infrastructure, and diverse ecosystems. This study undertakes a high resolution, multidecadal shoreline change analysis at Blakeney Point, a mixed sand-gravel spit on the UK's North Norfolk coast. The analysis spans two distinct management regimes: the 'first era' (1992-2005) where the eastern section of the barrier was periodically artificially reprofiled into a steep-sided trapezoid with a narrow crest; and the 'second era' (2006-2016) of no active intervention along the entire barrier. We find that over the past 130 years, Blakeney Point has retreated landward at a mean rate of 0.60 m a^{-1}. Along the eastern section of Blakeney Point, we observe an increase in shoreline retreat rate between the two eras of 3 to 30 times depending on the choice of shoreline proxy (High Water Line, ridge line, or vegetation line). The lower shoreline retreat rates during the first era suggest that reprofiling fixed the shoreline position of the eastern barrier. Termination of the reprofiling regime, in combination with storm surge events in 2007 and 2013, resulted in accelerated retreat along the eastern section towards a more landward position. This has had implications for the western section of the spit which appears to have benefited from alongshore westward transport of sediment during the non-interventionist era, resulting in slowed landward retreat rates during this period. The importance of storm surge events should not be understated. During 2013-2014, overwashing along the eastern section of the barrier resulted in vegetation line retreat of up to 127 m. This retreat behaviour was not matched at lower elevations on the subaerial beach, suggesting lateral spreading of the barrier, a behaviour which has been shown elsewhere to involve increased landward retreat and barrier disintegration. Our findings suggest a change in the morphological character of the barrier under the non-interventionist management regime, with clear implications for erosion**,** flooding and their interaction.

Introduction

Coastal environments are characterised by complex interactions between marine, terrestrial, atmospheric, and anthropogenic forcing. As such, these environments represent a substantial management challenge. Coastal erosion and flooding are hazards with the potential to negatively impact coastal ecosystems and communities. In the UK, it is estimated that up to 1.5 million properties are exposed to >0.5 % annual flood risk with 100,000 properties at risk of coastal erosion (Committee on Climate Change, 2018). Coastal management in the UK has been described as being "covered by a complex patchwork of legislation … carried out by a variety of organisations with different responsibilities" (Committee on Climate Change 2018, p.10). Consequently, in the past, coastal erosion and flooding hazards have been managed separately with responsibility for erosion falling to local authorities, while the Environment Agency (EA), a non-departmental public body, dealt with flooding impacts (Pontee and Parsons, 2010). There are now a series of policy documents advising on the management of coastal erosion and flooding risks in a more integrated fashion (Adaptation Sub

Committee, 2016; Environment Agency, 2015a, 2015b). This paper seeks to establish that effective coastal management should prepare for, and respond to, risks that emerge when coastal erosion and flooding interact (Pollard et al., 2018). Coastal management informed by an analysis of erosion-flooding interactions is especially important at present, given the increasing recognition by authorities in the UK and elsewhere that less interventionist management regimes incorporating natural features offer a more sustainable approach over the long-term (i.e. decades to centuries)(Bradbury and Orford, 2007; Dale et al., 2017; Myatt et al., 2003; Pontee, 2007).

Blakeney Point, a 13 km long shingle spit located on the North Norfolk coast, is one such natural feature that has experienced a recent shift towards a less interventionist management regime (Figure 1). The spit is set within a macro-tidal environment, with mean spring tidal range falling from 6.4 m at Hunstanton to 4.7 m at Cromer (Figure 1A) (Brooks et al., 2017). The site experiences a moderate wave climate, with the largest waves driven by northerly winds and associated long fetch. The spit can be broadly divided into two sections (Figure 1C). To the east of Cley, the barrier was actively reprofiled from the 1950s to maintain the crest height at ca. 8 m (Bradbury and Orford, 2007). However, reprofiling was terminated after 2006 to encourage a resumption of natural processes. To the west of Cley, the barrier has remained unmanaged at all times; it is characterized by a crest height of ca. 5 m (Bradbury and Orford, 2007). The two sections also differ in terms of hydrodynamic forcing with the western section being exposed to tidal flows from Blakeney Channel while the eastern section is backed by coastal and freshwater grazing marsh.

