Coastal saltmarsh managed realignment drives rapid breach inlet and external creek evolution, Freiston Shore (UK)

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Abstract

The creation of saltmarsh through the managed realignment of sea defences, implemented in northwest Europe as a sustainable coastal defence option, represents a substantial hydrodynamic perturbation to the local coastal system. The impact of a significantly increased tidal prism on hydromorphological features was investigated at Freiston Shore, Lincolnshire UK. Local tidal conditions and inadequate drainage at this realignment trial contributed to significant channel erosion due to the establishment of water surface slopes and pooling between the newly realigned site and the site-external intertidal zone. Very high spatial resolution aerial and blimp photography was used to monitor inlet evolution from breaching in August 2002 to March 2008, showing a highly non-linear response with breach channels increasing in width by up to 960% within 2.5 months. Airborne Laser Scanning/LiDAR and Terrestrial Laser Scanning quantified breach channel volume increases, showing a similar pattern. Breach channel evolution did not follow established tidal prism-channel width/cross-sectional area relationships that are often used to guide realignment design. Pre- and post-breach rates of external creek morphology change between 1999 and 2006 were also quantified, with intertidal creeks attached to the breach channels increasing significantly after realignment in both width and depth. This study highlights the physical processes affected by managed realignment, and the importance of understanding the causes of complex water surface slopes at multiple scales.

Keywords: erosion, geomorphology, hydromorphology, LiDAR, Terrestrial Laser Scanning, wetland

1. Introduction

Continuing loss and degradation of wetlands on low-lying mid-latitude coasts, and the appreciation of the ecosystem services provided by saltmarshes (Zedler and Kercher 2005) has led to the use of coastal management options that attempt to re-create saltmarsh on formerly reclaimed agricultural land. The ‘managed realignment’ of coastal defences by breaching the former sea defence line to create a new intertidal surface for saltmarsh development has been increasingly implemented in North-west Europe (Rupp-Armstrong and Nicholls 2007) and North America (e.g. Williams and Orr 2002), with

150 realignment trials identified since the early 1990s (Spencer and Harvey 2012). However, on a process level, managed realignment represents a sudden, significant hydrodynamic perturbation to the equilibrium that may exist between flood and ebb tidal discharge and channel dimensions. Such a sudden increase in the local tidal prism may have profound consequences for tidal circulation and intertidal zone erosion and deposition in general, and tidal flow and sediment transport patterns through inlet systems (sea defence breaches, existing intertidal creek networks) in particular.

The tidal prism is one of the main factors controlling tidal channel geometry (Vandenbruwaene et al. 2012a), such that an equilibrium channel form may be expected for a particular marsh tidal prism within a defined tidal range (O'Brien 1931, 1969, Williams et al. 2002). This geomorphological relationship can be used to assess inlet stability and to categorise inlets as erosional or depositional (Mirfenderesk and Tomlinson 2008). Optimal breach channel design should create a stable inlet for water exchange, with minimum scouring and jetting (Townend 2008). Breach dynamics are also important in the context of hydraulic efficiency of the wider intertidal zone. During the ebb tide, water stored at higher elevation within the hydraulically inefficient marsh surface *vs.* water removed within the lower elevation, hydraulically-efficient creek channels (of which breaches are a part) sets up a water surface slope, with an associated increase in flow velocities (Bayliss-Smith et al*.* 1979, Healey et al. 1981, French and Stoddart 1992), or 'channel-forming flows' (Williams et al. 2002). In some cases, the impacts of water surface slopes may extend well beyond the breach itself, impacting natural saltmarsh drainage systems seaward of the managed realignment area.

It is important to accurately quantify the volume of water exchange through breach inlets, as they control erosional processes at points of water exchange (breach channels) and water transfer (creeks), and sediment depositional processes close to these features. However, while single breach channel design may take into account the basic principles of hydraulic geometry, the detailed flow patterns that may result from breaching are, at best, difficult to predict if site geomorphology is complex, and/or a series of breaches, rather than a single breach, connects a managed realignment site to the existing intertidal zone. The configuration of feeder creeks outside, and engineered channels inside the realignment site, may lead to more complex flow patterns than simple periodic flood – ebb tide reversals, and unexpected (and potentially non-linear) morphological responses both of the breach channel themselves, and the tidal creeks that connect to them at more seaward locations.

This study fills an important knowledge gap regarding physical processes and disturbance in realigned marshes (Spencer and Harvey 2012) by investigating the short- (0-1 years) and medium-term (1-5.5 years) hydromorphological evolution of channels at a managed realignment site at Freiston Shore, eastern England. In particular, this study compares observed change in the sea wall breaches and intertidal creeks with established hydromorphological equations for optimal inlet design (O'Brien 1931, CIRIA 2004). Freiston Shore provided a rare experimental opportunity to quantify the impacts of a large hydrodynamic perturbation on water exchange and creek dynamics, and can provide important guidance for future saltmarsh creation.

