Hydrodynamics and sedimentary processes in the main drainage channel of a large open coast managed realignment site

Jonathan Dale[1*], Heidi M. Burgess[1], David J. Nash[1,2] and Andrew B. Cundy[3]

[1]School of Environment and Technology, University of Brighton, Brighton, BN2 4GJ, UK.

[2]School of Geography, Archaeology and Environmental Studies, University of the Witwatersrand, Private Bag 3, Wits 2050, South Africa.

[3]School of Ocean and Earth Science, University of Southampton, National Oceanography Centre (Southampton), Southampton, SO14 3ZH, UK.

[*]Corresponding Author:

Jonathan Dale

School of Environment and Technology, University of Brighton, Cockcroft Building,
Lewes Road, Brighton, UK, BN2 4GJ

Email: J.Dale2@brighton.ac.uk

Published in Estuarine, Coastal and Shelf Science, Volume 215, pp 100-111, 2018.

Authors' pre-print version

Keywords

Managed realignment; Hydrodynamics ; Suspended Sediment Concentration; Altimeter; Storms; United Kingdom, West Sussex, Medmerry Managed Realignment Site

Abstract

Managed Realignment (MR) is becoming increasingly popular with many coastal managers and engineers. Monitoring of MR sites has provided growing evidence that many of the saltmarshes created in these environments have lower biodiversity than naturally formed intertidal marshes, and may not fully deliver the anticipated ecosystem services such as carbon sequestration and coastal flood defence. Despite the importance of the sedimentary environment in developing an intertidal morphology suitable for plant establishment and succession, the evolution of the sediment erosion, transportation, deposition and consolidation cycle in newly breached sites is rarely examined. This study evaluates the hydrodynamics and concentration of suspended sediment exported and imported along the main drainage channel within the Medmerry Managed Realignment Site, West Sussex, UK, the largest open coast realignment in Europe (at the time of breaching). Measurements were taken over a one year period (November 2015 – October 2016) at the breach, at the landwards extremity where freshwater drains into the site, and in an excavated channel in the centre of the site. At the latter site, 1.7 cm of sediment accreted over the study period. Suspended sediment concentration (SSC) measurements indicate that, under ambient conditions, sediment is imported into and exported from the Medmerry site, although similar concentrations of sediment were recorded being internally redistributed around the site (typically 0.11 g/l measured in the breach area compared to 0.12 g/l measured in the centre of the site). Sediment is removed from the site following large (1-2 mm / hour) rainfall events, which take several tidal cycles to drain through the site. Peaks in SSC corresponding with lower intensity rainfall events, especially during periods when the intertidal mudflats have been exposed, have also been observed. Analysis of the hydrodynamics and patterns of sedimentation during and following storm occurrences (the 2015-16 Storms Eva, Imogen and Katie) however demonstrate the relative resilience (i.e. rapid recovery and minimal disturbance) of the site to extreme storm events.

1 Introduction

Intertidal saltmarsh and mudflat environments provide a range of ecosystem services including wildlife habitat, carbon sequestration and protection from coastal flooding (Barbier et al., 2011; Costanza et al., 1997; King and Lester, 1995; Moller et al., 2014). However, large areas of saltmarsh have been reclaimed and degraded for agricultural, industrial and urban development, and eroded as a result of rising sea levels and coastal squeeze (e.g. Doody, 2004). To compensate and restore these environments, a number of habitat creation and restoration schemes have been implemented. These include replanting schemes and the creation of new areas of intertidal habitat (Elliott et al., 2016) by de-embanking defences and constructing new defences inland; a process known as managed realignment (French, 2006).

Despite managed realignment (MR) becoming the most popular approach (in Europe and America) to restoring intertidal habitats and defending coastlines from the threat posed by sea level rise and a potential increase in storminess (Stocker et al., 2013), there remains a shortage of data regarding the success (or otherwise) of these schemes. The majority of studies that have been carried out have focused on vegetation colonisation (Esteves, 2013), and have indicated that MR sites have lower biodiversity, abundance of key species and ecosystem service delivery than anticipated (Garbutt and Wolters, 2008; Mazik et al., 2010; Mossman et al., 2012). In order to improve the delivery of ecosystem services it is imperative that the development, structure and functioning of MR sites is better understood. There are, however, a relative lack of data on the impact that MR has on on-site sedimentary processes, particularly the sediment Erosion, Transportation, Deposition and Consolidation (ETDC) cycle. The design of MR sites has (to date) focused on engineering initial site elevation, which controls the hydroperiod, the proportion of time inundated (Mitsch and Gosselink, 2000), and therefore colonisation by vegetation. This fails to account for the re-distribution and re-cycling of sediment following site inundation, and the influence of disturbances such as storm events on sediment supply and reworking (e.g. Cundy et al., 2007; Dzwonkowski et al., 2014;

Pethick, 1992), which may result in the development of different intertidal habitats than intended and influencing the ecosystem services provided.

A recent study by Dale et al. (2017) found different rates and rhythms of sedimentation at two heavily engineered, but spatially contrasting, sites in the Medmerry Managed Realignment Site, West Sussex, the largest open coast MR site in Europe (at the time of site breaching) over a one year study period (November 2014 – October 2015). At an exposed near-breach site, rapid accretion of sediment was observed during the flood tide, which consolidated during the ebb. Further inland, sediment was found to accrete during the flood tide and erode during the ebb, with periodic erosion and accretion matching semi-lunar and semi-diurnal tidal variability. Concentrations of suspended sediment at both of these sites were found to correlate negatively with salinity, reflecting the importance of internal sediment reworking and freshwater inputs within the site. However, this earlier study did not consider the extent of internal movement of sediment around the site in comparison to external inputs from the wider terrestrial catchment and from coastal sources.

In recent years, research into coastal sediment dynamics has evolved considerably, benefitting from advances in technology, providing an enhanced understanding of the movement of sediment within (and external inputs to and outputs from) estuarine settings (Ouillon, 2018). Studies have included *in situ* measurements, analysis of remote sensing data and numerical modelling studies into the interaction between hydrodynamics and the sedimentation processes within coastal and estuarine environments (e.g. Cundy et al., 2007; Deloffre et al., 2005; Kirwan and Murray, 2007; Nardin and Edmonds, 2014). Here, we assess the reworking processes initially identified by Dale et al. (2017), and the role of freshwater influx events, by examining high frequency *in situ* hydrodynamic and suspended sediment data (logged every 10 minutes) collected over the period November 2015 – October 2016 along the main drainage channel of the Medmerry site.

Specifically, the sources (external input vs internal redistribution), mechanisms of sediment distribution (including the role of high rainfall events) and patterns of accretion and erosion are examined in this study. These data provide a deeper understanding of the evolution of the sediment ETDC cycle and intertidal ecosystem development at the Medmerry site, not provided by Dale et al. (2017), and have implications for the effectiveness of engineering the design and construction of future MR sites to maximise the flood protection and ecosystem service benefits that they provide.

2 Study site

The Medmerry Managed Realignment Site is located on the western side of the Manhood Peninsular in West Sussex, in the Solent on the UK's south coast (Figure 1). Prior to realignment, a shingle barrier had protected reclaimed farm land. This shingle bank had previously protected a brackish lagoon which drained out through the neighbouring Pagham Harbour, on the eastern side of the Manhood Peninsular, before reclamation (Bone, 1996; Krawiec, 2017). Constant work was required during winter periods to raise, re-profile and recycle the barrier beach to maintain the necessary level of coastal flood defence. In a review of coastal flooding and erosion risk at the site, the existing defences were considered to be inefficient beyond the short-term (Environment Agency, 2007). As a result, MR was proposed, and implemented, as the most suitable long-term method of coastal flood defence. The scheme was also designed to compensate for the loss of protected intertidal saltmarsh elsewhere in the region. Over 80% of the Solent's saltmarsh is designated for nature conservation interests (Foster et al., 2014), but is currently under threat and is experiencing rapid decline caused by restricted sediment supply, pollution, rising sea levels and coastal squeeze (Baily and Pearson, 2007).

The construction of 7 km of new defences, reaching 3 km inland, began in autumn 2011. Four drainage outlets with tidal gates feed freshwater into the site during low water, draining the surrounding terrestrial catchment, with the main drainage network within the site consisting of re-profiled terrestrial drainage channels, known as rifes, and excavated channels. The site was inundated through a single breach cut in the shingle bank on 9th September 2013, forming a semi-enclosed, fetch and depth limited, semi-diurnal mesotidal system. Depth averaged current velocity, measured in the breach in September 2014, peaked at just under 1.5 m/s (Environment Agency, 2015). Following the breaching of the site, the breach has rolled back and widened. Coarse grained sediments (median grain size = 47.33 ± 0.91 µm) have been deposited within the area around the breach, probably of internal origin, and fine grained clay and silty sediments have been deposited further inland (Dale et al., 2017).

