Abstract: Sea level rise increases the pressure on many coastlines to retreat landwards which will lead to coastlines previously held in position through management, being allowed to retreat where this is no longer affordable or sustainable. Barrier beaches have historically rolled back in response to different hydrodynamic events and sea level rise, but very little is known as to how quickly and how far roll-back is going to occur once management has ceased. Data from more than 40 topographical surveys collected over 7 years along the 1.5 km long, almost swash-aligned shingle barrier at Medmerry (southern England) are used together with hydrodynamic data in a wide-ranging assessment of barrier roll-back. This study shows that roll-back is progressing through time along the barrier in downdrift direction in response to a gradual reduction in cross-sectional area through longshore transport. The Barrier Inertia concept provides a practical means to assess stability/instability for events experienced, but also a tool to assess the short- to medium term risk to the coast downdrift of the immediate study area where flood risk still needs to be managed. Roll-back is influenced particularly by the creation of an artificial tidal breach and removal of its sediment, the elevation of the underlying marsh and clay sediments, the number and severity of storms experienced and the presence of legacy groynes; roll-back has exceeded modelled predictions and expert judgement by an order of magnitude.

Keywords: shingle beach; coastal catch-up; longshore transport; marsh cliff erosion; overwash; overtopping; barrier stability; back barrier marsh; Barrier Inertia

1. Introduction

Unmanaged coastal barrier islands and beaches transgress with relative sea level rise where the back-barrier topography allows for this to occur. For gravel dominated barriers it is suggested that this may also occur in the absence of sea level rise [1]. For the mixed sand and gravel beaches of the south coast of England sea level rise associated roll-back is documented for example for the mid Holocene [2] and more widely for the last centuries through ground penetrating radar [3] or based on historical mapping [4–7].

Managed coastal barriers on the other hand are generally kept in position through active (beach recharge and recycling), passive (using structures such as groynes) or a combination of both types of sediment management. For many such managed shorelines, the pressure for morphological change has increased over the period of management, which in the southeast of England started in the early 18th century [8], due to historic sea level rise of between at least 0.2 and 0.3 m (broad extrapolation from [9]).

At several sites, this management becomes unsustainable into the future, raising the question as to what might happen if sediment management ceases and natural processes can return unchecked to these frontages. In the 1980s and 90s, a number of publications were dedicated to the natural ontogeny and in particular roll-back of coarse clastic barrier beaches focussing on barriers in Ireland [10–12] and Canada [13–15] followed from 2000 by publications on barriers like Hurst Spit [16], Porlock [17,18], Cley [19–21] and Sillon de Talbert [22–24], where previous management including sediment movement had ceased or hard structures been removed, or where new management was going to be introduced [16].
Overwashing and roll-back are also documented in other parts of the world although the conditions in terms of tidal range, grain size, nearshore bathymetry, underlying geology or degree of beach management are often significantly different from the study site and other locations in the United Kingdom. Roll-back associated with a sudden rise in sea level due to tectonic sinking has been observed on macro-tidal beaches in Alaska [25] and is suggested for a fine gravel beach in the micro-tidal environment of Hawke Bay, New Zealand [26]. Intense roll-back over the past decades due to storms and increasing sediment deficit is evidenced for the micro-tidal barrier fronting the Torreblanca Cabanes marsh in the Gulf of Valencia (Spain) [27]. At the same time, modelling of beach response to storms has become more advanced but is often restricted to short periods of observations on a small number of profiles (e.g., at the fine gravel barrier of Loe Bar, in southwest England [28], at Newgale in West Wales [29] or at Hurst Spit [30]) and appears to be poorer for macro-tidal coarse clastic barriers where roll-back has occurred (e.g., [31]). Recently the cross-shore response from Xbeach-G has been coupled with longshore transport for the micro-tidal fine gravel beach at Playa Granada in southern Spain [32].

A focus of most of the earlier studies was the process by which barriers roll back and more explicitly the conditions under which this happened. Overwashing is essential for the initiation of roll-back and has been investigated in flume experiments (e.g., [33]) and numerical models (e.g., [34]). This had been recognised much earlier and fed into the concept of barrier inertia (BI), which was first proposed in 1995 [15] and quantified for beaches similar to Medmerry (MMR) in 2000 [16]. The Medmerry barrier was covered under this aspect in a dedicated study [35,36] which nevertheless was hampered by the classification of events into overtopping or overwashing events through third party observations and the limited availability of topographic surveys and measured hydrodynamic data. Following laboratory experiments, the boundary conditions for barrier overwashing were simplified in 2008 [37] and in 2013 the original parametrisation was compared with the developing Xbeach-G model [38]. This comparison found that additional information in relation to the depth of the gravel beach toe and the beach slope might improve the BI model. In retrospect, it is striking that the dynamic component of BI, namely the hydrodynamic conditions (wave parameters and water level) appears to have been treated independent of its duration (see also [35] though it is acknowledged that the beach itself changes during a storm). This might be applicable to laboratory conditions where tides are rarely included, micro-tidal coasts or particular barriers like Hurst Spit [30], for which the BI model was developed, which have small tidal ranges (at Hurst the mean spring tide range is 2 m). However, using the maximum hydrodynamic conditions as the variable to test against the barrier geometry may be less applicable to locations with a larger tidal range where conditions an hour or two before the peak of the tide are likely to be more important as it takes some time for a barrier to move from overtopping to overwashing to crest lowering and roll-back in just one tide; for example, it is unlikely for crest lowering to keep pace with the falling tide as the distance over which the crest needs to be lowered and the sediment to be transported to the back increases while the energy to do this work decreases [17].

Studies have also usually focused on individual profiles or uniform laboratory set-ups [39] rather than how and why roll-back may change or progress along a beach and what role legacy structures like groynes might play.

A critical aspect for future coastal management is not just the processes or conditions that lead to roll-back, but the speed and potential (temporary) endpoint following the release from unnatural constraints termed coastal catch-up. This process has been recognised for some time in relation to coastal (cliff) erosion where it is said to constitute “a rapid (probably non-linear) catch-up process, i.e., the cliff reassuming its position had defences not existed by initially eroding at a rate much faster than the natural rate” [40]. The same should apply to barrier roll-back, in particular if the previously managed high barrier crest is over-washed soon after a change in management and thus makes successive overwashing more likely due to the reduced crest height [41].
Finally, a limitation of many previous studies has been the lack of high frequency spatio-temporal topographic data covering several storm events, thus often focussing on a very small number of events (often just one) for one site or profile (e.g., [31,38,42]) or having difficulty in attributing processes to individual driving conditions [36].

Recently, sites with higher spatio-temporal survey resolution have become available [21,43] and the present study is an extension of this early work at Medmerry. As such the paper addresses the following questions:

1. What is the profile response to changing hydrodynamic conditions and exposure of underlying geology?
2. How is profile response changing along the coast?
3. How are points 1 and 2 linked to the alongshore transport of beach material?
4. Is Barrier Inertia still a useful concept at high temporal resolution of events and how useful is it as a predictive tool?

Following an introduction to the study site (Section 2) and a description of the data and methodology in Section 3, the paper starts out by documenting beach volume changes of the MMR site and along the downdrift frontage to create a sediment budget (Section 4.1). This provides a framework for assessment of individual cross-shore profile response through time (Section 4.2) and alongshore progression of barrier roll-back (Section 4.3). The role of hydrodynamic conditions in profile ontogeny (Section 4.4) is explored first in broader terms before it is applied to the Barrier Inertia concept (Section 4.5). The wider impact of the findings and potential future research are given in Section 5 with the conclusion in Section 6.

