Research paper

Analysing the long-term stability and sustainability of a breached barrier beach, Porlock Bay, Somerset

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ABSTRACT

In many parts of the world, coastal managers have been compelled to make tough decisions in relation to resource allocation, coastal protection and habitat restoration. The creation of habitats through managed realignment initiatives are essential tools in the armoury of coastal managers. Porlock beach is an early example highlighting the decision to allow natural breaching without repair, as had occurred at this site in the past. Monitoring of these events is essential in understanding geomorphological evolution, but also to reassure the public in relation to the long-term stability of the barrier features. The planimetric beach change and inlet development at Porlock beach has been analysed from 1999 to 2014. The results suggest that after some initial significant change, the beach itself and the breached inlet as generally stabilised. The increase in barrier area observed across all datasets is not reflected in the first sample period, spanning 1999 to 2006, which can be correlated with previous findings in the locality. Seaward barrier boundary advancement and landward boundary recession correlate to increased beach area observations, and can be attributed to redistribution and flattening of the barrier following barrier roll-over and breaching. Overall, this research suggests that the barrier beach at Porlock, although still a dynamic feature is now relatively stable in relation to the planimetric features, overall area and inlet form.

KEYWORDS

Barrier beach, sustainability, managed realignment, geomorphology, stability, monitoring

INTRODUCTION

Coastal managers in all countries face difficult decisions in relation to improving and maintaining sea defences, as well as meeting other objectives such as the creation of new coastal habitats including salt marsh. Economic imperatives also mean that managed realignment is now seen as an effective tool for sustainable coastal management as well as essential for the creation of, inter-tidal environments which have historically been regarded by authorities as low-value (Doody, 2004, Baily and Pearson, 2007). At the same time it has to be recognised that the general public often perceive manage realignment in a negative way and need reassurance that managed realignment does not simply mean abandonment of coastal areas. The progressive understanding of geomorphological-ecological coastal processes and quantification of anthropogenic impacts have notably altered the approach of coastal managers whom increasingly recognise saltmarsh value in terms of coastal defence, conservation and recreation (Allen, 1992, King and Lester, 1995). As a result, coastal national policy and management within the UK has encouraged saltmarsh restoration and creation following the EU principles of Integrated Coastal Zone Management (ICZM), (McKenna et al., 2008, Ballinger et al., 2010). Furthermore, the Habitats and Birds Directives (EEC, 1992, EEC, n.d) dictate the prioritisation of important habitats and provide empirical guidelines to member states concerning sustainable coastal management (Ledoux, 2000). Consequently an increasing number of sites are being left to evolve in response to natural processes which includes allowing barrier beaches to breach and new areas of salt marsh to form behind these breaches.

This research critically evaluates the longer-term geomorphological change of the gravel barrier beach at Porlock Bay, Somerset, UK, following the breaching of the shingle ridge after a storm event on 28/29th October 1996. The primary aim of this research is to quantify rates of planimetric shoreline and beach width change, using remotely-sensed data acquired post October 1996. This research considers the long term stability and geomorphological change of a coastal barrier following the decision to allow it to breach. It is important that long-term monitoring is carried out on such schemes to assess the potential implications of further projects of a similar nature. This type of analysis may also reassure the public that allowing a barrier to breach does not lead to a longer term collapse in the wider coastal system, but is a process of gradual change and new stability. This research covers the period from 1999 to 2014 and continues the theme of previous work of Jennings *et al.* (1998), Bray and Duane (2001), Cope (2004), PCO (2009). Jennings *et al.* (1998) refer to Porlock as a unique "microcosm of the U.K. as a whole" (1998, p. 88). Bray and Duane (2001) provided the most comprehensive analysis of the contemporary geomorphology of the Porlock barrier thus far, supported by historical surveys of gravel volume and breach inlet migration. Importantly, recommendations for future monitoring and management are also provided. Limited historical discussion is available (Carter and Orford, 1993, Orford and Jennings, 1998), whereby past change rates are derived for temporal comparison with contemporary conditions. This research moves on from these previous studies to analyse the longer-term changes which have occurred since the breach in 1996. Through the analysis of channel formation, breach inlet change and planimetric change of the barrier itself, this analysis critically examines the evolution of the geomorphological system from 1999 to 2014.

MATERIALS AND METHODS

The coarse clastic gravel barrier beach at Porlock Bay, Somerset, is located on the macro-tidal Bristol Channel coastline, and is subject to prevailing westerly winds influencing longshore sediment transport processes (Figure 1 and Figure 2). The barrier extends from Gore Point to the headlands at Hurlstone Point and has experienced variable relative sea level rise since c. 8,000 cal. yrs BP, exacerbated by human reclamation of the hinterland (Jennings et al., 1998, Bray and Duane, 2001). The predominantly single-ridge barrier is formed upon Mercia Mudstone, a calcareous clay and mudstone sequence deposited in the Triassic period (BGS, 2002). The barrier material mostly comprises locally-sourced clays, silts, sands and gravels, formed as head or river terrace deposits and eroded locally from cliffs (BGS, 2013). Due to changes in sea level, a domain shift from drift to swash-alignment of the barrier was initiated, contributing to natural 'roll-over' and enhanced by increasing sediment depletion (Jennings et al., 1998).