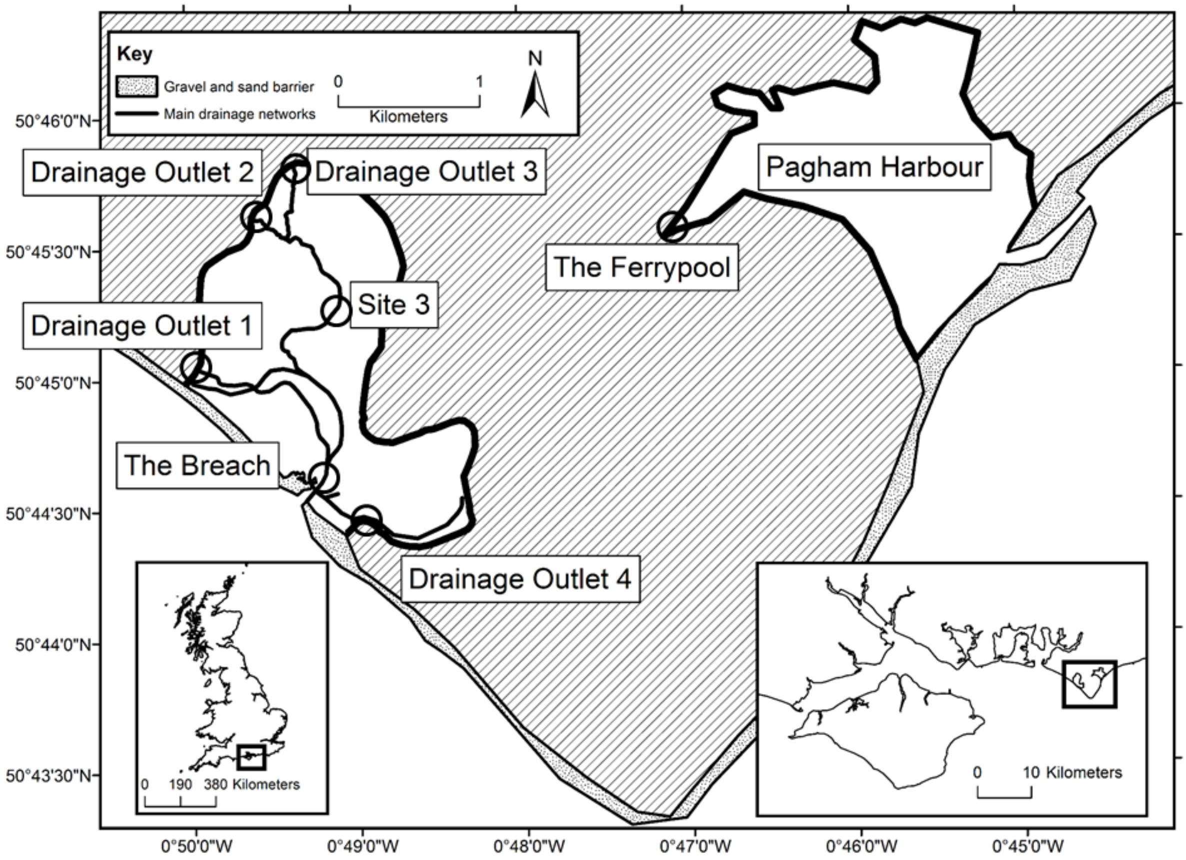


Figure 1: Location of the breach, Site 3 and Drainage Outlet 3 study sites and the Medmerry Managed Realignment Site and Pagham Harbour in the wider Solent region (insert). The Ferrypool, where prior to reclamation the Medmerry site used to drain through Pagham

Harbour is marked, as are the four Drainage Outlets where fresh water drains into the Medmerry site (see text for discussion).

3 Materials and methods

In order to assess sediment movement in the Medmerry site, high frequency measurements of the near-bed hydrodynamics were taken every 10 minutes over a one year period from three sites along Easton Rife, the main drainage channel within the MR site (see Figure 1 for locations). Measurements were taken from 1st November 2015 to 31st October 2016 (i.e. during the third year of site inundation) at the centre of the site (Site 3 of Burgess et al. (2016) and Dale et al. (2017)), and at two sites which had previously not been investigated; one at the breach, approximately 50 m landward of the shingle bank, and one at the landward extremity of the site near (*c.* 130 m downstream of) the culvert and tidal gates in Drainage Outlet 3 (DO3).

3.1 Hydrodynamic analysis

Hydrodynamic variations at all three sites were measured by YSI EXO2 Sondes fitted with conductivity, temperature, depth (CTD) and turbidity probes, deployed near the bed (i.e. 2 to 3 cm off the bed) in scaffolding rigs (see supplementary material) which sampled every 10 minutes continuously over the one year study period. Probes were deployed at -0.68 mOD (Ordnance Datum Newlyn) at the breach, 0.46 mOD at Site 3 and 0.41 mOD at DO3. Salinity was measured using the Practical Salinity Scale. Turbidity probes were calibrated for suspended sediment concentration (SSC) in the laboratory using re-suspended sediment samples and filtered water samples taken *in situ*, and were cleaned every 20 minutes during deployment via a central wiper fitted to the EXO2 Sondes. All probes were protected against bio-fouling by copper tape attached prior to deployment.

Local rainfall and freshwater depth measurements recorded during the 1 year study period (both provided by the Environment Agency, UK, see Figure 1 for locations) were used to assess any controls exerted by local weather conditions on trends and patterns observed in the hydrodynamic data. Rainfall was recorded at the Ferrypool where prior to reclamation the Medmerry site used to drain through Pagham Harbour (Bone, 1996), and freshwater depths were recorded on the landwards side of Drainage Outlet 4.

3.2 Sedimentation rhythms and mechanisms

High frequency bed elevation measurements were taken at Site 3, over the same one year period, in a channel cut and excavated during site construction. This channel leads up to a large borrow pit, an area where material was extracted to create the new coastal flood defences inland, lowering the elevation to encourage the development of a range of intertidal habitat. An NKE ALTUS altimeter system was used to measure patterns and rates of sediment accumulation and erosion. The altimeter consists of a 2 MHz acoustic transducer, supported on a tripod above the sediment surface, which measures the time required for an acoustic signal to return from the sediment surface to the transducer (Jestin et al., 1998). The ALTUS systems were deployed at the same location as in Dale et al. (2017), and bed elevations (± 2 mm) were logged every 10 minutes. The initial bed elevation was +0.63 mOD.

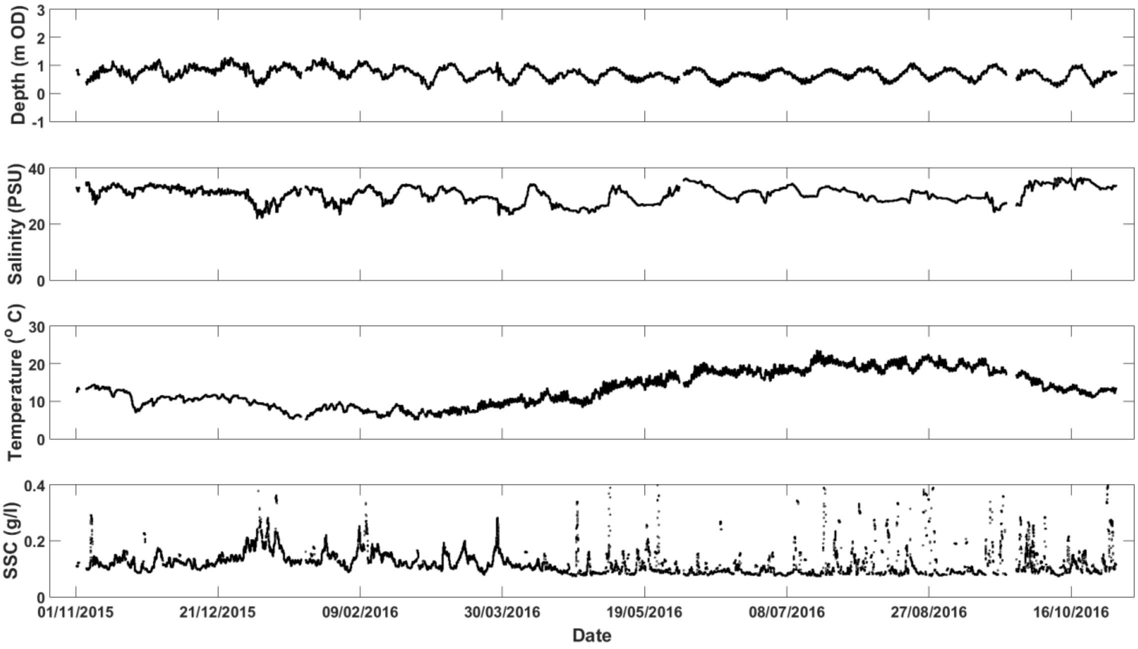
4 Results

4.1 Variations in hydrodynamics and sedimentation

To evaluate sediment sources and mechanisms of sediment distribution CTD and SSC data were collected, and are presented for the one year study period for breach

(Figure 2a), Site 3 (Figure 2b) and DO3 (Figure 2c) with a 12 hour (tidally average) running mean applied to smooth high-frequency changes caused by tidal variability. Missing data are due to suspect data (e.g. weed wrapped around sensors etc.) or equipment failure. The maximum recorded water depth at the breach was 2.75 mOD in December 2015, whereas the lowest water depth, -0.61 mOD, occurred in October 2016. The highest and lowest salinities measured were 37.7 and 0.48 respectively, both occurring in October 2016, although salinity values rarely fell below 20. Average high water salinity was 32.27 ± 3.33. The SSC varied throughout the study period although peaks were observed periodically, particularly in January to March 2016. The average SSC during flood and ebb tidal phases were 0.11 ± 0.06 g/l.

