Natural England Commissioned Report NECR317

Westward Ho!: Geomorphological Assessment

Northam Burrows Site of Special Scientific Interest (SSSI)
Westward Ho! Cobble Ridge Geological Conservation Review (GCR) Site
North Devon Area of Outstanding Natural Beauty (AONB)

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Foreword

Natural England commission a range of reports from external contractors to provide evidence and advice to assist us in delivering our duties. The views in this report are those of the authors and do not necessarily represent those of Natural England.

Background

Westward is an outstanding dynamic coastal system, unique as a rare and excellent example of a narrow cobble spit (see the Geological Conservation Review site account).

Natural England requested that Coastal Marine Applied Research (CMAR) undertake an assessment of the contemporary geomorphological development of Westward Ho! A conceptual model of long-term behaviour associated with barrier-spit morphology was presented. Before the shorter-term storm-driven response of the barrier was considered in context of recent barrier change. Current management measures were then compared with the long-term intent for sustainable management of the coast (as presented in the Shoreline Management Plan).

An analysis was undertaken in order to understand how the system is likely to evolve. This was based on an empirical equation relating to swash aligned gravel barrier shoreward movement to annual rise in mean sea level (Orford et al., 1995). A retreat of between 170 m and 270 m by 2120 (2.3 m/yr to 3.4 m/yr) is deemed likely dependent on different emission scenarios, linked to sea level rise.

The Natural Capital benefits of the site were analysed, to better appreciate the *elements of the natural environment which provide valuable goods and services to people.* It was estimated that Westward Ho! has a “Welfare Value” and “Natural Environment Value” ranging between £400,000 and £1.4M.

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Coastal Marine Applied Research

UNIVERSITY OF PLYMOUTH

A research-informed consultancy to address important issues in the coastal and marine environment

CMAR: Coastal Marine Applied Research

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Westward Ho! Geomorphological Assessment

Executive Summary

The gravel barrier at Westward Ho! is a unique and nationally important geomorphological feature that has captured the attention of visitors for generations. Its importance has been recognised with a host of designations attributed to the gravel barrier and dune system that together form the Northam Burrows Country Park. The exact origin of the gravel barrier (Pebble Ridge) is uncertain; however, there is consensus that the material was supplied from the rocky headlands to the south which provided the source for material moving northwards by littoral drift.

The Pebble Ridge itself provides some coastal defence functionality but reduced sediment into the system has resulted in steady barrier retreat. Historically, parts of the site have been used for landfill and this aspect is an on-going concern for the future management as the landfill site is currently dependant on rock armour and sediment recycling to prevent significant erosion.

Previous studies have identified barrier retreat and rotation to a more swash-aligned orientation, and this reflects typical behaviour of gravel barriers suffering from a lack of sediment input. This report provides an updated retreat rate of 0.75–1.45 m/yr along the ridge. There is no indication of greater retreat rates along the southern part of the barrier system; however, at pockets of erosion at the northern end are widespread as wave runup erodes the dune system that backs the gravel ridge at this location. Barrier response to storm events evidenced in survey data is consistent with expected gravel dynamics and characterised by crest build-up and rollover. Under continued sea-level rise we would expect this process to continue and, where allowed, a retreat of between 170 m and 270 m by 2120 (2.3 m/yr to 3.4 m/yr) is likely for a different emission scenarios.

The present management approach at the site is for minimal intervention to allow the natural system to evolve, in-keeping with the Shoreline Management Plan (SMP) policy of Managed Realignment (MR). Where storm damage/barrier breach occurs, the approach is to repair the barrier as necessary. Previous advice has advocated back-barrier re-nourishment to limit material loss due to alongshore processes; however, there is little evidence this is an effective management strategy. At the north of the site, the historic landfill site continues to require sediment recycling and there is no indication this need will decrease under current sediment inputs. There are clear ecosystem service benefits that can be attributed to the site, as evidenced by designations such as SSSI. More complex analysis can be applied to assign "Welfare Value" and "Natural Environment Value" which ranges between £400,000 and £1.4M for recreation and ecosystem worth. This is an area where more analysis is required to understand such valuations more carefully.

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1. Introduction

CMAR have been asked by Natural England (NE; Nick Williams) to undertake a geomorphological assessment of the Pebble Ridge at Westward Ho!. The area is undergoing a review of the most recent shoreline management plan (SMP), and, as part of this process, NE would like to have a better understanding on more recent barrier response and how future climate scenarios may impact the barrier evolution. The specific questions raised by NE include;

1. *Natural England would like to understand to what degree the barrier at Westward Ho! is geomorphologically functioning, which is consistent with the classical processes normally associated with an active gravel barrier (Orford et al, 1995) and displaying the 'classical dynamic equilibrium' shingle beach profile (Powell, 1990). Exhibiting the processes of overtopping, overwashing and barrier rollover.*
2. *We are intrigued as to why the barrier didn't adjust its form significantly in light of recent significant storm events e.g. 2013/14. What has been the effect of recent significant storms? What is the opinion of this, for example is the barrier overly high – has it been managed to too high a freeboard?*
3. *Is the current form of the feature and/or management inhibiting the barrier rolling over? Have past interventions at Westward Ho! left the site in a form that it now doesn't sufficiently overwash. Is the barriers long-term recession landwards in line with sea level being compromised (based on an empirical equation relating swash aligned gravel barrier shoreward movement to annual rise in mean sea level (Orford et al., 1995)).*
4. *What are the key benefits (ecosystem services) of a geomorphologically functioning barrier at this location?*
5. *What is the whole gravel barrier likely to look like in 20, 50, 100 years' time – approximately.*

This report address these questions and aims to provide some clarity over future management of the site. To do this the report is divided in the following subsections, followed by a summary.

1. Review of gravel barrier dynamics- conceptual models of long-term behaviour associated with barrier-spit morphology
2. Review of the long-term evolution of the barrier at Westward Ho!
3. Review of short-term storm-driven barrier response and recovery
4. Review of the Westward Ho! Current coastal management polices
5. Discussion on the long-term stability and resilience of the site under projected climate scenarios
6. Summary

1.1. Site Description

The landscape of Westward Ho! is dominated by a gravel barrier spit, referred to as the Pebble Ridge, that extends 3.5 km northwards from the town. The ridge is composed of cobbles and medium boulders (64 mm – 512 mm), transported north from the rocky coastline that extends south from Westward Ho!, and provides protection for Northam Burrows, the development and evolution of which has been the subject of numerous studies and reports (e.g., Stuart & Hookway, 1954; Halcrow, 1980; Keene, 1996; Orford 2004, 2005, Pethick, 2007, Black and Veatch, 2012).

Designated as Site of Special Scientific Interest (SSSI) for its coastal geomorphology and identified through the Geological Conservation Review Series (May & Hansom, 2003), the site at Westward Ho! depends on natural dynamism. Continued evolution in response to pressures, such as storm events and relative sea-level rise, is intrinsic to its scientific value. Additionally, the Northam Burrows is a Site of Special Scientific Interest (SSSI) as a habitat for a range of flora and fauna. The area is recognised as an Area of Outstanding Natural Beauty lying within the United Nations Biosphere Reserve. The area is also home to the Royal North Devon Golf Club and a historic landfill site is located at the northern end of the Burrows (Figure 1-1).

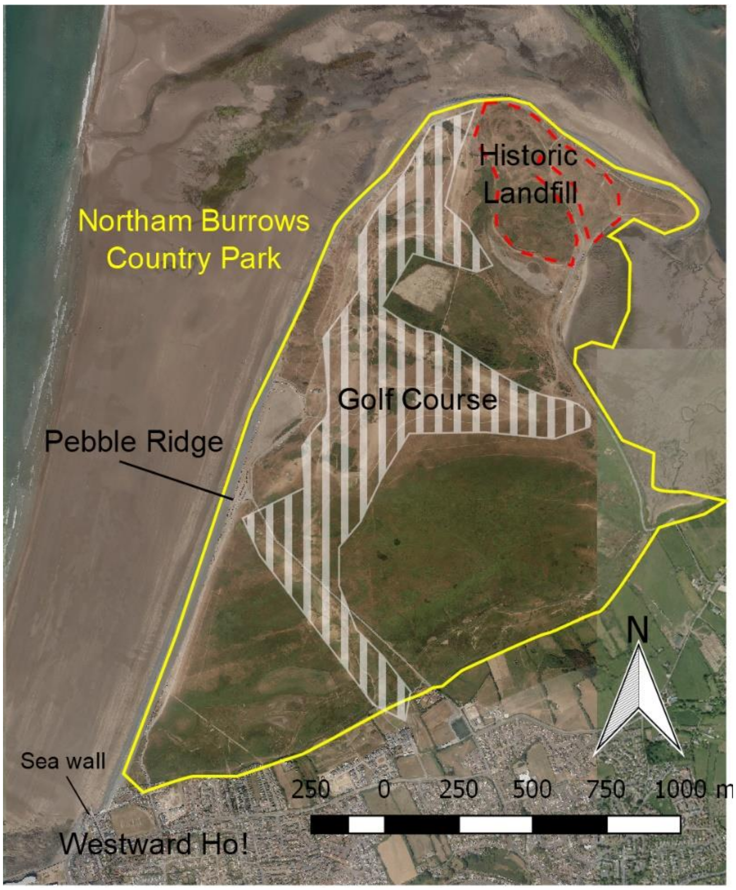


Figure 1-1. Aerial overview of the Northam Burrows Country Park with the historic landfill, golf course and Pebble Ridge identified.

Orford (2004) described the ridge as a coarse clastic sedimentary unit which is very rare within the UK. While natural in origination, the site has undergone various management practices in the last 50 years, including sea wall construction, re-cycling of material from the northern end to counter littoral drift and ad-hoc infilling to repair storm breaches.

Wave conditions for the area have been measured since 2009 by a wave buoy deployed in Bideford Bay (channelcoast.org). This dataset shows a westerly wave direction, reflecting the dominance of Atlantic weather systems driving waves up the north coast and into Bideford Bay. Annual 5% H_s exceedance wave heights for the period 2009–2019 range from 2.02 to 3.28 m, and a maximum H_s of 7.36 m attained during the 2013/14 winter (TR87, 2014). Westward Ho! experiences a macrotidal 7.7 m tide range and is also affected by fluvial outflows from the rivers Taw and Torridge.

2. Gravel Barrier Dynamics

The long-term stability and evolution of gravel-dominated coastal deposits, such as beaches and barriers, are controlled by particle size and shape, sediment supply, storm wave activity, relative sea-level rise and the surrounding base on which the deposits sit (Orford *et al.*, 2002). The impact each of these components has on gravel barrier/beach dynamics can be used to help develop a conceptual model of different morphological phases that will ultimately determine future shoreline position.

Sediment supply is for most gravel barriers a fundamental component which dictates its long-term stability. Gravel barriers usually exist within a drift-aligned state when sediment transport is along-shore dominated, or swash-aligned when transport is cross-shore dominated and along-shore transport is insignificant. The occurrence of either state is largely a function of wave breaker orientation in relation to the shoreline (Figure 2-1).

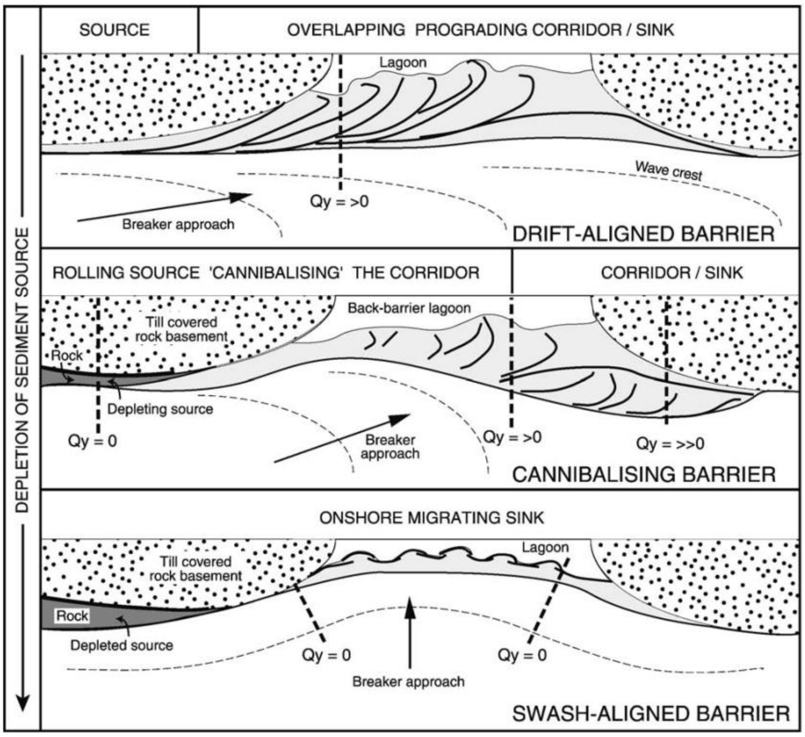
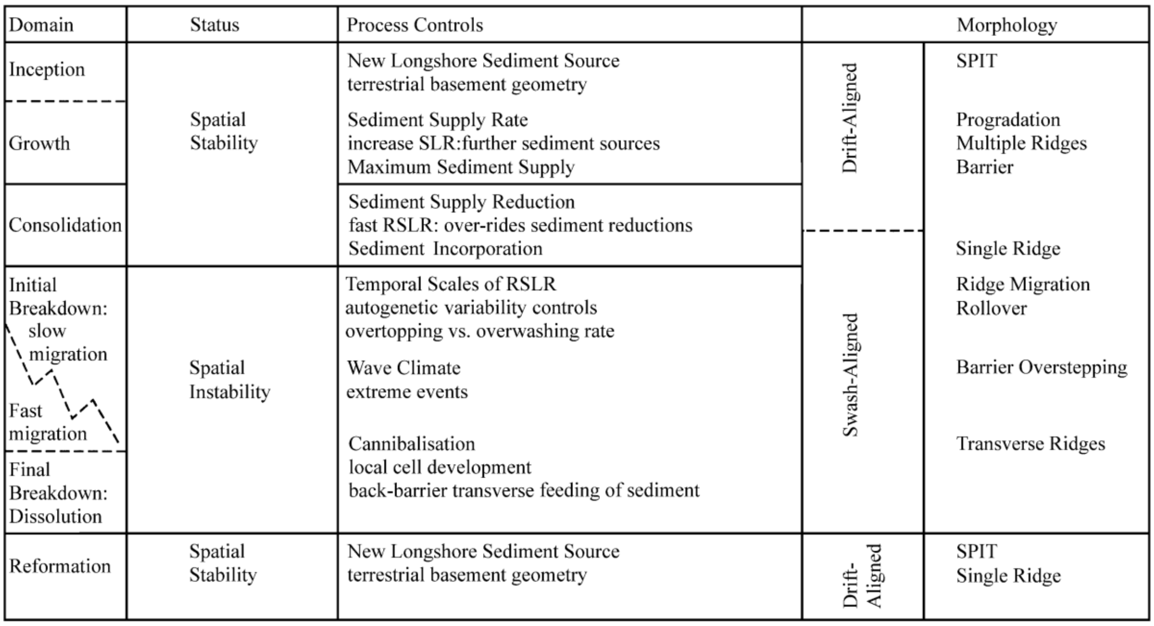


Figure 2-1. Conceptual diagram showing the change in a drift-aligned barrier to a swash-aligned barrier through a change in wave/sediment processes where Q = alongshore sediment transport. The diagram highlights the change resulting from the cessation of sediment supply and the change form alongshore transport to cross-shore sediment transport associated with swash-aligned barriers (Orford *et al.*, 2002).

The transition from drift to swash-aligned is dependent on the supply of material and the wave direction. Under conditions where the sediment supply is exhausted, such as for a drift-aligned site such as Westward Ho!, and wave approach remains relatively constant, alongshore transport along the barrier will see removal of material from the barrier referred to ‘cannibalising’ (Orford *et al.,* 1995). Further development of the barrier will depend, amongst others, on barrier anchor points and accommodation space. Where the barrier can ‘retreat’, the lack of sediment supply can result in a shift in barrier orientation to become more swash-aligned (Figure 2-1).