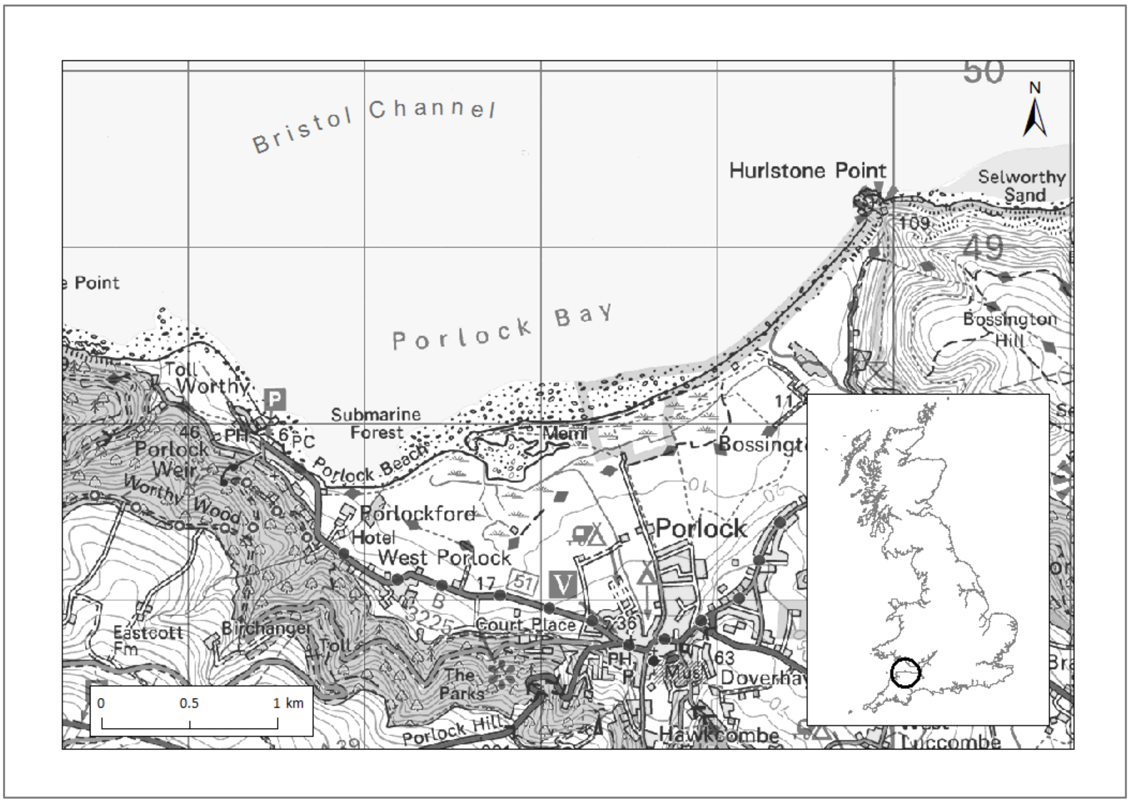

Figure 1. The location of Porlock beach, Somerset (Source: Ordnance Survey 1:50,000 raster downloaded from Edina Digimap).

Contemporary tidal range at Porlock has been recorded at 9m (PCO, 2009) and a unique tidal regime has developed, establishing an equilibrium between the seaward edge of the lagoon substratum and local regimes within the Bristol Channel (Bray and Duane, 2001). Combined with relative sea level rise, this process has resulted in periodic inundation of the lagoon behind the barrier at high water, and draining of the inter-tidal zone, sustaining saltmarsh formation (Figure 3).

Figure 2. Aerial photo showing and labelling the breach, landward boundary and seaward boundary (Image from Channel Coast Observatory, 2010).

Management of the barrier beach at Porlock can be traced back to the mid-nineteenth century to prevent breaching and flooding of the grazing land behind the beach (Cope, 2004). In the 1990s management agencies adopted a policy of non-intervention leading to an eventual breaching of the barrier in 1996 (Figure 2).In the past, management of the site has included hard engineering approaches including as groyne construction immediately east of the breach channel inlet and at Porlock Weir, in addition to Porlock ford sea wall (Bray and Duane, 2001, Blathwayt, 2010). Cessation of engineering in the 1990s, has helped to provide a 'natural' monitoring context to develop understanding of barrier response to breaching and formation of saltmarsh habitat. Since the abandonment of artificial defences, environmental and economic incentives for establishing a managed realignment site with Special Site of Scientific Interest (SSSI) designation have assisted with fulfilling national and EU sustainability targets. The barrier beach at Porlock breach following storms in 1996. The defence policy adoption at Porlock Bay and subsequent monitoring and analysis of environmental change can provide a useful analogue for geomorphological and ecological feedbacks in similar contexts. This research aims to provide an understanding of the longer-term stability of site between 1999 and 2014.

Despite the importance of coastal monitoring and surveying, relatively few sections of UK coastline have been historically consistently monitored, often due to accessibility constraints of inter-tidal regions (Baily and Collier, 2010). Modern survey methods have increasingly utilised remotely-sensed data for coastal analysis within a GIS. This study therefore makes use of aerial photography and LiDAR datasets between 1999 and 2014, available from Channel Coastal Observatory and the Department of Geography, University of Portsmouth (UOP).

The shingle barrier beach at Porlock has historically experienced landward retreat resulting from berm formation and overwashing cycles, and relative sea level rise (Bray and Duane, 2001). Permanent modification of the barrier beach has provided interesting context for analysing and monitoring geomorphological response to storm-breaching. Therefore, barrier area change and planimetric migration of the shoreline and breach inlet were undertaken digitally using ArcGIS 10.3 and USGS's Digital Shoreline Analysis System (DSAS) v.4, to generate rates of change. A combination of aerial photography and airborne LiDAR data were utilised for this research covering the period 1999-2014 to follow on from the work of Bray and Duane (2001) who analysed the period up to 1999. Initially, unrectified 1:4,000 photography captured in 1999 was rectified and georeferenced. In addition, orthorectified aerial photography was downloaded from the Channel Coast Observatory’s (CCO) online data catalogue for 2006, 2010 and 2013. Unfiltered 1m resolution LiDAR data was also downloaded from CCO's database for 2007, 2009, 2012 and 2014. The LiDAR provided height data with elevational and positional accuracies of ±0.15m and ±0.3m respectively (CCO, 2015). In order to capture planimetric shoreline positions from each dataset, manual heads-up digitisation was undertaken in ArcMap 10.3. Following the review of similar studies, the USGS Digital Shoreline Analysis System **(**DSAS v.4) was utilised as an appropriate tool for baseline and transect generation to quantify shoreline change.

Change rate calculation was undertaken using DSAS. The output included intersection and statistical rate tables output to a personal geodatabase. These rates were then processed and presented in graphic form within the results section of this paper. The requirement by DSAS of the inclusion of uncertainty values associated with each shoreline facilitated expression of change, whilst considering variable error sources and values across the datasets.

Further to analysing planimetric migration of the landward and seaward barrier boundaries, the original shapefiles digitised from each dataset were converted to polygons. The purpose of this was to derive values for the variation in beach width across the sample period, to provide qualitative discussion of correlation between these observations and those of planimetric change. These were further correlated with observations from breached and eroded barrier regions in order to develop understanding of the dynamic coastal processes at Porlock.

RESULTS

Linear regression rates (LRR) derived from DSAS have been utilised to assess planimetric shoreline change of both the landward and seaward boundary of the barrier beach at Porlock derived from 16 transects along the coast (Figure 3). The rates of change of the seaward and landward barrier boundaries indicate that the greatest change is in the central region (near the breach) with less change recorded in the western and eastern regions as shown in Figures 3 and 4.