2. Site

Medmerry is located on the mainland east of the Isle of Wight near the centre of the English south coast (Figure 1). It forms a 1.5 km long section of the 12 km long shingle barrier/fringing beach between Selsey Bill and the East Head sand spit. ‘Shingle’ is used in this paper as the local description of a gravel and pebble dominated mixed sediment (up to ~30% of sediment < 2 mm) upper beach that terminates with a distinct break of slope (or toe) in the intertidal fronted by a sub-horizontal intertidal sand covered platform at that extends into the sub-tidal Historically, the back barrier marsh was connected with Pagham Harbour, leaving Selsey as a slightly raised island of Quaternary raised beach deposits. Erosion of this previously more extensive island contributed to the barrier beaches either side of Selsey Bill sealing off the low lying channel and promoting sedimentation. As a consequence, the marsh area behind the shingle barrier ranges in elevation from ~1.5 to 3 mOD (Figure 2). The increasing management requirements due to regular overtopping and overwashing (details in [35]) to maintain the shingle barrier at Medmerry led to a large open-coast Managed Realignment project creating 183 ha intertidal habitats within a site of 400 ha contained between two rock arms at the beach and connected by a clay embankment following the landscape contours. Details about the Medmerry Managed Realignment (MMR) project are given in Maplesden [44]. In August 2013, a cut was made through the shingle barrier and the underlying marsh sediment to establish a tidal breach channel with no further management of the shingle beach except for the removal of redundant and life-expired timber groynes and some limited sediment movement on the west beach in 2014. The design of the cut dimensions was primarily concerned with the breach stability and the avoidance of closure under varying longshore transport rates and morphological evolution inside the site [45].
Figure 1. Overview of the study location in southern UK (a) and within a regional setting (b). Main map shows the 4 mOD contour prior to breach, marking the front and rear of the shingle barrier and the inside of the earth bund as the landward edge of the Managed Realignment site. Additionally, shown are historic Mean High Water (MHW) lines digitised from Ordnance Survey maps and the light blue line tracing the dug breach and drainage channels. The background aerial photo was flown on 20 August 2020 at low tide highlighting the displacement of the light coloured shingle barrier and some of the locations mentioned in the text.

Updrift (southeast) of the MMR site, a private (Bunn Leisure) scheme was completed in 2012 to protect a large caravan site [46]. This scheme provides a shingle beach fixed between two nearshore detached breakwaters. As a consequence, no sediment from east of the western Bunn Leisure breakwater is entering the study site, however, the bay west of this western breakwater and east of the eastern MMR rock arm (visible towards the southern boundary in Figure 1) was designed as an equilibrium bay that was anticipated to lose part of its beach recharge over time.
Figure 2. Overview of the frontage including swath bathymetry collected in the summer of 2013, LIDAR survey from 24 January 2015. Black profile lines were selected from the 20 m profile lines extracted from DEMs focussing on the MMR frontage between the rock arms and red profile lines are based on dedicated profile surveys and extracted from DEMs covering an overlapping area west of the western rock arm and further west.

Downdrift (northwest) of the MMR site, the shingle barrier continues for 1 km in the same shape and with the same hinterland elevation as inside the MMR site (Figure 2). From there, the hinterland rises a few metres above Highest Astronomical Tide and as a consequence is lined for the next 4 km with coastal properties and a timber groyne field to contain the shingle beach. Over the remaining 3 km from Profile 5a00179 (Figure 2) to East Head, sand from the Chichester Harbour ebb delta dominates the beach and widening foreshore towards the harbour entrance.

Mean spring tide range is 4.5 m at Selsey Bill, decreasing to 4 m at the entrance to Chichester Harbour placing the Mean High Water Springs contour at ~2.2 to 2.25 mOD. The 1 in 1 year significant wave height at the Bracklesham directional wave rider is 3.74 m (2008–2019) with annual maximum Hs over the last 11 years ranging between 3.28 and 4.47 m; the dominant wave direction is between 195° and 225° [47] against a pre-breach shoreline orthogonal between the MMR rock arms of 225°. Therefore, the beach is almost swash-aligned [48], especially considering wave refraction over the shallow sub-horizontal intertidal and subtidal topography. Apart from wind waves generated in the English Channel, the frontage is influenced by Atlantic swell and waves with bi-modal frequency distribution [49]. Longshore transport has been calculated and estimated in several studies ranging from measurements from maps to tracer studies of up to several tens of thousands of cubic metres per year. A review in 2004 [50] of various values from the grey literature settles on “A present day mean actual drift volume of between 2800 and 7000 m³ per year” which is broadly in line with the 2000 m³·y⁻¹ suggested by Cope in 2005 [36] for the ‘net drift of shingle’ towards the northwest. However, both sources fail to clarify to which part of this frontage the values apply, but the lower values support the notion of the barrier being almost swash-aligned.
2.1. Historic Changes and Design Predictions

It is thought that the barrier developed in the 6th to 7th century linking the Island of Selsey with higher ground at Bracklesham to the NW. The barrier has been subject to storms and roll-back for centuries and over the last decades, overwashing has been reported on several occasions, for example in 1910, and evidence of bulldozers pushing overwashed material back to the crest in 1950 was observed [51]. “Analysis of Tithe maps and Ordnance Survey maps has shown that mean rate of recession of the High Water Mark between 1672 and 1932 has varied from 1.0 to 1.4 m per annum” [52]. Some historic water lines from Ordnance Survey maps are shown in Figure 1, however, a more detailed account of their movement and any defence structures can be found in [43]. Between 1876 and 1896, MHW moved landwards by approximately 30 m which is equivalent to 1.5 my$^{-1}$. In the following decades, different structures were installed at different times but essentially those areas still free to retreat did so at a rate of 1.4 my$^{-1}$. Since at least 1950 [51], the entire frontage has been stabilised by groynes, reprofiling and recharges with no further retreat which could equate to a ‘retreat need’ of ~100 m based on past rates and ~70 years of forced stability.

A range of modelling was carried out for the design of the MMR scheme, and while mainly concerned with the stability of the inlet morphological change of the barrier was also looked at. This can be summarised by the statement that “the beaches appear to remain resilient to storm impacts” [45] and the design length of the rock armour along the rock arms to accommodate ‘erosion’ of 0.4 to 0.7 my$^{-1}$ over the 50 year design life [53].

With most of the modelling concerned about the breach area, the following scenario was envisaged: “Sediment from the [upstream private scheme] recharge will continue to move (slowly) along the coast in a westerly direction to reach the [ . . . ] breach site where it is likely that the material will contribute to the formation of an ebb delta and to the sediment accumulations along the eastern shore of the breach site. The ebb delta is likely to slowly grow to a size large enough to allow longshore transport sediment to effectively bypass the inlet opening and accumulate downdrift thus offsetting any erosion that may have occurred as a result of a small reduction of sediment supply immediately after the breach” [45].

3. Data and Methodology

The MMR project included a 5-year monitoring project that carried out frequent topographic surface surveys of the shingle barrier. Initially, these were focused around the breach area but with increasing spread of coastal change the survey area was extended to cover the entire 1.5 km between the rock arms. The frontage to the northwest was only surveyed as parts of the Regional Coastal Monitoring programme [54] with far fewer surveys consisting mainly of surveys along dedicated beach profiles twice a year but also a small number of LIDAR flights.

For the MMR site a total number of 13 LIDAR surveys cover the entire site and 32 ground based topographic surveys of increasing extent are available, covering August 2013 to October 2020. The ground based surveys were carried out at different intervals, often associated with storms or observational reports of coastal change. Topographic surveys were carried out using a Leica C10 terrestrial laser scanner and Global Navigation Satellite System (GNSS) equipment. The static set-up of the scanner was not ideal as the survey area grew along the beach and in the cross-shore direction with view shadows at the back slope of the shingle ridge requiring manual post-survey editing of the data (see below). Vegetation filtering behind the initial shingle barrier was of varying quality. In contrast, the LIDAR surveys provide very reliable data of the bare surface, however, both survey methods to not penetrate to the bottom of water-filled depressions and drainage ditches that started to change early on in the monitoring period when they also became influenced by sedimentation from the beach rolling back into them. Aerial photography was captured annually between 2013 and 2018 and most recently during the summer of 2010 providing additional data for interpreting the change observed in the topographic data.
3.1. Volume Analysis

To distinguish between loss of beach material and historic marsh clay inside the MMR site, it was necessary to reconstruct the historic marsh surface on which the beach was resting in 2013 (see Figure 3 inset). This work was carried out in ArcMap 9.3. Photographic evidence and DEM survey data from the eroding beach suggest that the seaward cliff of the marsh surface was located approximately under the front of the crest prior to breach. The data also show that elevation of that cliff is well represented by the marsh elevation behind the beach (see for example Figure 4 in [43]). In addition, the clay surface seaward of the cliff (or the toe of the marsh cliff) can be inferred to have been about 30 m seawards at a level of −0.7 mOD which equates to a slope of between 1:7.5 and 1:11. From there, the clay surface continues seaward at a slope of 1:50 to 1:60 for ~55 m to cover the spatial extent of interest for this study. From these contours, a 3D model of the underlying clay was created and combined with the LIDAR surveys landward of the shingle beach surveyed pre-breach and the first terrestrial laser scan survey post-breach to account for channels and the dugout portion of the breach area. In the area east of the breach, later LIDAR surveys of the back barrier area were also used to capture the changing location and topography of the drainage network just prior to roll-over. The volume change analysis was carried out by subtracting the marsh surface only from the LIDAR surveys due to their more extensive coverage and better capture of the landward portions of the rolled-back beach.