The initial development of a gravel barrier and the barrier crest elevation is a function of the sediment supply (discussed above) and wave runup. The distribution of wave runup on a gravel barrier is determined by the effective beach slope (itself largely a function of sediment size), breaker height and sediment size (controlling bed roughness and permeability). Westward Ho! is a complex site where the steep pebble barrier is fronted by a wide, gentle sloping sandy beach (‘composite’ gravel barriers; Jennings and Schulmeister, 2002) that acts to dissipate wave energy and reduces the runup extent compared with steeper homogenous gravel barriers (‘pure’ gravel barriers; Jennings and Schulmeister, 2002). The build-up of gravel barriers is driven by a balance between runup with sufficient swash energy to deposit material near the crest (**overtop**) and runup sufficient to move material to the back of the barrier (**overwash**). A dominance of overwash events leads to lowering of the barrier crest and barrier retreat (**rollback**) as the barrier ridge is shifted landward (Orford *et al.,* 1992). The balance between overwash and overtopping events is governed by the frequency and intensity of storm events which are responsible for elevated water levels due to storm surge and increased wave heights, both contributing to increased runup elevations. As such, future climate change impacts, including SLR (and rate) and changes in storminess, are likely to be the principle causes for cross-shore changes in barrier stability (Table 1; Orford *et al.,* 2002). These impacts of climate change will exacerbate the cannibalisation of the barrier system as a result of insufficient sediment supply and alongshore transport processes.

Table 2-1. Control domains and morphological phases identified from gravel-dominated barriers along the eastern shore, Nova Scotia (from Orford et al., 1996).



Domain	Status	Process Controls	Morphology	
Inception	Spatial Stability	New Longshore Sediment Source terrestrial basement geometry	Drift-Aligned	SPIT
Growth		Sediment Supply Rate increase SLR:further sediment sources Maximum Sediment Supply		Progradation Multiple Ridges Barrier
Consolidation		Sediment Supply Reduction fast RSLR: over-rides sediment reductions Sediment Incorporation	Swash-Aligned	Single Ridge
Initial Breakdown: slow migration Fast migration	Spatial Instability	Temporal Scales of RSLR autogenetic variability controls overtopping vs. overwashing rate		Ridge Migration Rollover
		Wave Climate extreme events		Barrier Overstepping
Final Breakdown: Dissolution		Cannibalisation local cell development back-barrier transverse feeding of sediment		Transverse Ridges
Reformation	Spatial Stability	New Longshore Sediment Source terrestrial basement geometry	Drift-Aligned	SPIT Single Ridge

Table 1 provides a summary of the many factors controlling barrier response to changes in sediment supply, wave climate and SLR. It provides a framework on which the possible morphology, under respective controls, can be found in the context of barrier evolution (Orford *et al*., 2002). This table provides an efficient overview of what is a complex, multi-faceted dynamic system where site-specific components will need to be identified to provide clarity in how a particular system has evolved and may continue to do so. If the sediment supply to a barrier is removed, this forces a shift in the dynamic equilibrium of a barrier. Disruption to sediment is likely to result in a barrier breakdown domain as the threshold for wave energy, crest elevation or other parameters are exceeded (Orford *et al.*, 2002). Once a breakdown phase is entered, non-equilibrium conditions are likely to dominate barrier response.

The additional factor that is not addressed in the discussion above is the human factor and the impact human intervention can have on a natural system. As will be discussed in the following section, the barrier at Westward Ho! appears to have experienced historic rotation, likely in response to limited sediment supply, and has evolved from a drift-aligned to a more swash-aligned feature. Importantly, coastal defence interventions have also been undertaken which will undoubtedly have impacted the behaviour of the barrier and will continue to do so.

3. Long-term evolution of the Pebble Ridge

It is beyond the scope of this report to re-examine historic shoreline positions of the Pebble Ridge; equally, there is no use in repeating previous work that has addressed this in existing studies (Pethick, 2007; Keene, 2009). The following section provides an overview of historic change, the accepted trends and some comparison of more recent data that will explore the latest observations in the ridge evolution.

While it is hard to be exact about how the Pebble Ridge originated, Orford (2004) summarises the most likely process which has implications on future management of the site:

> *The origin of the foreland structure is unknown. Emphasis tends to be given to the Pebble Ridge per se, given its strategic centrality to management issues, rather than on other element in the foreland. This is important as the sequence of ridge development identified over the last century indicates that the ridge is part of a finite sediment volume and this underlies the central problem that of a Pebble Ridge with an increasing sediment deficit. This issue has been implicitly ignored; though Halcrow (1980) probably get closest to the origin of the ridge, in identify the possibility of a massive pulse of sediment delivered through one-off landslips or fluvial extreme event from the Gore cliffs (10km up-drift) sometime in the 16th/17th centuries.*
>
> *There is a finite and limited supply of gravel to the system. It was probably a major pulse of sediment that forced the development of the gravel barrier as originally a drift-aligned spit lying further west and anchored to the coast near the Nose (the major turning point in hard rock coastal orientation from SW-NE to W-E).*
>
> *If the Pebble Ridge is only c 300 years old what is the age of the sand dunes to the north and what is the origin of both the terrestrial sediments exposed on the lower inter-tidal zone and the blue clay that basically underlies the foreland? There is no evidence that all of these features have been formed as a consequence of the Pebble Ridge placement and indeed it might be argued that all of these are related to earlier phases of barrier formation prior to the 16th/17th century.*

Historic analysis of shoreline positions from 1850 to 1997 by Keene (2009), utilising data from Stuart and Hookway (1954), suggests overall retreat of the barrier position and an anticlockwise rotation of the shoreline to make it increasingly swash-aligned (Figure 3-1). A more detailed map showing the southern end of the ridge gives a greater breakdown of the ridge retreat without indicating the response at the distal end of the barrier (Figure 3-2).

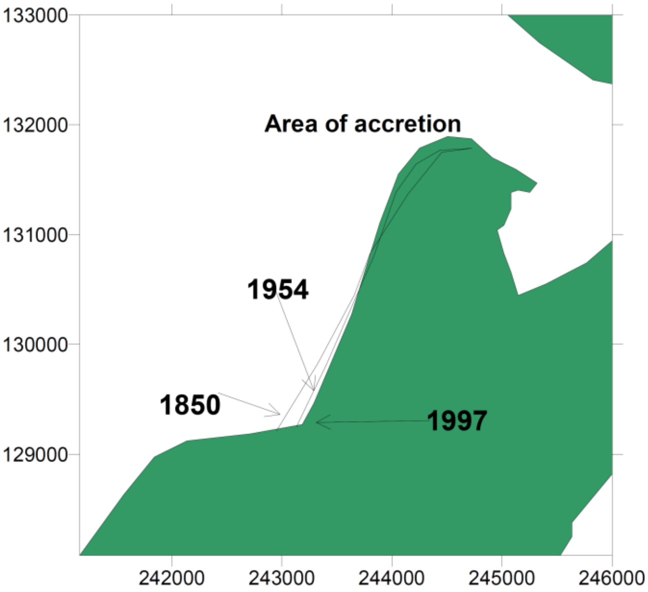


Figure 3-1. Movement of the Pebble Ridge 1850 – 1997. As presented in Black and Veatch (2012), originally from Keene (2009). Data for 1850-1954 from Stuart and Hookway (1954).

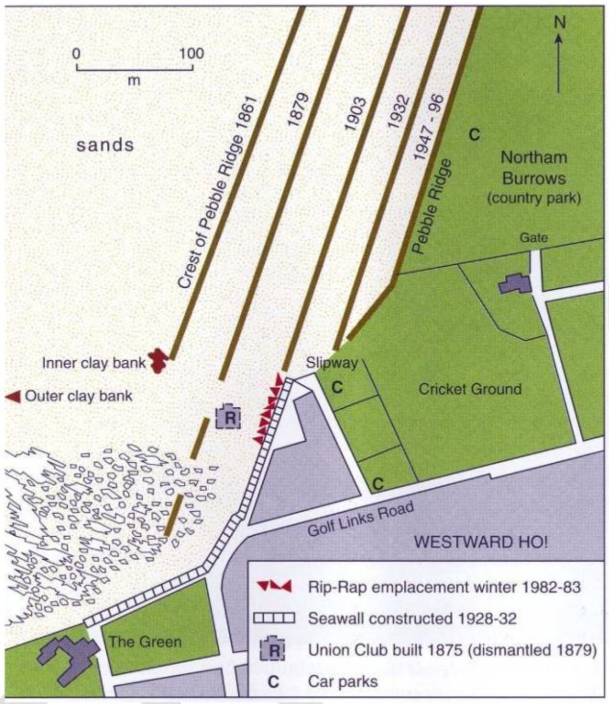


Figure 3-2. Movement of the Pebble Ridge near Westward Ho 1861 – 1996. As presented in Black and Veatch (2012), originally from Keene (2009).

These studies show a temporally variable retreat rate of 1.5 to 2.6 m/year (Black and Veatch, 2012), for the southern end of the Pebble Ridge (Figure 3-2). The historic shoreline mapping, and subsequent retreat rates, can be updated using the most recent aerial LiDAR (2017) available from the regional monitoring program (Channel Coastal Observatory; CCO). The historic mapping presented by Keene

(2009) uses the mean high water position which is often delineated on maps; however, it is not clear if the mean neap or spring high water is used. Using the LiDAR dataset, elevation contours can be extracted to show the position of mean high water neap (2 m Ordnance Datum Newlyn; ODN) and mean high water springs (4.3 m ODN; Figure 3-3). This updates previous work on the shoreline/ridge position and allows the calculation of the retreat rate over 48 years (for the period 1969–2017). At the southern end the shoreline position has retreated by 36–42 m, when compared to the MHWN and MHWS lines, which is a rate of **0.75–0.87 m/year** (Figure 3-3). At the northern end of the Pebble Ridge the shift is less clear and dependant on how the shoreline position is defined. Using the lower MHWN position there is little change in the barrier end; however, the higher MHWS does indicate retreat of between 60–70 m which is a rate of **1.25–1.45 m/year**.

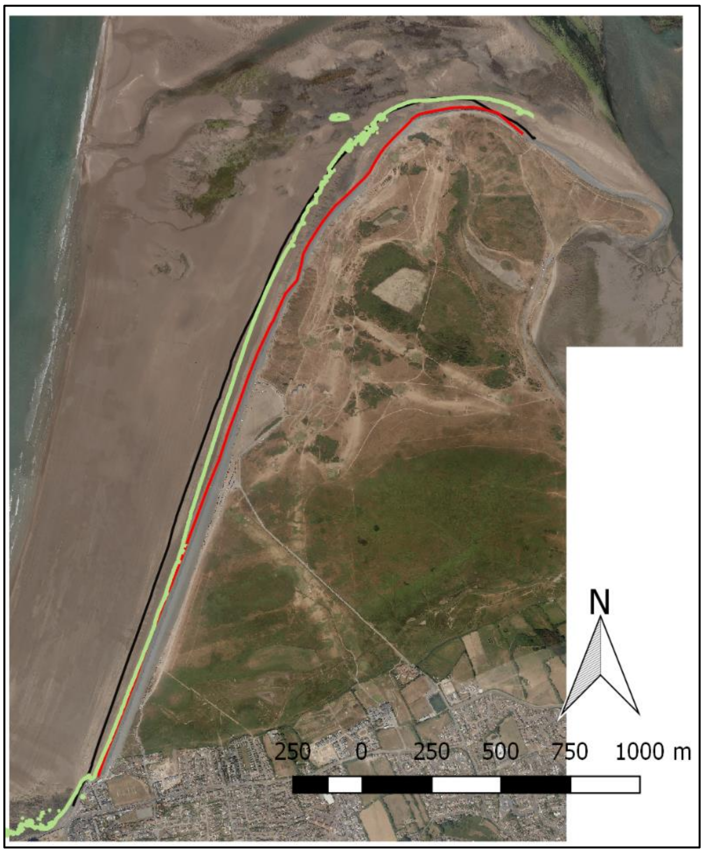


Figure 3-3. Shoreline evolution; High water line from Ordnance Survey map for 1969 (black line). Mean high water neaps (MHWN; green line) and mean high water springs (MHWS; red line) from 2017 aerial LiDAR provided by the Channel Coastal Observatory (CCO).

Of particular note at the northern end of Northam Burrows are the mass-loss regions of erosion which have affected the overall shoreline shape. As the gravel supply diminishes at this end, the thin strip of gravel at the base of the dunes provides less protection against elevated runup during extreme storm events, causing widespread dune loss (Figure 3-4). It is this process by which encroachment into the dune system has led to exposure of the historic landfill (Black and Veatch, 2012).

Figure 3-4, Site photos showing the northern end of the Pebble Ridge with a thin pebble bed fronting the dune system.

4. Short Term Behaviour

While long term trends in beach response provide a valuable insight into the behaviour of large scale systems, improved understanding of short term events also allows better understanding on the dynamics and processes operating as it is the integration of the short-term events over time that result in long-term evolution.

The regional coastal monitoring program undertakes topographic surveys (GPS), and captures aerial imagery and airborne LiDAR as part of a national project to monitor our coastline over the last ten years. An overview of the site, along with survey lines that are regularly sampled, is shown in Figure 4-1.

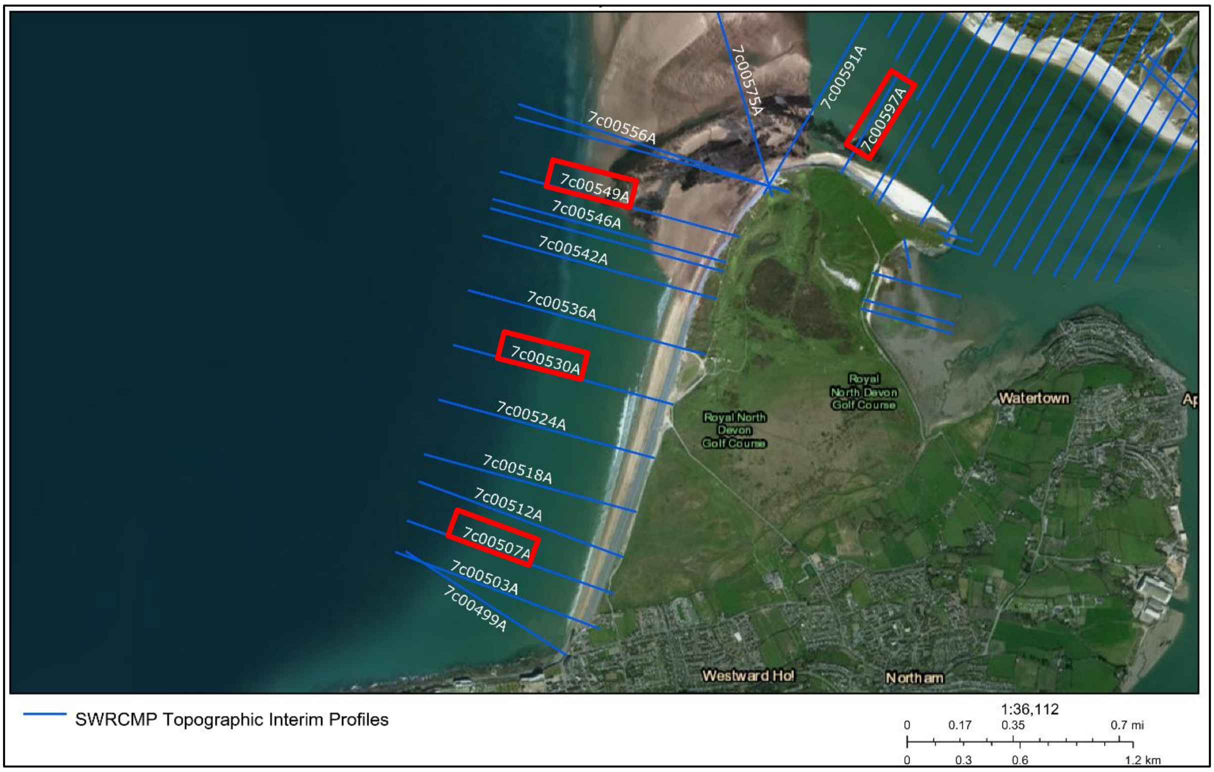


Figure 4-1. Aerial image of Westward Ho! showing the interim regional coastal monitoring topographic survey lines referred to within this document. The red boxes highlight the lines discussed further in the text and shown in Figure 4-4.

Topographic survey lines have been collected at Westward Ho! since 2010, usually twice yearly and following serious storm impacts. By combining the profile measurements throughout the survey period, the alongshore change in elevation and response of the barrier is shown in Figure 4-2. The results show a loss of material at the southern end of the ridge, adjacent to Westward Ho!, with accumulation present towards the centre of the ridge. There is some evidence of accretion at the southern end (light blue), however the figure does not show changes that are ± 0.25 m (clear on map) which could omit some accretion areas (Figure 4-2). The elevation changes at the northern end of the ridge and surrounding the dune-backed areas show a more erosive trend for the western facing section of the barrier with some pockets of accretion/erosion evident towards the estuary (Figure 4-3).