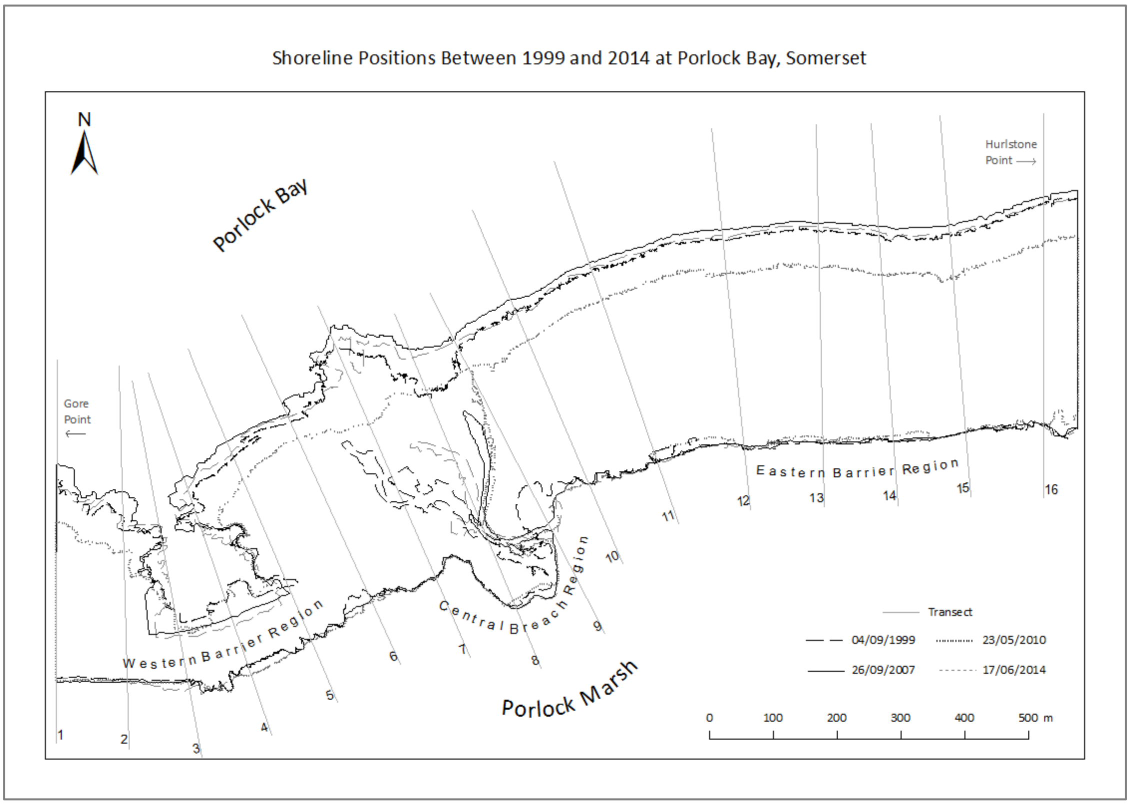

Figure 3. Showing the location of transects used for analysis along Porlock beach, and the planimetric barrier position across the study period.

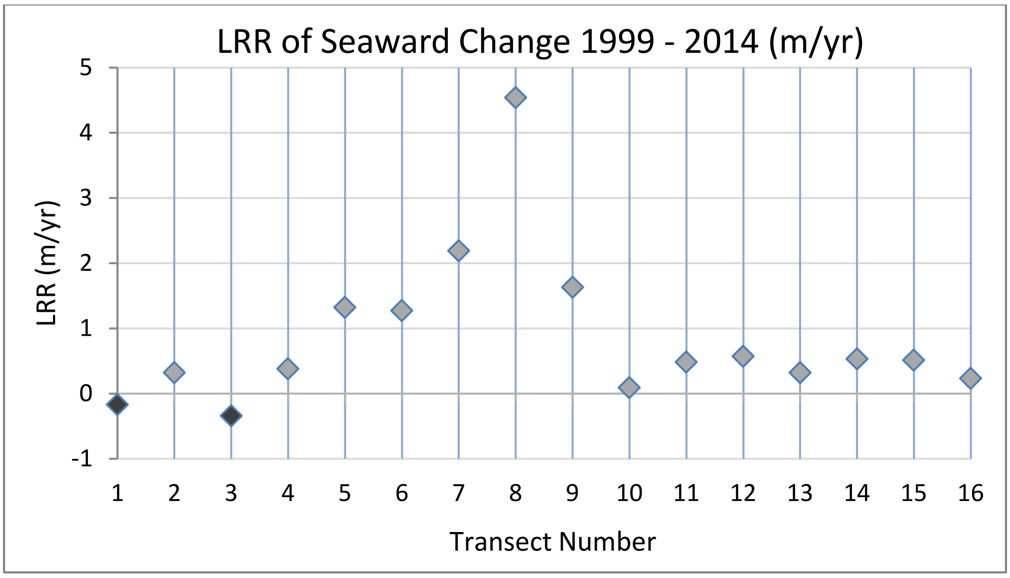

Figure 4. Linear regression rates across all transects for seaward barrier boundary, indicating greatest change in the central breach region for the period 1999-2014.

The LRR analysis of the seaward barrier edge provided an average change rate of +0.87m/yr across all transects with the greatest rates of change within the central region in close proximity to the breach channel. This central region indicates a general trend of accumulation of material throughout the study period which is also evident to a smaller extent, east of the breach channel. Furthermore, minor recession trends observed at the first and third transects, located west of the channel, could be a source of material for the accretion of material experienced downdrift.

For the purposes of analysing landward boundary migration, the terms receding and advancing are more appropriately utilised. For the landward boundary of the barrier, the rate of change averaged -0.39m/yr and derived values demonstrate some similarity to the migration trends observed at the seaward boundary, with several notable differences. Significant variability of change was recorded in the vicinity of the breach channel, the greatest advance attributed to transect 8, as with the seaward boundary. In this instance however, theoretical downdrift movement of material suggested previously, may not be applied here owing to significant advancement recorded immediately downdrift of substantial boundary recession. However, generally stable recession rates recorded from transect 9 onwards could potentially be attributed to longshore movement of material on the landward edge (Figure 5).

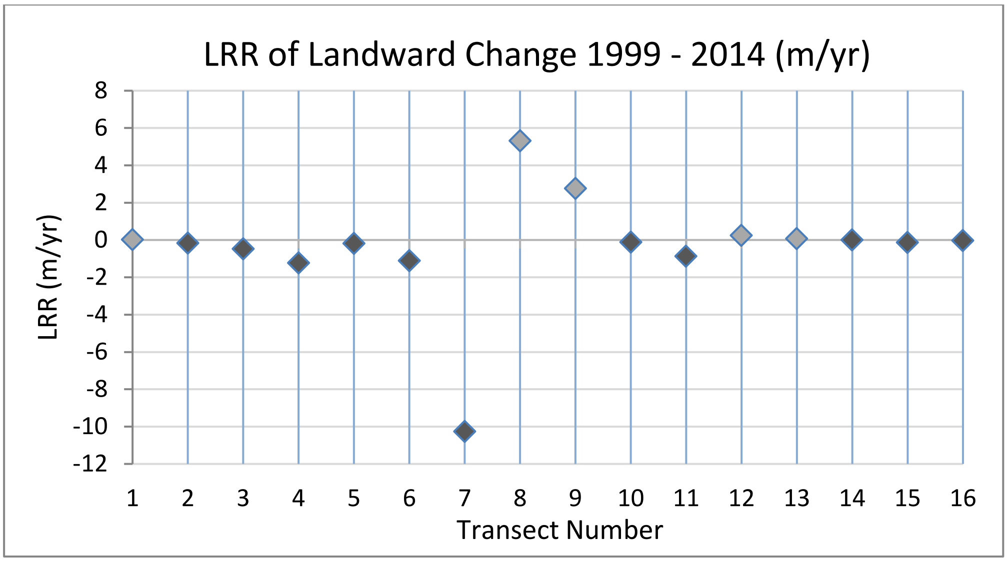

Figure 5. LRR across all transects for the landward boundary, expressing greatest dynamic change in the central barrier

The sample period 1999 to 2006 can be regarded as transitional in geomorphological terms following the 1996 breach. Results from this period are derived from DSAS and presented for all transects regarding planimetric migration of the seaward and landward boundaries (Table 1). Results derived from DSAS are presented for all transects regarding planimetric migration of the seaward and landward boundaries. In addition the Shoreline Change Envelope (SCE), Net Shoreline Movement (NSM) and End Point Rate (EPR) values have been calculated as averages across transect groups and on an individual transect basis. The assessment of change in this period revealed highly variable rates for each transect and sub-group. Table 1 summarises the NSM and EPR values derived for the seaward and landward barrier beach boundaries for this sample group.