![Figure 3](image-url)

**Figure 3.** Aerial orthophoto flown on 11 October 2018 showing the western end of the MMR frontage (the western rock arm can be seen in the northwest corner. The red grid shows the 100 m wide alongshore segments (last 2 digits of the number code starting from the eastern rock arm) and the up to five cross-shore segments (first digit). The black and blue lines are the profile positions for profile 59 and 79 shown in the inset for the marsh surface master profile (dotted lines) and the LIDAR survey flown at the same time. Red arrows in the profile plot and on the aerial photo point to the same short length of marsh surface exposed seaward of the shingle beach ridge.

For the downdrift frontage outside the MMR site, only the first ~4.5 km are included (Figure 2), because further downdrift sand takes over as the main beach material so that any volume changes are not representative of the shingle fraction. Far fewer surveys are available for this frontage and not all of them are full DEM surveys but many are simple
profile surveys. Therefore, these profile surveys and profiles extracted from DEMs (red profile codes in Figure 2) were used to assess volume changes by multiplying the changes in Cross Sectional Area (CSA) with the distance between the profiles using the profile analysis tool SANDS [55]. 26 profiles have been used with the distance between profiles varying between 127 m and 315 m with an average distance of 191 m. Inevitably, the derived volumes depend heavily on the accuracy and representativeness of the profile for a length of beach of more than 100 m length. For example, the presence of beach cusps can introduce local variations that may not be representative of the wider beach. In addition, surveys along this stretch have been carried out at different dates for different subsections so that these have been collated into summer and winter surveys which again can introduce variations in the calculated volumes unrelated to actual volume changes; for example, part of the volume in a downdrift subsection surveyed before the updrift subsection could have moved into updrift section by the time its survey was carried out.

3.2. Profile Lines, Contour Line Retreat and Cross Sectional Area (CSA)

Profile lines at 20 m alongshore distance where created through all surveys covered by the black profile lines in Figure 2. Profile lines were created by first generating a smoothed line from the 4 mOD contour of the pre-breach survey. Profile lines were then created at right angles to this smoothed line every 20 m extending 500 m land- and seawards. From the profile lines, the position and height of the highest point of the beach ridge was determined as well as the position of various contour lines reflecting the beach and the clay geology. For selected profiles shown in Figure 2 (due to the large manual editing requirements) a master profile of the underlying clay geology was constructed and merged with the pre-breach LIDAR survey using SANDS [55]. Each survey for this profile was then manually edited to remove the topography landwards of the rear shingle toe, and the subtraction of the surveyed profile from the master profile is the CSA of the beach ridge on top of the clay geology (see Figure 3 inset).

3.3. Hydrodynamic Condition and Wave Run-Up

Roll-back of beach barriers is determined by overwashing and overwashing is dependent on the crest height in relation to wave run-up [56] which is a combination of wave parameters, water level and beach properties like grain size, permeability and morphology (e.g., [31,57,58]). Wave data is available for the entire study period at 30 min intervals from the coastal monitoring wave buoy at Bracklesham 2.2 km seawards of the southern end of the MMR site with a bathymetry level of ~−14.7 mOD (Figure 1b). Water level data is taken from the CHIMET station [59] at the entrance to Chichester Harbour ~7.5 km away from the site. Missing records (January to May 2014) have been substituted by using the predicted astronomical tide for the CHIMET station plus the surge component from the tide gauge at Littlehampton 28 km east of CHIMET. Given the magnitude of the wave component during this period difference between this substituted data and measured are likely to be negligible for the analysis in this paper. From the joint 30 min interval time series of waves and water levels, data for the 3 h either side of high tide have been extracted and used in empirical run-up elevation calculations for shingle beaches [60,61].

For the analysis of changes in wave direction pre-and post-breach to put calculated rates of longshore transport in perspective with values from the literature the wave buoy data, which started in August 2008, was supplemented with wave hindcast data available from Cefas [62] for point 434 (Figure 1b).

3.4. Barrier Inertia (BI)

According to [63] BI = R_C B_A / H_s^3 where R_C is the distance between the maximum crest level and the still water level, B_A is the cross sectional barrier area above the still water level and H_s the significant wave height taken from the wave buoy. To explore the model of BI, its value was calculated at 30 min intervals from the buoy and tide gauges detailed in 0. Both barrier parameters (R_C and B_A) are based on the survey preceding the hydrodynamic
conditions (which might be days or months earlier) with $B_A$ being interpolated from the CSA at 2 mOD and 3.2 mOD based on the still water level. This results in BI values for every 30 min rather than just one for every high tide. Higher BI values indicate stability and lower values indicate overtopping and overwashing. The boundary between these morphological responses is given in the following equations when BI is plotted against the wave steepness $H_s/L_M$ where $L_M = gT_m^2/2\pi$ and $T_m$ is taken from the wave buoy data ($T_z$). Two boundaries from the literature have been used (Equation (1), Bradbury (2000) [16] and Equation (2), Obhrai et al. (2008) [37]):

$$\frac{R_C B_A}{H_s} < 0.0006 \left( \frac{H_s}{L_M} \right)^{-2.5375}$$  \hspace{1cm} (1) \\
$$\frac{R_C B_A}{H_s} < -153.1 \frac{H_s}{L_M} + 10.9$$  \hspace{1cm} (2)

4. Results

4.1. Wider Beach Volume and Sediment Budget

To distinguish between changes to the shingle barrier, the underlying marsh surface, and the intertidal platform, the volume analysis was split into 100 m long sections along the beach and into up to five sections across the beach as illustrated in Figure 3. In the example, the black profile in the inset represents a portion of the shingle barrier (profile 79) that has not yet overwashed by the survey date of 11 October 2018 and the beach profile overlays the master profile marsh surface. Zone 4 is the unchanged marsh surface landward of the shingle barrier; zone 3 is the shingle barrier up to the crest of the underlying marsh surface and represents the bulk of shingle volume in the cross section prior to roll-back; zone 2 is the slope of the marsh surface down to its toe and is overlain by a comparatively thin shingle beach (initially up to ~2 m); zone 1 is the shallow sloping clay platform covered by sand. Once the beach is rolling back (blue line for profile 59), zone 5 delimits the shingle barrier sitting on top of the marsh surface and the then seaward zones represent the areas of erosion of the marsh surface and underlying clay. The blue profile represents this situation showing, at the position of the red arrow in the profile and on the map, where marsh surface (zone 4) crops out for a few metres in front of the shingle barrier. This situation appears to be similar to the barrier ‘overstepping’ mentioned in Forbes et al. [13], however, the height of the cliff does not preclude sediment to move onto the marsh surface and continue to be part of the rolling-back barrier. While the retreating marsh cliff/seaward slope may be covered with sediment, this was generally found to very thin with clay cropping out on the slope and has been ignored for the volume calculations.

The volume development of these zones is shown in Figure 4. In this figure, the ‘shingle ridge’ volume is composed of the volumes for zones 5 and the positive volumes of zones 3 and 2 where appropriate. In the example shown in Figure 3 the shingle barrier volume in area x15 includes segment 215 and 315 while in the rolled-backed area x11 it is only in segment 511. In the transition areas x12 to x14 segment, 3xx is split manually along contour lines associated with the elevation of the marsh surface in that area.