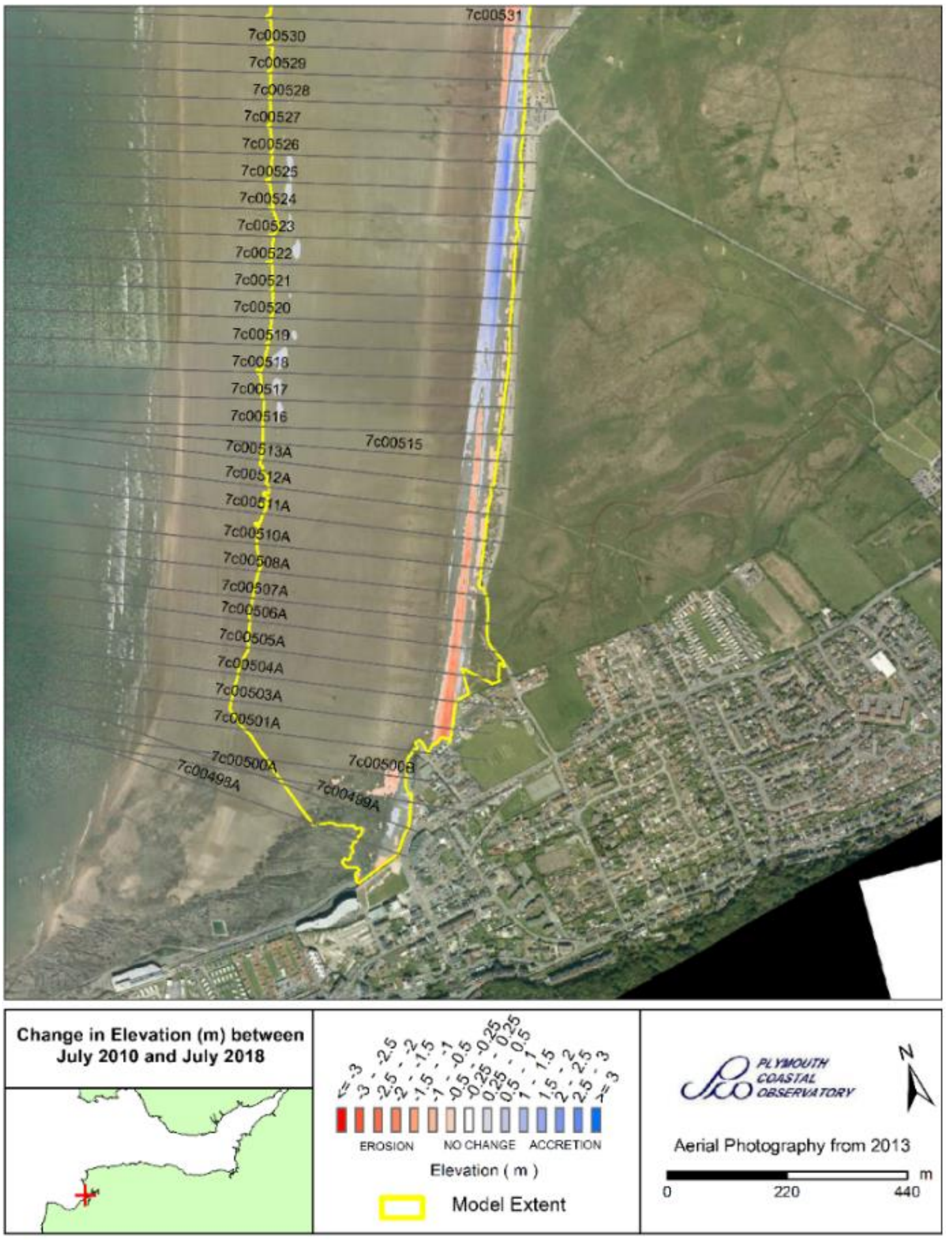


Figure 4-2. Change in elevation (m) between July 2010 and July 2018 along the Pebble Ridge, from the regional coastal monitoring annual survey report (AR76, 2018).

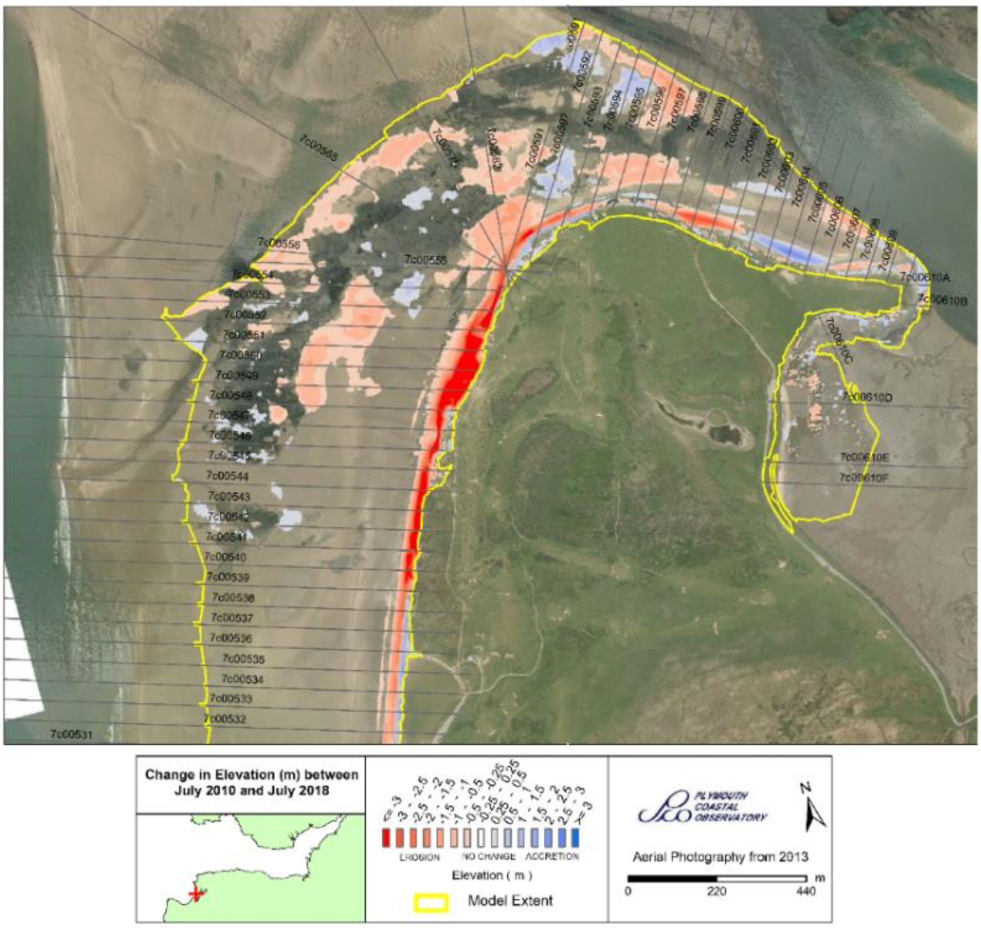


Figure 4-3. Change in elevation (m) between July 2010 and July 2018 for the northern end of Northam Burrows, from the regional coastal monitoring annual survey report (AR76, 2018).

By focusing on four lines that cover the length of the barrier, the trends evident within this dataset are examined and temporal detail that is missed on the larger scale LiDAR mapping is provided. The southern end of the barrier (line 7c00507A) has seen a net retreat in barrier crest of ~5 m (**0.5 m/year**) and drop in crest elevation of 0.5 m (Figure 4-4). There is evidence that some material from the face has remained on the back of the barrier although there appears to be a net loss of sediment at this profile. Towards the centre of the barrier line 5c00530 also shows material gain on the back slope of the barrier; however, the crest elevation has accreted by ~0.5 m. The crest position for this profile also appears to have shifted seaward as the front of the barrier has become increasingly steep. This response is symptomatic of a storm profile whereby overtopping processes build the crest through energetic swash events.

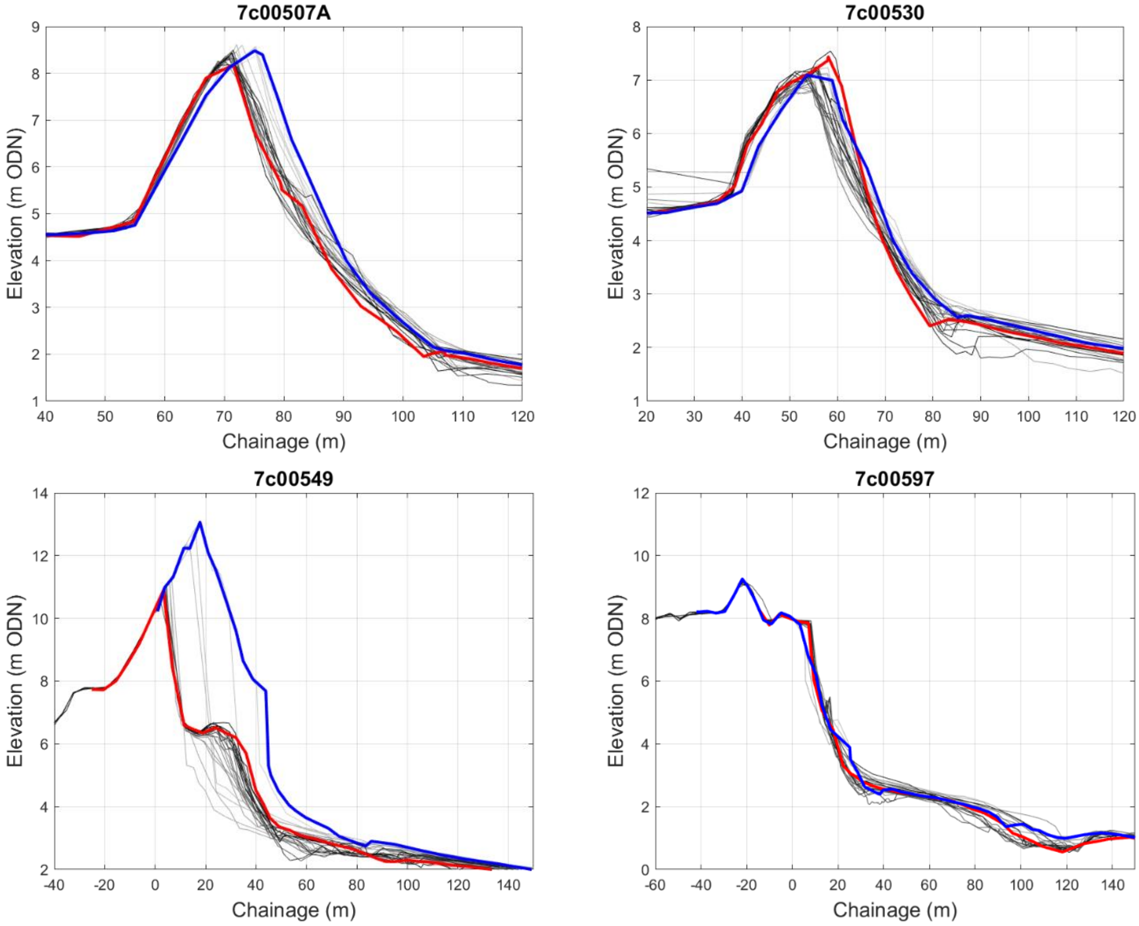


Figure 4-4. Topographic survey lines for four profiles along the Pebble Ridge (beach extent has been cropped). The plots show every profile line since 2010 to 2019 with more recent lines darker in shading. The first survey is blue and the most recent survey is red (channelcoast.org).

The third profile adjacent to the more developed dune system at the northern end of Northam Burrows (line 7c00549) shows the greatest net loss of material. This profile differs from the previous two as it is characterised by a sandy dune fronted with a gravel beach, rather than the gravel ridge previously evident (Figure 3-4; Figure 4-4). The crest of the profile (dune crest) has dropped by 2 m from a peak of 13 m ODN down to 11 m ODN in the most recent survey. The crest position of the profile has also moved landward by ~15 m (summarised in Table 4-1). At the base of the dune there is greater variability on the profile shape and this reflects the gravel beach at the foot of the dune. The final profile (line 7c00597) fronts the rock armour that defends the historic landfill at the northern end of Northam Burrows (Figure 4-1). This profile shows the least amount of change throughout the period of surveys with both crest position and elevation remaining constant likely due to the rock armour (Figure 4-4).

Table 4-1, Summary of profiles response between 2010 and 2019; Crest position (horizontal and vertical and the position of mean high water springs (MHWS) and mean high water neaps (MHWN)

Line Number	Horizontal Crest Change (m, positive = seaward, negative = landward)	Vertical Crest Change (m, positive = accretion, negative = erosion)	MHWS Position (m, positive = seaward, negative = landward)	MHWN Position (m, positive = seaward, negative = landward)
7 c00507A	-5	-0.5	-7	-4
7c00530	-5	-0.5	-10	-2
7c00549	-15	2	-15	-10
7c00597	0	0	0	0

4.1. Storm Response

Since surveys were started at Westward Ho!, as part of the regional monitoring program, the winter of 2013/14 stands out as a period of sustained energetic storms which caused widespread erosion in the southwest (Masselink *et al.*, 2016a, 2016b; Burvingt *et al.*, 2017). By focusing on the impact of this winter we can explore how the barrier responded to sustained energetic wave conditions.

To explore this dataset, we can utilise LiDAR mapping, provided by CCO, to give an area assessment as well as individual profiles for more detailed analysis. Additional observations are provided from in-situ camera installations used to map runup extent during a storm. Broadly speaking, the Pebble Ridge and northern Northam Burrows response is in-line with the longer-term profile response identified above: loss of material at the southern end, some accumulation at the centre of the ridge and more concentrated erosion at the northern end. With improved resolution from the more recent LiDAR data (±0.1 m), accretion is also evident along most of the back of the barrier extending from the southern end up towards the start of the dune system at Sandymere (Line 7c00536A; Figure 4-1; Figure 4-5), which supports the profile response shown in Figure 4-4. The northern end of Northam Burrows, presented using LiDAR data spanning a longer time period (Figure 4-6; 2009–2014), shows widespread erosion on the western edge of the dunes adjacent to pockets of erosion and accretion are evident around the northern section fronting the historic landfill.