1999-2006	Seaward Boundary		Landward Boundary	
Transect	NSM (m)	EPR (m/yr)	NSM (m)	EPR (m/yr)
1	-35.23	-5.03	-4.06	-0.58
2	-35.59	-5.08	-2.16	-0.31
3	-120.57	-17.22	-1.64	-0.23
4	-0.78	-0.11	+2	+0.29
5	-15.78	-2.25	+0.74	+0.11
6	+7.63	+1.09	-0.61	-0.09
7	+45.91	+6.56	-173.42	-24.77
8	+44.5	+6.36	+30.55	+4.36
9	-4.79	-0.69	-65.24	-9.32
10	-10.57	-1.51	-1.95	-0.28
11	-3.99	+0.57	-1.15	-0.16
12	-21.46	-3.07	+0.07	+0.01
13	-21.3	-3.04	+0.71	+0.1
14	-25.74	-3.68	+0.96	+0.14
15	-31.55	-4.51	-0.21	-0.03
16	-27.89	-3.99	-0.21	-0.03

Table 1. The NSM and EPR values of landward and seaward boundaries between 1999 and 2006 for Porlock beach.

The minimum and maximum measurements of change of the seaward boundary were found to be -0.78m and -120.57m, at transects 4 and 3 respectively. NSM across all transects averaged -16.08m, providing an average EPR of -2.23m/yr. Furthermore, erosion was observed at 81.25% of transects, with the remaining 19.75% of transects experiencing accretion or stability, implying minor recession across most of the site.

The transects were divided in to three groups to represent the middle, eastern and western edges of the beach. Group 1 cover transects 1-6 (western region); group 2 transects 7-10 (breach area) and group 3 transects 11-16 (eastern region). The evaluation of change by transect group revealed diverse seaward boundary shoreline migration trends within this transitional sample period. For this, average NSM and change rates for each group were derived and are summarised in Figure 6.

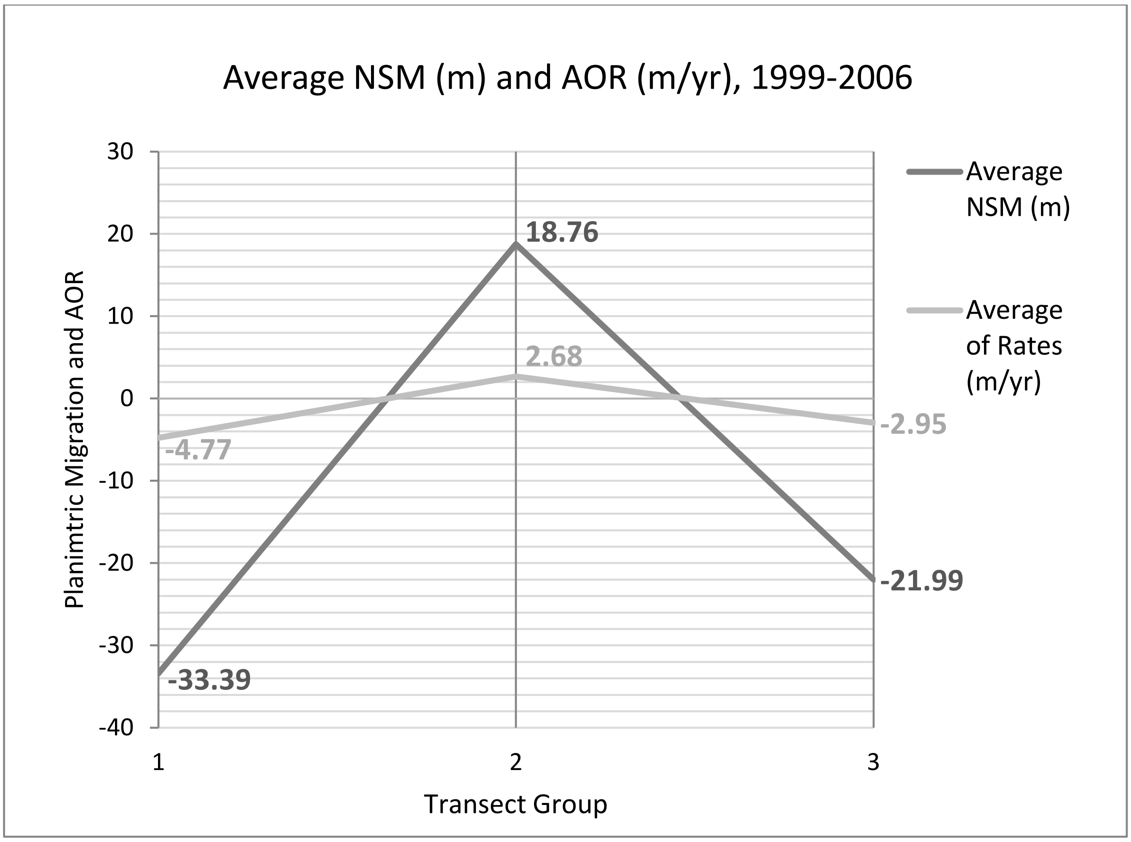

Figure 6. Transect Groups average NSM and Average of Rates of the seaward barrier boundary between 1999 and 2006

Further evaluation revealed erosion of the seaward boundary in the western and eastern regions, with accumulative phenomena in the central breach area. These observations support those derived from LRR analysis across the total sample period, discussed previously. The average of rates within transect group 1 was of the greatest magnitude (-4.77m/yr of erosion), whereas the seaward boundary of transect group 2 migrated the least (2.68m/yr of accretion). Overall, the results suggest average net erosion of the seaward boundary between 1999 and 2006, conversely to the general accumulative trends across the total study period.

The minimum and maximum measurements of landward boundary change are 0.07m and -173.42m respectively, between 1999 and 2006 (Table 4). Additionally, average NSM across all transects was -13.48m, resulting in a -1.92m/yr EPR. Landward boundary recession was observed at 62.5% of the transects whilst seaward migration was recorded at the remaining 19.75%. As with migration of the seaward boundary, NSM and EPR values were calculated for each transect group and are represented in Figure 7.