2. Regional setting

Freiston Shore is situated in The Wash embayment, eastern UK (Figure 1a). The Wash experiences a macrotidal regime (Mean Spring Tidal Range (MSTR) = approximately 6.5 m), and covers an area of 615 km^2 below the high water level, with a mean spring tidal prism of 2.8 x 10^9 m^3 (Ke et al. 1996). Mean High Water Spring (MHWS) equates to 3.3 m Ordnance Datum Newlyn (m ODN, where 0.0 m ODN approximates Mean Sea Level (MSL)), while Mean Low Water Spring (MLWS) equates to -3.0 m ODN. Mean wave heights of 1.2 - 1.4 m are experienced during southwesterly gales (mean wind speeds: 13.9 – 24.4 m s^{-1}) between November and March (Ke et al. 1996). The Wash is sediment-rich, with nearshore suspended sediment concentrations in the range of 200 mg l^{-1}, and reaching an order of magnitude higher during some events (Collins et al. 1981).

[FIGURE 1 HERE]

An extensive shallow-sloping intertidal zone fronts Freiston Shore (Figure 1b, 1c, Figure 2, Figure 3). The main depositional environments are well described, comprising three different sandbank environments and a lower mudflat below 1.5 m ODN, an algal-dominated upper mudflat up to 2.4 m ODN, and saltmarsh of varying density and composition from here to 3.3 m ODN (Evans 1965, with elevation data obtained from 2002 LiDAR/Airborne Laser Scanning (ALS) data used in this study, also Figure 2). Broad saltmarsh community distribution in the upper intertidal zone comprises seasonal pioneer *Salicornia europaea* at the most seaward extent, transitioning to dense *S. europaea* and *Atriplex portulacoides* and *Puccinellia maritima*-dominated communities at the most landward extent (Friess et al. 2012). Shore-parallel vegetation bands following the intertidal topography are based on broad species-specific tolerances to physical thresholds of tidal inundation and associated environmental parameters (Davy et al. 2011).

The contemporary shoreline has been heavily shaped by progressive land reclamation from at least the medieval period up until the 1980s (Doody 1987). Sea defences protect large areas of agricultural land (Figure 2), which are now below MSL due to disconnection from sediment supply, sediment compaction and dewatering after reclamation (Dixon et al. 2008). Freiston Shore was one of the final areas to be reclaimed between 1978 and 1982, extending 300 m seaward beyond the former shoreline (Figure 1). Its extreme seaward position made the sea wall a focus of erosion (Doody 2013) and the remaining fronting saltmarsh could not effectively attenuate incoming wave energy. Coastal defences were thus realigned back to an earlier position, inundating 66 ha of formerly arable land (Figure 1c; Nottage and Robertson 2005). This represented the largest realignment trial in the UK at that time. Prior to breaching, over 1200 m of primary drainage channels were created within the site (Nottage and Robertson 2005). The seaward defence line was breached in three locations on the 24th August 2002. Each breach consisted of a 50 m wide opening (determined on the basis of numerical modelling (Halcrow 1999) and referred to in this study as the *breach*). Within each of the three breaches, a channel (referred to in this study as the *breach channel*), 2 m wide and 1 m deep was excavated (Symonds and Collins 2007a), apparently designed to be similar in dimensions to adjacent natural channels at similar intertidal elevations.

[FIGURE 2 HERE]

[FIGURE 3 HERE]

3. Materials and Methods

The magnitude, and subsequent impact, of an altered hydrodynamic regime was examined in a number of dimensions through the integration of four different remote sensing techniques. 2-dimensional vertical aerial photography was collected by a low altitude blimp platform and fixed wing aircraft, while data from a Terrestrial Laser Scanner (TLS) and airborne LiDAR/ALS provided quantitative information in 3-dimensions (Table 1). These datasets were then used to quantify multiple aspects of hydromorphological change: increases in breach channel width (3.1), breach channel volume (3.2), creek width (3.3) and creek volume (3.4).

[TABLE 1 HERE]

3.1 Data sources and pre-processing

3.1.1 Fixed Wing aerial photography

Vertical aerial photographs of the study area were provided by the UK Environment Agency (EA) and the UK Natural Environment Research Council's (NERC) Airborne Research and Survey Facility (ARSF) (Table 1). Photographs were geocorrected to the British National Grid using Ordnance Survey line feature data and Ground Control Points (GCPs) surveyed by RTK GPS and Total Station, following Friess et al. (2012).