(a)



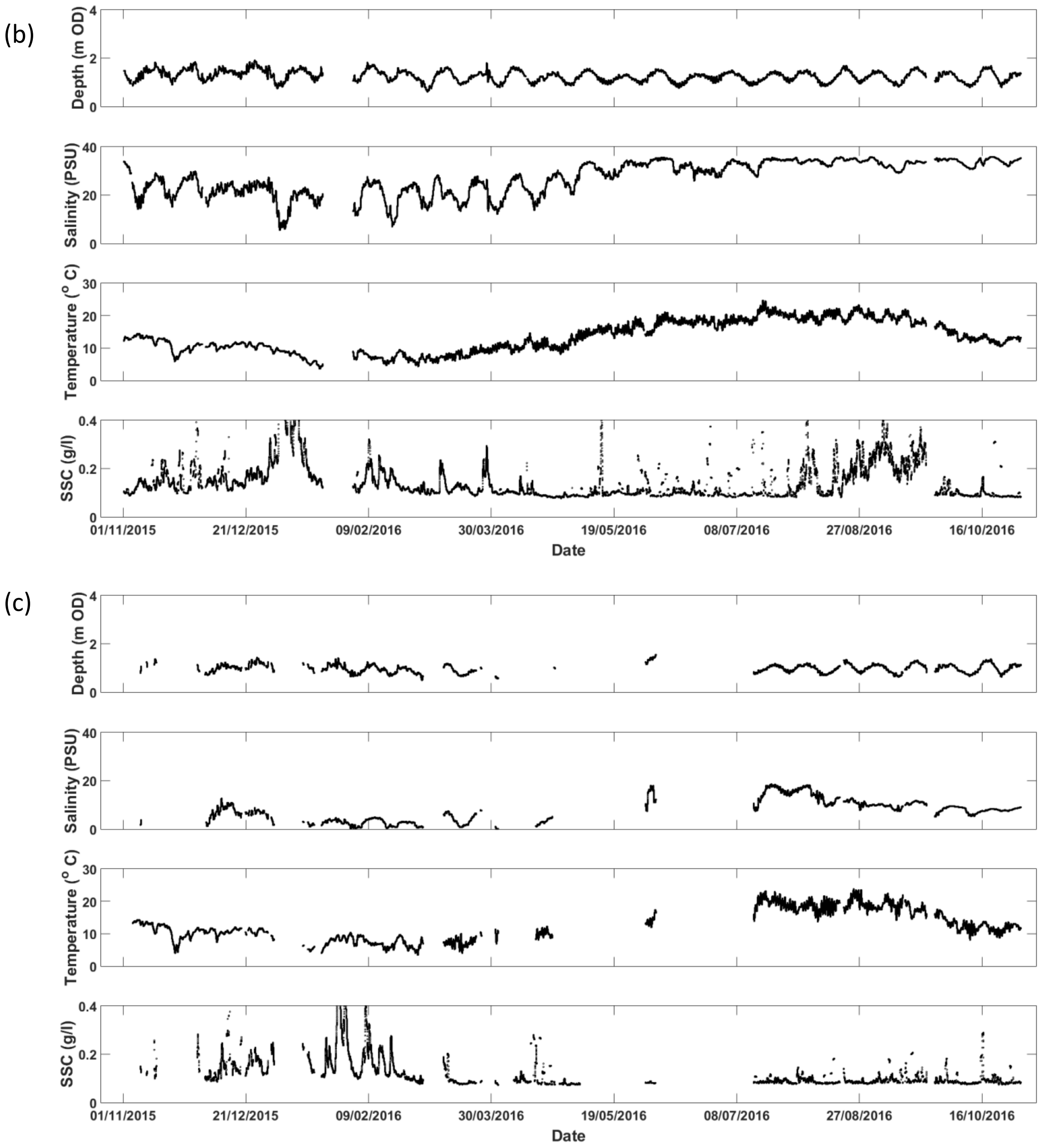


Figure 2: Tidally averaged hydrodynamic data, presented with a 12 hour running mean, for (a) the breach (b) Site 3 and (c) Drainage Outlet 3 (DO3). Raw non-averaged time series data are shown in the supplementary material.

