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Sedimentation rhythms and hydrodynamics in two engineered environments in an open coast managed realignment site

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Abstract

Managed Realignment (MR) schemes are considered by many coastal managers and engineers to be a preferable method of coastal flood defence and compensating for habitat loss, by creating new areas of intertidal saltmarsh and mudflat habitat. Monitoring of MR sites has tended to focus on short term ecological factors, resulting in a shortage of high frequency, high resolution long term measurements of the evolution of the sediment erosion, transportation, deposition and consolidation cycle (ETDC) in newly breached sites. This is particularly true of analysis of the formation and preservation of sedimentary rhythmites and evaluations of sedimentation rates (and their variability) in newly inundated intertidal environments. This study provides an evaluation of sedimentation rhythms and hydrodynamics from two contrasting sites within the Medmerry Managed Realignment scheme, the largest open coast realignment in Europe (at the time of site inundation). Bed sediment altimeter data highlighted different sedimentation patterns at the two sites; near constant deposition of sediment occurred near the breach resulting in 15.2 cm of sediment being accreted over the one year monitoring period, whereas periodic accretion and erosion of sediment occurred inland leading to 2.7 cm of net accretion. Differences in the relationship between suspended sediment concentrations and site hydrodynamics were observed on a semi-diurnal to annual scale. This study highlights the need for further consideration of the sedimentation processes in MR schemes in order to enhance the design and construction of these sites. Advancements in the understanding of these processes will increase the success of MR schemes in terms of the evolution of the sediment regime and the ecosystem services provided, particularly as they are more widely accepted as a form of coastal flood defence and intertidal habitat creation method.

Keywords

managed realignment; rhythmites; altimeter; hydrodynamics; suspended sediment concentration (SSC); intertidal mudflat morphology

1. Introduction

Large areas of saltmarsh have been drained and reclaimed over the past millennium for agricultural, industrial or urban development under the misunderstanding that they were of no value to society (Pethick, 2002). As a result, many European and North American coastal wetland environments have become severely degraded (Wolters et al., 2005). The international importance of intertidal saltmarshes and mudflats has only been realised in recent decades (Rotman et al., 2008). These environments provide a range of ecosystem, economic and cultural services such as wildlife habitat, carbon sequestration, immobilisation of pollutants, water quality improvements, social and recreation opportunities and protection from coastal flooding (Costanza et al., 1997; King and Lester, 1995; Moller et al., 2014; Moller et al., 1999, 2001; Tempest et al., 2015). Furthermore, these environments also protect (and reduce the cost of maintaining) engineered defences such as sea walls (e.g. King and Lester, 1995), which are becoming a growing concern due to questions over their medium to long term integrity under predicted sea-level rise scenarios (French, 2006).

Intertidal habitats remain under significant pressure and continue to be lost and degraded; approximately 50% of saltmarshes are estimated to be lost or degraded globally (Barbier et al., 2011) due in large part to alterations and influences caused by human activities (e.g. Gedan et al., 2009). These losses result from coastal squeeze caused by climate change and sea level rise, the construction of coastal defences, reduction in water and sediment quality, land reclamation for agriculture, industry and recreational use, and coastal development through the construction and expansion of ports and marinas (e.g. Doody, 2004; Jacobs et al., 2009; Kennish, 2002).

Recognition of the importance of, and the threats to, intertidal habitats have resulted in calls for an approach to coastal management that protects and allows for the sustainable use of these environments, via an ecosystem services approach (e.g. Balmford et al., 2002; Bockstael et al., 2000; Costanza et al., 1997; Turner and Daily, 2008). The ecosystem services approach provides a collective framework for coastal managers to consider the options available and to effectively communicate the consequences to various stakeholder groups (Granek et al., 2010). Environmental regulations (such as the European Habitats Directive 92/43/EEC) now enforce mitigation and compensatory measures for habitat loss (van Loon-Steensma and Vellinga, 2013). Several techniques have been used to compensate for intertidal habitat loss including increasing suspended sediment concentrations and decreasing current velocities (Boorman and Hazelden, 1995) through sediment recharge projects and the construction of offshore breakwaters (Doody, 2008), controlled reduced tide schemes (e.g. Jacobs et al., 2009) and de-embankment or managed realignment (e.g. French, 2006).