3.1.2 Low altitude blimp photography

Extremely high spatial resolution (<0.1m) aerial photography was acquired from a low altitude (<100 m), helium-filled (1.6 m^3) blimp platform in March 2008 to supplement the fixed-wing aerial photography available for the channels in each of the three breaches. A 7.2 mega pixel digital camera was mounted onto the blimp and recorded images at 60-second intervals. 1 m^2 marked targets in lines of 5 m were laid either side of the surveyed breach channel; the centre of each target was located by a Total Station survey to geocorrect the blimp image.

3.1.3 Airborne Laser Scanning

Last-return ALS (also known as airborne LiDAR) data was collected by the EA on the 16th November 2002 (2.5 months after breaching), and the Unit for Landscape Modelling, University of Cambridge (ULM) on the 4th November 2006, on behalf of NERC ARSF (Table 1). Both surveys were conducted at *ca.* MLWS to allow for maximum channel drainage and exposure. ASCII point data were converted into grids (in ArcInfo 8.3) of cell size 1.0 m point spacing (2002) and 0.5 m point spacing (2006).

3.1.4 Terrestrial Laser Scanning

The use of TLS in saltmarsh environments is still in its relative infancy as a research tool (though see Guarnieri et al. 2009). A ScanStation TLS (Leica Geosystems) was deployed in May 2008, conducting a scan either side of the channel at the south breach (Figure 4). Point spacing was set at 8 x 8 cm at a distance of 100 m, with a progressively finer spatial resolution at closer distances. The two scans were georegistered together using Cyclone 5.8.1 (Leica Geosystems) (RMSE = <0.004 m) and modelled as a Triangulated Irregular Network (TIN).

The TLS scan was combined with a rapid bathymetric survey to estimate below-water volume. Water depth close to MLWS was recorded at 1 m intervals along the 3 established transect locations (*see Section 3.2.1*), and at 2 additional transects, using both a portable depth sounder and levelling staff (Figure 4). Water levels in the breach channels were not subjected to tidal variation during the surveys; water height was measured at a known point at the start and end of each scan and showed only a ±1 cm change in water height. The bathymetric transects were converted to a grid (Kriging distance weighting with 3x3 Gaussian filter) in Surfer v8.0 (Golden Software), from which a coarse approximation of the below-water breach channel volume was calculated.

3.2 Breach channel data analysis

3.2.1 Mean breach channel width

The width of the three breach channels was calculated using fixed-wing aerial photography, blimp photography, ALS and TLS (Table 1). Breach channel width measurements from aerial photography, blimp photography and ALS were taken in ArcView 3.2 (ESRI), while measurements from TLS were derived using Leica Cyclone. For all techniques, breach channel width was determined at the same fixed and repeatable points (from three measurements at the extreme ends and middle of each breach) in all available images following breach channel construction (Figure 4). Some brief measurements of breach width expansion are discussed by Symonds and Collins (2007a), though not enough information is given on method or results to make a comparison with this present study.

Observations of breach channel evolution obtained at Freiston Shore were compared to equations that link tidal prism to optimal breach design. Firstly, the Spring tidal prism for the Freiston Shore realignment site was calculated from the volume defined by the ALS-derived surface (acquired November 2002) and a plane representing MHWS over the entire 66 ha site. This equated to a Spring tidal prism of 776 398 m^3. The calculated tidal prism was inputted into *Equation 1*, which is derived from previous observations of historical storm breaches and has been used to model optimum breach width for realignment design (CIRIA 2004, Townend 2008).

$$W = 37.9e^{1.8\times10^{-6}\,TP} \qquad [1]$$

Where W = breach width, and TP = MHWS tidal prism. Note that this equation is limited to a relationship between tidal prism and breach width, i.e. assumes a fixed relationship between the two-dimensional cross-sectional area of the breach and its width.

[42 HERE]

3.2.2 Cross-sectional area of breach channels

Breach channel profiles were collected from the 2002 and 2006 ALS digital elevation models across the middle of each breach (Figure 4) using ERDAS Imagine 8.5 (Intergraph). Channel cross sectional areas were calculated for a number of planes, relating to a) MSL (0.10 m ODN); b) bankfull (equivalent to the marsh surface elevation of 3.15 m ODN), c) MHWS (3.30 m ODN); and d) the top of the seawall (6.00 m ODN), relating to the full breach cross-sectional area (Figure 5).

[FIGURE 5 HERE]

Equation 2 refers to the relationship between tidal prism and optimal inlet cross-sectional area (Hughes 2002), rather than the simple breach channel width used in *equation 1* above. The relationship expressed in *equation 2* is well validated for studies of the geomorphological evolution of temperate saltmarsh inlets and channels (e.g. D'Alpaos et al. 2007, 2010) and has been used or described in the context of managed realignment breach design (CIRIA 2004, Townend 2008). In generic form, this relationship is expressed as:

$$A_c = CP^k \qquad [2]$$

Where A_c = equilibrium inlet cross-sectional area below Mean Sea Level, P = tidal prism and C and k are an empirically derived coefficient and exponent. In this study we calculated the equilibrium cross-sectional area according to a number of derivatives of this equation from previous studies (Table 2).