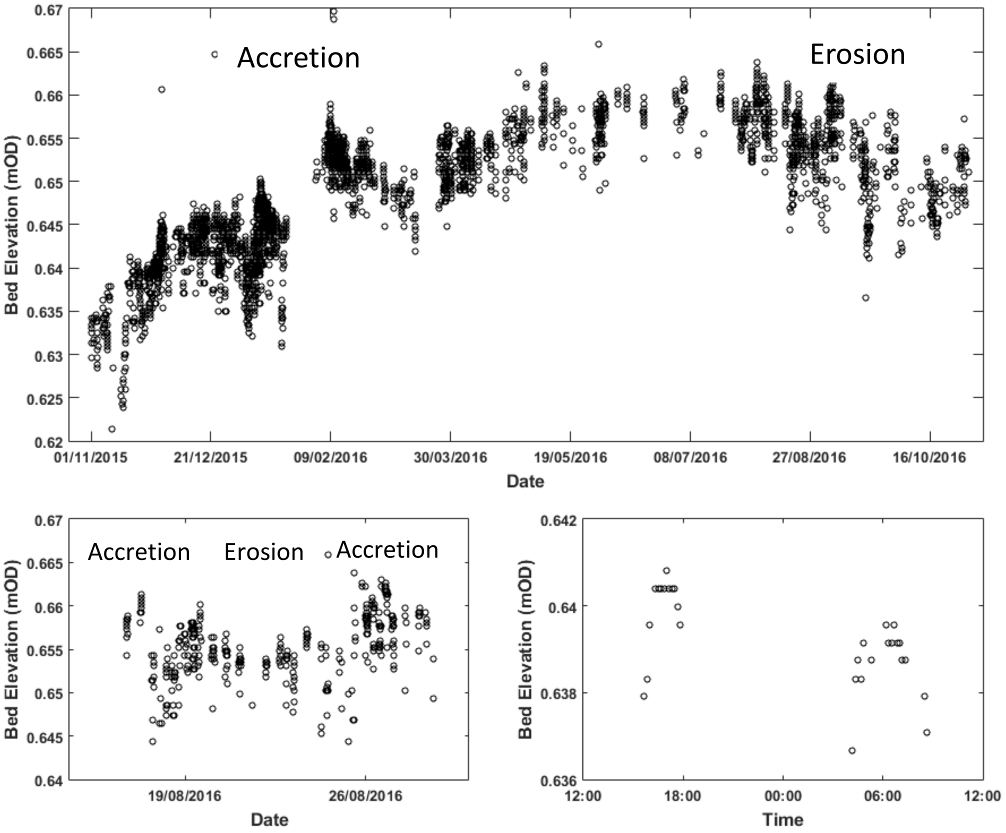


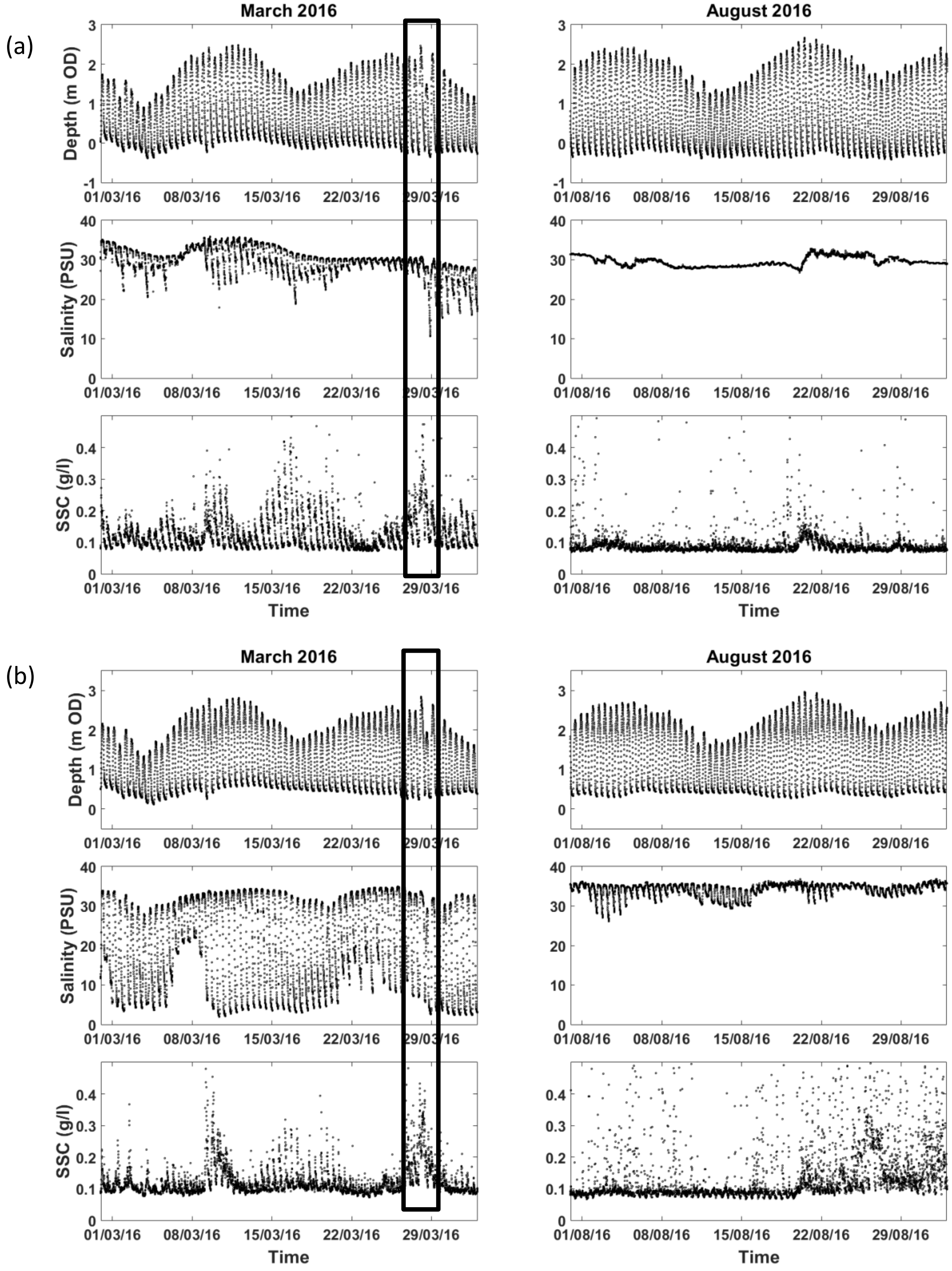
Figure 3: Bed elevation and rhythms of accretion and erosion over 12 month period (November 2015 – December 2016), a month period (August 3016, lower left) and 24 hour period (lower right) at Site 3.

Inland, at Site 3, the maximum water depth recorded was 3.09 mOD in December 2015. High water at Site 3 occurs approximately an hour after high water at the breach. The lowest recorded depth was 0.60 mOD in March 2016. A maximum salinity of 37.83 was recorded in May 2016 and a minimum of 0.88 in January 2016. The average high water salinity was 34.16 ± 3.68. More variability was measured in the SSC during the winter, and during August and September. Concentrations of suspended sediment tended to be slightly higher at Site 3 in comparison to the breach with 0.12 ± 0.08 g/l measured during flood and ebb tidal phases, although similar temporal trends were observed between the breach and Site 3, particularly during the winter months.

In the excavated entrance of the borrow pit at Site 3, 1.7 cm of net accretion was measured (Figure 3). While rhythmic semi-lunar and semi-diurnal sedimentation patterns were apparent in the data, these were overlain on a dominant seasonal trend, with accretion during the winter and erosion during the summer. This pattern was periodically interrupted by larger erosion and accretion events, such as storm events (discussed below), which appeared to be driven by additional variability separate from the seasonal, semi-lunar and semi-diurnal factors.

At the landward extremity of the site, DO3, a maximum measured water depth of 2.58 mOD occurred in June 2016. High water at this site occurs approximately 20 minutes after high water at Site 3, and 50 minutes after high water at the breach. Tidal amplitude was lower by almost a metre at DO3, compared to the breach and Site 3, and during some low tides the channel drained below a measurable water depth (< 1 cm). The salinity at DO3 remained relatively low, but more variable during the study period (average high water salinity of 10.76 ± 7.20), although a maximum salinity of 32.9 was measured in June 2016. An average SSC of 0.12 ± 0.11 g/l was measured during both the flood and ebb tides. The SSC demonstrated a high degree of variability until March 2016, after which the concentration of suspended sediment remained relatively stable.

Monthly winter and summer comparisons between depth, salinity and SSC at each site for March (winter) and August (summer) 2016, representative of ambient conditions, are presented in Figure 4. Examples of single spring and neap tidal events during both of these months are presented in Figure 5. During March clear differences in salinity between high and low water were observed at the breach (Figure 4a) and Site 3 (Figure 4b), although the variability was greater at Site 3 where a difference of 14.98 was measured between average high and low water salinity. This salinity difference was also seen during March on a semi-diurnal scale at Site 3, although salinity values at the breach demonstrated little semi-diurnal variability during spring tides but fluctuated during neap tides (Figure 5). At DO3 semi-diurnal changes in salinity varied in March according to the semi-lunar tidal cycle, with a greater variability in salinity occurring during spring tides as a result of larger inputs of saline water to the site. During neap tides, salinity values remained low with less variability due to reduced saline water incursion.



(c)

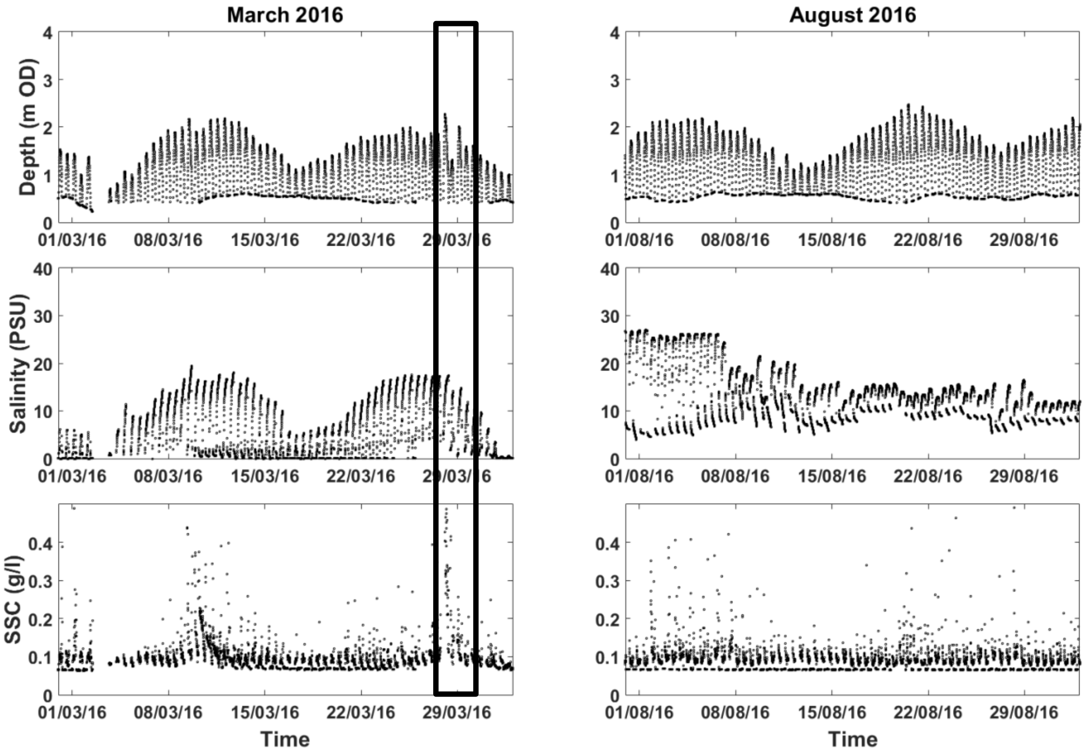


Figure 4: Comparison of depth, salinity and suspended sediment concentration (SSC) for March 2016 and August 2016 for (a) the breach, (b) Site 3 and (c) Drainage Outlet 3.