The first two surveys shown in Figure 4 (individual surveys are highlighted as dots on the ‘shingle ridge’ line) capture the pre-breach volumes. The sharp drop from the second to the third survey in autumn 2013 is due to the removal of the shingle ridge (7200 m³) and underlying marsh and clay (7000 m³) to create the breach over a length of 150 m. The shingle removed was deposited west of the western rock arm (~1200 m³) and east of the private scheme (~6000 m³) and thus outside of any future relevance for this study. The clay and silt was used onsite.
The shallow intertidal foreshore (zone 1) has changed very little over the last 7 years in contrast to any of the other zones. This confirms for a much larger area and longer time scale the initial findings in [43] that elevation changes at the low water line are small in absolute terms and in relation to other contour lines. Zones 2, 3 and 4, representing the marsh sediment and clay, have lost a total of 445,000 m$^3$. The rate of loss has been steady, though sector 4 shows a significantly larger dip over the winter 2019/20. The rolled-back shingle ridge zone (zone 5) shows a gradual increase following the initial larger increase over the winter 2013/14 when the entire east beach had rolled back and shingle recurves on both sides along the channel had formed. However, taking all sediment in the mobile shingle beach into account, it has lost 55,000 m$^3$ following the breach in August 2013.

Neither roll-back nor the exposure of underlying geology has occurred on the down-drift frontage west of MMR, so here the entire volume change relates to the mobile shingle sediment. Taking the summer 2013 volume as the baseline for this frontage, Figure 4 also includes the volume development for the frontage west of MMR on the secondary y-axis showing a total increase of 80,000 m$^3$ over the last 7 years. Figure 5 shows the volumes in a stacked chart suggesting that the total volume of the combined frontages has remained stable or increased slightly, i.e., as the original barrier beach inside MMR (red line) loses material to the downdrift frontage (black line) or into the increasing rolled-back barrier (green line), the total volume is largely maintained. However, the MMR frontage has lost 55,000 m$^3$ in comparison to the 80,000 m$^3$ gain of the downdrift frontage.

Figure 4. Change in beach volume over time for different beach zones in MMR (left hand y-axis). For location of beach segments in the cross-shore direction see Figure 3. Right hand y-axis for the change in volume west of MMR compared to the summer 2013 volume.

Figure 5. Stacked beach volume over time. Volumes for the non-rolled-back and rolled-back barrier (segments 3xx and 5xx in Figure 3) plus the shingle barrier volume west of MMR. Volumes are stacked so that the black solid line represents the total volume for MMR and the frontage to the west.
From a total volume budget perspective, the ‘missing’ 25,000 m$^3$ can be accounted for by the loss from the western bay of the private Bunn Leisure scheme (see ‘West Bay BL’ in Figure 1). Over the winter 2013/14 (between the surveys on 26 August 2013 and 30 March 2014), the beach placed in 2012 in an equilibrium bay shape associated with average wave conditions lost 19,500 m$^3$ due to more southerly waves and the readjustment of the bay shape. While this nearly balances out the sediment budget over the 7 year period, this substantial pulse of sediment cannot be detected in Figure 4 or Figure 5.

A major point of uncertainty of the volume calculations are the assumptions of seaward extent and slope of the marsh sediments under the barrier as these have not been surveyed on first exposure. Given the MMR frontage is 1.5 km long, a volume of 20,000 m$^3$ equates to 13.3 m$^3$m$^{-1}$. With the marsh cliff 2 m to 3.5 m high, the volume of 20,000 m$^3$ can reflect a difference of the marsh cliff position of between 6.7 m and 3.8 m which is quite possible. Therefore, if the marsh cliff had been further seaward than its assumed position, some of the 20,000 m$^3$ could have substituted the eroded clay. The other uncertainty concerns the infill of the breach and dug tidal channels landwards. As these areas contain water during laser scan surveys, changes in the depth of the channel cannot be recorded and the inlet and central channel areas have been masked out from the analysis based on this uncertainty. That sediment temporarily ‘disappeared’ into channels can be seen in aerial photos and the survey data on the east beach (Figure 6). This material, at least in part, appears to emerge again as can be seen in Figure 1 landwards of the drainage channel and is suggested in Figure 5 by the slight increase in the MMR barrier volume.

Figure 6. Position of the east beach barrier on 26 August 2013 (white lines are the 4 mOD contour at the front and the back) overlain over low tide orthophotos from June 2015 (left) and July 2018 (right) showing infilling of the main outfall channel (black lines) from the eastern leaf of the MMR site. Additionally, shown are the numbered profile lines.

Figure 7a breaks down the volume change for the frontage west of MMR into the spatio-temporal components. As volumes between profiles vary due to the distance between them. Figure 7a shows the volume change as a percentage of the summer 2013 volume. It shows relative stability at the eastern end (profiles 82–111)—though the three most easterly profiles have seen some small gain—and only in the last year profiles 82 and 85 have started to experience a loss. On the other hand, between profiles 111 and 165 the increase seen prior to breach continued more pronounced from 2013 both increasing the volume of individual profiles but also spreading the increase to more profiles, particularly downdrift where between 165 and 179 an initial loss persisted for several years but where all profiles are now at least slightly above the 2013 volumes. Figure 7b shows total volume changes between individual LIDAR surveys for the MMR frontage. The removal of shingle from the breach can be seen in the survey on 12 September 2013 for segment 5. At the end of the severe winter 2013/14, losses have been high from segments 6 to 8 with some of these losses most likely responsible for the gain in segment 5 by drawing
sediment into the recurve along the eastern side of the outflow channel. Following this initial change, the most important pattern is shown on the west beach where major temporary sediment loss progresses westwards with time followed by volume stability, that is, once the beach has rolled back onto the marsh surface the volume remains largely stable.

Figure 7. (a) Volume change at each profile downdrift of MMR as a percentage in comparison to the 2011 volume. (b) Beach volume change in m$^3$ between surveys for the MMR frontage.

Compared with previous estimates of longshore transport, the loss of 55,000 m$^3$ from the MMR frontage would equate to an average of ~7800 m$^3$y$^{-1}$ passing the western rock arm in a northwesterly direction; adding the loss from the Bunn Leisure scheme or using the gain on the frontage west of the MMR scheme would result in ~11,400 m$^3$y$^{-1}$. This is higher than rates suggested from studies in the early 2000s and primarily due to the particularly stormy winter 2013/14 [64] resulting in a loss of 27,000 m$^3$ (Figure 5) or nearly half the loss over the entire 7 years. Taking the remaining loss since that winter, the average rate drops to a more comparable rate of ~5600 m$^3$y$^{-1}$ which nevertheless is still double the rate suggested more recently [36]. It is likely that this relates to the fact that the entire post-breach period was experiencing a higher percentage of higher waves than during either the 5 years pre-breach based on the wave buoy (see also [65]), or compared to the 20 years prior to 2000, on which the literature value is based, based on the hindcast wave data (Figure 8). In addition, groynes were largely still functional prior to 2010 on the MMR site which led to a lower rate of longshore transport than the essentially open, ungroyned beach following the breach.

Figure 8. Percentage occurrence of wave height for different directional sectors: (a) Bracklesham wave buoy, where ‘Pre’ data relates to the period August 2008 to July 2013 and ‘Post’ covers August 2013 to July 2020, (b) Cefas hindcast point 434 where ‘Pre’ data relates to the period January 1980 to December 1999 and ‘Post’ covers August 2013 to December 2019.
4.2. Profile Response

Section 4.1 (see also inset in Figure 3) has highlighted that the primary process occurs in the cross-shore direction with the beach ridge rolling back over the back barrier marsh. Figure 9 shows profile 71 as an example (some additional examples can be found in [43]). The profile change can be described in modification and expansion of the five ‘response categories’ in [16]:

- ‘overtopping and crest raising’ illustrated between 26 August 2013 and 10 January 2014, which also moved the maximum crest elevation seaward,
- ‘barrier face erosion and accretion’ illustrated between 10 January 2014 and 13 January 2016,
- ‘overwashing with small scale crest retreat’ illustrated between 13 January 2016 and 09 August 2016, and between 11 January 2017 and 17 March 2017,
- ‘large scale overwashing with crest destruction and overwash fan’ illustrated between 12 October 2017 and 07 December 2017, which in this case did not move the highest crest point, though it changed from being at the back of the crest to the front,
- ‘crest build-up with crest advance’ between 07 December 2017 and 11 October 2018 and
- ‘large scale overwashing with full roll-back’ between 15 October 2019 and 13 March 2020.