[TABLE 2 HERE]

3.2.3 Volume of breach channels at bankfull stage

Bankfull breach channel volume was calculated in August 2002 (the initial constructed breach channel volume), shortly after breaching in November 2002 and later in November 2006 by ALS, and in May 2008 using TLS (south breach only).

- Initial breach channel volumes for August 2002 were derived for the south, central and north breach respectively, using the initial channel dimensions described by Symonds and Collins (2007a), and the breach channel length derived from ALS in November 2002 (the shortest time interval available after breaching).
- ALS grids from November 2002 and 2006 were inputted into a model created in ERDAS Imagine to calculate bankfull breach channel volume. For each pixel, the model calculated the elevation difference between the breach floor and the average top of the breach channel (measured across the middle of the channel), equating to a tidal level of ~3.15 m ODN, or 0.15 m below MHWS (Figure 5). Each calculated value was grouped into 10cm bins, roughly equivalent to the vertical error of the ALS instrument (e.g. French et al. 2005, Hladik and Alber 2012). Error is represented by calculating volumes using the average, minimum, and maximum pixel value for each bin.
- Measurements of bankfull breach channel volume were calculated from the TLS data from May 2008 Leica Cyclone, in the same manner as calculated for ALS.

3.3 Tidal creek data analysis

3.3.1 Tidal creek width

Geocorrected, fixed-wing vertical aerial photography collected on 10 occasions between 1999 to 2006 (Table 1) was used to determine change in the widths of the major creeks extending seawards from each of the three breaches, and in two control creeks, located 300 - 500 m from the south breach and 550 - 600 m from the north breach. 40 control points were monitored along the 5 channels, at locations that could be easily identified across all photo mosaics (Figure 6). The channel length sampled depended on available aerial photography coverage but, where possible, channels were surveyed from the outermost sea wall to the subtidal zone. This resulted in 1024 m, 1189 m and 1463 m survey distances for the south, central and north creeks respectively. The south and north control creeks were monitored over lengths of 1506 m and 1847 m respectively.

[FIGURE 6 HERE]

3.3.2 Tidal creek volume at bankfull stage

The breach channel volume model described in *3.3* was applied to the three creeks attached to the breach channels that extended southeast across the shallow-sloping intertidal zone. The creeks were divided into sections where the average surface elevation difference from landward to seaward was <15 cm (the z-axis error of the ALS instrument). The average elevation of each channel section was used to determine the bankfull plane, and volume for each was calculated as per *Section 3.2.3.*

4. Results

4.1 Changes in breach channel width

From an assumed initial width of 2 m, rapid increases in average channel width was observed at all three breaches between August and November 2002, immediately after realignment (Figure 7). Lateral channel expansion was greatest at the central breach, expanding from 2 m to 32 m from August 2002 to February 2008. Within the first 2.5 months the central breach channel increased by 19.2 m (achieving 66% of the 2008 breach channel width). Expansion rates reduced between November 2002 and August 2003 (5.8 m in 9 months, or 7.7 m a^{-1}), and then again until August 2005 (2.2 m a^{-1}). After this date no discernible breach channel width change was observed.

The south and north breach channels responded similarly to the central breach channel, though to a lesser magnitude. The south and north channels expanded to 71% (16.2 m) and 70% (11.4 m) of their 2008 channel width respectively after 2.5 months. By August 2003 the south breach had achieved 87% of the 2008 channel width, and showed little change after this time period. The north breach continued to expand at a reduced rate from November 2002 to February 2004, at which point 93% of the 2008 breach channel width had been achieved. The reduction in expansion rate between Aug 2002 to Nov 2002, and Nov 2002 to 2008 was significant (t-test, $p=<0.05$) for all three breaches.

Using *Equation 1,* the increased tidal prism required a total breach width of 153.3 m, or 51.1 m per breach. As of February 2008 the widths of the three breach channels (varying between 16.3 m and 32.0 m) were far below this theoretical equilibrium width. Instead, the optimum breach width calculated by *Equation 1* most closely relates to the larger breaches in the seawall, which were approximately 50 m in width each, rather than to the channel widths.