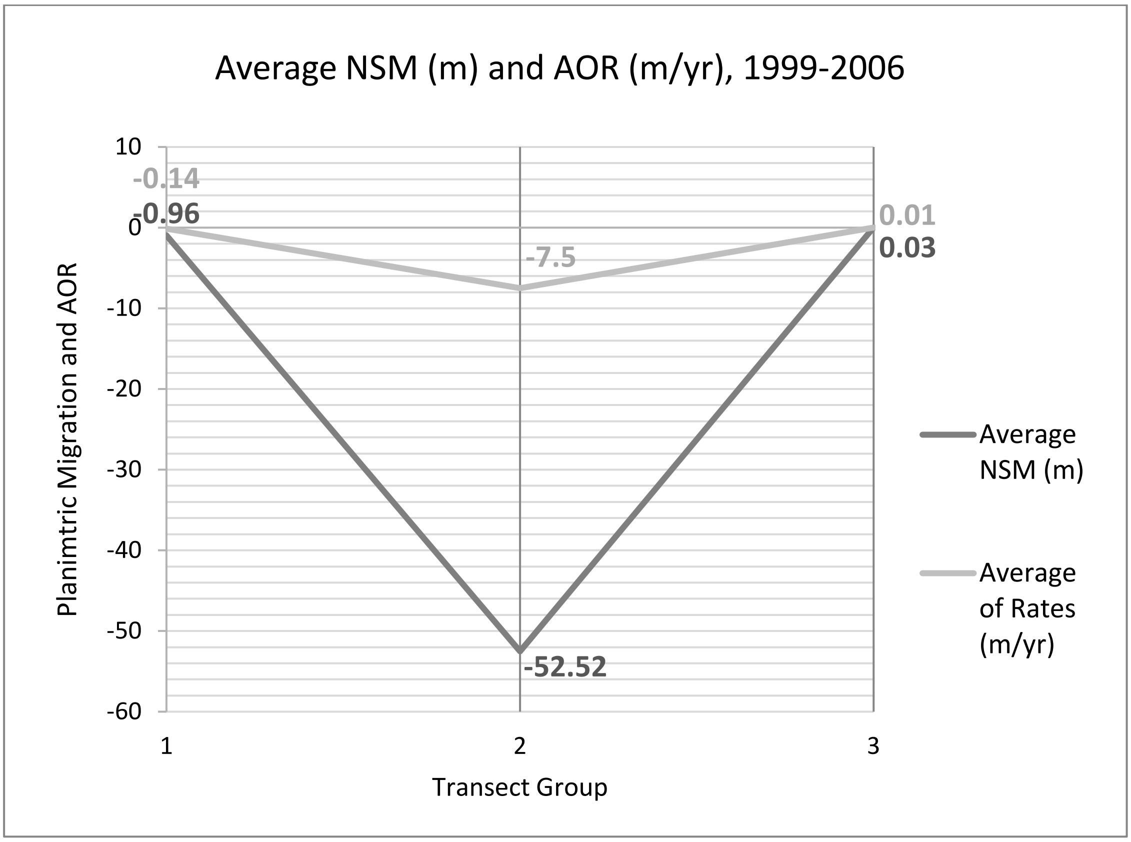

Figure 7. Transect Groups average NSM and EPR of the landward barrier boundary (1999-2006)

Analysis of the planimetric migration of the landward boundary revealed recessional patterns in the western and central regions, with some advancement in the eastern barrier area. The AOR within transect group 2 was greatest (7.5m/yr of erosion), whilst the landward edge of transect group 3 experienced the least change (0.01m/yr of accretion). Conclusively, average NSM between 1999 and 2006 indicates recessional trends, replicating that of landward barrier migration between 2007 and 2014. Assessment of both boundaries highlighted the central breach channel region as subject to the most significant change between 1999 and 2006, evidently consistent up to 2014.

The 2007 to 2014 data sets represents the remaining sample period, commencing 11 years after breaching. Increased data availability over the last decade has resulted in the inclusion of eight datasets within this sample period, providing a more robust and detailed assessment of change.

These rates were calculated in order to characterise the progressive geomorphological evolution observed since initial barrier response to breaching. The results summarised in Table 2 are the derived NSM and EPR values for the seaward and landward barrier boundaries, between 2007 and 2014.

2007-2014	Seaward Boundary		Landward Boundary	
Transect	NSM (m)	EPR (m/yr)	NSM (m)	EPR (m/yr)
1	-15.67	-2.24	7.37	1.05
2	-25.47	-3.64	-1.21	-0.17
3	167.46	23.92	-11.88	-1.7
4	-7.46	-1.07	-16.64	-2.38
5	4.27	0.61	-3.04	-0.43
6	1.36	0.19	-2.68	-0.38
7	7.46	1.07	-0.28	-0.04
8	6.27	0.9	113.48	16.21
9	1.28	0.18	-21.73	-3.11
10	-10.32	-1.47	-0.13	-0.02
11	-5.85	-0.84	-10.99	-1.57
12	-5.49	-0.78	-0.08	-0.01
13	-0.42	-0.06	2.99	0.43
14	0.97	0.14	-1.06	-0.15
15	-1.95	-0.28	0.82	0.12
16	-2.1	-0.3	-2.93	-0.42

Table 2. Depicts NSM and EPRs of seaward and landward boundaries between 2007 and 2014.

The minimum and maximum measurements of change of the seaward boundary were found to be --0.42m and 167.46m, in the eastern and western regions at transects 13 and 3 respectively. Across all transects, NSM averaged 7.15m, providing an average EPR of 1.02m/yr. Erosion was observed at 56.25% of transects, and accretion or stability was observed at the remaining 43.75% of transects, indicating reduced erosional transect rates and greater rates of accretion at transects.

As well as the analysis of the specific beach areas discussed so far, it is also important to consider the changes in beach area which have occurred during the study period. The digitisation of the landward and the seaward edge of the beach allowed the analysis of the total area of the beach to be calculated. The area values of all the beach measurements and the change between sample years are provided in Table 3. From this, NAC (net area change) across the total sample period was derived as +18,254.46m², generating an EPR of 1,216m²/yr averaging 1.09%/yr.

Sample Year	Beach Area (m²)	Change (m²)	Change (%)
1999	504,309.85		
2006	485,867.73		
		-18,442.12	-3.66
2007	521,402.86		
		+35,535.13	+7.31
2007	544,316.82		
		+22,913.96	+4.4
2009	542,337.88		
		-1,978.93	-0.36
2009	504,691.66		
		-37,646.27	-6.94
2010	422,315.52		
		-82,376.14	-16.32
2012	552,053.89		
		+129,738.38	+30.72
2013	547,782.21		
		-4,271.68	-0.77
2014	522,564.31		
		-25,217.9	-4.6

Table 3. Sample barrier area change, 1999 to 2014 for Porlock beach.