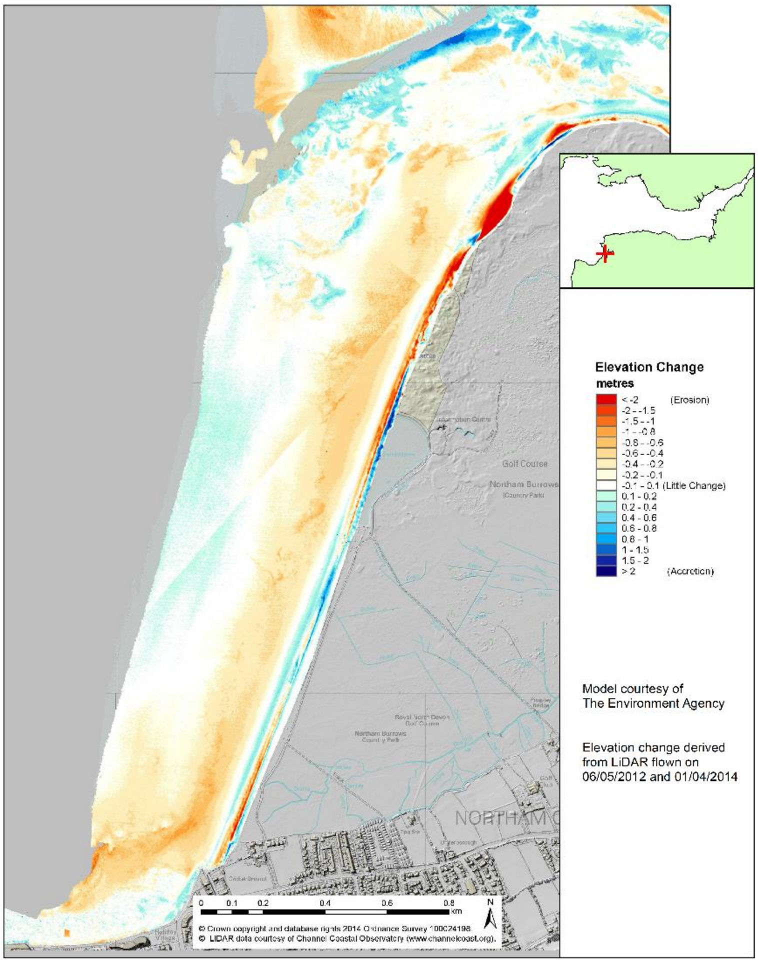


Figure 4-5. Elevation changes derived using LiDAR data between May 2012 and April 2014 showing the Pebble Ridge and Northam Burrows

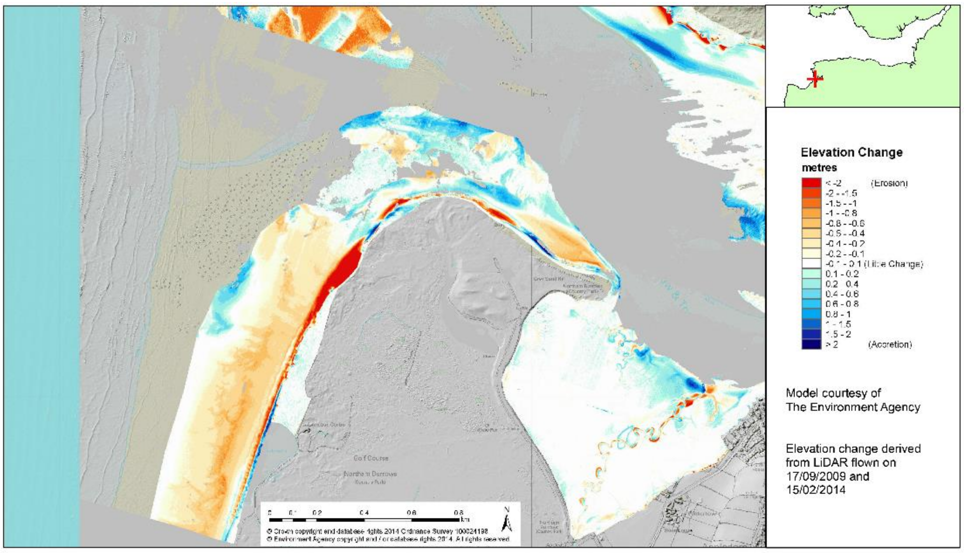


Figure 4-6. Elevation changes derived using LiDAR data between September 2009 and February 2014 showing the north end of the Pebble Ridge and Northam Burrows

The individual profile response to the storm events of 2013/2014 can also be used to explore the natural barrier response (Figure 4-7). The southern profile (7c00507A) reflects the LiDAR data and shows erosion to the front of the barrier and some rollback accumulation on the back of the barrier. Importantly, the pre-post profiles show a small increase in crest elevation which we would expect to see in response to overtopping processes. This observation also shows that the crest lowering, evident in Figure 4-4, was not a result of the storm period. Mid-way along the barrier a similar response is observed with loss on the front and material gain at the back of the barrier (7c00530). At this profile, the accumulation at the back of the barrier and loss in crest elevation suggests a more dominant overwashing regime.

Profile steepening, resulting in accumulation at the base of the dune, dominates the response at the northern end of Northam Burrows (7c00549; Figure 4-7), while net loss of material across the most northern profile (7c00597) is recorded. There is no evidence of overtopping or landward migration at this area of the SSSI.

These results provide an indication to response during a particularly energetic winter and while the long term behaviour in Figure 4-4 may differ from the storm response, for these individual profiles, it is important to consider the overall barrier response.

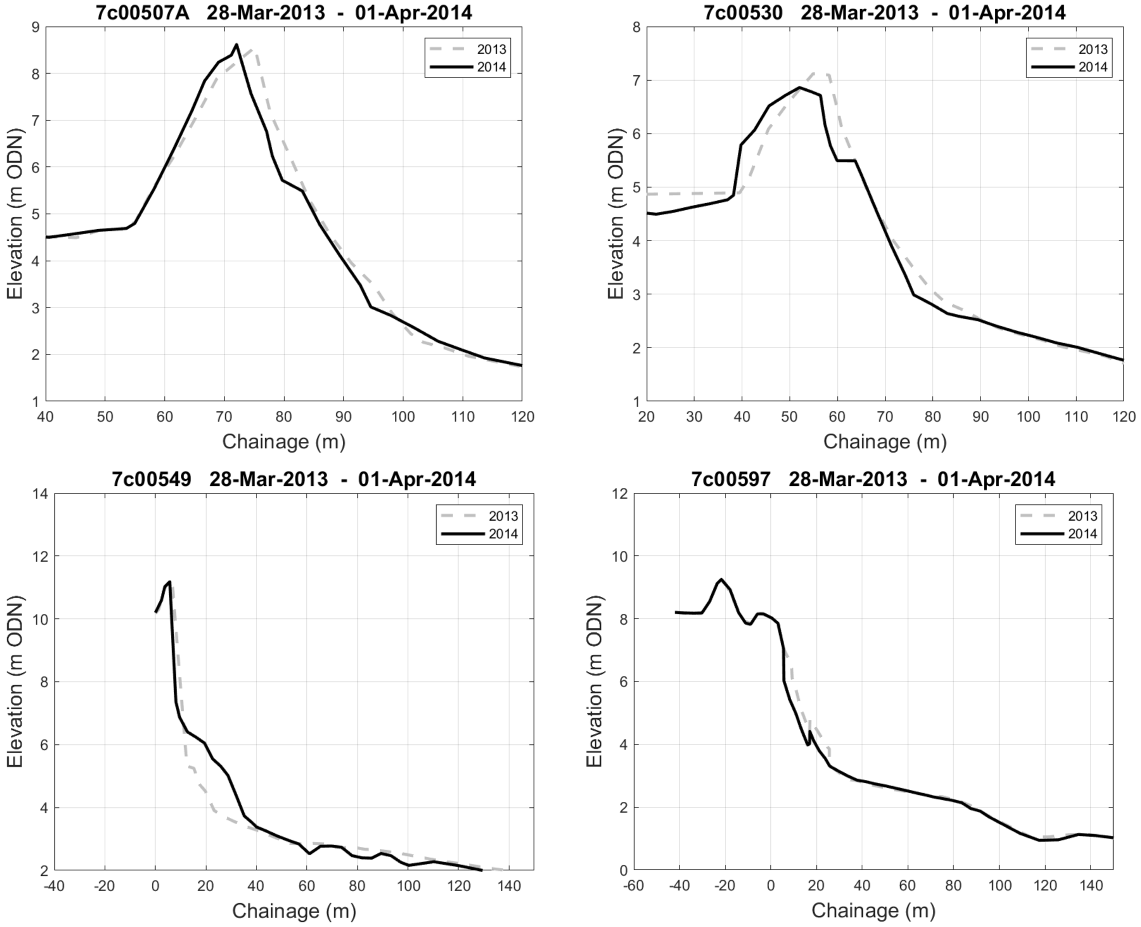


Figure 4-7. Topographic survey lines for four profiles along the Pebble Ridge (beach extent has been cropped). The plots show the pre and post survey lines for the 2013/2014 winter which was characterised by a series of very energetic storms (channelcoast.org).

In November 2013, The University of Plymouth, Coastal Processes Research Group undertook a storm response survey at Westward Ho! as part of a three-year project called New Understanding and Prediction of Storm Impacts on Gravel Beaches (NUPSIG). The project undertook storm response surveys at a number of sites in the UK including Loe Bar, Chesil, Slapton and Hayling Island. The data have subsequently been used to develop the gravel specific model XBeach-G which is based on the storm impact model for sandy beaches XBeach (McCall et al., 2014).

The storm that was measured in November 2013 was the first large event of a very energetic winter with waves heights of H_s = 6 m and peak wave period of T_p = 15 seconds (Poate *et al.*, 2016). What sets Westward Ho! apart from other gravel sites is the large sandy beach fronting and underlying the Pebble Ridge. This acts to dissipate much of the energy that reaches the barrier and therefore reduces the impact storm events have. As such, elevated water levels are required to result in significant overtopping, overwashing and subsequent rollback of the Pebble Ridge. During the November storm event small amounts of overtopping was observed at the survey site (mid barrier; Figure 4-8), insufficient to result in rollback, but sufficient to steepen the front of the barrier. As discussed in Section 2, wave runup distribution (vertical excursion above still water level) is fundamental in gravel barrier elevation and transgression. During this event runup extent peaked at 2 m above the still water level which resulted in small scale overtopping.

Figure 4-8. Photo taken at Westward Ho! on the 3rd November 2013 showing small scale wave overtopping of the Pebble Ridge barrier.

The topographic surveys support the overtopping observations from the site, with bed change focused at the interface with the sand (> 50 m cross-shore position) where bed loss is evident (Figure 4-9). On the barrier itself evidence of steepening is shown on the front side of the ridge (30–50 m cross-shore position), with material moved from the top of the ridge and some accretion towards the base. Much of these changes are small and the variability on the back of the barrier (< 30 m cross-shore position) reflects the precision of the survey method given the size of the pebbles in this area (~0.2–0.4 m).

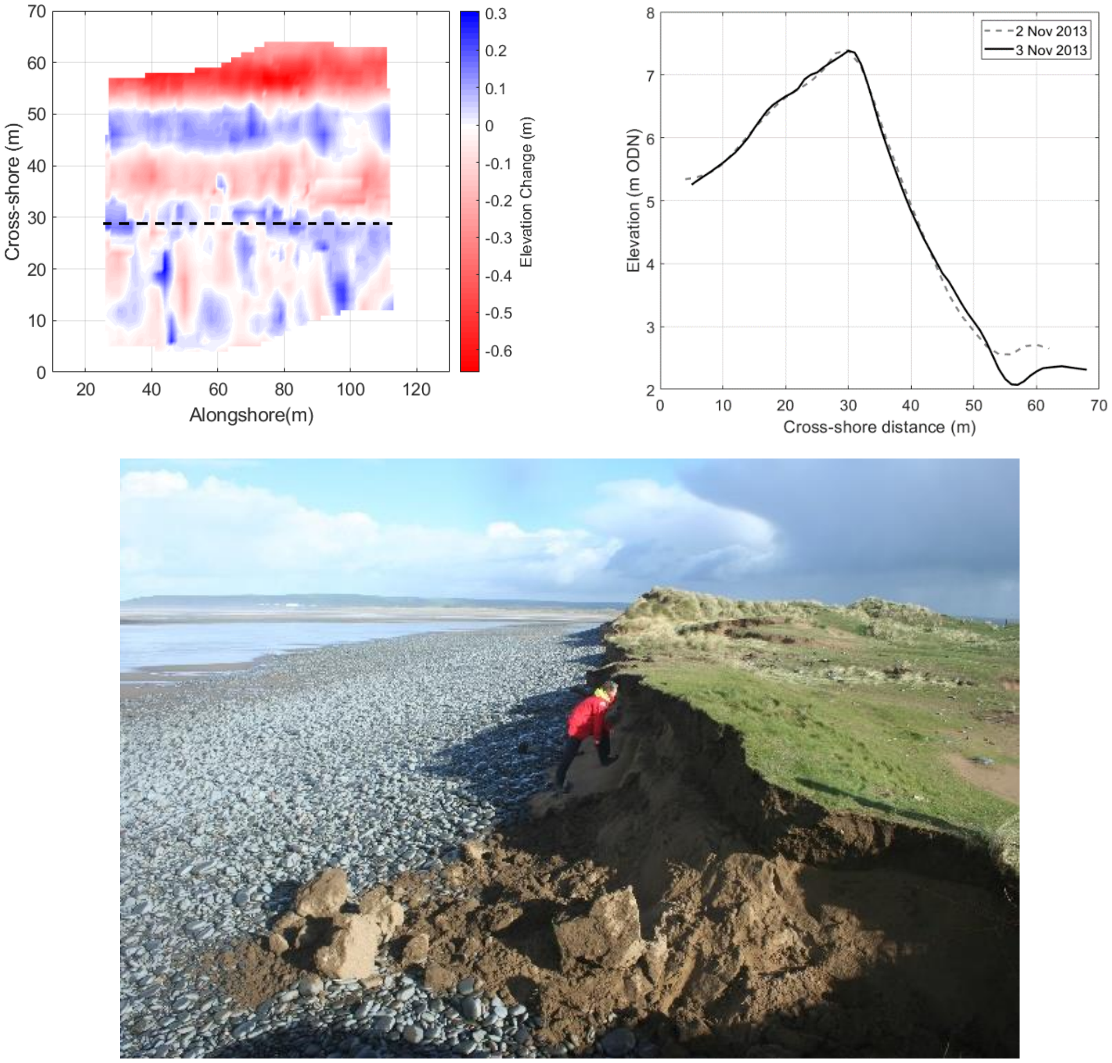


Figure 4-9. 3D Topographic change during November 2013 (top left panel), dashed line denotes Pebble Ridge crest, top of plot (>50 m) is the beach. Profile response during storm from 70 m alongshore (top right panel). Photograph of dune erosion to the north of the field site (bottom panel).

Further north from the survey site, where the dune system develops, post-storm photos show dune loss and dune cliffing behind the smaller pebble beach (right panel; Figure 4-9). This response reflects the contrasting pockets of erosion/accretion evident around the historic landfill and northern end as material is removed and redistributed around the headland.

4.2. Aerial Surveys

Aerial images have been collected by Torridge District Council in 2018 and 2019. The council utilised an Unmanned Aerial Vehicle (UAV) to conduct flights over the Northam Burrows extent. At the time of this report the aerial imagery had not been geo-rectified or processed to allow the generation of digital elevation maps that could be further used to compare with historic surveys.

CMAR were provided with a hard-drive, via PCO, containing ~85 GB of data made available by TDC. There is very little metadata within the files structure beyond folders named with what we believe to be flight dates and areas covered termed 'Phases'. Flights were undertaken in March 2018, covering the northern end of the Burrows focusing on the rubble defences. In 2019 a more regular survey pattern was employed with survey flights taking place in January, February, March, April, July, August, September and October. The focus of the flights has been on five 'Phases' which extend from the slipway at Westward Ho!, although the extent and naming of these regions varies within the datasets provided (Figure 4-10).

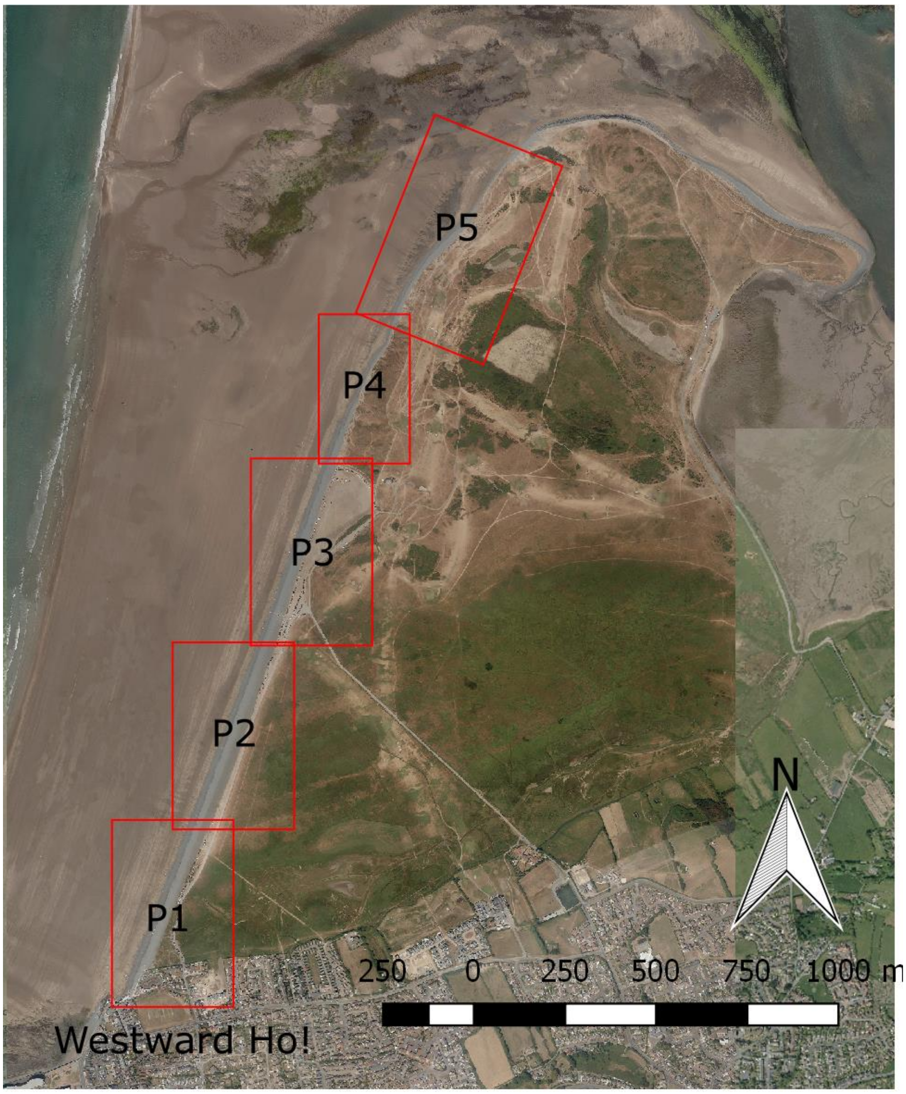


Figure 4-10. Aerial overview of Northam Burrows indicating the five Phases areas that have been mapped using UAV surveys in 2018 and 2019.