The only response not shown by this profile is one of crest lowering due to cut back of a landward sloping crest because the starting crests were either generally horizontal or sloping seawards like profile 71. However, an example of this response (though some overtopping and sediment deposition on the rear slope did occur) can be seen in Figure 10.
Figure 10. Comparison of 2 profiles 20 m apart showing synchronous and asynchronous behaviour together with the plan-shape change (inset) at this temporary processes boundary. Inset shows the beach (rotated by 45° from north) on 18 June 2015 showing both profiles and their neighbours. Additionally, note the beach cusps with a wave length of ~8 m.

However, it is important to bear in mind that the surveys are not pre- and post-event surveys and are often several months apart so that they were shaped by multiple events and processes. Along the entire frontage these ‘evolutionary steps’ or response categories happened in different locations at different times. Figure 10 shows an example of the neighbouring profiles 47 and 48 which are just 20 m apart. Both profiles started out almost identical and underwent almost identical changes over 17 months of barrier face erosion, with mild overwashing and crest lowering. However, the storm on 20 February 2015 removed only more of the beach face leaving a very narrow ridge standing in profile 48 while at profile 47, it resulted in a major overwash event that reduced the crest height by up to 1.2 m and created a 28 m long overwash fan. As the inset in Figure 10 shows, an almost continuous overwash fan extends from profile 47 eastwards, while none is visible at profile 48 and westwards. However, this asynchronicity was only short-lived and for example the latest survey in October 2020 shows the two profiles to be as similar as two profiles 20 m apart might be expected to be. For example, 48 shows some of the original marsh surface on the beach side while 47 does not, yet the beach ridge is almost identical.

On a previously managed frontage like Medmerry legacy structures provide spatial focus for overwashing and crest lowering. It is well known that groynes can increase wave height towards the upper beach either through simply funnelling oblique waves along its updrift face or through more complicated process interactions [66] leading to outflanking pressure. In the case of Medmerry, the timber groynes carry on through the barrier and re-appear on the back slope. This is captured in the ground photos in Figure 11. In addition, shoreline perturbations introduced by groynes may incite resonance along the beach and create beach cusps (see profile 49 in Figure 10 inset which runs across a groyne located in a cusp embayment) that have been found to act as initial pathways for overwashing [11]. However, even without these legacy structures beach cusps form readily along the frontage due to the frequency of bimodal-frequency or swell wave conditions [49].
Figure 11. (Left) Photo along groyne between profiles 53 and 54 taken on 18 February 2014 showing overwashing guided by the groyne; (Right) Photo looking west along the access path behind the barrier with overwash fan along profile 42 behind the groyne. Arrows point to the landward termination of the groynes. Photo taken following the February 2014 storms.

While most profile responses described can happen under stable CSA within a profile as a function of more extreme hydrodynamic conditions in a flume [56,67], the profile analysis suggests that for the roll-back observed and the corresponding hydrodynamic conditions, reduction in CSA was a pre-requisite and is covered in more detail in Section 4.4.

4.3. Alongshore Progression of Roll-Back

To assess the roll-back progression along the frontage as suggested in Figures 1 and 10 a number of indicators have been explored including the maximum height and position of the crest (illustrated in Figure 9 and shown in Figure 12), the position of a range of seaward contours (illustrated for the 3 mOD contour in Figure 13 and the 1 mOD contour in Figure 14), the width of the crest at certain contours and the CSA of the shingle beach component (Figure 15c). The vegetation line recently explored along the Cley barrier [21] was not deemed suitable as it would have reduced the temporal resolution to annual and the extent of overwash fans (that determine the vegetation line) could not be extracted with any certainty from the survey data.

Figure 12. Position of the maximum crest elevation in relation to the starting position on 26 August 2013 for selected surveys and selected profiles from east (right hand side) to west (left hand side). For profile locations see Figure 2.
Figure 13. Position of the 3 mOD contour on the seaward side of the shingle barrier for all surveys at all profiles 20 m apart.

Figure 14. Position of the 1 mOD contour on the seaward side of the shingle barrier representing the position of the lower beach and the marsh cliff where it is exposed for all surveys at all profiles 20 m apart.

Figure 12 shows the alongshore change of the position of the maximum crest elevation for selected surveys and profiles. As already indicated in Figure 9, the position of the maximum crest elevation may not capture cross-shore development due to the possibility of the maximum crest elevation remaining in the same position while the crest has lowered and overwashing has occurred. However, the general development suggests that the east beach rolled back faster than the eastern end of the west beach, that there are periods of rapid change, more gradual change or no change which appear to happen simultaneously on both sides of the breach and that roll-back is progressing westwards, though some western areas have experienced seaward advance of the crest prior to cut-back and roll-back.
Figure 15. Distance of the maximum crest height position in relation to that on 26 August 2013 (a), maximum crest elevation (b) and CSA (c) for all surveys and selected profiles. The white area between profiles 24 and 34 represents the breach and channel area splitting the graphs into the shorter east beach and the longer west beach. The western rock arm is located between profiles 80 and 85. Note that the time axis does not have equal intervals and that the legend in panels (b,c) covers profiles which were not surveyed on these dates.

Overall, the reduced data shows a very similar development to that shown in Figure 13 for the 3 mOD contour based on all profiles (20 m spacing) and almost all surveys (only three surveys with almost identical results have been removed). The 3 mOD contour was chosen because it is higher than the marsh surface behind so is not capturing the marsh cliff when exposed and it is low enough to capture shingle accumulations that do not stand high above the marsh surface. However, it does not capture the disintegration of the east beach following the winter 2017/18 very well (see also Figure 1). At the most eastern profile (profile 11), retreat is lagging behind compared with those profiles towards the
centre of the east beach because of wave energy dissipation along the side of the western rock arm (e.g., [68]). Contact between beach and the eastern rock arm was eventually lost after January 2019 as can also be seen in Figure 1. Landward movement has been most rapid and started immediately following the breach either side of the breach channel reaching more than 100 m inland within a year after the breach and now extends more than 200 m inland along the recurves from the east and west beach. This led initially to a sharp change in orientation which over time, especially visible on the west beach, changed to a much more gradual change in alignment with an almost straight alignment from the western point at which roll-back is starting to occur to within ~80 m of the channel (see also Figure 1). Within this nearly straight line are a number of ‘steps’ with the most pronounced around profiles 42 and 43, where the back barrier marsh surface remains in its most seaward position (Figures 14 and 16).

![Image](image_url)

**Figure 16.** View of the eastern end of the west beach highlighting areas where the back barrier marsh surface crops out extensively. Inset shows a view eastwards towards profile 49 (white arrow on map) showing a 1 m high cliff, taken on 12 October 2020. The white lines show the front and back of the crest pre-breach as in Figure 1 for reference.

While Figure 16 provides an illustration of the area of marsh surface cropping out in front of the barrier, Figure 14 shows the positional change through time using the 1 mOD contour that best represents the cliff of the marsh surface when exposed on the seaward side of the barrier in direct comparison with the position of the 3 mOD contour in Figure 13. The east beach initially retreated parallel up to 2016 following which an embayment formed at profile 14 and then widened westwards to profile 17 until the beginning of 2018. In the winter 2018/19, the retreating bay captured the main outflow channel for the eastern area of the MMR site with associated further rapid erosion of the marsh surface. At the eastern end of west beach, first signs of the more resistant marsh surface cropping out can be seen at profile 40 in March 2014. This small area of resistance has disappeared by spring 2015, starts developing again in the winter 2015/16 between profiles 39 to 51 and in the following focusses on profiles 40 to 45.