[FIGURE 7 HERE]

4.2 Changes in breach channel cross-sectional area

The rapid increase observed for the breach channel width was also reflected in other breach channel geometries such as the channel cross-section, especially in the central breach channel (Figure 8). All breach channels had expanded in cross-sectional area in the 2.5 months after breaching, from an assumed bankfull cross-sectional area of 2 m^2 to 20.0 m^2 (central breach), 16.6 m^2 (south breach) and 10.6 m^2 (north breach). Between November 2002 and 2006 the central breach cross section area increased to 107.6 m^2 (a 5280% increase from the original breach channel dimensions), while the south and north breach channels expanded to 50.0 m^2 (2400%) and 30.3 m^2 (1415%) respectively. These are conservative estimates of cross-sectional increase, as ALS was not able to fully penetrate residual water still contained in the breach channel in 2006.

[FIGURE 8 HERE]

With a Spring tidal prism of 776 398 m^3 for the Freiston Shore realignment site, *Equation 2* predicts a range of total inlet cross-sectional areas depending on coefficient/exponent source (Table 3). The actual cross-sectional areas of the three breaches observed at Freiston Shore were lower than predictions, in some cases by 1-3 orders of magnitude, especially when compared to the MSL plane (Table 3).

[TABLE 3 HERE]

4.3 Changes in breach channel volume at bankfull stage

The initial volumes for the south, central and north breach channels were calculated as 162 m^3, 150 m^3 and 120 m^3 respectively. A rapid and significant increase in the channel volume between MLWS and bankfull stage (see Figure 5) was observed at all 3 breaches by November 2002 (Table 4). This change was greatest (in percentage terms) at the north and south breach channels, whilst a saltwater pool had formed behind the former sea wall defence line at the central breach. However, by November 2006 this breach channel had increased by the greatest extent in both percentage and volumetric terms, by an average volume change of 5744%. Over the longer term, the channel in the north breach showed the least change in MLWS – bankfull volume (1446%).

[TABLE 4 HERE]

TLS extended the timeline of data collection for the channel in the south breach by a further 18 months. TLS calculated a MLWS – bankfull stage volume of 3649 m^3, a further increase of 595 m^3 between November 2006 and May 2008. The rapid bathymetric survey estimated a very coarse breach volume from MLWS to the bottom of the breach channel of 1328 m^3, giving an expected approximate total breach channel volume at the south breach of 4977m^3.

4.4 Impacts of breaching on creek width seaward of the realignment site

The three creeks connected to the channels in the breaches on their seaward side responded in a similar fashion to the breach channels after the renewal of tidal exchange (Figure 9a). The south, central and north creeks showed no measurable changes in width characteristics prior to realignment (1999-2001). By August 2003 (earliest post-breach image, so not necessarily the final date of large-scale change) all three creeks attached to the south, central and north breach channels had experienced a large increase in their width. The overall magnitude of creek change paralleled that observed at the breaches. The central creek showed the largest overall change in width (an average of 11.8 m between 2001 and 2006), while the south and north creeks increased in width to a lesser extent (average of 8.4

m and 4.0 m respectively). The central creek in particular showed a spatial pattern of creek width expansion, with greater expansion closer to the breach (for example, three measured locations within 230 m of the breach increased by 13.9-18.7 m between 2001 and 2006) compared to measurement locations further seaward (e.g. 5.7-10.3 m increase between 2001 and 2006 approximately 940-1230 m away from the central breach).

[FIGURE 9 HERE]

Creek width expansion was only evident on the creeks directly attached to the breach inlet channels. The control creeks (Figure 6, Figure 9b) showed no significant variation in channel dimensions before or after realignment. Differences between each of the breach-impacted creek channels (south, central and north) and combined 'control' channels across the time series from 1999 to 2006 were highly significant ($p=0.001$) for the south and central channels, and less so for the north channels ($p=0.005$).

4.5 Changing creek volume

The north creek showed the least change in volume, increasing by 42% from 14 913 m^3 to 21 181 m^3 between November 2002 and 2006. This is in comparison to the south creek channel, which increased in volume by an average of 152%, from 3291 m^3 to 8285 m^3. The central creek channel increased in volume from an average of 11388 m^3 to 48797 m^3 (328% increase) by November 2006, a rate of increase statistically different to the other creeks ($p=<0.001$). Similar to the observations of width expansion, the highest proportion of percentage change in volume of the central creek occurred within the first 300 m of channel length seaward from the breach. In total, it was estimated that 47 518 – 49 838 m^3 of material was eroded along the 3.7 km length of all three creeks, or >62000 m^3 when including breach channel eroded volumes also.