The results of the net area change analysis suggest a highly dynamic coastal feature where there is significant variation around an equilibrium state. Whilst it is clear that there have been significant periods of erosion, particularly in the earlier years of study, the overall change in beach area suggests an increase across the whole study period. The minimum change value at the site was recorded between the years 2007 and 2009, at -1,978.43m², resulting in erosion of 0.364% of the total barrier beach. The maximum change was identified between the years 2010 and 2012, resulting in an increase in barrier beach area of approximately 30.72%. Variation across the total sample period further demonstrates the significantly lower beach area in the 2010 aerial photography dataset. LRR analysis provides a change rate of 3602m/yr, equating to +0.71% of 1999 beach area per year. Although these methods of rate calculation provided variable results, a general increase in beach area across the sample period was deduced. From a coastal management point of view, this supports the decision to allow a breach to occur as the overall beach area has generally been maintained if not increased.

One further variable which can be examined and may be of interest to coastal managers, is the stability and nature of the breach inlet itself. This analysis aims to characterise the nature of post-breach barrier evolution and to further demonstrate the variability of distinct geomorphological features identified on site. The first region of interest was the breach channel, which is located approximately centrally to the study site and has experienced dynamic evolution across the total study period. The indicative digitised breach channel boundaries are organised in order of chronology in Figure 5.8 to provide a qualitative descriptive of the extent of change.

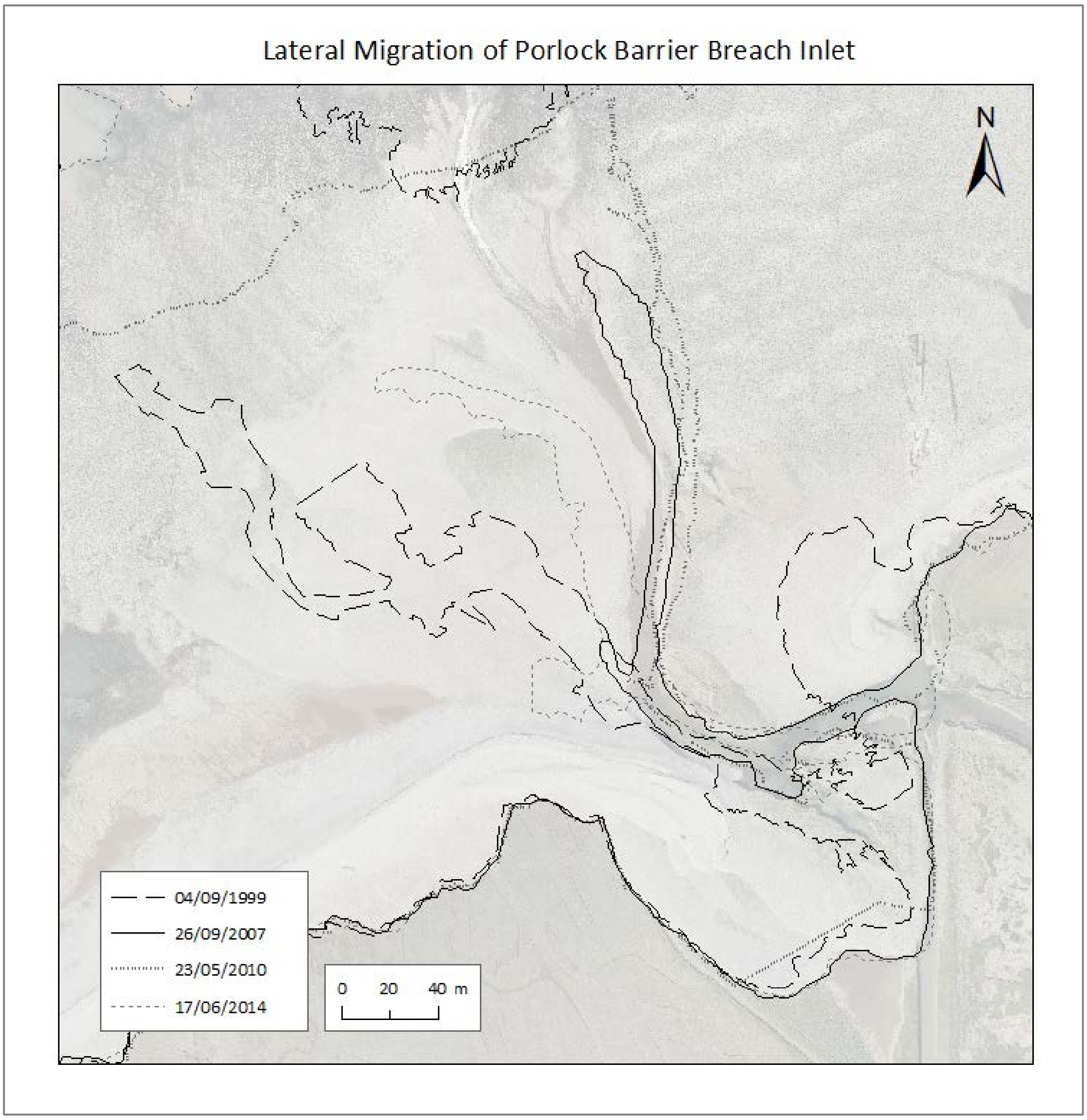

Figure 8. Lateral breach inlet migration across the study period.

Figure 8 suggests that the breach channel can be observed as generally migrating laterally in an eastward direction throughout the sample period, until 2012. The position seemingly stabilised thereafter before retreating westward again until the end of the sample period. Furthermore, the geometry of the channel can be regarded as increasing in uniformity and decreasing in width as it migrates laterally eastward. Conversely westerly channel morphologies were more variable and sinuous, however these represent a small proportion of the sample period (1999 and 2014). Figure 8 depicts the observed migration of the seaward barrier boundary in the area of erosion west of the breach inlet. Further analysis was necessary here owing to the excessive erosion and absence of barrier material, evident across all datasets.

Digitised shorelines are again provided in order of chronology to facilitate visual assessment of change across the sample period.