Figure 15 shows heat maps for the spatio-temporal ontogeny of the position and height of the maximum crest elevation and the CSA for selected profiles. The position of the maximum crest height shows a very similar pattern to the position of contour lines except that the original crest was an engineered sub-horizontal feature. This resulted in the maximum elevation being anywhere between the front and rear of this feature. This could lead to a change from the rear to the front through small-scale overtopping and deposition on the front edge or a change from the front to the rear through only small-scale erosion of the front edge. However, once overwashing and roll-back had started, the maximum height of the crest reflects better the behaviour of the barrier. The maximum elevation of the barrier
(Figure 15b) shows for each profile times of stability or gradual change and abrupt drops associated with major overwashing events. On the east beach, these started immediately after the breach, progressing eastwards with a drop of >1 m in the winter 2013/14 all along the east beach. From winter 2017/18, the crest has largely disappeared from the east beach. On the west beach, the abrupt drop in maximum crest elevation progresses westwards through time. Once dropped, levels are generally lower from approximately east of profile 53 which coincides with the frontage where the marsh surface crops out in front of the barrier. This would suggest that while the outcrop is not reducing the impact of waves during severe events to reduce crest height and roll back of the barrier, it reduces the ability of waves during smaller events to build the crest up again due to the discontinuity of sediment (as suggested in the case of barrier overstepping [13]) or impact on wave breaking and shoaling. Finally, CSA values in August 2013 were different along the frontage due to the different level of the underlying marsh surface (see Figure 2) and different crest levels (Figure 15b). This difference has been largely maintained as CSA reduced over time to levels of 10 to 30 m² for the profiles with low starting CSAs and 50 to 70 m² for profiles with higher starting CSAs. Similar to previous figures, Figure 15c shows the change progressing from the breach westwards on the west beach and from the breach eastwards on the east beach during the first year. As roll-back conserves shingle barrier CSA, changes observed must relate to the longshore loss of sediment described in Section 4.1.

4.4. Overwashing Conditions

To assess the hydrodynamic conditions that drive the cross-shore response, run-up has been calculated for all conditions. Conditions that created a run-up to higher than 4 mOD have been plotted in Figure 17 for selected profiles together with the water level, Tz and Tp, CSA, crest elevation and position of the 3 mOD contour. It is clear from the Tp plot that almost all run-up events had a swell component which has been demonstrated to create higher overwash volumes [30]. When comparing crest elevations with run-up elevations one needs to bear in mind that the run-up calculations used are based on the assumptions of a typical beach in Southeast England, that is, similar to the barrier at the time of breach. Roll-back of the barrier creates longer and shallower slopes (see Figure 10) which introduces more shoaling related energy loss [69] that reduces run-up at the rolled back position compared to the pre-breach position. The comparison between run-up and crest elevation is therefore more appropriate for the conditions when the barrier was close to its pre-breach location than at later stages in the roll-back process. Figure 17 shows the similarities and differences between profile ontogeny within the MMR site.

Profile 15 in the centre of east beach changed almost immediately following the breach in autumn 2013 by decreasing the CSA and retreating the beach face in particular during the first November storms. Run-up during the storm in January 2014 exceeded the maximum crest height and together with a narrowed crest, led to crest lowering of about 1 m and roll-back of the crest by 20 metres. Further storms in early 2014 rolled the crest further back but maintained crest elevation and CSA. The winter 2014/15 had a number of storms that primarily reduced CSA, rolled back the beach and gradually lowered the crest. With CSA reduced from the breach condition of ~80 m² to ~40 m², the storms in the winter 2015/16 drove the beach another 50 m landwards lowering the maximum crest level to 3 mOD. Winter 2015/16 only saw a few events that still rolled the barrier back but otherwise had little impact. The storm in January 2017 lowered the crest to below 2 mOD and thus below the storm still water level. Essentially, the CSA of <30 m² reflects the infilling with shingle of the drainage channel that ran behind the east beach and thus does not reflect a surface projecting shingle ridge. No new ridge has reformed along this profile line in the past 3 years though Figure 1 shows shingle ‘regrouping’ landwards of the drainage channel.
Figure 17. Time series of wave run-up (markers are the maximum value per calendar week), maximum height of crest (both on the left y-axis), CSA and position of the seaward 3 mOD contour in relation to the pre-breach position where positive values indicate erosion (both on the right y-axis). The bottom panel shows Tz and Tp coincident with wave run-up value. Black numbers on the right hand side are the profile numbers.
Profile 34 lies almost opposite profile 15 on the west beach. It is the easternmost profile that is not affected by the recurve into the MMR site channel and thus allows for an investigation into shore parallel roll-back. Figure 15b shows a decrease in CSA and retreat of the beach face immediately following the breach and prior to the first November storm which, despite having run-up levels lower than the crest level and not having caused any change in profile 15, lowered the crest by >1 m, rolled back the beach by ~10 m and reduced the CSA by 20 m². This loss of CSA has most likely been the result of sediment having been driven into the breach prior to the storm rather than being lost alongshore towards the west. It shows that the reduction in CSA through longshore transport can weaken the barrier to the point of roll-back even without the hydrodynamic conditions leading to overwashing. With run-up in January 2014 exceeding the lowered crest and smaller barrier, the beach rolled back another ~40 m, but while roll-back continued in the spring, CSA and crest levels increased again. In fact, winter 2014/15 saw the crest level rising to above 4 mOD. As at profile 15, the winter 2015/16 saw a further ~50 m of roll back as well as a reduction in crest height and CSA. CSA has remained quite stable since then at around 50 m² with fluctuations of the crest height between 3.3 and 3.9 mOD, but a continued storm related roll back of the barrier.

Profile 44 represents the frontage at the western border of the marsh surface cropping out in front of the beach ridge. CSA started to decrease later than in the profiles to the east during the January 2014 storm through loss from the front of the beach indicated by the retreat of the 3 mOD contour, while crest elevation remained unchanged. The first drop in crest height (~0.8 m) occurred in March 2014 with no comparable change in CSA or change in contour line position and no overwashing event. Profile data and ground photos show that this was a last-ditch management intervention that flattened and slightly widened the crest to infill some overwash throats from the February 2014 storms that had overwashed and rolled back the barrier to the east. Further loss of CSA over spring and summer 2014 narrowed the barrier through erosion from the front leading to overwashing up to January 2015 with associated roll-back of ~15 m and crest lowering of ~1.4 m. Crest level, CSA and contour position deteriorated further up to and during the winter 2015/16 but since then CSA has remained around 50–60 m², increasing to over 70 m² in summer 2018. Similarly, crest elevations have been fluctuating between 3.3 and 3.6 mOD, rising to above 3.9 mOD in 2020. At the same time, the contour position has seen periods of stability (e.g., summer 2016 to December 2017) punctuated by storm related roll-back (e.g., December 2017 and winter 2019/20).

Following a brief increase in CSA in the autumn of 2013, CSA for profile 53 dropped steadily until autumn 2015/16. This was accompanied by a steady retreat of the contour line of up to ~10 m, but an initial slight increase of the crest elevation followed by a slight dip and general stability. The roll-back of ~30 m, drop in crest by ~1 m and reduction in CSA by ~70 m² occurred in the early winter of 2015/16. Following this, crest levels have been maintained around 4 mOD, i.e., ~0.5 m higher than for profile 44, CSA has been steady at about 40 to 50 m² in 2016 and 2017 and at about 30 to 40 m² following further roll-back during winter 2017/18 and 2019/20.

The development for profile 68 is very similar to that for profile 53 except that the peak in CSA came in spring 2015 (accompanied by a seaward move of the 3 mOD contour), that the roll-back occurs over the entire winter 2015/16, and that the reduction in crest elevation is very small over most of the study period at around 4.5 mOD, dropping to below 4 mOD only at the last survey linked to the storms in 2019 and 2020. This drop is associated with further roll-back but the CSA remained unchanged.

Profiles 80 and 85 are at the western end of west beach and have been the latest to be impacted by roll-back. Both show an increase in CSA in 2015 which started to drop at profile 80 in 2016, while at profile 85 this was delayed till 2018. Retreat of the contour line position reached 10 m in winter 2018/19 for profile 80 and in winter 2019/20 for profile 85. Crest lowering for both happened in the winter 2019/20 though at profile 85 this has only
led to a lowering to 4.77 mOD and the crest is still within the cross-section of the barrier in its pre-breach configuration, i.e., roll-back has not yet happened.