5. Discussion

5.1 Impacts of an increased tidal prism on breach channel and external creek dimensions

Significant hydromorphological change was experienced at Freiston Shore immediately after breaching. Realignment allowed the local maximum Spring tidal prism to increase by 776 398 m^3. The erosional response of the breach channels was noteworthy, with the central breach channel in particular increasing in width from 2 m to >32 m within 5.5 years. The breach channel response to realignment was also non-linear, with 66-71% of final breach width achieved in the first 2.5 months after realignment. Thus, erosional impacts were high-magnitude and short-term, with a decreasing magnitude of change over the medium term (1-4 years). A number of processes are likely to have contributed to the significant magnitude of breach channel erosion, and associated external creek expansion. We suggest three principal reasons, related to 1) Freiston Shore's large tidal prism; 2) constrained breach inlets; and 3) the establishment of water surface slopes at multiple scales.

Firstly, the macrotidal setting of The Wash means that the MSTR is large, especially relative to other realignment sites in the UK. Prior to 2002, realignment trials were smaller in size and generally located in areas of the United Kingdon with a smaller MSTR, such as the Essex estuaries (see Wolters et al. 2005. The tidal prism during the period of breaching (August 2002) was particularly high due to the coincidence with equinoctial spring tides. A larger volume of water was exchanged over a single tidal cycle, equating to higher water flow velocities. Initial erosion was caused by greater water current velocities than predicted through each of the breaches on the flood tide (recorded at the south breach by Symonds and Collins (2007a) as reaching >2.5 m s^{-1}).

The second factor that is likely to have contributed to erosion at the breach channels was the movement of a large tidal prism through a constrained inlet. While the full breaches in the sea wall were modelled sufficiently according to *Equation 1,* this optimal breach width was created in the sea wall largely above MHWS. The breach channels – with the bankfull elevation 0.15 m below MHWS, and 3-4 m below the top of the full breach in the seawall – were the hydromorphological features that most interacted with the transported tidal prism. Rapid erosion occurred after breaching as the original dimensions of the breach channels (2 m) were substantially smaller than modelled breach dimensions such as *Equation 1.* The breach channels were not large enough to accommodate the increased water volumes, including water that would otherwise have drained laterally from marsh surfaces via sheet flow but was constrained from doing so due to the remaining sea wall. This led to pooling, with the realignment site remaining submerged for up to 12 hours, after the first post-breach spring tides, and the ebb phase lasting 2.5 times longer than the flood (Symonds and Collins 2007a). Similarly, the external creeks were originally adjusted to a much smaller tidal prism being exchanged on the fronting saltmarsh only (Symonds and Collins 2007b); they could not initially cope with the increased tidal prism, so eroded rapidly to accommodate the increased water volume being drained on the ebb.

Thirdly, the initial constraining effect of the breach channels, a relatively undeveloped internal drainage network, and subsequent pooling at high tides established two ebb tide water surface slopes. The primary water surface slope was established at high tide and the start of the ebb, and operated over a large-scale, between the high elevation, hydraulically-inefficient realignment site and the lower elevation, hydraulically-efficient external intertidal zone. This promoted higher ebb velocities and ebb tide erosion at the breaches, while water was able to rapidly drain laterally on the external saltmarsh by overland flow and the rapidly enlarged external creeks. The speed and volume of overland flow on the external saltmarsh after realignment was such that ephemeral creek networks were formed to cope in areas where complex creek geomorphology encouraged overbank flow on the ebb (Symonds and Collins 2007b).

A secondary water surface slope was produced later in the ebb tide, as the tidal level lowered to approximately the surface elevation. A water surface slope established due to the hydraulic inefficiency of the internal vegetated marsh surfaces compared to drainage through the hydraulically-efficient external creek channels, as measured in mature back-barrier marsh systems in N. Norfolk, U.K. (Green et al. 1986). Peak velocities generated as a result of this water surface slope may surpass critical thresholds beyond which sediment is entrained and leads to creek bed erosion and channel incision (French and Stoddart 1992).

The two water surface slopes described generally operate across-shore, though an along-shore water surface slope may also be apparent. This third slope focused water flow towards the central breach and external creek, causing increased erosion here compared to the north and south breaches. The along-shore water surface slope was probably established due to a subtle decrease in elevation towards the central breach (Symonds and Collins 2007a, Figure 3). This observation is further supported by the pattern of saltmarsh vegetation colonization after realignment: while the turbulent, low elevation surface surrounding the central breach was covered by bare mud in 2003, and only pioneer *Salicornia europaea* in 2006, the higher elevation areas away from the central breach were rapidly colonized by *S. europaea* in 2003 and mixed mid-marsh communities by 2006 (Friess et al. 2012). Furthermore, a terrestrial vegetation gradient was also apparent prior to realignment, with site photos and airborne multispectral imagery showing dense, hydraulically-inefficient grass in the southwest and northeast corners of the realignment site, and hydraulically-efficient bare surfaces close to the central breach (Smith et al. 2007). Observations of the impact of elevation and terrestrial vegetation gradients on water flow have implications for pre-realignment site preparation. Site elevations may need to be levelled, and terrestrial vegetation consistently distributed or removed if the goal is to ensure evenly distributed water circulation within the site.