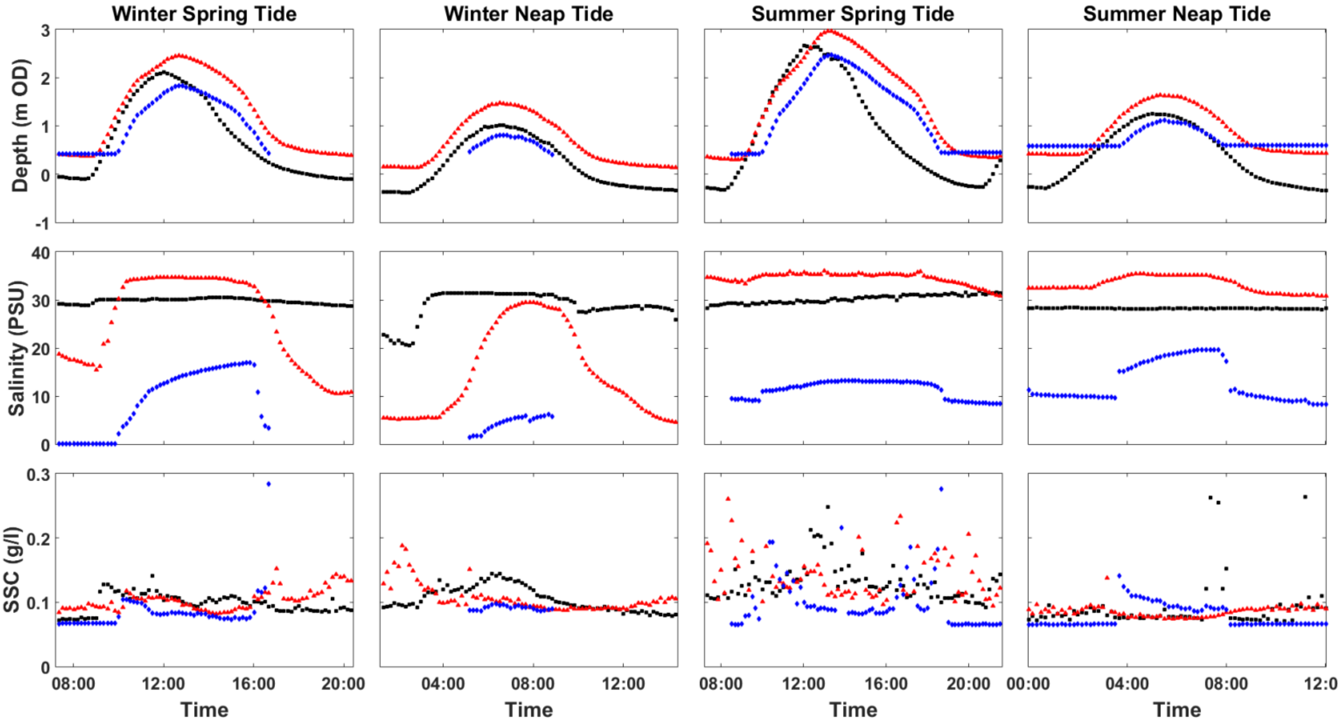


Figure 5: Comparison of depth, salinity and suspended sediment concentration (SSC) over a tidal cycle for the breach (black squares), Site 3 (red triangles) and Drainage Outlet 3 (blue diamonds) for a winter spring tide (24/3/2016), a winter neap tide (2/3/2016), a summer spring tide (20/8/2016) and a summer neap tide (12/8/2016).

During March, variability in SSC was observed at all three sites (Figure 4a). Similar variability in the concentration of suspended sediment was observed during spring tides, whereas during neap tides DO3 did not share the same variability. For example, during the neap tides in the middle of March, increased concentrations of suspended sediment were recorded at the breach and at Site 3, but not at DO3. The increased levels of suspended sediment, matched by a high freshwater discharge event (indicated by lower salinity values during low water) at the breach, seen towards the end of the month are reflective of a storm event (Storm Katie) which occurred at this time (see section 4.3). At the breach, a sharp peak in SSC occurred during the flood tide (Figure 5), although average SSCs across the flood and ebb tide (described above) suggest near-equal concentrations of suspended sediment were imported to and exported from the site. In contrast, higher SSCs were measured at Site 3 and DO3. At these sites, SSC peaks occurred during the flood phases, and larger peaks were measured during the ebb tide. A peak in SSC was also detected at low water at Site 3.

During August (Figure 4b), salinity values remained relatively constant (30 to 32) at the breach. Measurements at Site 3 indicated a small amount of tidal variability in salinity, with greater variability occurring at DO3 during the spring tides at the start of August. However, this variability is not repeated during the spring tides later in the month. This is demonstrated further in analysis of individual tides (Figure 5). Fluctuations in the levels of suspended sediment were more scattered and showed less consistency with tidal cyclicity. During spring tides, peaks during both the flood and ebb tidal phases can still be identified, whereas during neap tides these peaks are less distinct at DO3 with SSC decreasing throughout the tidal cycle (Figure 5).

4.2 High Suspended Sediment Concentration Events

Periods when high SSCs were measured at the breach and at DO3 were analysed to assess the upstream and downstream suspended sediment movement and sediment sources (i.e. terrestrial vs. marine) to the borrow pit entrance at Site 3. Two types of high SSC events are presented in Figure 6: (1) high SSCs repeated for a number of tides (Figure 6, left hand graphs); and (2) single tides with high SSCs (Figure 6, right hand graphs). Although the SSC was recognised to generally peak during flood tides at the breach, during multiple tides with high levels of suspended sediment the maximum SSC tended to occur during the ebb tide and low water (Figure 6, left graphs). During these events, relatively high SSCs (> 0.5 g/l) were measured during the ebb tides and during low water at Site 3. These high concentrations of suspended sediment fell rapidly by around 0.35 g/l during the start of the flood tide. At DO3, peaks in SSC were measured during the early flood and late ebb tides, decreasing during the period of tidal inundation.

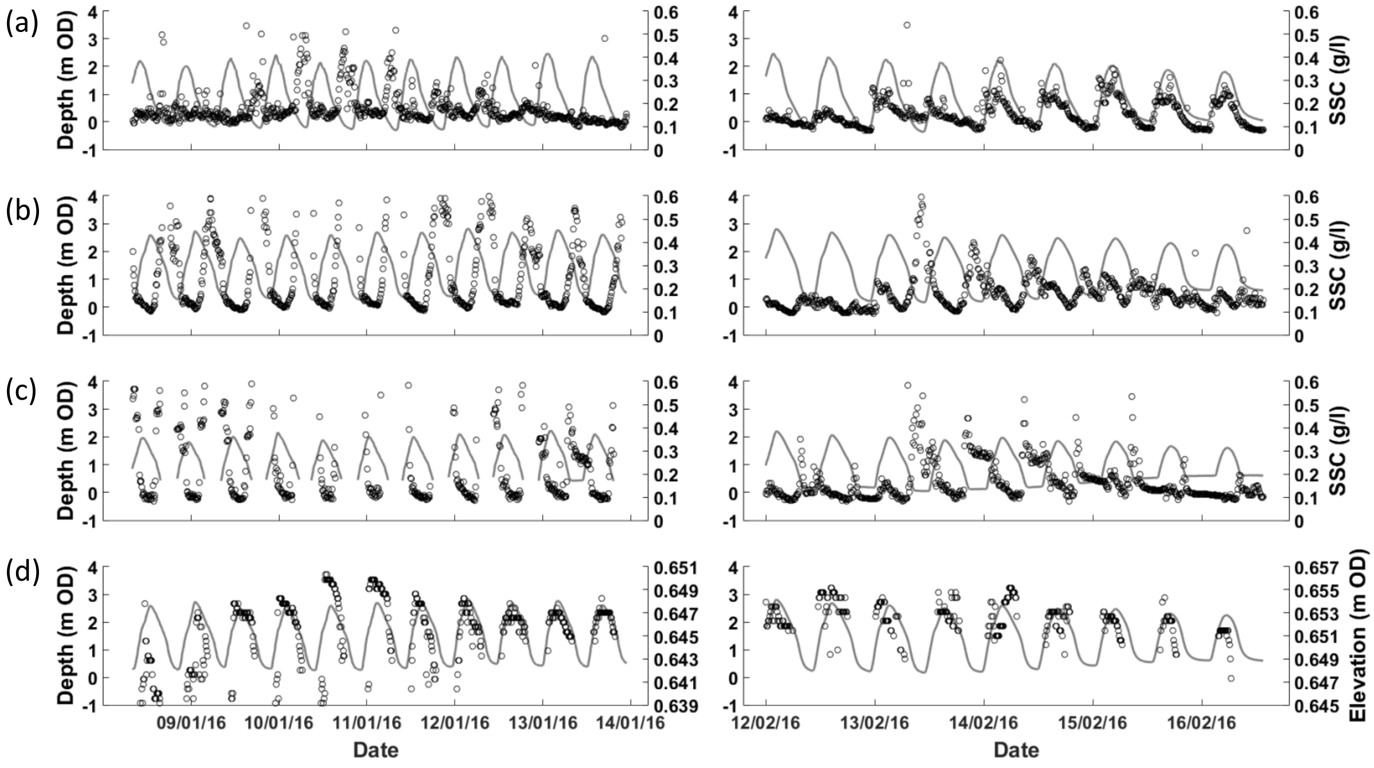


Figure 6: Depth against suspended sediment concentration (SSC) at (a) the breach, (b) Site 3 and (c) Drainage Outlet 3, and (d) depth against bed elevation at Site 3 for multiple tides (left, 10th – 12th January 2016) and a single tide (right, 13th – 14th February 2016) with high SSC.

Throughout the example illustrated in Figure 6 (left graphs), bed elevation measurements indicated that around 5 mm of sediment were accreted following inundation on the flood tide. Bed elevation peaked at high water and decreased sharply during the ebb tide. By the start of the succeeding flood tide, bed elevation had fallen to a similar level to that of the previous tide. When levels of SSC within the breach decreased, the sedimentation rhythms returned to a typical (more symmetrical) pattern of accretion during the flood tide and erosion during the ebb (c.f. Dale et al., 2017).

During the single high SSC event shown in Figure 6 (right graphs), levels of suspended sediment at DO3 peaked at low water, with smaller increases occurring during the following four low waters. SSCs at Site 3 also peaked at low water, and decreased by almost 0.5 g/l until halfway through the following ebb tide. At the breach, SSCs continued to display a trend of importing sediment during the flood. Bed elevation at Site 3 decreased during the tides directly preceding and succeeding the peak in SSC, but from approximately the same starting bed elevation each time, suggesting sediment was accreted whilst the sensor (but not the bed) was exposed. Sediment was then accreted during the following tide, before returning to a pattern of rhythmic depositions and erosion.