4.5. Barrier Inertia (BI)

The BI concept (Section 3.4) can be used retrospectively to assess (a) what the beach and environmental conditions were during known overwashing events, (b) periods of likely overwashing to investigate beach profiles for morphological signs of this having occurred and (c) as a predictive tool to assess the likelihood of overwashing for sections of beach that have not been overwashed yet [35]. For the Medmerry datasets, there are no dedicated pre-and post-storm surveys that bracket a single event. Therefore, the period covered by surveys that show crest lowering (Figure 17) have been identified and BI values calculated for all 30-min conditions within that time window and with a still water level > 2 mOD. These have been plotted for a selection of events and profiles in Figure 18 together with BI thresholds (1) and (2). For profile 15, the values have been linked by lines to illustrate more clearly the sequence over a tidal cycle and the number of values during different tidal cycles. For example, the event on 04 January 2014 covered 2.5 h and started with a BI value of 1.04 on the still rising tide but as water level rose a bit more, wave height fell away leading to higher BI values; the same applies to 02 January 2014. On the other hand, the line and points for 03 January 2014 represent the combination of the morning and lunch time high tides with low BI values over 2.5 h each; the same applies to the 01 January 2014 with low BI values over 1.5 h each. The most BI values for one tide are shown for profile 34 on 03 November 2013 and an example for only one value during a tidal cycle can be found for profile 75 on 31 December 2017.

![Figure 18. 30-min BI values plotted against Hs/Lm for selected profiles (the two figures preceding the hyphen in the legend) and dates together with published threshold curves (1) and (2).](image)

Whether only one event (and then which) created the crest lowering (1.1 m) and roll-back (20 m) observed for example for Profile 15 between 10 December 2013 and 10 January 2014 cannot be resolved from the data because of the feedback created by loss of CSA and crest lowering during an event at high tide and the resultant changed geometry of the beach for the following high tides. However, the event on 31-12-2013 is quite short, covering 1.5 h, and thus is highly unlikely to have achieved the observed change on its own, but it is likely to have narrowed the crest and removed CSA from the profile. The two
high tides on 01 January 2014 would then have had a larger effect that would have been further exploited by the longer waves on 02 January 2014.

For profile 41 on the other hand, crest lowering from 4.29 to 3.48 mOD and roll-back of the 3 mOD contour by 13 m (with lowering by 1.3 m but no roll-back prior to this between 10 January and 07 February 2014), and for profile 63 crest lowering from 5.39 to 4.37 mOD with no roll-back occurred between 07 February and 04 March 2014 with only one tide (14 February 2014) with low BI values. For profile 41, there was a ‘preparatory’ high tide with just one value on 01 February 2014 just above the threshold which is the only candidate for the 1.3 m crest lowering mentioned above that reduced $B_A$ from 16 to 5.4 m$^2$, and then followed on 14 February 2014 by very low BI values over 1.5 h. For profile 63, the starting $B_A$ area was 29 m$^2$ which would explain the higher BI values and more limited profile response.

The benefit of the BI approach to identify overwashing that is not obvious from the topographic data can be shown using profile 75 as an example (Figure 18). It is located at the western end of the MMR frontage which does not show any change in crest elevation or position before December 2017 although CSA has been decreasing prior to that Figure 15. However, running the BI calculation for the entire period has identified four BI values on 14 February 2014 that are comparable, though slightly higher than for profile 63. On closer inspection of the annual aerial photography, the crest around profile 75 (and most of the western section of the MMR) shows subtle changes on the backslope (Figure 19) mainly in terms of vegetation loss and some new sediment landward of the access track suggesting a few individual waves overwashing during the event resulting in some sediment transport but no detectable morphological change. The $B_A$ area for the event was 46 m$^2$ so that for the event on 14 February 2014 three difference profile responses could have occurred depending on the BI value.

Most of the data suggests that the straight Obhrai threshold seems to fit the data better than the Bradbury curve, i.e., that there are plenty of events with BI values that can account for the observed overwashing and crest lowering below the Obhrai threshold, whereas only a very small number make it to and below the Bradbury line. The exceptions appear to be events and profile responses on 14 February 2014 illustrated by profiles 41, 63 and 75. However, this event was dominated by swell waves leading to the widespread overwashing of Hurst Spit during the same event [6] yet the wave spectra do not explicitly form part of the threshold equations. The Obhrai line is based on laboratory flume experiments with two wave steepnesses, namely 0.06, close to most of the data for Medmerry, and 0.01
reflecting swell waves. It is therefore not surprising that conditions calculated with steep waves but composed of less steep waves fall below the Obhrai threshold although the profile response at least for profile 75 should have plotted above it.

Finally, the BI concept can be applied to assess when the frontage west of MMR is likely to experience overwashing and roll-back. Figure 20 summarises the point in time when roll-back occurred at each profile west of the breach. The definition used for the start of roll-back is subjective and based on profile behaviour but is generally taken to be when the crest of the rolled back beach is landwards of the rear slope of the beach as surveyed on 26 August 2013. An example is given in Figure 10 where the barrier at the survey on 24 January 2015 has not rolled-back at either of the two profiles, while profile 47 has rolled back by the survey on 16 June 2015. In Figure 20 the date is given for each profile survey prior to roll-back and post roll-back, i.e., providing a bracketing time range because the exact date cannot be ascertained with certainty. As an alternative measure, the date of the survey for when the seaward 3 mOD contour was more than 15 m landwards from the start position on 26 August 2013 is also given, representing a significant amount of thinning and loss of CSA. Again, the example profiles in Figure 10 show the different in position of the 3 mOD contour on 24 January 2015 compared to 26 August 2013 to be 17 m for profile 48 and 19 m for profile 47. It is clear that different definitions of roll-back initiation provide different date as shown in this example and in Figure 20. To link the initial roll-back events to the state of the beach at that time, the cross-sectional area of the barrier above 2.3 mOD is shown for the same pre- and post-survey date but also for the survey preceding the pre roll-back survey (CSA pre+1 R-B). For the frontage west of the western rock arm, the two ‘pre’ lines simply refer to the last two available surveys as roll-back has not happened. Finally, the CSA above the same level at the start (26 August 2013) is also shown in black. The level of 2.3 mOD for the CSA calculation was chosen because it is the average water level for the events shown in Figure 18.

![Figure 20](image-url)

**Figure 20.** Summary diagram showing for the frontage east of the western rock arm the time of surveys between which the first roll-back has occurred at each profile together with CSA of the Barrier Area above 2.3 mOD for the same surveys. Broken horizontal line is the average ‘CSA pre R-B’ of 40 m² with the two dotted lines representing the standard deviation. For the area west of the rock arm, the two brown lines are the CSA for the last two surveys. See text for more details.

Figure 20 shows that barrier roll-back from the starting position on 26 August 2013 has sometimes progressed westwards gradually (up to summer 2015 and between spring 2016 and winter 2019) and sometimes in large steps (early winter 2015 and winter 2019/20) when several profiles rolled-back during the same storm event (bearing in mind that the entire
barrier was overtopped by at least a few waves during the storm on 14 February 2014). It also shows that in all cases the barrier had become smaller in terms of the CSA prior to the event compared to the starting point on 26 August 2013; in some cases this CSA loss occurred during the preceding survey interval. The difference between pre- and post-roll-back CSAs shows large variations but there is a significant correlation ($\rho = 0.39$, $p < 0.005$) between the two which is even more pronounced for the roll-back of profiles 48 to 66 ($\rho = 0.8$, $p < 0.0001$). The average pre-rollback CSA was 40 m$^2$ ($\sigma = 10$ m$^2$) and it is evident that there is a stretch 100 m long west of the western rock arm (profile 87) that has already (by October 2020) fallen to within the band of CSA that is likely to result in overwashing and roll-back under storm events similar to those experienced several times in the last 7 years. This has come about due to continued longshore transport that has led to beach loss over the last two surveys and which will be exacerbated in the near future when the rock arm, which has so far terminated within the beach, emerges from the beach and will increasingly act as a groyne with associated downdrift consequences.