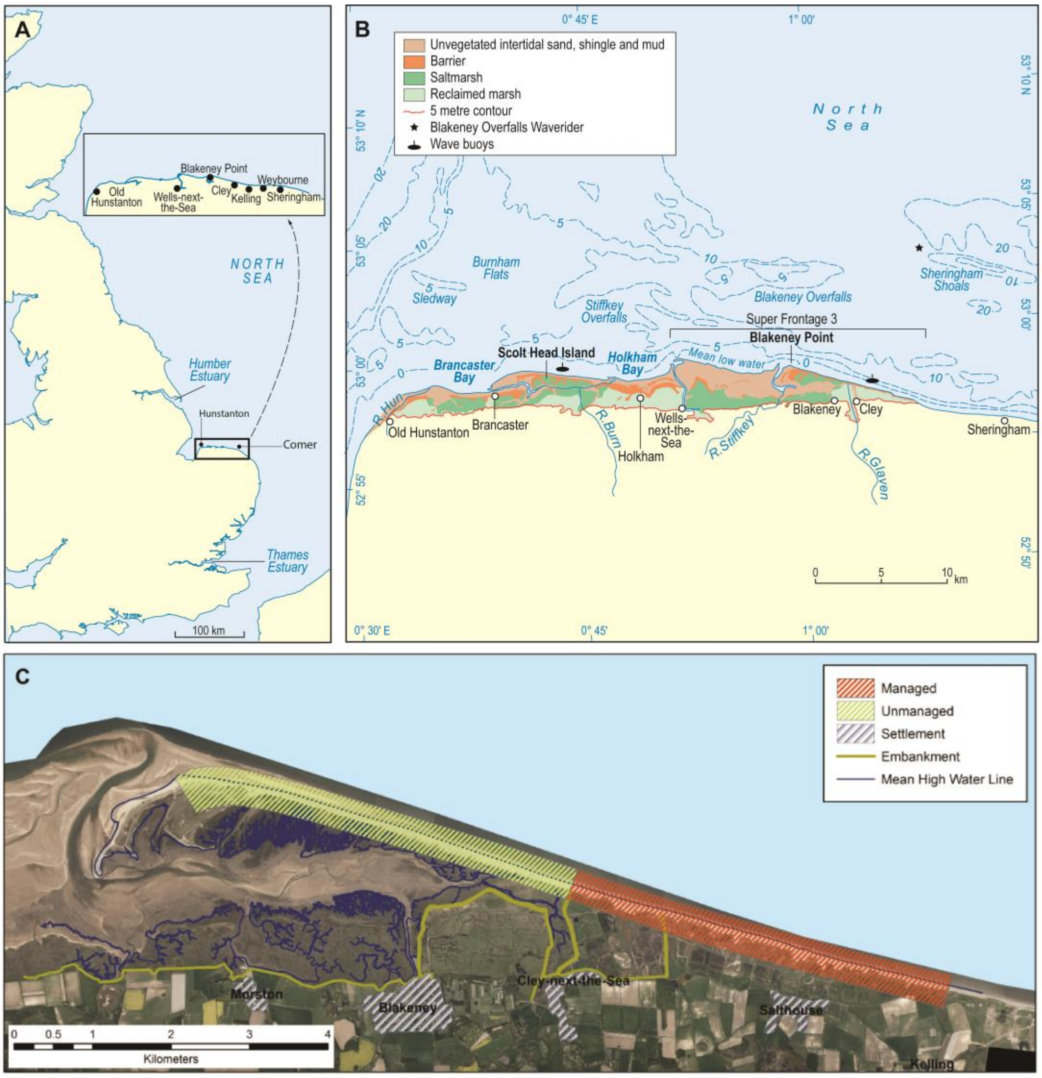

Figure 1: Study site location. A: the UK's North Sea coast; B: the barrier coastline of North Norfolk; C: Blakeney Point. The orange hashed area was actively managed

throughout the post-WWII era, until 2005. The yellow hashed area has always remained unmanaged.

