WILL NATURE WORK WITH US? EROSION AND FLOODING IMPACTS ON A UK BARRIER

JAMES A POLLARD[1], SUSAN M BROOKS[2], TOM SPENCER[1], ELIZABETH K. CHRISTIE[1], IRIS MÖLLER[1]

1. *Department of Geography, University of Cambridge, Downing Place, Cambridge CB2 3EN, UK. jp646@cam.ac.uk, ts111@cam.ac.uk, ekc28@cam.ac.uk, im10003@cam.ac.uk.*
2. *Department of Geography, Birkbeck, University of London, Malet Street, London WC1E 7HX, UK. s.brooks@bbk.ac.uk*

Abstract: 'Barrier island' refers to a diverse collection of coastal landforms that often support substantial human populations, critical infrastructures, and ecosystems. Globally, many coastal barriers are experiencing climatically altered environmental forcing coupled with increasing anthropogenic pressures. This paper undertakes high resolution shoreline change analysis to reveal how Blakeney Point, a mixed sandy-gravel barrier located on the UK's East Coast, has evolved over centennial, decadal and event timescales. We seek to establish the implications of barrier evolution, under contrasting management regimes, for present erosion and flooding hazards. Interrogating a series of alternative shoreline proxies reveals a series of interdependent behaviors. Over the 130-year period of study, Blakeney Point is shown to be rolling landward at a mean rate of 0.60 m a^{-1}. Assuming continued landward retreat over the coming decades, future flood-generating storm events will encounter more landward shoreline positions than today. Superimposed on this trend, we observe the presence of alongshore migrating erosional hotspots which give rise to unpredictable morphologies at any given location on the spit. Finally, we find that instances of barrier setback are driven by individual storm events, which makes barrier retreat both highly variable and discontinuous in time and space. This is illustrated by the presence of overwash, particularly along stretches of the barrier that have experienced a recent shift in management regime towards a non-interventionist approach.

Introduction

Barrier islands are highly dynamic across a range of spatial and temporal scales. Furthermore, many are densely populated, carrying critical infrastructure assets of national importance (McNamara and Werner 2008). Global environmental change is giving rise to non-linear forcing conditions including accelerating sea-level rise (Nerem et al. 2018), altered storm character (Stott 2016), and growing human pressures (Neumann et al., 2015). Combined, these forcings have the potential to affect highly uncertain interactions between barrier islands, the habitats they comprise and the human activities they support. The potential for hazardous outcomes (eg: erosion flooding) places substantial value on understanding barrier system dynamics.

Here, we present a multi-temporal (centennial, decadal, event-based) analysis of Blakeney Point, a mixed sand-gravel barrier located on the UK's east coast (Figure 1). Through a high-resolution reconstruction of barrier morphological

change over the past 130 years, we seek to establish the varied ways in which coastal erosion and flooding interact. Low-lying barrier islands have been characterized by Pollard et al. (2018) as a coastal setting that is particularly susceptible to erosion-flooding interaction. Blakeney Point is therefore an appropriate site to quantify the determinants of erosion-flooding interaction and the degree to which this interaction has been altered by recent management regime change. Ultimately, we aim to provide insight into whether the recent shift to a less interventionist regime has beneficial outcomes in terms of erosion and flood risk and whether, in our efforts to 'work with nature', nature will indeed work with us.

Fig. 1. Blakeney Point site map. A: The UK's North Sea coast; B: the barrier coastline of North Norfolk; C: Blakeney Point, red section indicates the 2064 transects used to calculate shoreline change.

Study Site

Blakeney Point is a 13 km shingle spit which stretches from the shore at Kelling out into the sea at an angle of 16º to the mainland where it terminates opposite the village of Morston (Oliver 1913). The back barrier area is characterized by relict spit recurves that extend landwards at right angles to the main beach. The spit recurves have encouraged the development of intervening saltmarsh of varying character through controlling the degree of tidal influence to which the saltmarsh segments are exposed. Atop the shingle ridges, extensive dune systems have developed, though only towards the western end. The absence of dunes towards the eastern end of the spit gives rise to a large body of relatively mobile shingle (Oliver 1913).