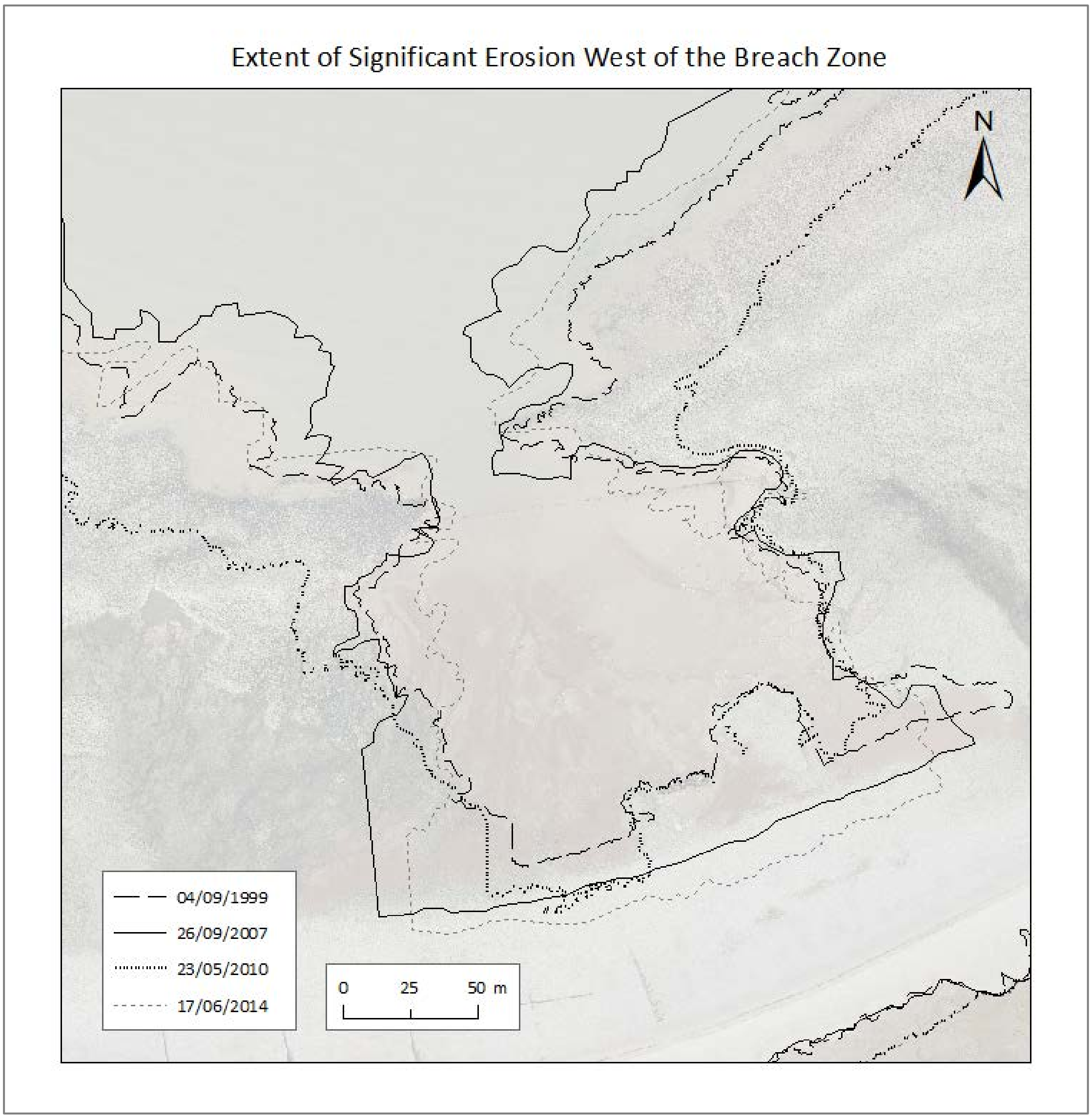

Figure 9. The areal extent of excessive barrier erosion west of the breach channel is depicted across the study period.

The derived shorelines emphasises the highly variable morphology of this barrier section; visible on the seaward boundary is potentially oscillatory shoreline dynamism, with periodic changes in direction of migration. Additionally, a small area of accretion located south of the eroded area was observed as subject to periodic erosion and deposition across the sample period, before near-total erosion of material by 2014. Furthermore, the corners of the eroded barrier region, located either side of the area of accretion also depict periodic accumulation and loss of material across the sample period.

This study has assessed the rates of the planimetric migration and beach area change of Porlock gravel barrier-beach between 1999 and 2014. Furthermore, the interpretation of breach channel migration and erosional trends in the western barrier region are provided to enhance understanding of local sediment transport processes since breaching. Analysis of significant geomorphological features highlighted general lateral migration (west to east) of the breach channel prior to 2012, where this trend reversed prior to recent stabilisation. Additionally, increasing erosion observed west of the channel between 2007 and 2014 can be correlated with accumulative records in the eastern, downdrift region.

The LRR and area values derived for the total sample period represent long-term phenomena; notably however planimetric migration and area change within the early period (1999-2006) do not correlate to these overall findings. A causal relationship is expected between planimetric shoreline migration and beach area variation, and this was observed consistently. For example between 1999 and 2006, average recession of the seaward edge was 2.23m/yr, exceeding that of the landward edge (1.92m/yr recession), reflected by area decrease of -3.66%/yr. These findings correlate to those observed by Bray and Duane (2001) regarding barrier area reduction (1988-2000) following natural crest material redistribution from cessation of intervention. Therefore, assuming the HWM is a suitable shoreline proxy for these datasets, the observed area loss between 1999 and 2006 could be attributed to accelerated erosion of material to the growing ebb tidal delta to regain geomorphological equilibrium.

Alternatively, erosion of the seaward boundary during this period may relate to initial infilling of the former agricultural zone after the breach event. Bray and Duane (2001) attribute previous 'hard' engineering as discontinuing barrier plan-form, further challenging barrier integrity. Since cessation of crest maintenance in the early 1990s, Bray and Duane (2001) noted recession rates double those recorded prior to 1988, indicating rapid redistribution of the sediment influx. Geometric design modification of the groyne at Porlock Weir has increasingly considered geomorphological trends and sediment supply in protecting the western barrier region (Blathwayt, 2010).

In addition, breach inlet evolution following the 1996 storm was observed (Figure 8); the channel positions between 1999 and 2006 demonstrate long-shore dominance through rapid lateral feature migration (easterly). This record is supported by observations by Bray and Duane (2001), whereby the rate of inlet headward extension averaged ~1m/month (July 1999 to December 2000). Subsequently, extension and migration of the breach channel could also be correlated to growth of the ebb tidal delta, which partially detracts from barrier volume but may enhance wave attenuation and protection of material.

Analysing the site in greater detail provides further speculation on the evolution of sediment transport processes at the site since permanent breaching. Local sediment inputs identified from previous research were therefore consulted and correlated with geomorphological observations from this study. Notably, the area of significant erosion west of the breach channel was also analysed, attempting to document localised sediment transport processes present. Between 1999 and 2006, this area grew as the seaward boundary receded, averaging -4.77m/yr. Greater, positive change rates derived from the central barrier region are primarily attributed to widening of the boulder frame from the incising breach inlet (Bray and Duane, 2001). Additionally, erosion west of the breach channel has likely fed the barrier immediately downdrift through dominant longshore transportation processes.

In contrast to observations made from 1999 to 2006, the second sample period (1997-2104) provided results for planimetric barrier boundary migration and beach area change which can be correlated with those for the total study period. In relation to this, average migration rates for the seaward and landward barrier edges were derived as 1.02m/yr and 0.42m/yr respectively, emphasising advancing evolution of the barrier in more recent years. Furthermore, the rates of accretion derived for the 2007-2014 period correlate to the observed ~1.68m/yr increase in beach area across the same period. Theoretical redistribution of diminished barrier sediments proposed prior to 1999 may be applied here also, potentially accounting for the observed net increase in beach area when considering low contemporary coarse-clastic sedimentary input (Cope, 2004).