4.3 Response to storm events

In addition to being a habitat restoration and compensation scheme, the Medmerry site was constructed to improve coastal flood defence on the Manhood Peninsular. A series of storms impacted the UK during the winter of 2015-16, the first year they were assigned names by the UK Met Office. The sedimentary response to three of the storms that had the greatest effect on the South Coast (Storms Eva, Imogen and Katie - see Table 1), are assessed here in terms of variations in SSC (Figure 7) and bed elevation (Figure 7).

Table 1: Three of the 2015-16 winter storms selected to assess the response of the Medmerry Managed Realignment Site to storm events. Data were provided by the Environment Agency, UK (contains Environment Agency information © Environment Agency and database right) from the Ferrypool, Pagham Harbour (see Figure 1 for location).

Storm Name	**Date**	**Duration**	**Total Precipitation (mm)**	**Maximum Precipitation (mm/hr)**	**Maximum Wind Speed (m/s)**
Eva	24th December 2015	15 hours	4.27	1.74	11
Imogen	7th -8th February 2016	43 hours	5.6	0.78	18.75
Katie	27th – 28th March 2016	42 hours	12.2	2.14	24.15

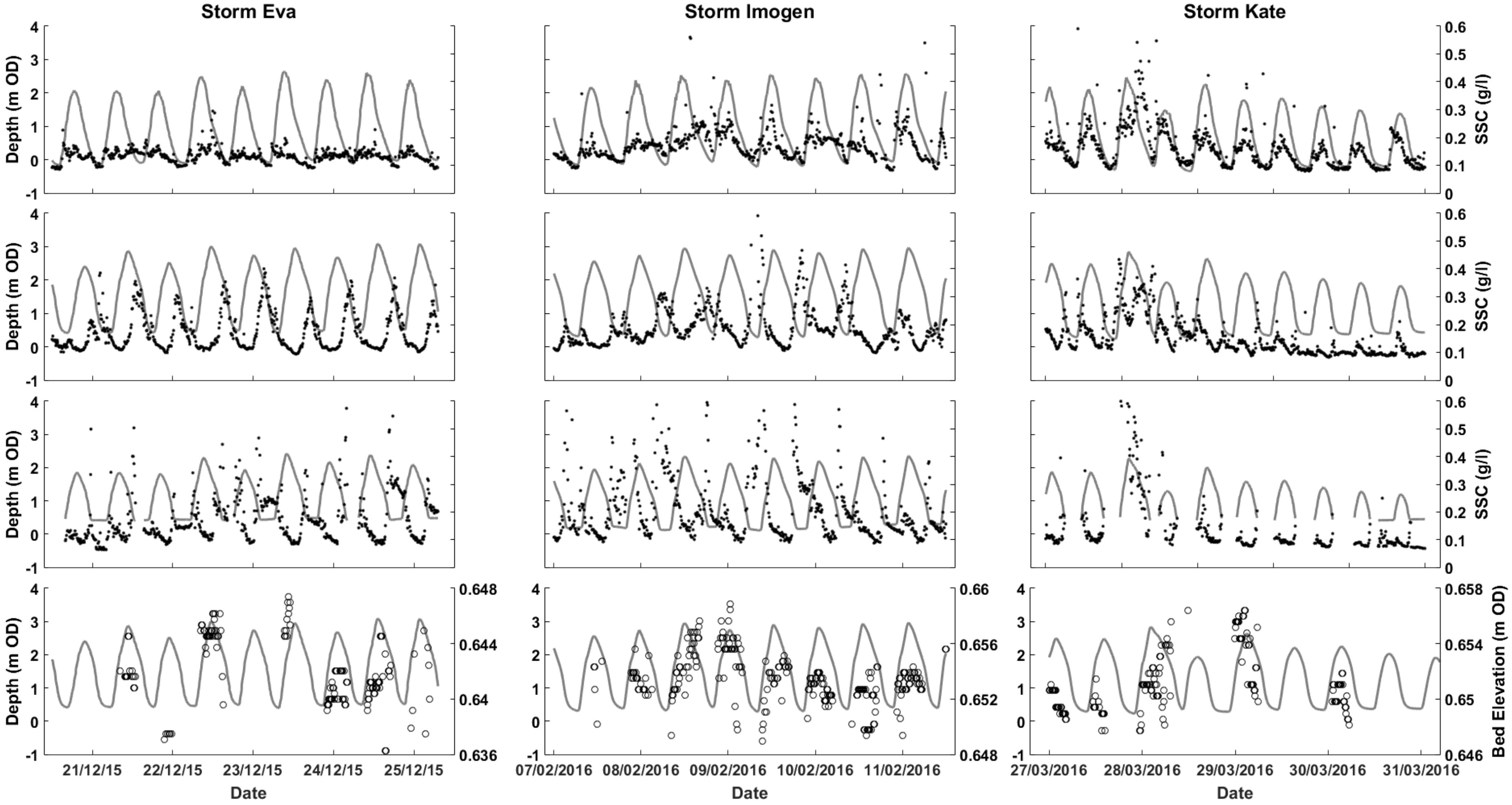


Figure 7: Depth against suspended sediment concentration (SSC) for the breach (top row), Site 3 (second row) and Drainage Outlet 3 (third row) and changes in bed elevation at Site 3 (bottom row) during Storms Eva (23rd – 24th December, left), Imogen (7th – 8th February, middle) and Katie (27th-28th March, right).

During Storm Eva, the SSC at the breach increased by 0.19 g/l during the flood tide and continued to increase during the start of the ebb, decreasing during the latter part of the outgoing tide. At Site 3, the ebbing tide had almost 0.1 g/l more suspended sediment than had previously been the case before the storm. Afterwards, the SSC decreased at Site 3 to a similar concentration as before the storm. SSCs at DO3 peaked on both the flood and ebb tides, decreasing during both high and low waters, with the exception of the low water after the storm when SSCs remained high. Bed elevation measurements were intermittent during this period, but suggest that sediment accreted during the storm and the tide the following day, before eroding (Figure 7).

Storm Imogen had a similar effect as Storm Eva on SSCs at the breach, although concentrations of sediment were greater and remained higher after the storm. SSC peaked at 0.6 g/l during low water at Site 3, decreasing during the flood and increasing again during the ebb tide. At DO3, SSCs were more variable than during Storm Eva, demonstrating a pattern of increasing during the ebb and decreasing during the flood. Bed elevation at Site 3 increased during the storm and remained relatively constant during the following tidal cycle. However, at the start of the next tide, bed elevation was 2 mm lower than before the storm and increased again during the tidal cycle. Sedimentation then reversed back to the rhythmic pattern of accretion and erosion observed for the majority of the monitoring period.

The SSC also increased at the breach, to 0.54 g/l, and at Site 3, to 0.41 g/l, during Storm Katie, peaking during the ebbing tide and then rapidly decreasing. At DO3, SSCs were high (0.6 g/l), decreasing during the ebb tide and remaining low during the following tides. Bed elevation at Site 3 increased during the storm and, although no data were collected during the subsequent tide (presumed to be due to the smaller amplitude of this tide and therefore not sufficiently inundating the sensor), bed elevation decreased during the tide the following day.

5 Discussion

5.1 Source of suspended sediment

To assess the sources of sediment, mechanisms of sediment distribution and patterns of accretion and erosion, and the influence of storm events within the Medmerry Managed Realignment Site, hydrodynamic measurements were taken from November 2015 to October 2016 from three sites (the breach, Site 3 and DO3) along the main drainage channel, Easton Rife. Bed elevation measurements were also taken from the middle site (Site 3). Observations from other locations have suggested that MR sites are importers of, and sinks for, sediment from external sources. For example, Rotman et al. (2008) calculated that 54% of the material accreting within the Freiston Shore Managed Realignment Site, Lincolnshire, UK, had originated from eroding saltmarshes outside of the site. Dale et al. (2017) suggested, however, that due to Medmerry being located on the open coast away from any pre-existing external marshes, and also lacking in significant fluvial sources, the majority of sediment being transported around the site originated from internal sources.

Measurements of the SSC taken from within the breach reveal that, under typical conditions, the Medmerry site both imports and exports sediment. The SSC peaked during the flooding tide and decreased during high water and the ebb tide (Figure 5). The source of this imported sediment in the breach area remains unknown, but may originate from former intertidal early Holocene saltmarsh deposits exposed within the breach itself, which have been recognised as the source of increased concentrations suspended sediment offshore reported by local fishermen (Colin Scott, ABPmer, *personal communication*, 2017), or from the eroding Mixon barrier islands offshore.

Peaks in SSC were measured during both the flood and ebb tidal phases at Sites 3 and DO3, indicating the resuspension, redistribution and recycling of sediment around the site during both stages of the tidal cycle. Similar observations were made by Mitchell et al. (2006) at neighbouring Pagham Harbour, which naturally breached during a storm in 1910 AD, where sediment is transported from seawards locations or is resuspended locally (or both), and builds up at the landward extremities of this site.