Another important feature of the North Norfolk coast is the periodic impact of extreme water level events from storm surges. In the period 1883-2014, 21 surge events were documented as having substantial coastal impacts along this coast (Brooks et al., 2017, 2016; Christie et al., 2017). At present the spit affords flood protection to the communities of Morston, Blakeney and Cley (Environment Agency, 2010), so assessing the extent of future flood protection is a question of upmost salience to these landward communities. In combination, the recent management regime changes and extreme water level events at Blakeney Point provide an opportunity to study erosion-flooding interaction and the implications of this interaction for managing a complex coastal system.

Methods

Shoreline change analysis is a common approach towards characterizing coastal system behaviour (Brooks and Spencer, 2010; Burningham and French, 2017; Hapke et al., 2011). In this study, shoreline reconstruction over the past century was possible using First Edition County Series Ordnance Survey maps which were surveyed at Blakeney Point in 1886. Historical map sheets were obtained from the Cambridge University Library at a scale of 1:2500. Additionally, to assess shoreline change over decadal timescales, shoreline proxies were extracted from a series of vertical aerial photographs collected by the EA. Vertical aerial photographs were taken annually in the summer and were available for the years 1992, 1994, 1997, 2001, 2003, and annually thereafter until 2016. Each shoreline was extracted over a shoreline length of 10 km, covering both the managed and unmanaged sections shown in Figure 1C.

The shoreline as mapped on the 1886 Ordnance Survey map is the Mean High Water Line (MHWL). For detailed accounts of the procedures taken by surveyors see Harley (1975) and Oliver (1996)). Three shoreline proxies were extracted from the vertical aerial photographs: the High Water Line (HWL), defined as the wet/dry line created by the high tide immediately prior to the time of aerial photograph capture; the ridge line, defined as the point of highest elevation on the supra-tidal beach; and the vegetation line, defined as the point of transition between the beach and landward vegetated dune. The large complex of recurved ridges at the western end of the spit (beyond the unmanaged section indicated in Figure 1C) was deliberately excluded from this analysis because of difficulties in defining and extracting shorelines here due to the highly mobile sand and shingle that comprises this part of the spit.

Shoreline extraction from Ordnance Survey maps is relatively straightforward. First the map was digitized and then the MHWL was vectorised automatically using the ArcMap's (v.10.6) ArcScan Toolbar. The HWL and vegetation line proxies were predicated on visually discernible differences in pixel values on the vertical aerial photographs. To improve extraction, vertical aerial photographs were imported to ArcMap and subjected to both vertical and horizontal Sobel convolution functions. This image enhancement technique emphasizes the contrast between pixel values, thus making shoreline position clearer. The enhanced image was then converted to a bitonal image, enabling shoreline vectorization in a semi-automated fashion. As applied to the HWL and vegetation line, this method reduces the subjectivity that would be introduced through a purely manual extraction approach. The ridge line does not have such a distinct visual representation but is characterized by a clear elevation signal. This characteristic enabled extraction through reference to the closest time-matched cross-shore topographic surveys alongside the vertical aerial photograph. In all instances, some manual tidying was required to ensure a single continuous shoreline was produced.

Shoreline change analysis was performed using the open source R-package, Analysing Moving Boundaries Using R (AMBUR) by casting shore-normal transects along a 10 km stretch at 5 m alongshore spacing (Figure 1), giving 2064 transects (Jackson et al., 2012). Transects were filtered to smooth the transect orientations, using a 5 transect moving window, and then inspected visually to ensure that transects did not cross one another before intersecting the shorelines.

Results

Based on the MHWL, mean total retreat rate over the period 1886-2016 was calculated at 77.63 m, an annual retreat rate of 0.6 m a^{-1}. These summary figures, however, conceal substantial alongshore variability (Figure 1), with total shoreline change ranging from a retreat of 146 m towards the middle of the spit to an seaward accretion of 351 m at the western most end.