The correlated area increase and shoreline migration trends in this period may result from the aforementioned redistribution of barrier sediment following cessation of artificial defences. However, contrasting trends in the earlier period likely indicate additional influential variables, including gravel depletion, relative sea level rise and increased storminess which were not quantitatively accounted for within this study. However, following observations by Bray and

Duane (2001) and Cope (2004), barrier area increase observed between 2007 and 2014 could be attributed to barrier widening and flattening (cut-back), and sediment redistribution. This may imply coastal squeeze and encroachment of the barrier into the saltmarsh zone, particularly considering natural roll-back resulting from variable relative sea level rise since barrier formation ~8,000 years BP (Bray and Duane, 2001). Cope (2004) summarises the post-breach evolution as transitional from a fringing barrier form to a double barrier-spit form, facilitating unprecedented hydro-geomorphological regimes in the modified landform. Observed barrier and tidal delta area increase could suggest enhanced wave attenuation in a period of climatic uncertainty, despite potentially impacting longshore transport processes regarding the predominantly swash-aligned barrier (Cope, 2004).

Despite observations of steady barrier volume decrease since 1988 (Bray and Duane, 2001), the period of 2007 to 2014 represents a more stable phase of area increase, supporting the idea of gradual sediment redistribution. Variable change rates across the site necessitated analysis by transect group, providing more detailed assessment of each barrier section. A reduced breach inlet change envelope compared to the previous period was observed, however the 2014 dataset depicted notable oscillatory lateral migration prior to apparent stabilisation. Greater change of the seaward edge in the western barrier and less change in the central region could therefore be attributed to the stabilisation and western migration of the inlet during this period. Notably, observed extension of the inlet washover fans is not supported by the rate of advance derived in this region (3.26m/yr). Conversely, average rates of recession (washover extension) derived for the western and eastern regions correlate to those observed across the total study period. Furthermore, transect casting in the area of significant erosion west of the breach channel may have produced unrepresentative migratory rates of the seaward edge. Transect 3 experienced the greatest rate of change between 2007 and 2014 (167.46m NSM). Disregarding this transect as an outlier instead indicates greatest change centrally, correlating with observations from the previous sample period and across the entire sample period.

Considering the observations made across the sample period(s), several key trends were emphasised owing to their notable correlation. Primarily, barrier area increase following breaching was recorded, confirming previous observations of sediment diminishment and subsequent redistribution (Jennings et al., 1998). Despite reflecting the natural oscillatory trend of breaching and re-sealing since barrier formation (Bray and Duane, 2001), the observations made within this study suggest potentially enhanced longshore transport and erosion processes resulting from these historical trends. This is particularly evident from the significant material loss from the western barrier, but is contradicted by overall observations of increased beach area. Likely a result of sediment redistribution and barrier flattening, the defensive capacity of the barrier is challenged with decreasing barrier height. However, transportation of this material to the protective ebb tidal delta may provide barrier protection and more effective wave attenuation. Cope (2004) defined the breach channel as "currently stable" (2004, p. 88) following eastern migration reflecting drift direction. In contrast, this study details more recent trends of westward migration, potentially indicating sediment supply reductions or variable drift and swash intensity. This observation can be further related to barrier height, asserting that reduced vertical accretion has diminished sediment available for reworking, potentially simultaneous with widening of the dissipative ebb tidal delta. Renewed stabilisation of the breach channel is therefore anticipated, reaching equilibrium between sediment input from the western region and deposition of material into the eastern region and the ebb tidal delta. As the barrier experiences progressive widening and flattening, the material and energy required for migration is expected to diminish further. Despite the recession of the landward edge, the barrier does not appear to significantly encroach upon the fringing saltmarsh zone, supporting Doody's (2004) assertion that modern managed realignment has intended to offset inter-tidal losses as agricultural land value reduced. A similar example of successful mitigation is at Medmerry, West Sussex, whereby adoption of a managed realignment coastal policy has enhanced wave attenuation and habitat capacities (Burgess et al., 2015). Similar results may be anticipated in the Porlock environment, in which observed barrier widening and rollback, combined with continued sediment redistribution could preserve the saltmarsh zone and diverse ecology.

Additional factors regarding climatic variability should be considered, notably forecasted RSLR by 2100 estimated between 0.28m and 0.61m under drastic emissions reductions, and between 0.52m and 0.98m under unmitigated emissions growth (IPCC, 2014). Research by Horton et al. (2014) concluded greater predictions for global RSLR and increased storminess, reflecting "the substantial uncertainty that remains in predicting the magnitude of future sea-level rise" (Horton et al., 2014, p. 5). If accurate, the capacity of the gravel barrier and the ebb tidal delta to attenuate enhanced wave action, thus protecting fringing saltmarsh habitat will likely reduce, even within scientifically designated sites. Accelerated recession and area loss may also be expected as higher ocean levels can more frequently overwash the lowered barrier. However, noted links between RSLR and increasing sediment supply may correlate anticipated relative sea level rise with enhanced local supplies.

CONCLUSIONS

This study has mapped and quantified planimetric shoreline migration and barrier area change between 1999 and 2014 for Porlock gravel barrier beach. The rates of change were calculated across all barrier transects across two sample periods of equal length. Assessment of the different sample periods suggested initial erosion of both barrier edges between 1999 and 2006, correlating with similar observations by Bray and Duane (2001). Between 2007 and 2014, these trends were reversed as barrier area generally increased, migrating seaward and landward. This can largely be attributed to sediment redistribution following breaching, resulting in widening and flattening of the barrier with sustained sediment supply to the growing ebb tidal delta. Additionally, breaching has altered barrier morphology and sediment transport processes. Evolution of the breach inlet has likely disturbed sediment supply and transport processes further, although possible recent stabilisation of the channel inlet has been suggested.

Monitoring the response of a gravel barrier to breaching has provided an important opportunity to develop upon previous research at Porlock and aims to provide context for future 'soft' engineering coastal strategies and reassure the public of the viability of such schemes. Developing geomorphological understanding of gravel barrier responses in a SSSI should be a primary motive for researchers in order to ensure regulation and conservation of protected sites and to ensure effective coastal management strategies. Enhanced certainty of anthropogenic contributions to anticipated relative sea level rise necessitate advanced planning and monitoring of coastal defence techniques in order to best mitigate the effects of climate change. Barrier encroachment into the protected saltmarsh habitat must be mitigated if observed widening trends are to continue, sustaining habitat integrity. Continued research should be conducted to explore breach permanence and ability of the barrier to reseal following overwashing. Additionally, the observations made within this study combined with those of former research conducted may assist with coastal decision-making in similar contexts of greater uncertainty.

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