Blakeney Point is set within a macro-tidal environment with a mean spring tidal range falling from 6.4 m at Hunstanton to 4.7 m at Cromer (Fig. 1A) (Brooks et al., 2017). Its position on the North Sea gives rise to a moderate wave climate, with the largest waves driven by northerly winds and associated long fetch. The North Norfolk coast is also vulnerable to extreme water level events in the form of storm surges. In the period 1883-2014, twenty-one surge events were identified as having had substantial coastal impacts (Brooks et al., 2017; Brooks et al., 2016; Christie et al., 2017). Additionally, easterly winds such as those experienced in 2018 during the late February to early March 'Beast from the East' have been observed to effect extensive coastal change, even in the absence of elevated water levels.

Since at least the seventeenth century, the evolution of Blakeney Point reflects the interaction between natural and anthropogenic influences. For example, the eastern end of Blakeney Point was reclaimed over a century ago through the building of earthen embankments (Oliver 1913). A more intensive management regime has occurred in the post-WWII era, whereby the eastern end of the spit was actively re-profiled to maintain the crest height at ca. 8 m (Bradbury and Orford, 2007). West of Cley, the barrier has remained unmanaged and is characterized by a crest height of ca. 5 m (Bradbury and Orford, 2007). Since 2006, the eastern end of Blakeney Point has been subjected to a less interventionist management approach. Given recent endorsements of coastal management schemes that work with, rather than against, nature this case study provides a valuable opportunity to quantify the impact of management regime change on shoreline erosion rates, overwash processes and associated flood hazard.

Methods

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Shoreline change analysis is a well-established approach for characterizing coastal behavior over a range of scales. Shoreline proxies were extracted from historical maps and vertical aerial photography (Table 1), with each shoreline spanning 10 km. The large complex of recurved ridges at the western end of the spit (beyond the transect locations 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. Three different shoreline proxies were extracted from the vertical aerial photographs: the High Water Line (HWL), defined as the wet/dry line created by high tide prior to 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 shoreline proxy present on historical maps is the Mean High Water Line (MHWL). In total, the combination of data sources and shoreline proxies resulted in 60 digitized shorelines over the period 1886 to 2016.

Table 1. Summary of shoreline proxies

Shoreline proxy	Time Period	Data source	Frequency
High Water Line	1992 - 2016	Vertical aerial photography	1992; 1994; 1997; 2001; 2003; annual thereafter
Ridge Line	1992 – 2016	Vertical aerial photography	1992; 1994; 1997; 2001; 2003; annual thereafter
Vegetation Line	1992 - 2016	Vertical aerial photography	1992; 1994; 1997; 2001; 2003; annual thereafter
Mean High Water Line	1886 - 2016	Historical maps	1886; 1905; 1928; 1957; 1973; 2016

The procedures required to define, and extract shorelines varied depending on the shoreline proxy and data source. The HWL and vegetation line proxies were predicated on visually discernible differences in pixel values. To improve extraction, vertical aerial photographs were enhanced using both vertical and horizontal Sobel convolution functions. This procedure emphasized contrast between pixel values, making the shoreline clearer. The enhanced image was then converted to a bitonal image, enabling shoreline vectorization in a semi-automated fashion. Using a standard approach to vectorize the HWL and vegetation line 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, which enabled extraction through reference to the closest time-matched cross-shore topographic

surveys alongside the vertical aerial photograph. The historical maps were inspected in hardcopy before being digitized and georeferenced. Once imported to GIS, the MHWL was vectorized automatically. In all instances, some manual tidying was required to ensure a single continuous shoreline was produced.

It is essential that the errors associated with shoreline definition and extraction are accurately and robustly quantified. If shoreline changes lie within the error bounds of the shoreline position, it is not possible to assert directional shoreline change. Three sources of error were quantified through reference to Sutherland's (2012) equation:

$$RMST = \sqrt{RMSS^2 + RMSI^2 + RMSV^2} \qquad (1)$$

where RMST = root-mean-square total error, RMSS = root-mean-square source error, RMSI = root-mean-square interpretation error, and RMSV = root-mean-square variability error. Equation 1 was used to calculate total error associated with each of the 60 shorelines. Mean error estimates for each shoreline proxy are presented in Table 2.