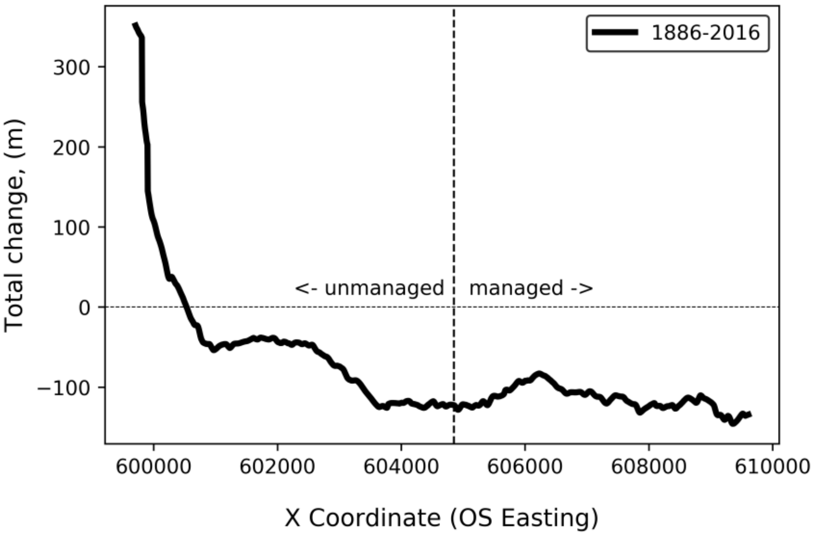

Figure 2. Total shoreline change of the MHWL over the period 1886-2016 based on historical maps. Note that management of the eastern section did not characterise the entire period shown.

When conducting the shoreline change analysis (Table 1), Blakeney Point was divided spatially into two sections and temporally into two eras according to past management regime. West of Cley (yellow hash, Figure 1C), and east of Cley (orange hash, Figure 1C) represent the unmanaged and managed sections of Blakeney Point respectively. The 24-year study period was subdivided into a first era (1992-2005) during which the section to the east of Cley was actively reprofiled; and a second era (2006-2016) characterised by a non-interventionist approach along the entire spit.

Table 1: Mean total shoreline change and shoreline change rate for managed and unmanaged sections of Blakeney Point, for the two eras.

Section	**Period**	**Total change (m)**			**Change rate (m a^{-1})**		
		HWL	Ridge Line	Vegetation Line	HWL	Ridge Line	Vegetation Line
East of Cley	1992-2005 (first era)	-0.30	-1.99	-6.57	-0.02	-0.16	-0.51
	2006-2016 (second era)	-5.82	-4.27	-14.49	-0.59	-0.43	-1.46
West of Cley	1992-2005 (first era)	-1.70	-14.30	-11.60	-0.13	-1.11	-0.90
	2006-2016 (second era)	-8.10	-8.37	-6.29	-0.82	-0.85	-0.64

The section to the east of Cley experienced an increase in both the total change and change rate between the two eras for all shoreline proxies. The shoreline change rate is used to control for the differing timespans of the two eras. The HWL displayed a retreat rate that was 30 times greater in the second era compared to the first. Between the two eras, the ridge line and vegetation line showed a mean retreat rate increase of 2.7 and 2.9 times respectively. During the second era, comparing relative retreat rate between shoreline proxies reveals that the vegetation line has been retreating at approximately 3 times the rate of either the HWL or the ridge line. The section west of Cley displayed more variable total change and retreat rates between the two periods. The ridge line and vegetation line proxies recorded a decrease in the total change and retreat rate between 1992-2005 and 2006-2016. This contrasts with the HWL which showed an increase in both the total change and the change rate.

During the first era, the area to the west of Cley retreated at substantially higher rates than to the east of Cley, regardless of the choice of vegetation proxy: HWL (6.5 times), ridge line (7.0 times), vegetation line (1.8 times). During the second era, the section west of Cley was still retreating faster than the east of Cley according to two of the shoreline proxies, albeit at a reduced rate: HWL (1.4 times); ridge line (2.0 times). The vegetation line provides a contrasting case in that the eastern section retreated 2.3 times faster than the western section in the second era, relative to the first.