5.2 Mechanisms of sediment distribution

Higher levels of suspended sediment at the Medmerry site were found to relate to lower salinity values by Dale et al. (2017). In this paper, however, bed elevation measurements have recorded changes beyond the rhythmic patterns of accretion and erosion identified in this previous study. Analysis of consecutive tides with elevated concentrations of suspended sediment presented here indicate that during these events material is flushed completely from the system and discharged to the open coast during low water. During these events, SSCs increased during the flood and ebb tides at both internal sites, but decreased over high water. A sharp increase in bed elevation of around 5 mm was observed at Site 3 during the early flood tide, followed by a rapid decrease during the ebb.

An explanation for the peaks in SSC observed in January 2016, shown in Figure 6 (left side graphs), is provided local rainfall and freshwater depth measurements (both provided by the Environment Agency, UK, see Figure 1 for locations). Rainfall measurements indicate that the increased SSCs were recorded two days after 8.6 mm of rain fell within a 7 hour period (Figure 8a). Freshwater input measurements increased for two days following this intensive rainfall event and coincided with the period of consecutive elevated high SSC (Figure 8a). Freshwater depth decreased on the ebb tide and during low water (whilst the tidal gates were open), but built back up again during the flood tide and high water (whilst the tidal gates were closed, preventing freshwater input). Dale et al. (2017) proposed that the relationship between SSC and salinity resulted from terrestrial input external to the site, as has been suggested elsewhere (e.g. Fettweis et al., 1998). This suggestion is supported here (at least for sites more peripheral to the breach area), given the multiple tides with elevated SSCs which match the time taken for freshwater depth on the terrestrial side of the site to decrease. A similar trend has been observed in Pagham Harbour (*authors' unpublished data*) which also has similar tidal gates located in a sea wall constructed in the 18th century (Mitchell et al., 2008).

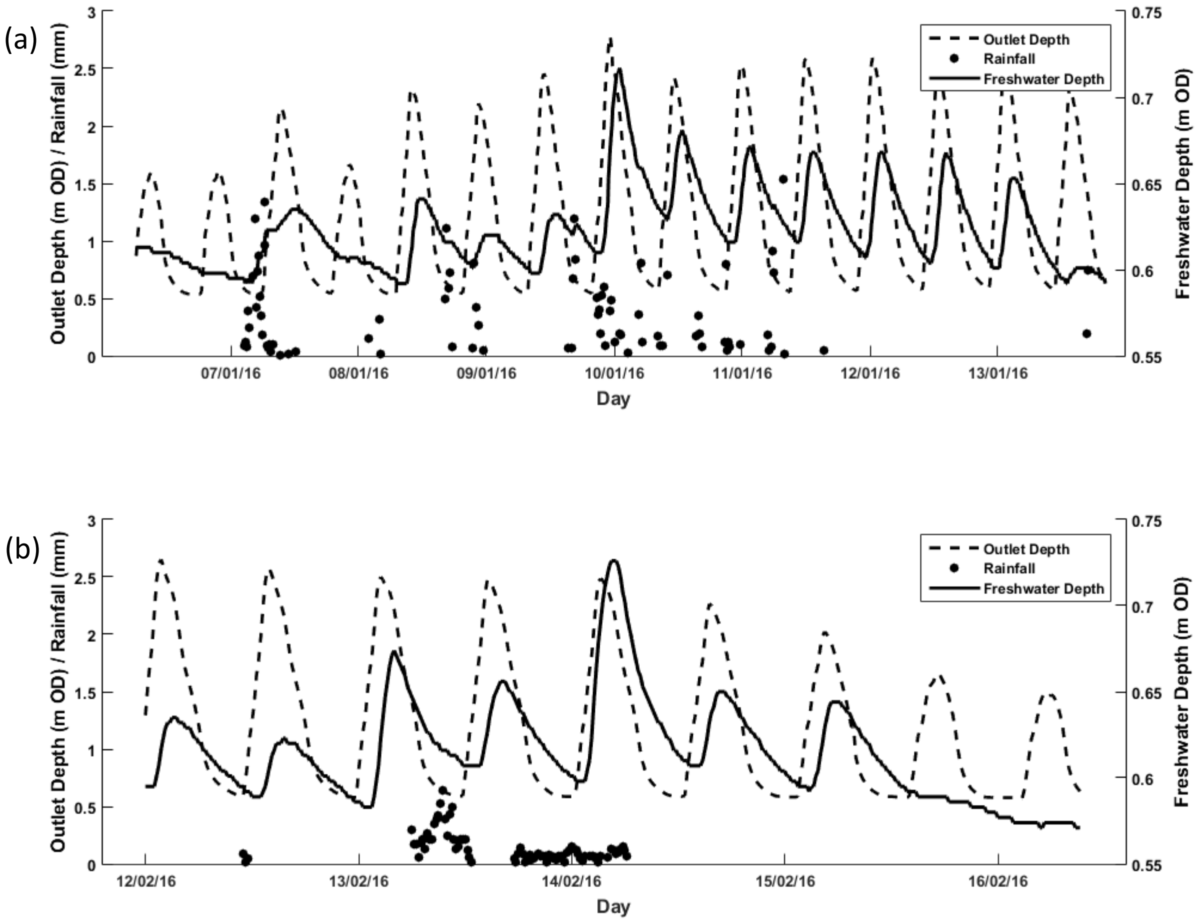


Figure 8: Water depth on the outlet (seaward, dashed line) and inlet (terrestrial, solid line) sides of Drainage Outlet 4 at the Medmerry Managed Realignment Site and rainfall (mm per hour; dots) from the Ferrypool (see Figure 1 for location) for (a) the period of multiple tides with high suspended sediment concentration and (b) single tide with high suspended sediment concentration exemplified in Figure 6. Data provided by the Environment Agency, UK (contains Environment Agency information © Environment Agency and database right).

In addition to multiple tides with high SSC, single high SSC events have also been observed inland, at Site 3 and DO3. During these events, SSCs at the breach continued to peak on the flood tide and decrease during the ebb. Individual high suspended sediment load events occurred during low water (Figure 6, right side graphs) but, when compared to changes in the freshwater input to the site (Figure 8), increased freshwater input occurred during the subsequent low water. An alternative explanation could be internal erosion caused by run off during rainfall events. Rainfall data from the Ferrypool site suggests that 7.11 mm of rainfall occurred over 7 hours during the period of exposure (Figure 8b) for the single high SSC event exemplified in Figure 6 from February 2016. Visual observations have been made of pluvial water draining not only over the terrestrial land within the Medmerry site but also over the forming saltmarsh and mudflat exposed at low water, resulting in an increase in suspended sediment. However, the impact of rainfall on the erosion of cohesive sediments requires much further investigation (e.g. Tolhurst et al., 2006), particularly in newly inundated MR sites undergoing the transition from terrestrial soil to intertidal sediment, as it may well have a significant impact on the sediment ETDC cycle within these environments.

5.3 Influence of storm events on site sedimentary processes

MR schemes are implemented to restore and compensate for habitat loss and degradation, and also to improve coastal flood defence. Analysis of three storm events during the 2015-16 winter revealed that, despite variations during each storm, suspended sediment and bed elevation measurements indicated that the Medmerry sedimentary system recovered relatively quickly (within ~four tidal cycles). Mitchell et al. (2006) suggested that the main input of coastal sediment to the adjacent Pagham Harbour occurred during storm events. However, SSC measurements at Medmerry suggest that sediment is exported from the system during storm events.

Previous studies (e.g. Moller, 2006; Moller et al., 2014) have focused on the effect that saltmarsh vegetation has as a form of natural coastal flood defence during storm events. However, little attention has been given to the influence (and response) of intertidal fine grained sediments during storm events. This study provides an insight into the sedimentary processes during storm events, through analysis of changes in bed elevation and concentration of suspended sediment. Further consideration is required of site design, including the use of areas of lower elevation and drainage networks, to maximise the defence provided by these environments. These findings need to be contextualised with baseline measurements of the sedimentary processes during the evolution of these sites from a terrestrial to intertidal system. Further long-term data of multiple storm events will allow for consideration of the impact storms have on the cycling of sediment, changes in bed elevation, and the wider sustainability of creating new areas of intertidal mudflat as a method of coastal flood defence. This is of particular importance in response to projected increases in the magnitude and frequency of storm events resulting from climate change (Stocker et al., 2013).

6 Conclusion

This paper aimed to evaluate the sources of sediment, mechanisms of sediment distribution and influence of storm events in a large open coast MR site. Results demonstrate that, under ambient conditions, suspended sediment is cycled around, and largely remains within, the Medmerry site. Measurements of the SSC indicate that approximately equal concentrations of suspended sediment are imported to the site from, and exported to, the wider coastal environment. The impact of this sediment movement on the wider coastal system around the Manhood Peninsula, particularly to the west in the direction of littoral drift, remains unclear and requires further investigation. Increases in the SSC during the ebb tide at the breach, providing evidence of gross sediment export from the site, were only measured during repeated periods of high SSC. Dale et al. (2017) found that high levels of suspended sediment matched periods of lower salinity, suggesting freshwater input and runoff as possible driving forces. This study provides an improved understanding of the sources, both internally and externally, and the movement of suspended sediment at the Medmerry site. Measurements of the SSC in comparison to freshwater input and local rainfall measurements indicate that following larger rainfall events (1-2 mm / hour), which take several (2-3) tidal cycles to drain through the site, sediment is exported from the site. In addition, peaks in SSC have been measured corresponding with lower intensity rainfall events, especially during periods when the intertidal mudflats have been exposed.