Table 2. Summary of shoreline error in meters

Data source	Shoreline proxy	Mean RMSS	Mean RMSI	Mean RMSV	Mean RMST
Vertical aerial photography	High Water Line	0.64	4.65	0.12	4.77
Vertical aerial photography	Ridge Line	0.64	7.03	0.00	7.13
Vertical aerial photography	Vegetation Line	0.64	1.14	0.00	1.31
Historical maps	Mean High Water Line	2.65	1.09	0.13	3.00

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

Results

Results of the shoreline change analysis are summarized in Table 3. Historical maps analyzed over the period 1886-2016 show a mean landward retreat of the MHWL at Blakeney Point of 77.63 m, a mean annual retreat rate of 0.60 m a^{-1}. The maximum landward retreat over this period was -146 m, recorded towards the eastern limit of the study area. Over the same time period, the distal end of Blakeney Point extended westwards by 346 m, resulting in a maximum accretion of 351 m in the seaward direction.

Measured over the period 1992-2016, the HWL and ridge line display similar mean total shoreline and annual change rates. The mean total change and change rate, as measured by the vegetation line, is 42% and 54% higher than the HWL and ridge line respectively. When looking at the median values, all three proxies extracted from vertical aerial photography appear relatively more similar. This suggests that some extreme areas of retreat captured by the vegetation line proxy are skewing the mean values upwards.

Table 3. Summary statistics by shoreline proxy.

		HWL (1992 – 2016)	Ridge Line (1992 – 2016)	Vegetation Line (1992 – 2016)	MHWL (1886 – 2016)
Total change (m)	Mean	-14.57	-13.49	-20.76	-77.63
	Median	-16.82	-14.12	-14.23	-106.64
	Standard Deviation	15.78	11.63	29.77	75.63
Change rate (ma^{-1})	Mean	-0.61	-0.56	-0.87	-0.60
	Median	-0.71	-0.59	-0.60	-0.82
	Standard Deviation	0.66	0.48	1.25	0.58

Further interrogation of the HWL reveals the presence of 'hotspots' of erosion and accretion that migrate alongshore. Figure 2 displays a shoreline change rate for five successive periods, of approximately five-year timespans. We observe hotspot switching whereby an area of erosion in one period becomes an area of accretion in the next. There is also evidence of hotspot migration (indicated on Figure 2 by arrows) where one erosional hotspot appears to shift westwards in each successive period.
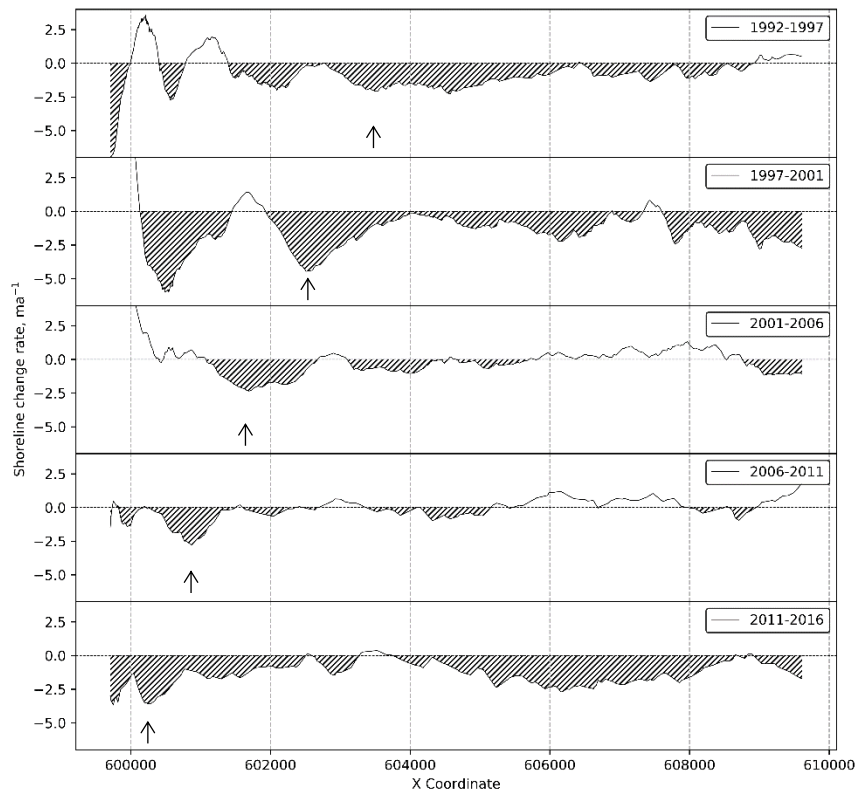
Fig. 2. Alternating and migrating hotspots of erosion and accretion captured by the HWL over the period 1992-2016.