Further interrogation of the vegetation line can be used to explain the reason for accelerated retreat in the second period. Figure 3 displays vegetation line retreat for two years in which storm surges with substantial coastal impacts occurred (Brooks et al., 2016). Storm surges are known to have impacted the North Norfolk coast on 7 - 11 November 2007 and 5 December 2013. In 2007-08, the greatest total shoreline changes for a single transect were 74 m, 41 m, and 73 m (Figures 3B, 3C, and 3D respectively). In 2013-14, the equivalent figures were 94 m, 116 m, and 127 m (Figures 3B, 3C, and 3D respectively). Along the section of coastline shown in Figure 3A, during the 2013-14 event, of 27 distinct overwash fans recorded, 13 represented reactivation and enlargement of fans formed by earlier events.

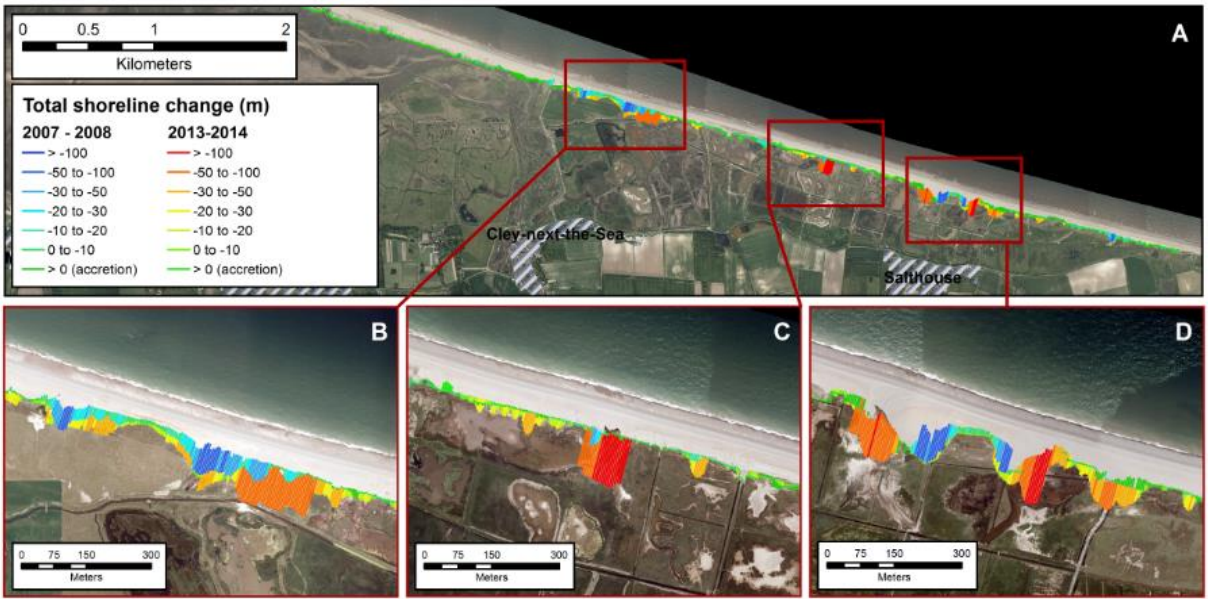

Figure 3. Vegetation line retreat during 2007-2008 and 2013-2014 obtained from vertical aerial photographs. A: The Cley-Salthouse barrier; B:, C:, D:, sections of highest vegetation line retreat with evidence of overwash reactivation.

The extreme instances of shoreline retreat shown in Figure 3 contributed to higher mean total shoreline retreat rates for the years mentioned. Figure 4 shows the relative contribution of the overwashing to the total shoreline retreat during the second era. In addition to displaying the difference in total shoreline change between the east and west sections, Figure 4 shows that along the entire length of the spit, the retreat during 2013-2014 dominated the shoreline change signal for the second era.