MR sites such as Medmerry are designed to restore and compensate for intertidal habitat loss and to improve coastal flood defence. Analysis of the hydrodynamics and patterns of sedimentation during three storm events indicate that, during these events, bed elevation in the excavated channel at Site 3 increased and higher SSCs were measured across the MR site. Despite these variations, bed elevation decreased to a level similar to the elevation before the storm. Further consideration of the response and resilience of MR sites to storm events is required, in addition to analysis of the hydrodynamics and the wider functioning of the ETDC cycle as a result of different rates and quantities of freshwater and marine inputs. This includes analysis of the threshold required for the erosion of exposed intertidal sediment, which requires analysis of multiple storm and intense rainfall events, consideration of tidal variability (extent of exposure) and the characteristics of the rainfall event itself. It remains uncertain whether suspended sediment has been eroded from the wider catchment and transported through the site, or whether it is derived from an internal source within the Medmerry site. Further research is required to investigate these sources, here and at similar sites, which can then be used to advance the quality and reliability of numerical models and the design of MR sites, maximising the level of coastal flood defence and wider ecosystem services they provide.

Acknowledgements

The authors would like to thank; Magda Grove and Matt Leake (both University of Brighton) for their assistance with fieldwork; Dave Harker (University of Brighton) for his technical support; Peter Hughes (RSPB); and Callum Firth for his guidance during JD's studentship. Financial support was provided by the Environment Agency (UK) for JD's studentship. Insightful and constructive reviews were provided by four anonymous reviewers.

References

Baily, B., Pearson, A.W., 2007. Change detection mapping and analysis of salt marsh areas of central southern England from Hurst Castle Spit to Pagham Harbour. J Coastal Res 23, 1549-+.

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. Ecological Monographs 81, 169-193.

Bone, A.E., 1996. The shaping of the Selsey coastline: a review of the geomorphology, archaeology and history. Tertiary Research 16, 5-14.

Burgess, H., Kilkie, P., Callaway, T., 2016. Understanding the Physical Processes Occurring Within a New Coastal Managed Realignment Site, Medmerry, Sussex, UK, Coastal Management, pp. 263-272.

Costanza, R., d'Arge, R., deGroot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253-260.

Cundy, A.B., Lafite, R., Taylor, J.A., Hopkinson, L., Deloffre, J., Charman, R., Gilpin, M., Spencer, K.L., Carey, P.J., Heppell, C.M., Ouddane, B., De Wever, S., Tuckett, A., 2007. Sediment transfer and accumulation in two contrasting salt marsh/mudflat systems: the Seine estuary (France) and the Medway estuary (UK). Hydrobiologia 588, 125-134.

Dale, J., Burgess, H.M., Cundy, A.B., 2017. Sedimentation rhythms and hydrodynamics in two engineered environments in an open coast managed realignment site. Mar. Geol 383, 120-131.

Deloffre, J., Lafite, R., Lesueur, P., Lesourd, S., Verney, R., Guézennec, L., 2005. Sedimentary processes on an intertidal mudflat in the upper macrotidal Seine estuary, France. Estuar. Coast. Shelf Sci 64, 710-720.

Doody, J.P., 2004. 'Coastal squeeze' - an historical perspective. Journal of Coastal Conservation 10, 129-138.

Dzwonkowski, B., Wong, K.C., Ullman, W.J., 2014. Water Level and Velocity Characteristics of a Salt Marsh Channel in the Murderkill Estuary, Delaware. J Coastal Res 30, 63-74.

Elliott, M., Mander, L., Mazik, K., Simenstad, C., Valesini, F., Whitfield, A., Wolanski, E., 2016. Ecoengineering with Ecohydrology: Successes and failures in estuarine restoration. Estuar. Coast. Shelf Sci 176, 12-35.

Environment Agency, 2007. Pagham to East Head Coastal Defence Strategy, Worthing.

Environment Agency, 2015. Medmerry Managed Realignment - March 2015 report, Bristol.

Esteves, L.S., 2013. Is managed realignment a sustainable long-term coastal management approach? J Coastal Res Special Issue 65, 933-938.

Fettweis, M., Sas, M., Monbaliu, J., 1998. Seasonal, neap-spring and tidal variation of cohesive sediment concentration in the Scheldt Estuary, Belgium. Estuar. Coast. Shelf Sci 47, 21-36.

Foster, N.M., Hudson, M.D., Bray, S., Nicholls, R.J., 2014. Research, policy and practice for the conservation and sustainable use of intertidal mudflats and

saltmarshes in the Solent from 1800 to 2016. Environmental Science & Policy 38, 59-71.
French, P.W., 2006. Managed realignment - The developing story of a comparatively new approach to soft engineering. Estuar. Coast. Shelf Sci 67, 409-423.
Garbutt, A., Wolters, M., 2008. The natural regeneration of salt marsh on formerly reclaimed land. Applied Vegetation Science 11, 335-344.
Jestin, H., Bassoullet, P., Le Hir, P., L'Yavanc, J., Degres, Y., Ieee, I., 1998. Development of ALTUS, a high frequency acoustic submersible recording altimeter to accurately monitor bed elevation and quantify deposition or erosion of sediments, Oceans'98 - Conference Proceedings, Vols 1-3. IEEE, New York, pp. 189-194.
King, S.E., Lester, J.N., 1995. The value of salt-marsh as a sea defense. Marine Pollution Bulletin 30, 180-189.
Kirwan, M.L., Murray, A.B., 2007. A coupled geomorphic and ecological model of tidal marsh evolution. Proceedings of the National Academy of Sciences of the United States of America 104, 6118-6122.
Krawiec, K., 2017. Medmerry, West Sussex, UK: Coastal Evolution from the Neolithic to the Medieval Period and Community Resilience to Environmental Change. The Historic Environment: Policy & Practice 8, 101-112.
Mazik, K., Musk, W., Dawes, O., Solyanko, K., Brown, S., Mander, L., Elliott, M., 2010. Managed realignment as compensation for the loss of intertidal mudflat: A short term solution to a long term problem? Estuar. Coast. Shelf Sci 90, 11-20.
Mitchell, S.B., Burgess, H.M., Pope, D.J., 2006. Stratification and fine sediment transport mechanisms in a semi-enclosed tidal lagoon (Pagham Harbour, West Sussex). Water and Environment Journal 20, 248-255.
Mitchell, S.B., Burgess, H.M., Pope, D.J., Theodoridou, A., 2008. Field studies of velocity, salinity and suspended solids concentration in a shallow tidal channel near tidal flap gates. Estuar. Coast. Shelf Sci 78, 385-395.
Mitsch, W.J., Gosselink, J.G., 2000. Wetlands. John Wiley & Sons, New York.
Moller, I., 2006. Quantifying saltmarsh vegetation and its effect on wave height dissipation: Results from a UK East coast saltmarsh. Estuar. Coast. Shelf Sci 69, 337-351.
Moller, I., Kudella, M., Rupprecht, F., Spencer, T., Paul, M., van Wesenbeeck, B.K., Wolters, G., Jensen, K., Bouma, T.J., Miranda-Lange, M., Schimmels, S., 2014. Wave attenuation over coastal salt marshes under storm surge conditions. Nat. Geosci 7, 727-731.
Mossman, H.L., Davy, A.J., Grant, A., 2012. Does managed coastal realignment create saltmarshes with 'equivalent biological characteristics' to natural reference sites? Journal of Applied Ecology 49, 1446-1456.
Nardin, W., Edmonds, D.A., 2014. Optimum vegetation height and density for inorganic sedimentation in deltaic marshes. Nat. Geosci 7, 722-726.
Ouillon, S., 2018. Why and How Do We Study Sediment Transport? Focus on Coastal Zones and Ongoing Methods. Water 10, 1-34.
Pethick, J., 1992. Saltmarsh Geomorphology, in: Pye, K., Allen, J.R.L. (Eds.), Saltmarshes: morphodynamics, conservation and engineering significance. Cambridge University Press, Cambridge, pp. 41-62.
Rotman, R., Naylor, L., McDonnell, R., MacNiocaill, C., 2008. Sediment transport on the Freiston Shore managed realignment site: An investigation using environmental magnetism. Geomorphology 100, 241-255.

Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M.M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., 2013. Climate Change 2013 The Physical Science Basis. Cambridge University Press, New York.

Tolhurst, T.J., Friend, P.L., Watts, C., Wakefield, R., Black, K.S., Paterson, D.M., 2006. The effects of rain on the erosion threshold of intertidal cohesive sediments. Aquatic Ecology 40, 533-541.