Figure 3 displays vegetation line retreat from vertical aerial photographs captured in 5/07/2013 and 24/07/2014. Although there is evidence of vegetation line set-back along the entire barrier, overwash fans are restricted to the Cley-Salthouse barrier (Figure 3A). The greatest total shoreline changes are 94 m, 116 m, and 127 m in Figures 3B, 3C, and 3D respectively.
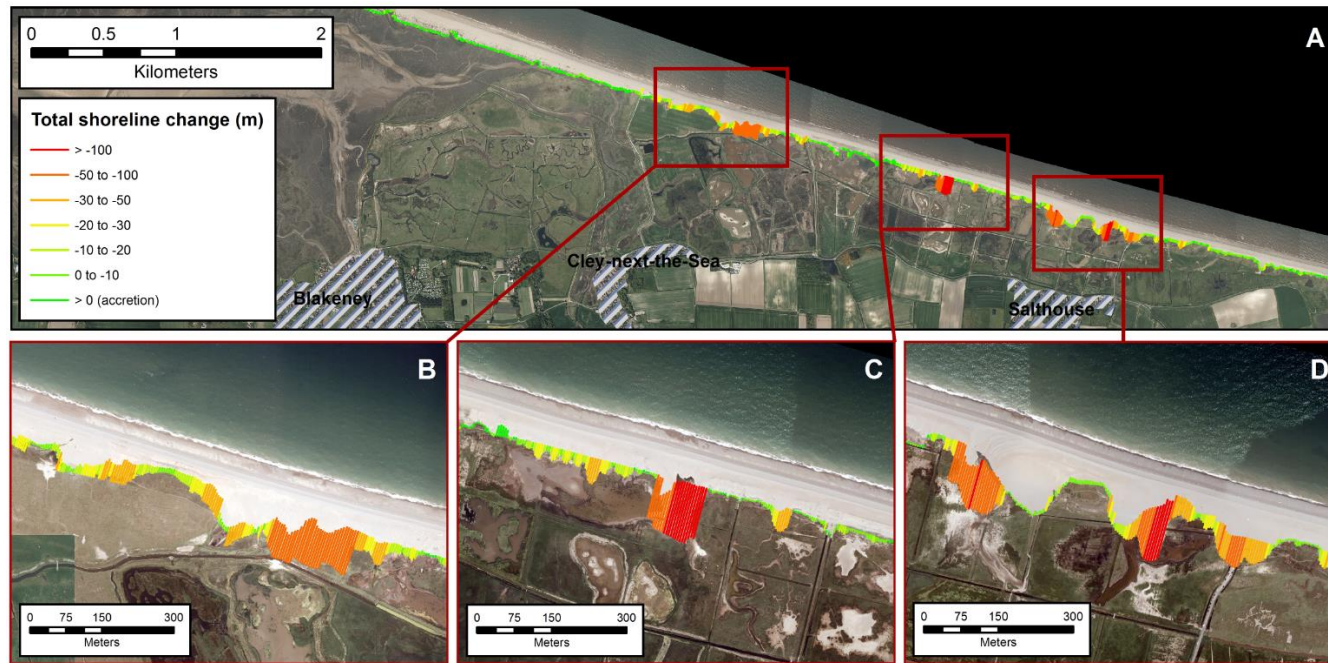
Fig. 3. Vegetation line retreat between 2013 and 2014 vertical aerial photographs. A: The Cley-Salthouse barrier; B:, C:, D:, sections of highest vegetation line retreat.