For each area flown multiple images are collected and can then be 'stitched' together to create a single image covering a larger extent. Examples of the stitched images for each Phase are show in Figure 4-11 to Figure 4-15.

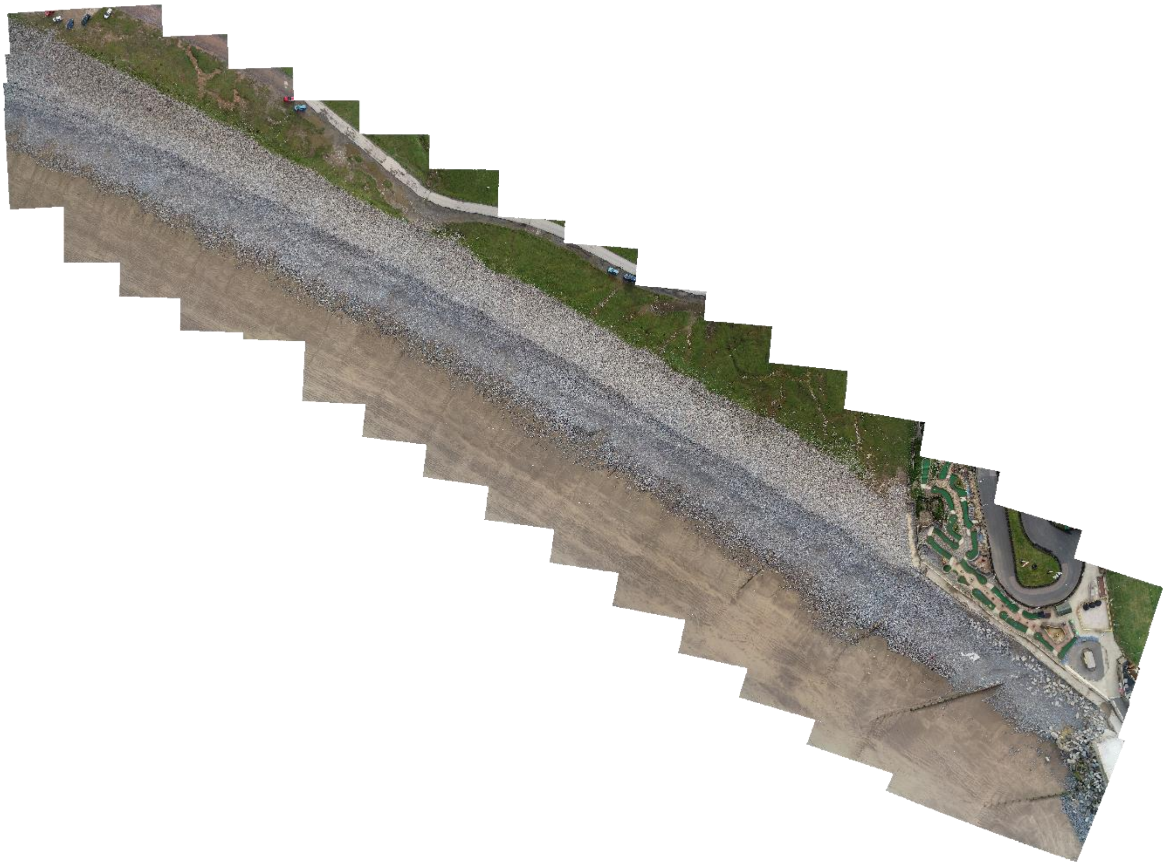


Figure 4-11. UAV aerial imagery survey of the Pebble Ridge. An example of Phase 1 extent collected in April 2019.

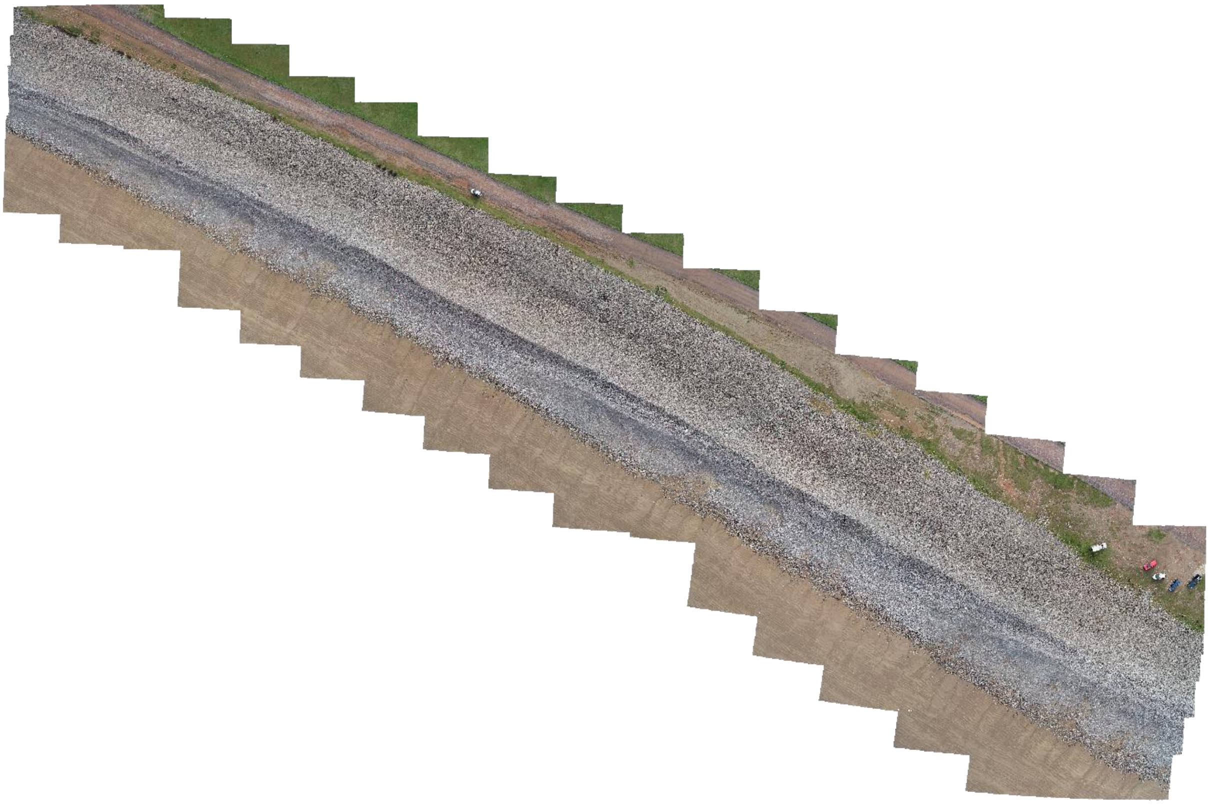


Figure 4-12. UAV aerial imagery survey of the Pebble Ridge. An example of Phase 2 extent collected in April 2019.

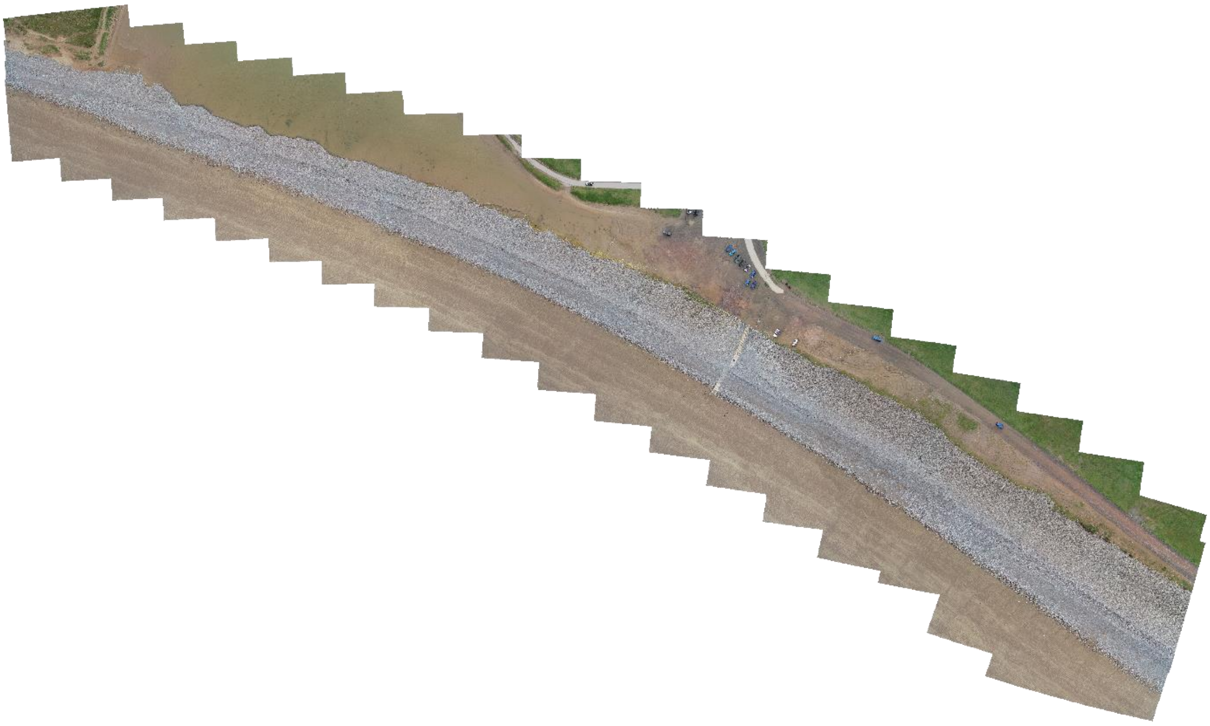


Figure 4-13. UAV aerial imagery survey of the Pebble Ridge. An example of Phase 3 extent collected in April 2019.

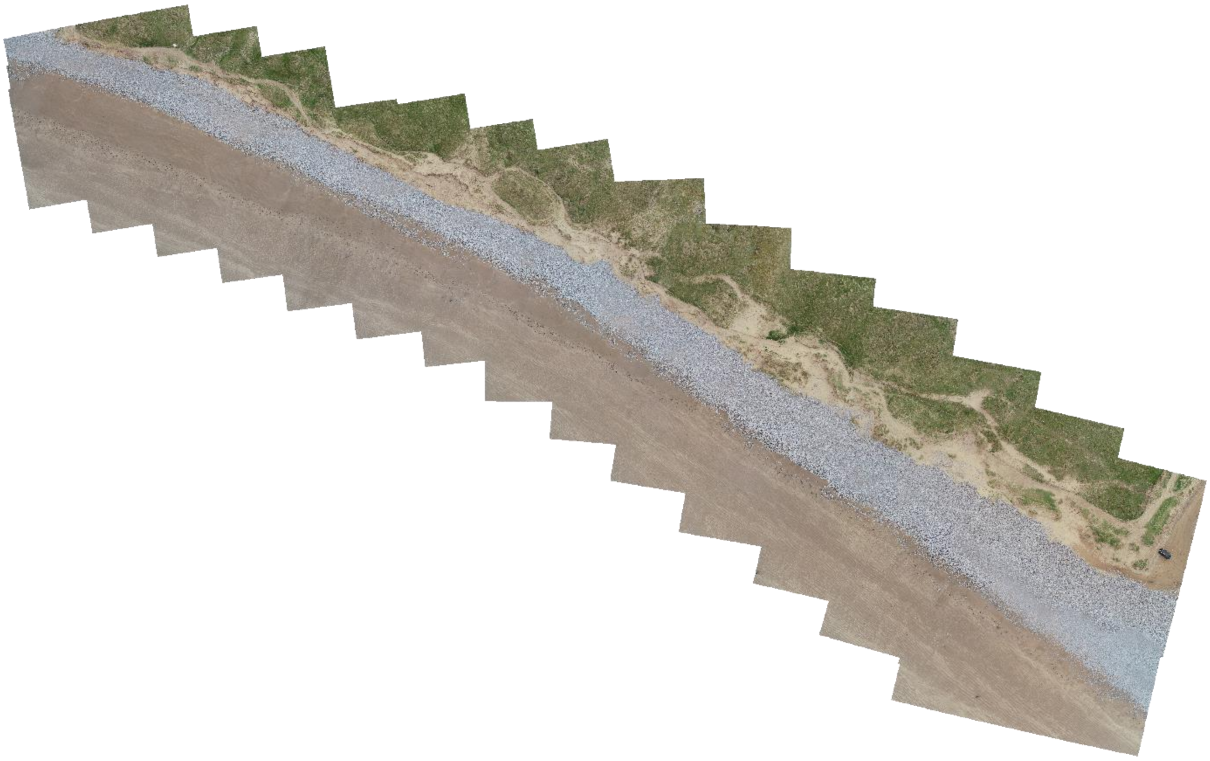


Figure 4-14. UAV aerial imagery survey of the Pebble Ridge. An example of Phase 4 extent collected in April 2019.

Figure 4-15. UAV aerial imagery survey of the Pebble Ridge. An example of Phase 5 extent collected in April 2019.

Aerial photogrammetry is increasingly being used to explore changes in coastal topography, providing a cost-effective means by which large survey extents can be examined in a relatively short period of time. The resolution of the images allows for details assessments to be made through preliminary feature-mapping and more advanced photogrammetry methods. It is expected that this dataset shall form the basis for future analysis and comparison through the generation of digital elevation maps that can be compared to historical LiDAR and GPS surveys. At present this stage of the analysis has not been undertaken and it is beyond the scope of this report to do this. It is possible, however, to explore individual images of more localised areas to examine changes in the shoreline position to highlight areas prone to erosion (Figure 4-16). By using features consistent between images it is possible to identify response between survey dates. This is clear in Figure 4-16 where the proximity of one of the golf course greens is evidently closer to the dune edge between February and September 2019. The distance of retreat is not readily available without further processing; however, the distance from a reference feature (red circle) indicates the distance to the dune edge has halved (Figure 4-16).

Figure 4-16. Aerial image from Phase 4 area showing the proximity of one of the greens which make up the golf course. The upper image is taken in February 2019 and the lower image is from September 2019. The red circles identify common features between the two images and highlights the loss that has taken place.

While it is useful to collect such data, it is critical to ensure coherent metadata are collected to allow further analysis. The use of ground control points (GCPs) allows image rectification into real-world coordinates providing direct comparison with other aerial image datasets. Such steps can be retrospectively applied by surveying in known points found between images should further analysis be required.

5. Westward Ho! Management Approaches

5.1. Historic Management Advice

Prior to the 2010 Shoreline Management Plan (discussed below) two reports were commissioned by Natural England discussing the status of the Pebble Ridge and advice on future management practices (Orford, 2004 and 2005).