5.2 Comparison of breach dimensions with models of equilibrium inlet dimensions

After initial rapid erosion, the breach channels stabilized at a width of 16.3 m to 32.0 m, not reaching the full width of 51.1 m per breach as predicted by *Equation 1*, nor reaching the equilibrium cross-sectional areas predicted by O'Brien (1931) and others using *Equation 2*. A similar observation was made during the breaching of a realignment site in the hypertidal Bay of Fundy (Van Proosdij et al. 2010). Several reasons may account for this phenomenon. Firstly, since much of the widest part of the full breach is at an elevation above tidal influence, the breach channel is eroding out to achieve the V- or U-shaped channel form typical of channels in muddy, vegetated substrates (Lawrence et al. 2004, D'Alpaos et al. 2006). Being at the bottom of the channel, its equilibrium width is necessarily narrower than the top of the channel. Secondly, the heavy clay sea wall, and the compacted natural marsh upon which it had once sat, would have a higher shear strength than natural marsh soils, in a similar manner to the former agricultural soils within the realignment site (Watts et al. 2003) and for other flood embankments (*sensu* Boorman and Hazelden 2012). Especially when we consider cross-sectional area, *Equation 2,* designed for larger estuarine or sandy inlets may not be the most appropriate to model the erosion of consolidated clay surfaces. Thirdly, when considering cross-sectional area, technical limitations dictate that we may not be measuring the full breach geometry in 2006, due to residual water remaining in the breach, and poor water penetration by ALS (experienced also by Van Proosdij et al. (2010) when monitoring realignment channel depths).

The results of this study suggest that it is crucial to address water pooling, water surface slopes and tidal asymmetry in realignment implementation. This can be achieved by adequate breach design and promotion of site drainage. Breach channels must be of sufficient dimensions to encourage flood dominance, in which channel siltation is preferable to ebb-dominated erosion (Townend et al. 2010). Water surface slopes and negative hydromorphological impacts can be controlled by breach inlet design and increasing drainage capacity within the managed realignment site. Lawrence et al. (2004) showed how increasing channel cross-sectional area decreases flood-ebb asymmetry and slope; at Freiston Shore larger original breach channel dimensions would have decreased the potential for water storage and the establishment of water surface slopes. In tandem with increased breach dimensions, increased internal drainage capacity would also have lessened water surface slopes by quickly draining the marsh surface and removing excess water through hydraulically efficient channels. Internal creek networks may develop spontaneously in restoration sites if the site elevation is low, and the substrate erodible (Vandenbruwaene et al. 2012b). However, internal surface elevations inside Freiston Shore were similar to the surrounding marsh (Figure 1c) due to the short time period between reclamation and restoration, and the internal substrate had higher shear strength, due to prior cultivation practices (Spencer et al. 2012).

5.3 Sedimentological and ecological impacts of water surface slopes

The hydromorphological impacts observed at Freiston Shore are not divorced from other biophysical processes occurring in the local area. Erosion of breach channels and external creeks released a substantial volume of sediment into the local coastal zone (Rotman et al. 2008, Spencer et al. 2012), calculated in this study to exceed 62 000 m^3 over four years of measurements. Sediment plumes emanating from the site were observed by airborne remote sensing after breaching (Smith et al. 2007), smothering commercial oyster beds 1.5 km seaward of the realignment site (Dixon et al. 2008). In some areas close to the breaches, surface elevation gains of almost 8 mm a^{-1} were observed, in comparison to natural rates of surface elevation change of 0.26-0.28 mm a^{-1} just a few hundred metres away from the breaches (Spencer et al. 2012). These newly deposited surfaces were raised to an elevation suitable for rapid seaward saltmarsh colonization; the pioneer saltmarsh fronting Freiston Shore exhibited a significant acceleration in seaward migration rates, from 3.8 m a^{-1} in the 17 years prior to breaching to 21.3 m a^{-1} in the 4 years after breaching (Friess et al. 2012). Indeed, in the 4 years after breaching it was still unclear whether the Freiston Shore managed realignment site had reached a hydro-geomorphological equilibrium with the surrounding intertidal zone (Rotman et al. 2008). Thus, Freiston Shore provides an important example of how hydromorphological processes can drive interlinked geomorphological and ecological change in coastal wetlands.

5.4 Hydromorphological impacts at other realignment sites

While observations are scarce, realignment impacts on directly connected hydromorphological features have been hypothesized more generally (French 2006). Pethick (1993) estimated that an increase in tidal prism of $1x10^6$ m^3 caused by a hypothetical 100 ha realignment site in the Blackwater Estuary, UK, would increase the main estuary channel width by 10 m. French (2008) showed that a managed realignment scenario in the Blyth Estuary, Suffolk could potentially increase flood tide velocity by 20% (though realignment area/tidal prism increase was not given), with modelled impacts on saltmarsh extent shown to be greater than the saltmarsh loss caused by worst-case scenarios of sea-level rise over the next 50 years.