Discussion

Understanding barrier dynamics over a range of timescales is critical to establish how our management of these systems impacts on coastal erosion and flooding hazards. In the first instance, this requires robust approaches towards defining and extracting shorelines, and quantifying the associated error. This prerequisite ensures that genuine shoreline changes can be distinguished from the noise introduced by data collection, pre-processing and analysis. Comparing the root-mean-square-total errors for each shoreline proxy in Table 2 to the net shoreline movement values in Table 3 confirms that the shoreline changes observed exceed the error envelope for both vertical aerial photograph and historical map derived shorelines for their respective measurement periods.

Historical maps facilitate analysis over centennial timescales, revealing a mean landward retreat of Blakeney Point of 0.60 m a^{-1} over the period 1886-2016. This results in a more landward shoreline and reduced back-barrier area. This landward rollover can be expected to continue, if not increase, into the future given assertions that sea level rise provides a first order control on barrier island retreat by providing a baseline elevation for storm processes (Horsburgh and Lowe 2013; Masselink and Van Heteren 2014). Despite the relatively low rate of barrier retreat, the net shoreline movement over timescales of relevance to management are substantial. Assuming a constant future retreat rate, the median shoreline position would be 27 m and 68 m inland by 2050 and 2100 respectively. This can be considered a low estimate given projections for the Lowestoft tide gauge (located to the east of Blakeney Point), which suggest that sea level rise will accelerate from 2.7 mm a^{-1} (1950-2011) to between 5.1 mm a^{-1} and 7.0 mm a^{-1} (2030-2050) depending on the emissions scenario (Wahl et al. 2013; Palmer et al. 2018).

Elsewhere in the world, gravel barriers have been observed to undergo dramatic transitions in response to increases in storminess (Forbes et al. 1991) and relative sea level rise (Rodriguez et al. 2018) resulting in rapid landward retreat, and the dominance of overwash processes. If such a transition were to occur at Blakeney, landward communities that currently benefit from the spit's flood protection function would likely experience elevated extreme water levels (Environment Agency 2010). Even in the absence of barrier lowering or breakdown, long-term erosion sets the scene for future flood-generating storm events given that such events will encounter more landward shoreline positions (Grilli et al. 2017). Sediment supply, underlying geology and human intervention can all be expected to influence shoreline retreat rates to varying degrees along the length of the spit. For example, as the barrier crest rolls landwards, it will uncover relict recurves on the seaward side with the potential to act as sources of sediment supply or even anchor points that buffer retreat of the system. Alternatively, the spatial variability

introduced by such anchor points could promote barrier disintegration (Bradbury and Orford 2007).

Over decadal and sub-decadal timescales, comparison of shoreline change from the three proxies obtained from vertical aerial photography illustrates that choice of shoreline proxy exerts an influence on shoreline change values. The HWL and ridge line display lower standard deviation values than the vegetation line, making them useful proxies for looking at alongshore trends. The alongshore migration of erosional hotspots shown in Figure 2 illustrates how the morphology of the intertidal beach varies over sub-decadal timescales. Associated hotspot 'reversal' has been observed elsewhere following storm impacts, albeit on sandy beach systems and at shorter timescales (days to weeks)(List et al. 2006). This behavior can be explained by the process of wave focusing and dissipation on extruding and inverted points on the shoreline respectively. This reversible hotspot behavior has been found to have an important role during extreme water level events and may help to identify the areas that will experience the most severe erosion during a storm and the locations most able to recover afterwards (List et al. 2006; Brooks et al. 2017). In any given location, the presence of migrating erosion hotspots may play an important role in enhancing or moderating local water levels during storm events (Houser et al. 2008). The critical relationship between foreshore morphology, including the presence and pervasiveness of dunes, relative to maximum water level during a storm is the underpinning assertion of Sallenger's (2000) barrier island impact regimes which have found widespread application (eg: Sallenger et al. 2006; Houser et al. 2008).