Orford (2004) stated that a more natural approach should be applied to the Pebble Ridge, allowing it to rollback and to only re-nourish the back side of the ridge. This approach is designed to help facilitate the rotation of the barrier to become more swash aligned - a change that is already identified as the long-term trend (Orford, 2004). Orford argues that continued re-nourishment at the front of the ridge only serves to maintain the longshore drift of material and limit the more natural re-alignment of the barrier to become more swash-aligned. The threat of relative SLR also advocates removal of the landfill site at the end of Northam Burrows. It is argued that the potential for future contamination is a concern and requires continued protection to the distal end of the barrier and the access road to maintain its stability. Orford’s (2004) review was followed up with additional work in 2005 that looked more closely at possible management approaches. Again, a change from feeding the front of the ridge was advocated *“Sediment should be supplied to the rear of the barrier, to be incorporated into the feature, as the barrier rolls back, rather than on the front maintaining current drift potential. It may help in the long-term to reinforce the southern end with major sediment feeding, so as to reduce the rate of retreat. This will also encourage the development of swash alignment in the down beach direction.”* (Orford, 2005). The report highlights the importance of storm events on driving barrier rollback as a geomorphological process, and one that should not be disrupted through continued ridge repair. While the ridge remains in a drift-aligned orientation, longshore transport will continue to supply material to the northern end and therefore provide some protection to the historic landfill site. Orford (2005) concludes with a range of management options; **No Intervention**, whereby the barrier will gradual retreat at the southern end, through longshore transport, and eventually fail through barrier breakdown; **Maintenance**, whereby historical re-nourishment practices will continue as sediment supplies build up at Northam Burrows (6,000 m^3), exposing it to future erosion and landfill exposure; and **Restructuring** of intervention on a sustainable basis whereby the re-nourishment is undertaken to the back of the barrier to promote realignment and the landfill is removed (Orford, 2005).

5.2. Shoreline Management Plan

The SMP for Westward Ho! including Northam Burrows states *“…to continue to provide a sustainable long term solution for managing flood and erosion risk to people, property,* *infrastructure and the former landfill site, while working with the natural processes as far as possible*." This will be achieved, it states, through letting the Pebble Ridge rollback and become more swash-aligned with minimal human interference. However, it also accepts management is required to ensure reduced flood risk to settlements behind Northam Burrows (Halcrow, 2010).

The short, medium and long term management policy foresees rollback of the Pebble Ridge immediately north of Westward Ho! of 250 m in the long term at the southern end. Where breaching occurs, the Pebble Ridge would be repaired where necessary; however, for the most part the realignment should be natural. This approach would be supported by an earth bank or rock revetment to protect settlements.

At the northern end of the barrier the historic landfill site would need to be monitored closely and the policy of managed realignment carefully considered against erosion of this area.

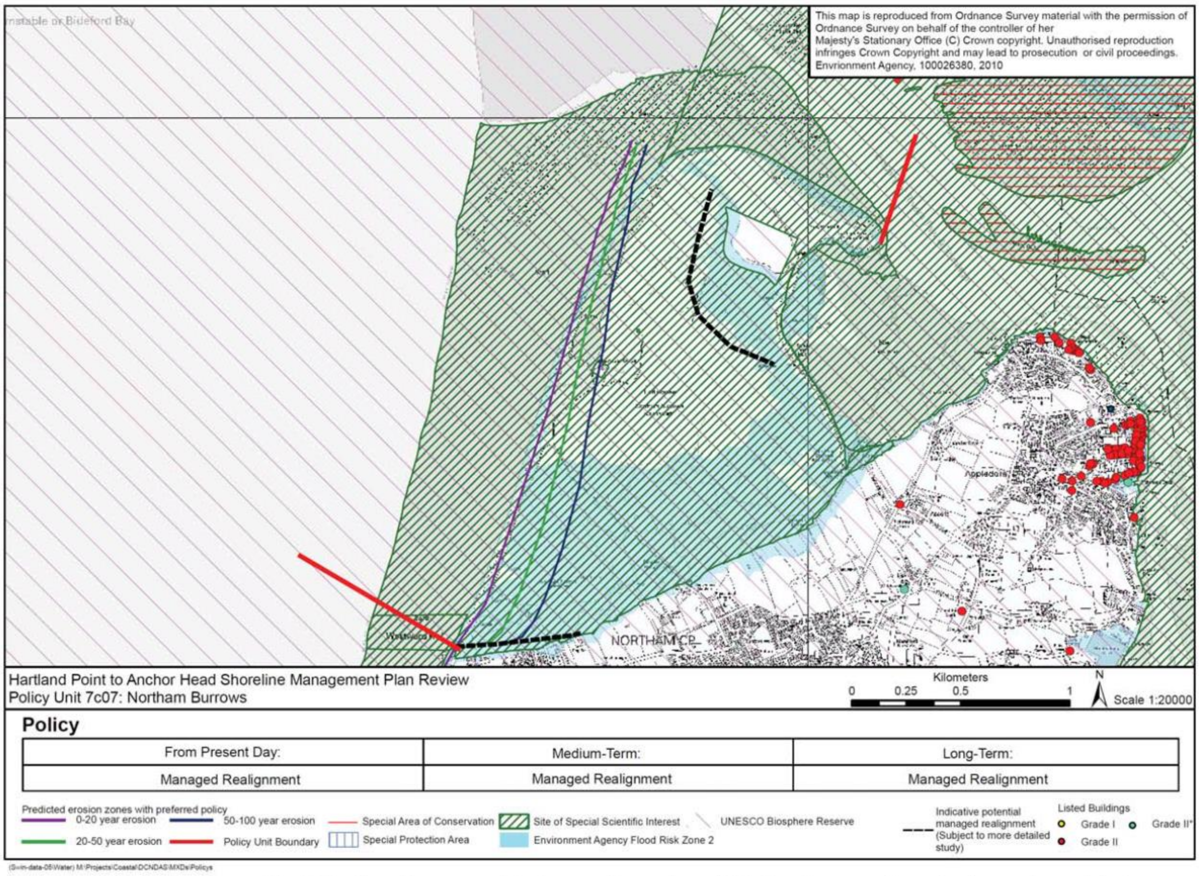


Figure 5-1. SMP policy map showing the policy designation as well as the expected realignment of the Pebble Ridge.

Since the publication of the SMP, Black and Veatch (2012) were commissioned to undertake a Coastal Management Study of the Taw Torridge Pebble Ridge. The report was commissioned to better manage coastal erosion and flood risk along the Pebble Ridge and Northam Burrows. To achieve this, the report’s objective included a review of hydrodynamics acting on the ridge, a review of morphological evolution of the site and likely future stability given a no intervention policy and to develop future management options that address climate change impacts, regional designations and the historic landfill. This comprehensive report utilises historic work, including the studies discussed above, and aims to use these to identify future management practices best suited to the site. In conclusion it recommends that *“The preferred approach recommended by this study, is to allow the Pebbleridge to evolve naturally, whilst continuing to repair any breaches as far as practical and to encourage migration by recharging the back of the ridge”*. Further focus of the recommendations in the report are on future defences that would be required to protect properties at the southern end of the ridge which goes beyond the scope of this study. The report further supports Orford (2004) and Pethick (2007) who advocate a minimal intervention approach, beyond breach repairs and re-nourishment to the back of the ridge to help with long-term realignment.

5.3. Council Management Activity

Historically, annual re-nourishment of the ridge was undertaken, using gravel from the northern end of the barrier; however, this has not been done in the last 15 years (Tara Jenkins, formerly TDC, pers com).

Pethick (2007) provides a more detailed summary of historic nourishment activities which includes data from the first SMP (Halcrow 1998) that stated 60,000 m^3 of material was used to re-nourish the southern end of the ridge between 1974 and 1978. This was followed by a re-cycling campaign with 15,000 m^3 per year moved between 1981 and 1986 reduced to 7,500 m^3 per year between 1986 and 1998. Orford (2004) put the current volume of material being moved alongshore at 5,000 m^3 given a lack of any source material into the system.

Communication with Torridge District Council (Chris Wilson) identifies that some ad-hoc re-profiling and pebble movement has been undertaken in recent years (Table 5-1); however, as shown, records of such works are light in detail and therefore of limited use for indicating impact the actions have had. There is no evidence in the limited records of nourishment activities taking place at the back of the ridge in line with the most recent advice.

Table 5-1. History of Management Activity on the Pebble-ridge

Date	Management Activity
5-8 November 2012	Beach recycling from the foreshore fronting the affected site. Creation of a sloped Pebble Ridge face with rock armour toe. Estimated quantity: 200-300m^3 (awaiting estimation of Engineer who undertook the works) **Location**: At the northern end of the ridge Line 7c00597
Spring 2014	Repair works following winter storms, southern end of the Pebble Ridge
20-22 March 2019	Localised pebble movement to allow sleeper bridge over the Pebble Ridge to be maintained. Small impact to ridge directly adjacent to sleeper walkway due to plant movement. **Location**: Central section of Pebble Ridge
22 March 2019	Localised re-profiling of beach to increase the upper crest to prevent overtopping. No loss of material in re-profiling, however due to unnatural profile loss was evident in the storms that occurred. Estimated quantity: 80 m^3 moved from the beachface to upper crest **Location**: Vicinity of Line 7c00503A (southern end of the ridge fronting the Go-Kart track)

*other management activities are likely to have happened and not been recorded.

6. Long-term Resilience and Climate Change

As discussed in the preceding sections, the rate of barrier retreat is alongshore variable (0.75–1.45 m/year) and the volume of material being moved alongshore is estimated at 5,000 m^3. The long-term and short-term evidence is that landward crest movement is occurring primarily along the Pebble Ridge up to the dune-dominated region at the north of the Burrows. In this area, wider erosion has taken place and is likely to continue to do so under future SLR (and even without SLR). These observations support Pethick (2007), who stated the ridge is retreating at a rate of 1.5 m/year as a result of wave overtopping and the retreat rate is predicted to increase in response to sea-level rise, and could reach 4 m/year by 2100 (Pethick 2007). Natural alongshore transport of material along the ridge is predicted to account for ~5,000 m^3/year towards the mouth of the Taw Torridge Estuary. This rate, Pethick (2007) states, would result in the barrier removal within 1000 years; however, the impact of increased overtopping events, in response to SLR, would have a greater impact on the barrier in the short-term. As the SMP states, the preferred approach is to maintain a natural management approach where possible and to allow the barrier to become more swash-aligned.

In 2012 Torridge District Council undertook a strategic flood risk assessment (SFRA) for Bideford and surrounding areas where future development may take place (Hyder 2012). As part of this, they undertook detailed modelling of flood extents designed to replicate a 1:200 year event given a future SLR of 1m (red shading; Figure 6-1). Additionally, the Hyder study also modelled wave overtopping for a 1:200 year event under future SLR of 1m (blue shading; Figure 6-1). The results of this work further highlight the low-lying extent of much of the Burrows and how exposed it is overall to future inundation.

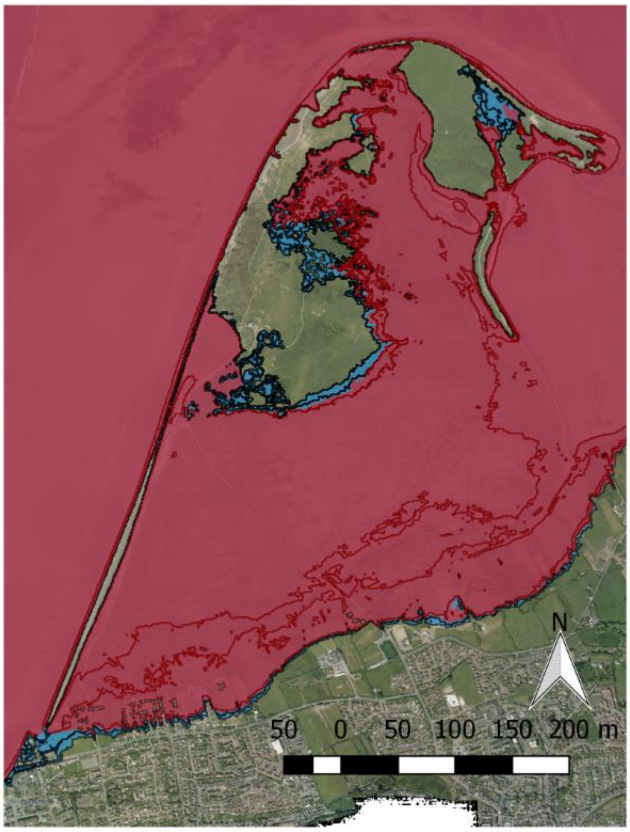


Figure 6-1. Strategic Flood Risk Assessment map for Westward Ho! and the Pebble Ridge. The shading indicates two different future flooding scenarios that were run as part of this assessment; red is the impact of sea-level rise on tide levels for a 1 in 200 year event; blue is the sea-level rise for a 1 in 200 year tide level plus wave overtopping (Hyder, 2010).

6.1. Future Barrier Retreat

As discussed in Section 2, over time scales of years to centuries, the effects of SLR drive shoreline and barrier retreat. Barrier beaches respond to SLR by ‘rollover’, building up the crest followed by crest lowering (Orford *et al.*, 1991). This process involves ‘overwashing’ – the transferring of sediment from the shore-face to the back barrier area – which is an episodic rather than continuous process. The modelling undertaken as part of the SFRA did not account for any changes in the current elevation of the Pebble Ridge or long-term changes in the barrier orientation. The most recent SMP indicates retreat distances of 150–250 m could be expected by 2110 with maximum retreat observed at the southern end of the barrier (Figure 5-1).

On sandy coasts, the most widely used method for predicting shoreline response to SLR is the ‘Bruun rule’ (Bruun, 1962), which works on the hypothesis that as sea level rises, the shoreface adjusts by moving landward as a result of shoreline erosion, whilst maintaining its equilibrium shape. The Bruun rule assumes that shoreface erosion on the upper beach is balanced by shoreface accretion on the lower beach, and the resulting change in shoreline position, δy, is predicted with equation (1):

$$\delta\gamma = -S\frac{W}{h+B} \tag{1}$$

where S is the rise in sea-level, $W = 2800$ m, is the cross-shore width of the active shoreface, $h = 12.5$ m, is the height of the active shoreface (here taken as the depth of closure), and $B = 6$ m, is the height of the subaerial beach. Because of its widespread use, the Bruun rule will be applied in this section as a preliminary model to estimate the future retreat of Westward Ho! Pebble Ridge. However, its intended use is on sandy beaches, not gravel barriers, and it has been argued that the Bruun rule should be abandoned altogether because its scientific assumptions are invalid and other more sophisticated models have superseded it (Cooper and Pilkey, 2004). Moreover, Bruun rule predicts offshore sediment transport, whereas the roll-over process that characterises the behaviour of the Pebble Ridge, constitutes onshore sediment transport.

The future retreat of the Pebble Ridge will primarily be predicted here using a more recent model, specifically developed for gravel barriers. Over meso-term time-scales (1–100 years), the rate at which a gravel barrier will naturally retreat landward has been found to relate to the rate of local sea-level rise, as well as the characteristic size, or 'inertia', of the barrier (Orford *et al.*, 1995). A comparison of barrier retreat rates in Europe and Canada by Orford *et al*., (1995) suggests that the retreat efficiency (the change in retreat rate per unit increase in the rate of SLR) is related to the barrier size or barrier inertia (cross-sectional area multiplied by crest height above mean sea level). Increasing rates of SLR therefore increase the rate at which a gravel barrier will migrate landward, and, additionally, smaller barriers will migrate faster than larger barriers (Figure 6-2).

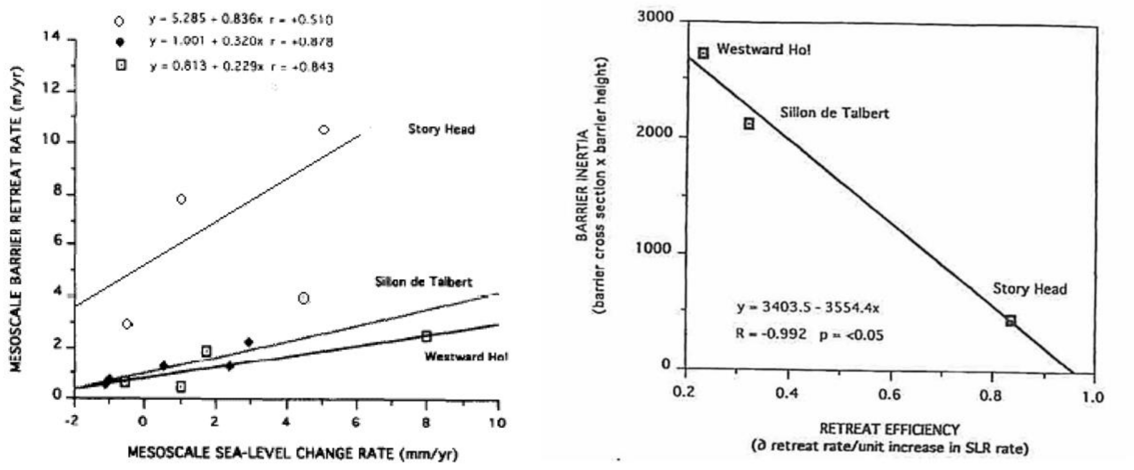


Figure 6-2, Left panel: relationship between barrier retreat rate and sea-level rise (SLR) rate determined from three gravel barriers in Europe and Canada by Orford *et al.*, (1995). Right panel: relationship between the gradient of each line in the left panel (barrier 'retreat efficiency'), versus the geometry of the barrier ('barrier inertia').