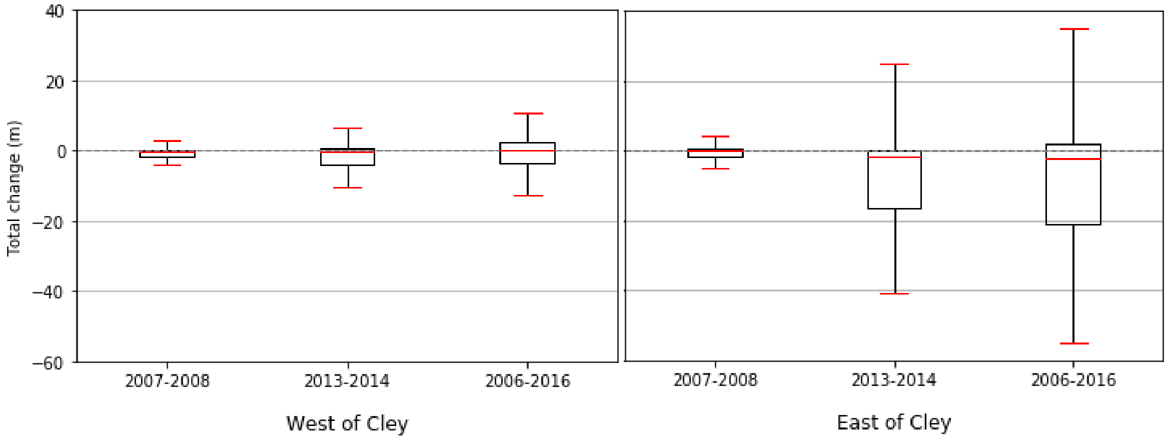

Figure 4. Total shoreline change contribution of years with recorded storm surges during the second (unmanaged) era. For the west of Cley, median values were -0.30, -0.29, and 0.31, for the years 2007-2008, 2013-2014, and 2006-2016 respectively. For the east of Cley, median values were -0.06, -1.79, and -2.03, for the years 2007-2008, 2013-2014, and 2006-2016 respectively.

Discussion

The evolution of Blakeney Point over the past 130 years reflects a complex interplay between boundary conditions (sea level and sediment availability), episodic high energy events (storm surges) and management regime change. The high-resolution shoreline change analysis conducted here reveals the varying importance of each of these influences at different points in the spit's evolution. In establishing the relative contribution of boundary conditions, storms and human intervention, the impossibility of isolating each of these influences in a setting of such complexity is clear. In the context of coastal management, it is essential to devise policy with an explicit appreciation of the uncertainty that emerges from complex interactions between multiple influences.

Shoreline evolution

Over centennial timescales, Blakeney Point has been rolling landwards and extending westwards (Figure 2). The landward retreat, particularly along the eastern section of the spit, can be attributed to overwashing processes, as elaborated below. Whilst the shorter-term and event-based dynamics of local sediment transport are not well known, the westward extension of the spit appears to reflect the longshore sediment transport driven by the dominant direction of wave approach (Hardy, 1964). Westward transport of sediment eroded from the eastern section represents a morphological coupling in the alongshore direction which has important implications considering the difference in management history between east and west. At the centennial scale, landward retreat has averaged <1 m a^{-1}. While these retreat rates are an order of magnitude lower than elsewhere on the UK's East Anglian coast (Brooks and Spencer, 2012), over multi-decadal timescales, this total shoreline change has nevertheless been substantial. The nature of this change, as discussed below, is highly sporadic, non-linear and driven by extreme events, such that retreat rates over individual decades can far exceed the centennial average. As coastal management extends its remit to multi-decadal timespans, it becomes important to recognise that future elevated water level and associated wave events, with the potential for landward flooding, will encounter future shorelines positioned closer to the mainland (Grilli et al., 2017). As such, extreme event forecasting must aim to incorporate the impact of changes in shoreline position, extent of overwashing and breach dynamics when modelling flooding impacts.