However, detailed measurements of tidal prism and creek dimensions as in this study are rare. The first realignment site in the UK, Northey Island, Essex, Southeast England, increased the Blackwater Estuary channel by as little as 0.4 m (no timescale given), (Pethick 1993), though this site was substantially smaller (0.8 ha) in area and tidal prism than Freiston Shore, so is not strictly comparable. A 21 ha estuarine realignment at Tollesbury in Essex showed little hydrological impact at the breach. The breach channel was similar in initial dimensions to the channels at Freiston Shore, but increased by only ~3 m immediately after breaching, almost an order of magnitude lower than the erosion observed at Freiston Shore over a similar time period (Friess 2010). HR Wallingford (2002) observed through bathymetric surveying some deepening of larger creeks (0.2 - 0.6 m between 1994 and 2001) adjacent to the Tollesbury realignment site, Essex. It was presumed that realignment was responsible as much of this increase occurred in the two years succeeding breaching, though (unlike in this study) no pre-breach surveying of natural channel variation was undertaken. Tollesbury did not experience large hydromorphological impacts as it is a smaller site (21ha) in a mesotidal setting (MSTR = 4.3 m), representing a smaller tidal prism increase relative to Freiston Shore. Tollesbury also had a lower internal surface elevation compared to the external marsh (~1 m lower on average, evidenced by poor vegetation recruitment), as it was reclaimed more than 150 years ago (Garbutt et al. 2006). Both factors contributed to a smaller ebb water surface slope compared to Freiston Shore.

van Proosdij et al. (2010) describe breach inlet evolution for a realignment site in the Bay of Fundy, Canada. This site was only 10 ha in size, and even though it was situated in a hypertidal system, the maximum tidal prism of 152 150 m^3 was still much smaller than the MHWS tidal prism of 776 398 m^3 calculated for Freiston Shore. While erosion of creeks inside the site were substantial, an excavated creek 2 m wide only eroded to 12 m in width after four years, and appears to be stabilizing. Erosion has been less than that of Freiston Shore in part due to a smaller tidal prism, but also because water flow was not constrained through this one breach channel; once overbank flow occurred, water could also pass through four other breaches. Thus, the breach channel erosion and the volume of eroded sediment were substantially lower than at Freiston Shore.

6. Conclusions

Saltmarsh creation by managed realignment can lead to a significant hydrodynamic perturbation to the local coastal system, with potentially substantial changes in breach channel and creek morphologies on the surrounding intertidal zone as the area adjusts to the sudden imposition of a new hydrodynamic regime. This study describes a large-scale experiment that was used to test geomorphological theories of creek development and intertidal drainage, with important implications for the design of future coastal realignment sites.

A number of factors contributed to the erosional dynamics observed at Freiston Shore. These included the large increase in tidal prism; the constrained points of water exchange; and the inadequate drainage capacity both inside and outside the realignment site. These factors led to the creation of seaward sloping ebb tide water surfaces. These water surface slopes, and the erosion associated with them, were maintained until erosion increased breach dimensions and external channel volume sufficiently for the intertidal system to adjust and reduce tidal asymmetry. Although initially rapid, such erosion may be constrained by the consolidated nature of the breach side substrate that is heavily compacted under the weight of the breached seawall (itself made of heavily consolidated clay material), such that adjustment of both breach channel width and cross-sectional area may be expected to continue at a slower rate for a considerable period of time. Importantly for site design considerations, hydromorphological change in response to realignment is highly non-linear, both spatially (constrained to attached creek networks only) and temporally (with a high proportion of erosion occurring soon after breaching), and the application of existing theoretical relationships between tidal prism and tidal channel width or cross-sectional area of tidal inlets may be flawed where drainage patterns are spatially complex and flow paths vary on the flood and ebb tides on high spring tides within sites with multiple breaches.

The magnitude of the changes at previous realignment trials in Europe and North America were substantially less than that observed at Freiston Shore, but should not give a false sense of security: experience at Freiston Shore suggests that erosional impacts may increase as larger, macrotidal and open coast sites are realigned, particularly if breach dimensions and drainage are not appropriately engineered prior to breaching. New trials (especially those in macrotidal, open coast settings) require effective understanding of how complex factors such as tidal prism, drainage and water surface slopes contribute to the creation of tidal flow regimes. The aim of such understanding must be to provide a more stable and predictable evolution of future realignment morphology and reduce their impact on linked geomorphological and ecological processes.

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