Figure 6-2 (right panel) presents the relationship between retreat efficiency and barrier inertia observed by Orford *et al*. (1995). From this paper, the Pebble Ridge barrier (characteristic cross-sectional area of around 340 m^2 and crest height of 8 m, inertia = 2720 m^3/m) would be expected to have a retreat efficiency of around 0.23 as defined by Orford. The formula requires the predicted changes in retreat rate and SLR to be added to estimates of current retreat rate and SLR in order to make a prediction of future retreat.

$$R2 = R1 + Re(SLR_p - SLR_h) \tag{2}$$

Where R2 = future retreat rate, R1 = historic retreat rate, Re = retreat efficiency, $SLR_{p\,=}$ predicted SLR and SLR_h = historic SLR (1.5 mm/yr).

To correctly predict the rate of retreat of Westward Ho! barrier using Orford *et al*.'s (1995) formula (Figure 6-2), a contemporary average retreat rate of 1.1 m/year will be used, based on the results in Section 3; Figure 3-3. This value was estimated as the average rate of crest retreat from an analysis of historic maps and aerial LiDAR of Westward Ho!, between 1969 and 2017, and represents a reasonable estimate of historic barrier retreat. The contemporary rate of relative SLR (over which the retreat rate was calculated) will be estimated using the Newlyn tide gauge analysis presented by Orford *et al*. (1995), which gives a value of 1.5 mm/yr.

Using the UKCP18 predictions of local relative sea level from Figure 6-3, future increases in sea-level rise rate can be applied to Orford *et al*.'s (1995) formula in order to predict the change in barrier retreat rate from the estimated contemporary value of 1.1 m/year, to increased rates due to the effects of accelerating SLR. Following guidance for Shoreline Management Plans, sea-level rise rate over three epochs has been considered:

- Epoch 1: 0 - 20 years (2019 to 2040), medium emission scenario = 4.7 mm/yr SLR
- Epoch 2: 20 - 50 years (2040 to 2070), medium emission scenario = 5.6 mm/yr SLR
- Epoch 3: 50 - 100 years[2] (2070 to 2120), medium emission scenario = 5.7 mm/yr SLR

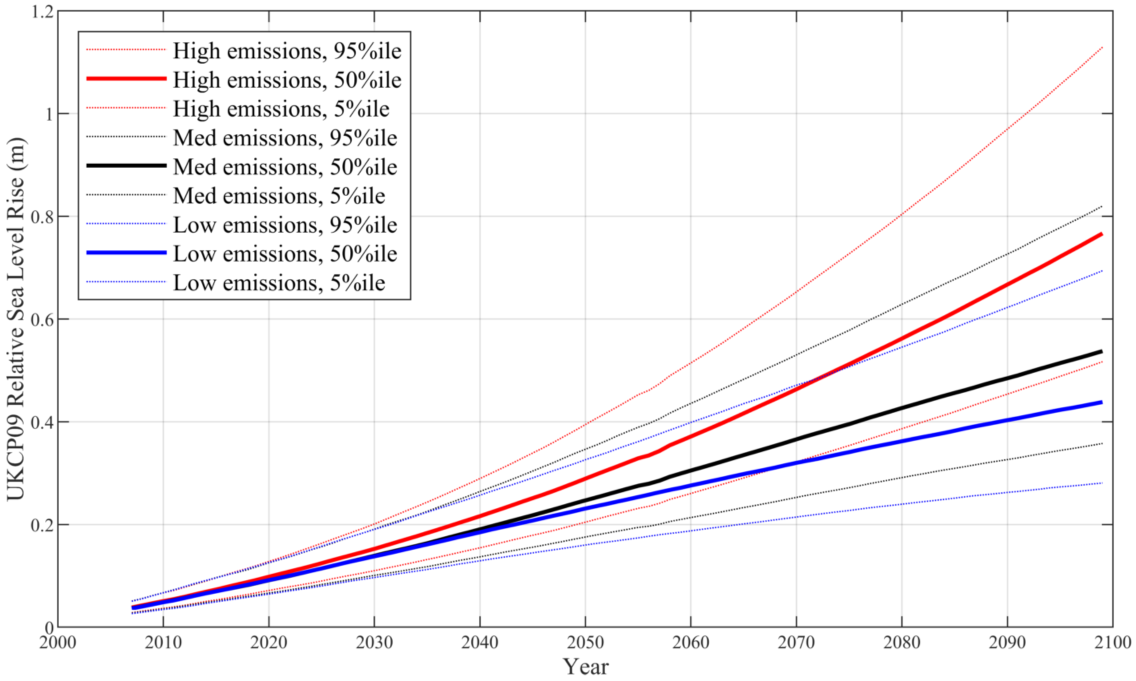


Figure 6-3. UKCP18 predictions of relative sea-level rise (SLR) at Westward Ho!, under high, medium, and low emissions scenarios (from https://ukclimateprojections-ui.metoffice.gov.uk/). Lower (5th percentile), median (50th percentile), and upper (95th percentile) predictions are shown for each scenario, indicating the magnitude of uncertainty, determined from an ensemble of UKCP18 model predictions.

Figure 6-4 shows the retreat of the barrier crest under different SLR scenarios, as predicted by Orford *et al*. (1995), relative to its current position in 2017. These data are summarised in Table 6-1, Table 6-2 and Table 6-3 for the low, medium, and high UKCP18 emissions scenarios, respectively. Barrier retreat predicted using the Bruun rule is also presented in the tables and in Figure 6-5, for comparison. The predictions from Orford *et al*.'s formula indicate that accelerating SLR will increase the rate of landward barrier migration in each epoch, and that the historic rate of barrier retreat will, in future, be exceeded under any of the future emissions scenarios. In comparison, the Bruun rule predicts that under a low and medium emissions scenario the estimated rate of barrier retreat over the past century will decrease for the next century, while high emissions scenarios would result in faster retreat over the next century, compared to the estimated historic rate of retreat (Figure 6-5). It should be stressed that the Bruun rule predictions are used here only to provide a comparative model, and it is expected that in reality the barrier will respond as per the predictions of Orford *et al*.'s formula, which are based on observations of real gravel barriers.

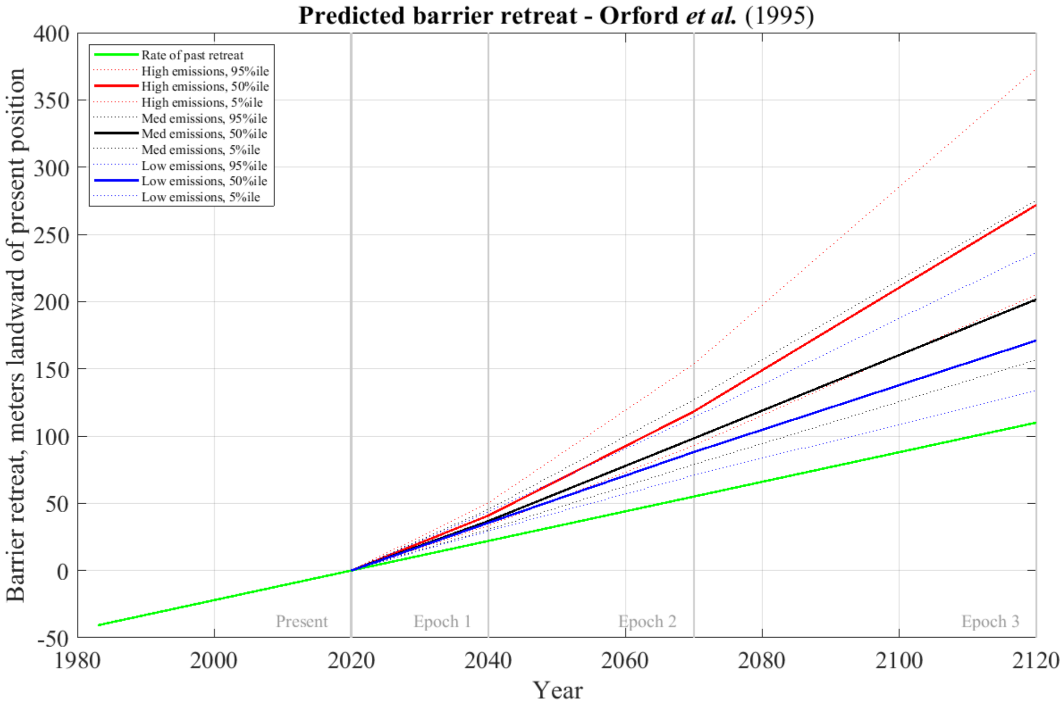


Figure 6-4. Retreat of Westward Ho! Pebble Ridge due to SLR predicted using Orford et al.'s (1995) model (Figure 6-2) for different UKCP18 emissions scenarios. Epoch 1 is years 2020 to 2040 (0 - 20 years), epoch 2 is years 2040 – 2070 (20 – 50 years), and epoch 3 is years 2070 – 2120 (50 – 100 years). Lower (5th percentile), median (50th percentile), and upper (95th percentile) predictions are shown for each scenario, indicating the magnitude of uncertainty in the UKCP18 sea-level rise predictions.

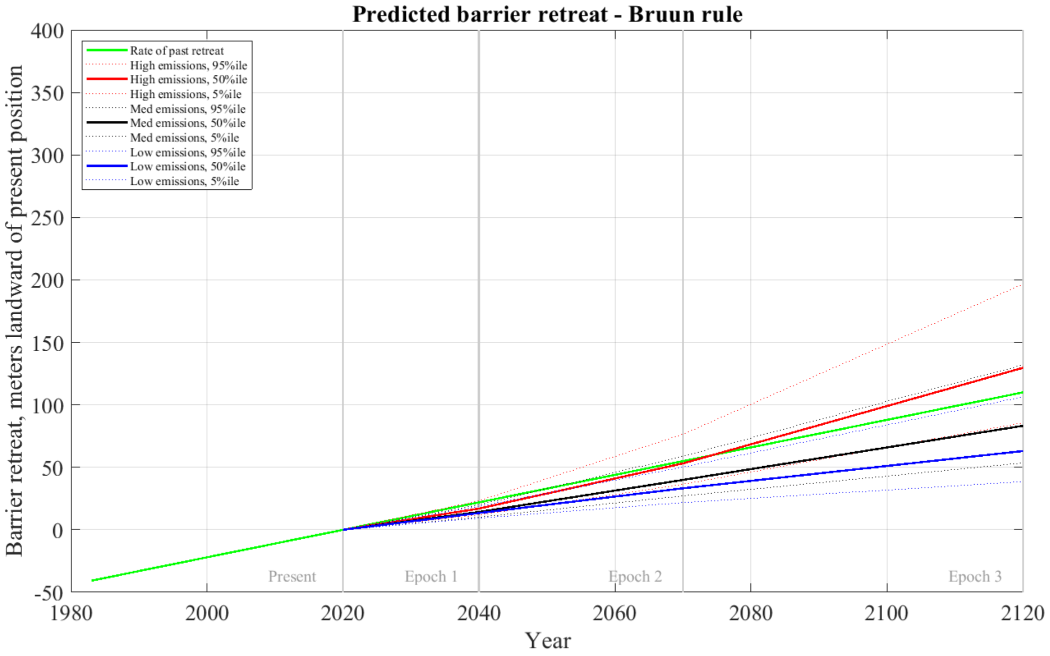


Figure 6-5. Retreat of Westward Ho! Pebble Ridge due to SLR predicted using Bruun rule (Bruun, 1962) for different UKCP18 emissions scenarios. Epoch 1 is years 2020 to 2040 (0 - 20 years), epoch 2 is years 2040 – 2070 (20 – 50 years), and epoch 3 is years 2070 – 2120 (50 – 100 years). Lower (5th percentile), median (50th percentile), and upper (95th percentile) predictions are shown for each scenario, indicating the magnitude of uncertainty in the UKCP18 sea-level rise predictions.a

Table 6-1. Predicted retreat rate and retreat distance of the Pebble Ridge under varying sea-level rise from a low emissions scenario (50th percentile prediction). Values are given to 2 significant figures.

Timeframe	UKCP18 rate of sea-level rise (mm/year)	Orford *et al.*, (1995)		Bruun rule (Bruun 1962)	
		Retreat rate (m/year)	Retreat distance (m landward)	Retreat rate (m/year)	Retreat distance (m landward)
0 – 20 years	4.43	1.39	58	0.41	22
20 – 50 years	4.36	1.76	109	0.66	40
50 – 100 years	3.95	2.34	170	1.04	62

Table 6-2. Predicted retreat rate and retreat distance of the Pebble Ridge under varying sea-level rise from a medium emissions scenario (50th percentile prediction). Values are given to 2 significant figures.

Timeframe	UKCP18 rate of sea-level rise (mm/year)	Orford *et al.*, (1995)		Bruun rule (Bruun 1962)	
		Retreat rate (m/year)	Retreat distance (m landward)	Retreat rate (m/year)	Retreat distance (m landward)
0 – 20 years	4.71	1.61	63	0.56	25
20 – 50 years	5.65	2.05	125	0.85	51
50 – 100 years	5.72	2.72	201	1.29	83

Table 6-3. Predicted retreat rate and retreat distance of the Pebble Ridge under varying sea-level rise from a high emissions scenario (50th percentile prediction). Values are given to 2 significant figures.

Timeframe	UKCP18 rate of sea-level rise (mm/year)	Orford *et al.*, (1995)		Bruun rule (Bruun 1962)	
		Retreat rate (m/year)	Retreat distance (m landward)	Retreat rate (m/year)	Retreat distance (m landward)
0 – 20 years	5.60	1.99	74	0.81	32
20 – 50 years	7.96	2.58	159	1.20	74
50 – 100 years	10.10	3.45	273	1.77	130

7. Summary

This report provides an update and review of the range of work that has already addressed the origin, behaviour and future of the Pebble Ridge at Westward Ho!. It is evident the site is of national importance and plays a function in providing flood protection to properties as well as a unique habitat for flora and fauna. The area has been exposed to active management and interaction through the recycling of material, the siting of a historic landfill and the subsequent defence of this historic landfill. The barrier is exposed to large waves and has experienced multiple breaches in response to storm events. Its long-term behaviour has been relatively steady and consistent with a limited sediment supply the barrier has retreated (most noticeably at the southern end) becoming less ‘drift-aligned’. How the barrier will continue to behave and respond to increase SLR can be predicted under current management and suggests current retreat rates could double in the next 100 years. This section will aim to provide a synthesis of the previous chapters through the original scope outlined by NE for this report.

1. Natural England would like to understand to what degree the barrier at Westward Ho! is geomorphologically functioning, which is consistent with the classical processes normally associated with an active gravel barrier (Orford *et al.,* 1995) and displaying the ‘classical dynamic equilibrium’ shingle beach profile (Powell, 1990). Exhibiting the processes of overtopping, overwashing and barrier rollover.

Topographic analysis of the barrier behaviour over the last ten years shows a response consistent with accepted concepts in gravel barrier response. The orientation of the Pebble Ridge allows alongshore transport to move sediment to the north where it is deposited at the estuary mouth. Cross-shore processes are characterised by storm events which steepen the front of the profile, as material is moved to the crest or, where overwashing occurs, deposited to the back of the barrier. These observations are consistent with previous studies and are responsible for the pace of retreat that has been mapped previously and within this study (~1.1 m/year).

2. We are intrigued as to why the barrier didn’t adjust its form significantly in light of recent significant storm events e.g. 2013/14. What has been the effect of recent significant storms? What is the opinion of this, for example is the barrier overly high – *has it been managed to too high a freeboard?*

The evidence presented here shows a consistent barrier response to significant storm events in 2013/2014 winter; namely, build-up of the back-barrier and change in crest height. Some localised breaching was reported and resulted in in-filling of the barrier in-line with current management practices.

There is no evidence within the available data to suggest the barrier has been built up to create a freeboard that is “too high”. The crest of the barrier has been established through storm events driving overwashing and overtopping and as such it continues to rollback slowly while providing an effective defence. Unlike gravel-only barriers the wide dissipative beach fronting the barrier provides significant wave dissipation limiting wave impacts during storm events. Of interest is that the presence of the dune system to the north does prevent rollback from occurring, and therefore the movement of gravel as it might further south along the Pebble Ridge.