One of the most important types of barrier response to extreme water levels occurs when the combination of water level and wave runup during an event exceeds the dune crest resulting in landward overwash of sediment and water. Overwash has been identified as a key process for explaining barrier response to changing environmental conditions (Masselink and Van Heteren 2014) and represents an example of instantaneous erosion-flooding interaction (Pollard et al. 2018). The role of overwash in shoreline retreat is challenging to establish in the absence of high resolution shoreline reconstruction owing to morphological 'signal shredding' (Lazarus et al. 2019) whereby shorelines undergoing persistent retreat under sea level rise retain limited information about their past position. Here, through extracting the vegetation line at near annual frequency, it is possible to quantify shoreline retreat resulting from overwash. The high alongshore and interannual variability in overwash occurrence is largely responsible for the high standard deviation values associated with the vegetation line proxy.

Figure 3 clearly illustrates vegetation line retreat along the eastern end of Blakeney Point. This retreat is a result of both barrier overwash and breaching. During the storm surge of 5 December 2013, Blakeney Point beached in two

locations, and subsequently 'self-healed' over 5-6 months (Spencer et al. 2015). Vegetation line retreat at this particular location reflects both the transition to a new management regime and physical forcing provided by extreme water level conditions. Concerning management regime change, Orford et al. (2018) argue that overwash occurs as the barrier relaxes towards a more 'resilient' equilibrium profile precluded by the previous management regime of oversteepening by periodic bulldozing. Alongside the influence of management regime change, the vegetation line retreat presented in Figure 3 can be explained by the unusually energetic winter experienced by southern North Sea coasts in 2013/14 (Brooks et al. 2016). Further, the majority of retreat is likely attributable to the storm surge of 5 December 2013 associated with Cyclone Xaver. The extent of vegetation line setback during this event was extreme, even in the historical context of barrier retreat. Numerous transects shown Figure 3C and 3D experienced shoreline retreat in excess of the mean total change over the past 130 years. Alongside the erosional impacts, the marshes behind Blakeney Point experienced 91 ha inundation, equivalent to 1/3 of the back barrier area (Spencer et al. 2015). Overwash and breaching of earthen flood defenses, provided conduits for the landward intrusion of this flood water (Spencer et al. 2015).

Conclusions

Barrier islands are critical components of many coastal systems worldwide (Masselink and Van Heteren 2014). Across a diversity of settings, interactions between people, ecosystems, and barrier islands have led these environments to be described as 'coupled landscapes' (McNamara and Werner 2008). Blakeney Point exemplifies this coupling since it is impossible to explain the morphological evolution of the barrier in isolation from its coastal management history.

Through high resolution shoreline change analysis of multiple shoreline proxies, this paper has established several expressions of erosion-flooding interaction at Blakeney Point with implications for the way in which the barrier is managed in the future. At centennial scales, an appreciation of the processes leading to the current shoreline position is important for determining future shoreline positions. Furthermore, future shorelines are likely to display morphological variability in the longshore direction, as demonstrated here by both reversible and migrating hotspots of erosion. Both shoreline position and morphology may alter landward flood volumes making an awareness of the processes responsible for a barrier's pre-storm state critical to understand barrier response to storms and recovery.

The storm surge event of 2013/14 provides an insight into the processes of erosion and flooding impacts during extreme events. The response was dominated by extensive barrier overwashing, particularly along the stretch of Blakeney Point that had previously been artificially steepened. The recent turn in coastal

management towards working with nature means that such management regime changes are likely to become more common. At Blakeney Point, the less interventionist management regime has resulted in a stark difference in the way the spit responds to extreme events. To quantify the link between erosion and flooding hazards, future work will employ numerical modelling of storm surges at Blakeney Point to improve our understanding of the role of these events in the future evolution of the spit and the consequences for coastal management.

Acknowledgements

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