Analysis of vertical aerial photography over the period 1992-2016 has facilitated a detailed insight into the possible impact of the management regime change on Blakeney Point. Due to the differing timespans of the two eras, annual retreat rates are most useful when comparing between the two time periods. To the east of Cley, the increase in total shoreline change and retreat rate of the ridge line and HWL suggest that, in fulfilling its primary objective to limit landward flooding, the reprofiling regime also reduced shoreline retreat across the full extent of the subaerial beach (Table 1). This 'pinning' of the shoreline appears to have had downdrift implications which have been recorded in the shoreline change rates of the section to the west of Cley. Here, the spit retreated faster during the first era (while the eastern end was being actively managed), regardless of shoreline proxy. This contrasts with the centennial scale trend during which the western end of the spit retreated more slowly than the eastern end, or even accreted, due to the longshore transport of sediment in a westerly direction and the buffering to erosion that was afforded by this additional input of sediment (Figure 2). The higher than average retreat rate of the western section during the first era may indicate that longshore sediment transport was reduced by the active reprofiling, resulting in reduced buffering and increased landward retreat. It is also worth noting that the western section may receive sediment through the migration and welding of bars across the Blakeney Channel inlet, a process that has been proposed elsewhere for Scolt Head Island (Brooks et al., 2017). As such, faster retreat in the west may also be partly due to variability associated with the distal end of the spit which displays substantial dynamism due to its unconsolidated shingle composition, low profile, and tidal and sediment exchange across the ebb tide delta at the mouth of the Blakeney Harbour channel. This is supported by the higher variability of shoreline change in the western section when comparing across shoreline proxies and time periods.

A key strength of extracting multiple shoreline proxies is the ability to investigate relative movement on different parts of the barrier. To the eastern end of the barrier, the total retreat rate of the vegetation line was over 3 times that of the ridge line in both the first and second era. From a barrier evolution perspective, this suggests that overwash processes redistributed barrier sediments over a greater area, resulting in barrier lowering and landward retreat. This stretching of a barrier as overwash occurs has been observed by Orford et al. (1996) on the coastal barriers of Nova Scotia, Canada. At Blakeney Point, overwash and stretching is now focussed towards the eastern end of the barrier, which was previously actively managed. By contrast, the down-drift western section is being buffered by sediment supply from the eastern section, at least in the second era. The western section currently displays vegetation line retreat that is comparable to the ridge line retreat, suggesting that overwash and spreading of the barrier is not yet occurring here. Rather, and as suggested by the higher retreat rates, the western section is rolling landward in a more conventional sense. It has been suggested that ‘cannibalization’ of one part of the barrier is a critical step in the disintegration of barriers that have insufficient sediment supply to maintain their crest elevation with sea level rise (Forbes et al., 1995, 1991). The data shown here suggests that the centennial scale evolution of Blakeney Point could well follow this trajectory.

Extreme events

The vegetation line proxy provides insight to the processes operating towards the back-barrier limit of the subaerial beach, a part of the beach that is only impacted by extreme water level events. The vegetation line recorded a reversal in the relative retreat rates of the eastern and western sections between the two eras. In the second era, the eastern section was retreating faster than the western section. This is likely explained by the occurrence of extensive overwash during the second era which was spatially restricted to only the eastern section (Figure 3). Overwash is a well-documented impact of storms in barrier island settings with erosional and flooding consequences (Sallenger, 2000). Through an analysis of cross-shore profiles extracted from digital elevation models, Orford et al. (2018) argue that increased prevalence of overwash after the termination of reprofiling at Blakeney Point occurred because the barrier has been able to respond more naturally to extreme water level events. This explains why the section to the west of Cley has not recorded a similar increase in retreat rate. The barrier to the west of Cley is characterised by a lower ridge height and so can be regarded as in equilibrium with extreme water level events (Orford et al., 2018). Reduced ridge height is partly due to sediment being stored lower on the beach profile. During extreme events, the presence of a shallow frontal slope leads to a greater degree of wave dissipation in the nearshore zone, thus reducing overwash capacity.

Overwashing of the spit’s eastern section most likely occurred during the storms of November 2007 and December 2013. The morphological impact of these events was captured by successive vertical aerial photographs taken during summer in 2007-2008 and 2013-2014 (Figure 3). It is difficult, if not impossible, to separate entirely the impact of these extreme water level events from the management regime change. It is worth noting, however, that four storm surge events with coastal impacts were recorded in each of the eras (Brooks et al., 2016). Given that storm character exerts a first order control on shoreline response, the occurrence of the same number of storms simply indicates that the spit was exposed to extreme water level events in both eras. The increased overwash during the second era, in the eastern section, is therefore best explained by both the severity of storms in the second era, and the management regime change.