3. Is the current form of the feature and/or management inhibiting the barrier rolling over? Have past interventions at Westward Ho! left the site in a form that it now doesn't sufficiently overwash. Is the barriers long-term recession landwards in line with sea level being compromised (*based on an empirical equation relating swash aligned gravel barrier shoreward movement to annual rise in mean sea level (Orford et al., 1995)).*

The analysis presented within this report does not offer any indication that rollover is being inhibited by management practices. The current approach, for the majority of the Pebble Ridge, is to infill breach or storm damage. Independent re-profiling at the southern end is poorly documented and ad-hoc; however, there is no evidence that this action would have a significant impact on the wider barrier response.

Historic action to build a seawall at Westward Ho! is likely to have had an impact on sediment transport; however, the long-term concern is the lack of material coming into the system which is believed to have ceased. The expected result is the barrier will continue to retreat, as it has done, with greatest retreat rates to the south due to rollback AND longshore removal of sediment without any input from the south. Future rates of retreat, driven by SLR and storm events, are predicted to increase over the next 100 years from ~1.1 m/year up to ~ 2.34 m/year for low emission scenario up to ~3.45 m/year for a high emissions scenario.

4. What are the key benefits (ecosystem services) of a geomorphologically functioning barrier at this location?

The area is a unique geomorphological feature and is recognised as such through its SSSI designation as documented in the Geological Conservation Review Series (GCR), as well as being an Area of Outstanding Natural Beauty lying within the United Nations Biosphere Reserve. Additionally, the Northam Burrows is a Site of Special Scientific Interest (SSSI) as a habitat for a range of flora and fauna. While the origin of the site is unclear, the combination of the barrier and dune system has allowed a geomorphologically important site to evolve that supports a wide range of grassland, salt marsh, dunes and intertidal habitats (Orford, 2004). Additionally, these habitats work to provide a coastal defence to communities along the shoreline of Westward Ho! and Appledore. Regardless of changes to the barrier, the low lying area of the Northam Burrows will experience increased frequency of inundation, in response to SLR, and as such will likely transition towards more saltmarsh habitats, especially if breaches are not repaired (see example of Porlock gravel barrier). This process will be dependent on sedimentation processes, e.g., availability and wave exposure, should the barrier fail.

Estimating the ‘value’ of an area or assigning an economic figure to an ecosystem is a complex and increasingly applied area of research. Work by Day and Smith (2018) has resulted in an Outdoor Recreational Valuation (ORVal) tool that was developed by the Land, Environmental Economics and Policy (LEEP) Institute at the University of Exeter (http://leep.exeter.ac.uk/orval). The primary purpose is to try and help managers understand the benefits that are derived from accessible greenspace in England and Wales:

ORVal’s key functions (Day and Smith, 2018):

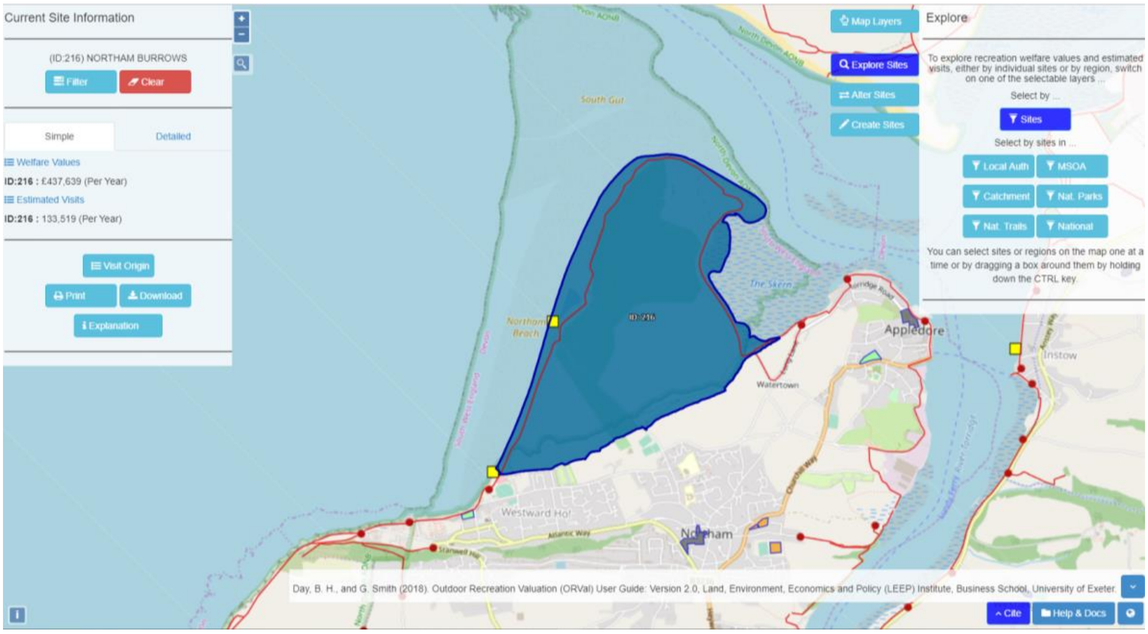
*(1) It allows users to explore the visitation and welfare values that are generated by **currently accessible greenspaces**. Welfare values can be viewed at individual site level or aggregated by regions.*

*(2) It allows users to estimate how visitation and welfare values might change if the **characteristics of a recreational greenspace were changed**.*

*(3) It allows users to draw new recreation sites on the map, define their characteristics and estimate the visitation and welfare values that might be generated by **creating that new greenspace** in that particular location*

The tool is underpinned by a Recreation Demand Model which is a statistical model that can predict the number of visits that are made by adult residents of England and Wales to a greenspace. The online tool provides a Welfare Value of £437,639 (per year) and an estimated visit of 133,519 to the Northam Burrows (Figure 7-1). This information is based on the following land cover usage:

Land Covers:
Total: 245.06ha
Managed Grass: 64.13ha
Agriculture: 0.06ha
Natural Grass: 10.00ha
Saltmarsh: 10.69ha
Coastal: 139.81ha
Other Land Cover: 20.38ha
Water Margins:
Rivers Canals: 1533m
Seaside: 2417m
Estuary: 2850m



(ID:216) NORTHAM BURROWS

Welfare Values

ID:216 : £437,639 (Per Year)

Estimated Visits

ID:216 : 133,519 (Per Year)

To explore recreation welfare values and estimated visits, either by individual sites or by region, switch on one of the selectable layers ...

Select by ...

Select by sites in ...

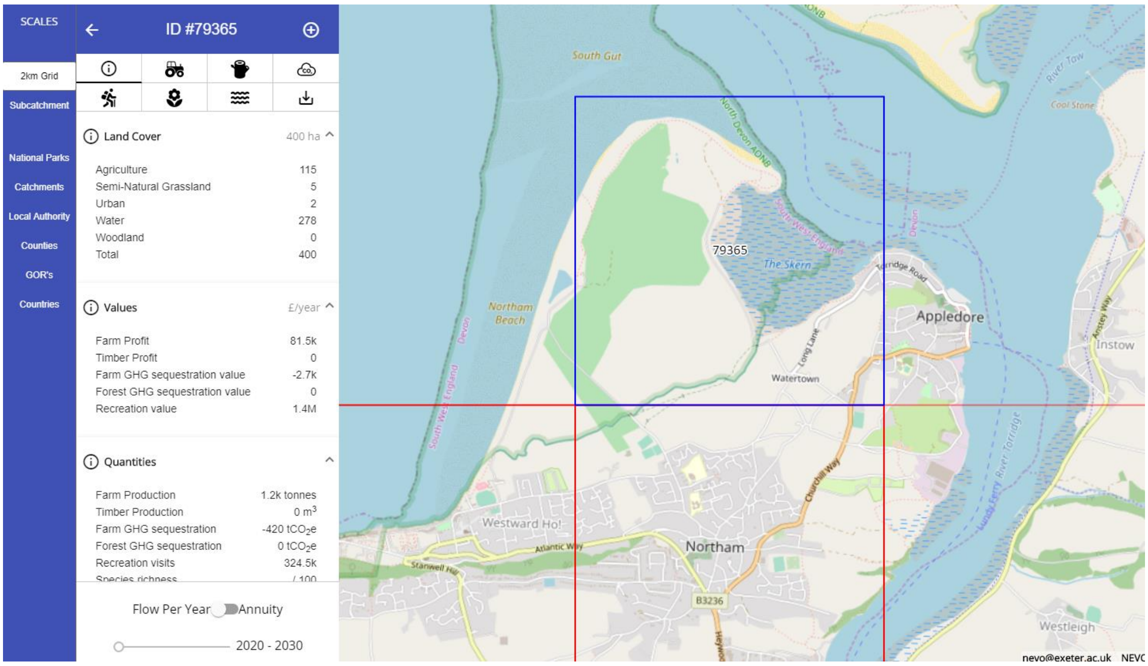
You can select sites or regions on the map one at a time or by dragging a box around them by holding down the CTRL key.

Day, B. H., and G. Smith (2018). Outdoor Recreation Valuation (ORVal) User Guide: Version 2.0, Land, Environment, Economics and Policy (LEEP) Institute, Business School, University of Exeter.

Figure 7-1. Screen-grab of the ORVal Tool showing the Northam Burrows extent that is selected and associated Welfare Values assigned to it (Day and Smith, 2018).

Similar principles are applied to the online Natural Environment Valuation Tool (NEVO) that was developed to help users explore, quantify and make predictions about the benefits that are derived from existing and altered land use in England and Wales (**www.leep.exeter.ac.uk/nevo**). The NEVO tool allows users to explore 2-km grid squares, catchments, National Parks or a range of other spatial extents. As such the area of reference is not necessarily limited and so interpretation of the results needs to be undertaken with care (Figure 7-2). The NEVO tool provides a £/year value of £1.4 M recreation value (Paths, Parks and Beaches), as well as details on carbon/biodiversity/timber/water.

Although neither of these tools focus on geomorphological importance of the site, they do provide an overview of the benefits provided through a range of ecosystem services that need to be considered as part of any fully connected management plan.



Land Cover	400 ha
Agriculture	115
Semi-Natural Grassland	5
Urban	2
Water	278
Woodland	0
Total	400

Values	£/year
Farm Profit	81.5k
Timber Profit	0
Farm GHG sequestration value	-2.7k
Forest GHG sequestration value	0
Recreation value	1.4M

Quantities	
Farm Production	1.2k tonnes
Timber Production	0 m^3
Farm GHG sequestration	-420 tCO_2e
Forest GHG sequestration	0 tCO_2e
Recreation visits	324.5k
Species richness	/ 100

Flow Per Year / Annuity

2020 - 2030

Figure 7-2. Screen-grab showing the NEVO interface. The blue square is the most suitable one for Northam Burrows although this does not align perfectly and records no beaches in its area.

5. What is the whole gravel barrier likely to look like in 20, 50, 100 years' time – *approximately.*

The current management strategy is to undertake remedial barrier work in response to storm breaches/barrier collapse. Additionally, the northern end of the barrier is to remain protected to ensure the historic landfill is not exposed as the cost of re-homing the historic waste is prohibitively expensive. There is also an understanding that future flood defences will be required to provide protection for Westward Ho! at the southern end of the Pebble Ridge. Each of these will have some impact on the future for the barrier. The available data and future projections on barrier behaviour would suggest longer term evolution will continue in line with previous studies, namely continued barrier retreat, although continuation of historical rotation is less clear. The northern end of Northam Burrows is likely to experience further erosion events and sediment release during storms for areas not protected by rock armour. The dunes are, by nature, less resilient once exposed and losses will be accelerated as alongshore sediment supplies reduce further. The rates of retreat have been presented using Orford *et al.'s* (1995) model which broadly support the current SMP projections. The complexities of an estuarine system, that will experience impacts from climate change to both fluvial and tidal processes, further adds to the difficulty in trying to forecast how the estuary mouth and adjacent dune system will respond. The increase in inundation, through extreme flood events will also be a factor that will impact on the site, although the impact of storm events will have the greatest influence on the geomorphology.

References

AR76 (2018), Annual Survey Report 2018, Hartland Point to Sand Point, South West Regional Coastal Monitoring Programme, 326pp.

Black and Veatch Ltd (2012), Taw Torridge Estuary Coastal management Study: Pebbleridge Study, 59pp

Bruun, P. (1962). Sea-level rise as a cause of shore erosion. *Journal of the Waterways and Harbors Division*, **88**, (1), 117-132.

Burvingt, O., Masselink, G., Russell, P. and Scott, T., (2017). Classification of beach response to extreme storms. Geomorphology, 295: 722-737.

Cooper, J. A. G. and Pilkey, O. H. (2004). Sea-level rise and shoreline retreat: time to abandon the Bruun Rule. *Global and Planetary Change*, **43**, (3), 157-171.

Day, B. H., and G. Smith (2018). Outdoor Recreation Valuation (ORVal) User Guide: Version 2.0, Land, Environment, Economics and Policy (LEEP) Institute, Business School, University of Exeter.

Halcrow. (1998). Bridgwater Bay to Bideford Bay Shoreline Management Plan, Volume 1 – Strategy Document. North Devon & Somerset Coastal Group.

Hyder (2010), Strategic Flood Risk Assessment, Level 2 Final Report, Torridge District Council 240pp

Keene P (2009). Coastal management and Coastal erosion at Westward Ho! and NW Devon 1850-2000. Thematic Trails: 7 Norwood Avenue, Kingston Bagpuize, Oxford OX13 5AD

McCall, R.T., Poate, T.G., Masselink, G. Roelvink, J.A., Almeida, L.P., Davidson, M. and Russell, P.E., 2014. Modelling storm hydrodynamics on gravel beaches with XBeach-G. *Coastal Engineering*, 91, 231–250.

Masselink, G., Scott, T., Poate, T., Russell, P., Davidson, M., Conley., D. (2016a). The extreme 2013/2014 winter storms: Hydrodynamic forcing and coastal response along the southwest coast of England, Earth Surf. Process. Landforms, 41, pp. 378-391 https://doi.org/10.1002/esp.3836

Masselink, G., Castelle, B., Scott, T., Dodet, G., Suanez, S., Jackson, D., Floc'h, F., (2016b). Extreme wave activity during 2013/14 winter and morphological impacts along the Atlantic coast of Europe. Geophys. Res. Lett. pp. 2135-2143

May, V.J., Hansom, J.D. (2003). *Coastal Geomorphology of Great Britain*, Geological edition. Joint Nature Conservation Committee, Peterborough, pp. 754.

Orford, J.D., Hinton, A.C., Carter, R.W.G., Jennings, S.C., (1992). A tidal link between sea-level rise and coastal response of a gravel dominated barrier, Story Head, Nova Scotia. In: Woodworth, P., Pugh, D.T., De Ronde, J., Warrick, R.G., Hannah, J. (Eds.), Sea-Level Changes: Determination and Effects. Geophysical Monograph Series, vol. 69. American Geophysical Union, Washington, DC, pp. 71– 79.

Orford, J., Carter, R., McKenna, J. and Jennings, S. (1995). The relationship between the rate of mesoscale sea-level rise and the rate of retreat of swash-aligned gravel-dominated barriers. *Marine Geology*, **124**, (1-4), 177-186.

Orford, J.D., Forbes, D.L. and Jennings, S.C., (2002). Organisational controls, typologies and time scales of paraglacial gravel-dominated coastal systems. Geomorphology, 48(1): 51-85.

Orford J. (2005). Further Geomorphological Advice in Respect of Westward Ho! SSSI. English Nature, October 2005.

Pethick J. (2007). The Taw/Torridge Estuary: Geomorphology and Management. Report to Taw/Torridge Estuary Officers Group (February, 2007).

Poate, T., Masselink, G and McCall, R., (2016). A new parameterisation for runup on gravel beaches. *Coastal Engineering*, 117, 176-190.

Scott, T., Masselink, G., O'Hare, T., Saulter, A., Poate, T., Russell, P., Davidson, M. and Conley, D., (2016). The extreme 2013/2014 winter storms: Beach recovery along the southwest coast of England. Marine Geology, 382(Supplement C): 224-241.

Stuart A & Hookway, R. (1954); Coastal erosion at Westward Ho! Report to the Coast Protection Committee of Devon County Council.

TR87, (2018). Coastal Wave Network Annual Report 2017, National Network of Regional Coastal Monitoring Programmes of England, 238pp.