To address the flood risk posed by overwashing west of the western rock arm which is also impacted by legacy structures, planks have been removed from the groynes in that area and shingle has been placed behind these groynes along short stretches that have the most vulnerable cross-shore profile (Figure 21), pre-empting the natural process illustrated in Figure 11). West of profile 100 the overwashing risk is very low in particular as the beach has grown since 2013, however, the future loss of CSA needs to be monitored.

Figure 21. Management intervention in 2021 showing before (top on 12 October 2020) and after (bottom on 29 January 2021) groyne plank removal and increasing the CSA behind the groyne at the back of the beach. Pole in the top photo is 3 m long.

5. Discussion

Speed and magnitude of the coastal ontogeny over the 7 years since the breach is incompatible with any modelling or ‘expert knowledge’ prior to the breach and bears no relationship to the development envisaged, as quoted in Section 2.1. This assumed an average rate of up to 0.7 my$^{-1}$ for design purposes or up to 1.5 my$^{-1}$ based on historic data. After 7.16 years (August 2013 to October 2020), mean annual roll-back based of the position of the 3 mOD contour ranges from 27 to 28 my$^{-1}$ on the east beach (profiles 14–19) to 21 my$^{-1}$ at the eastern end of west beach (profiles 34, 35) to 2 my$^{-1}$ just east of the western rock arm (profiles 84, 85). The average across all profiles within the MMR site is 16.6 my$^{-1}$ or one order of magnitude higher than the historic rate. Profiles 34 to 36 have retreated between 152 to 146 m and while 2nd order polynomial trend lines have a slightly better $R^2$ value and optical fit (Figure 17) over the last few years than linear trends, there are no indications that the barrier has reached a more stable position in this retreated position.
In fact, the barrier at these profiles is positioned landwards of the marsh cliff which is also still eroding and this erosion will increase wave power on the barrier which is therefore highly likely to roll back further.

At the soft cliffs of Happisburgh [70], lowering of the lower intertidal foreshore in front of defences was identified as the driver for accelerated coastal catch-up that has overtaken what was deemed to be a ‘natural’ trajectory of retreat. As suggested in an earlier study for the historic period [43] and evidenced as an example in Figure 9 for the time post-breach, there is very little change in elevation on the lower intertidal platform to either drive the coastal catch-up process or accompany it. This would point to sea level rise as being the main driver for the overall catch-up process.

Based on historic progression and retreat rates together with the length of time the beach has been held in place for, a catch-up distance of 100 m was suggested in Section 2.1. Using a rate of sea level rise of 0.002 m\(^{-1}\) since the 1950s and the estimate of 0.65 m retreat per 0.001 m of sea level rise [15] would similarly deliver a catch-up distance of ~90 m. All profiles east of profile 47 have retreated by more than 100 m with profile 34 by 152 m. This mismatch could be due to the historic rates based on maps being too low, that extrapolating historic retreat rates is not an appropriate method to estimate catch-up distances or that published rates of retreat in relation to sea level rise are not applicable to the MMR site.

The most likely reason for roll-back distances observed so far and to be expected into the future are the fundamental changes to the barrier beach post-breach. Natural barriers tend to roll back as a closed unit, and in a swash aligned [14,15] or sediment rich drift aligned setting any local patterns of barrier lowering and breaching are repaired through natural processes within a short period of time [42]. There are no historic reports or indications from historic maps that the Medmerry barrier was breached and developed an inlet and neither, for example, has this been the case for the longer, more drift aligned southern coast of Dungeness [71]. In contrast, the artificial breach has changed the sediment dynamics by first removing 7200 m\(^3\) over a length of ~230 m and creating new accommodation space for shingle to migrate landwards along the new channel, drawing in beach sediment from about a hundred metres to the west and east and thus creating conditions for this section to roll back due to reduced CSA. On the west side of the breach, this started to change the coastal alignment to more swash alignment in that section (a rotation of ~20°) reducing sediment loss which pushed longshore transport and CSA loss onto the next section, creating a process of alongshore progressing roll-back as the next section started to become more swash-aligned. On the east beach on the other hand, the loss of CSA into the area along the channel had little time to change the plan-shape before wholesale roll-back took place. However, the barrier breakdown shown at the east beach is not due to further sediment loss alongshore but through temporary loss into shore parallel channels. The removal of the sediment and creation of the wide opening are what differentiates MMR from the natural breach at Porlock where the barrier remains largely unchanged since the breach in 1996 [18]. This suggests, based on only this one comparison, that a smaller breach channel to start its natural development together with leaving the excavated sediment in the system close to the channel could avoid the large scale changes observed at MMR, albeit at the risk of the smaller breach closing again [45].

Thus far, the progressing roll-back has rotated the coast line towards being more swash aligned. The average shoreline orthogonal from the western rock arm to the breach is 215°, in line with the dominant wave direction. The process has also moved the remaining CSA on top of the marsh surface, where it generally sits above MHWS level. Both of these outcomes contribute to a reduction in longshore transport through reducing the wave angle and reducing the opportunity for hydrodynamic processes to move this sediment by being largely out of reach under normal conditions. The remaining CSA will ensure future roll-back under hydrodynamic conditions that are likely to happen on an annual basis, in particular as the remaining CSA appears to be too small to lead to crest build-up. Along most parts of the west beach, the land drops landwards (Figure 2 and profile 79 in Figure 3
inset) which could accelerate roll-back due to reduction in crest height for a given CSA. On the east beach these hydrodynamic conditions are likely to continue the emergence of beach material that has been temporarily ‘hidden’ as channel fill and start to push it towards higher ground (Figure 2) in front of the perimeter embankment.

These changes inside MMR will reduce sediment input into the downdrift frontage, which will be exacerbated by the emergence of the western rock arm as a groyne, making the planning of measures to manage roll-back while providing flood protection a priority. This needs to avoid the outcome seen on the east beach, which is a possibility with landward drainage ditches that can reduce CSA as the beach rolls back. This can be balanced by adding sediment to the existing CSA (as shown in Figure 21) or by infilling of landward ditches and depressions. As the beach plan shape is very likely to become more swash-aligned through continuation of the process on the West Beach, moving the beach artificially into a more swash aligned position is a possibility, however, where this beach joins the section of beach further west where roll-back is not possible due to properties immediately behind the beach, longshore transport pressure will create a focus for future erosion.

6. Conclusions

Roll-back of the macro-tidal mixed sediment barrier at the wave-exposed site of Medmerry in southern England is fundamentally linked to its cross-sectional area (CSA) as used in the Barrier Inertia concept. This has been established along the 1.5 km long barrier using more than 40 full surface topographical surveys and wave and tide conditions recorded from nearby collected over more than 7 years since the barrier was artificially breached in 2013. Changes in CSA were initiated by creating the breach and removing the excavated shingle from the site, creating accommodation space for shingle from either side to move into the breach, reducing CSA and initiating roll-back of barrier sections closest to the breach. Re-orientation of rolled-back sections to a more swash-aligned plan-shape position pushed longshore transport loss further downdrift, leading to a reduction in CSA in these sections which in turn led to overwashing and roll-back to progress along the entire frontage in a downdrift direction. The relationship between CSA and observed overwashing and roll-back provides a predictive framework for other barriers, in particular for the ~1 km long barrier downdrift and outside of the managed realignment site where flood risk management is still required. The speed of roll-back, averaged over the entire length and time, exceeds 16 my⁻¹ which is an order of magnitude higher than historic shoreline retreat rates and has led to roll-back distances in the earliest affected sections that are nearly double the catch-up distance based on either historic rates or those based on the sea level rise experienced at the site.

The study demonstrates the benefit of the Barrier Inertia concept, in particular when used with data for short time intervals over the tidal cycle of a storm on a macro-tidal barrier, in explaining the observed morphological barrier response. However, this only applies to the first instance of roll-back when the barrier and foreshore geometry is similar to that for which the Barrier Inertia concept was developed. A more detailed study using a longshore coupled XBeach-G or XBeach-X model that includes the longshore transport from the sediment budget established in this study, and can include the more resistant underlying marsh and clay surface over which the barrier roll-back is needed to explore the reasons behind the already long distance and continuing process of coastal catch-up. This could benefit predictions of coastal change for similar sites where management of a shingle barrier is going to be stopped.

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