The role of individual storm characteristics on shoreline change is further emphasised by Figure 4 which shows that the storm surge event of 5 December 2013 dominates the shoreline change signal as recorded by the vegetation line for the second era. The same cannot be said for the storm captured by the shoreline change in the period 2007-08. One explanation for this is the extreme nature of the storm of 5 December 2013, which has been regarded as the most severe east coast surge since 1953 (Spencer et al., 2015; Wadey et al., 2014). Figure 3B, 3C, and 3D, corroborates this point by showing that landward retreat of the vegetation line in areas of greatest overwash during 2013-14 exceeded that of 2007-08. A further important influence is storm sequencing. The shoreline encountered by the 2013 surge event differed drastically from the profile encountered by the 2007-08 storm when reprofiling had only recently terminated. Overwash reactivation during the 2013-14 event indicates that the limited signal of the 2007-08 event may partly be an overshadowing effect due to the larger, more energetic storm coming second in the sequence. A final complication is added by shoreline recovery processes which have been observed to generate reversals in the direction of shoreline change in the days, weeks and years after extreme water level events (Brooks et al., 2017; List et al., 2006). We do not attempt to explicitly reconstruct shoreline recovery processes here but note that it is possible that the impacts of the 2007-08 event may partly be masked by vegetation reestablishment.

Conclusions

In the UK, coastal management that relies on environmental processes, with limited human intervention, is being increasingly advocated. For example, the Shoreline Management Plan for the North Norfolk coast poses four strategic questions pertaining to the management of the coastal frontage between Old Hunstanton and Kelling Hard including:

"*As sea level rises the pressure on the flood defences will increase and in the future national funding may not be available for continued flood risk management. Can we increase the role of natural processes and reduce the dependence of the north Norfolk coast on man-made intervention?"* (Environment Agency 2010, p. 58).

Through high resolution analysis of multiple shoreline proxies, this paper reveals that increasing the role of natural processes at Blakeney Point has given rise to novel erosion-flooding interactions, with implications for landward communities. The post-WWII reprofiling regime, measured here over the period 1992-2005, appears to have limited landward retreat and overwashing of the eastern section of the spit. During this first era, the western end of the spit experienced increased landward retreat due to the resultant sediment starvation. In the second era, 2006-2016, a combination of management regime change, and exceptional storm surge events, resulted in extensive overwashing of the eastern section of the barrier. The retreat here has been discontinuous in the cross-shore direction, with the vegetation line proxy retreating at over three times the rate of the barrier ridge. The resultant spreading and lowering of the eastern section could indicate a fundamental shift in the character of this part of the spit, a possible prelude to increased overwashing and landward retreat. The western section appears to have benefitted from the return to a natural processes regime in the east, with lower retreat rates recorded in the second era.

Over near-future decadal timescales, continued retreat of the spit will fashion future shorelines that will occupy ever more landward positions. As such, modelling studies that wish to forecast the impact of future storm events must aim to either incorporate this landward retreat into model boundary conditions or acknowledge the uncertainty that shoreline movement (both before and during an event) will introduce into model outputs. When seeking to understand shoreline evolution at this locality, it becomes clear that the steady retreat of Blakeney Point, as it appears when averaged over multiple decades, is more accurately described as a series of periodic set-backs associated with extreme water level events. Current 'epoch-based' approaches to forecasting future shoreline position neglect the reality that shoreline change is often driven by extreme events which result in dramatic short-term coastal changes, interspersed with longer periods of stasis. This dynamism is best captured through attention to the vegetation line proxy which records overwash deposits that are characteristic of storm impacts on low-lying barrier islands.

The 2018 Committee on Climate Change report, *'Managing the coast in a changing climate',* makes several recommendations regarding management of the UK coast. Among these recommendations is the need to design policy that is sustainable in economic, social and environmental terms (Committee on Climate Change, 2018). Returning Blakeney Point to a more 'natural' state has resulted in discernible changes to the morphological behaviour of the spit, particularly in response to extreme storm surge events. It remains to be seen whether this change satisfies the recommendations of the Shoreline Management Plan, "… to increase natural processes gradually while continuing to provide flood defence where this is technically possible and economically viable" (Environment Agency 2010, p.61). In the future, continued monitoring will be a priority, to assess the vulnerability of the spit to the erosional impacts of extreme events and quantify its ability to provide a flood protection function during them.

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