This paper focuses on managed realignment (MR), the technique of re-locating the land/sea border in-land by lowering, removing or breaching the previous defences and constructing new or maintaining previous secondary defences. MR allows tidal inundation of the formerly defended low-lying coastal hinterland (e.g. Tempest et al., 2015) which usually consists of land that had previously been reclaimed for agricultural use. Many coastal managers advocate MR as a preferred management strategy (French, 2006) as it provides new areas of intertidal habitat and improves the standard of coastal flood defence. Despite the growing popularity of MR there remains however a shortage of data regarding its success (or otherwise). This has been explained by a lack of long-term monitoring (Spencer and Harvey, 2012) with the monitoring that has been carried out focusing on vegetation changes, which occur on a comparatively short timescale (Kentula, 2000), as a measure of success.

An important yet poorly understood issue is the evolution of the sediment Erosion, Transportation, Deposition and Consolidation (ETDC) cycle within MR sites. ETDC processes vary temporally and spatially, and significantly impact on the development of newly inundated intertidal environments and their associated habitat (Rotman et al., 2008) and therefore site ecosystem services. Whilst sufficient sediment accumulation is required for habitat creation (e.g. raising bed elevation sufficiently to allow colonisation by salt marsh flora) excess sedimentation could prevent the desired habitat from becoming established. An understanding of the sediment source and supply is also required. For example the saltmarsh neighbouring the Freiston Shore MR site (UK) experienced rapid erosion (Symonds and Collins, 2007) following site inundation. Eroded material were transported into the MR site, building in the newly inundated area at the expense of the adjacent saltmarsh and undermining the success of the habitat creation scheme (Rotman et al., 2008).

Research elsewhere has provided high frequency analysis of intertidal sediment erosion and accretion processes, particularly the formation and preservation of rhythmic intertidal sedimentation patterns (henceforth referred to as rhythmites), to evaluate ETDC processes and sedimentation rates in more established estuarine and coastal areas (e.g. Deloffre et al., 2007). This paper presents an investigation of sedimentary rhythmites and ETDC processes in a recently breached and inundated estuarine environment: the Medmerry Managed Realignment site, West Sussex, UK. Specifically, we evaluate:

(a) Local hydrodynamics and its influence on sediment supply, and erosion / accretion.

(b) Differences in the rates of sedimentation and erosion, patterns of sediment accumulation and sediment supply and sources between two engineered sites at varying distances from the breach.

These differences in pattern and rate of sedimentation may have long term implications for the evolution of the ETDC processes and the sediment regime, and therefore the ecosystem services provided.

2. Study Site

The Medmerry Managed Realignment Scheme (Figure 1), the largest open coast MR site in Europe at the time of site inundation (occupying 450 hectares), is located at the eastern end of the Solent (the stretch of water between Hurst Spit, Hampshire and the Needles on the Isle of Wight in the west and the Manhood Peninsular in West Sussex to the east, including the north coast of the Isle of Wight). Coastal flood defence at Medmerry was formerly provided by a shingle barrier beach, which was managed by the Environment Agency (UK). To maintain the necessary defence standard to protect the coastal hinterland constant work was required each winter to raise, recycle and re-profile the shingle bank. Nevertheless, the defences remained vulnerable during storm events; the bank was breached 14 times between 1994 and 2011, flooding homes, local holiday caravan parks and agricultural land. The coastal flooding and erosion risk was reviewed in the Pagham to East Head Coastal Defence Strategy (Environment Agency, 2007), which concluded that the existing defences were unable to prevent flooding and would no longer be effective beyond the short-term. MR was endorsed, after a review of the available options, as the most suitable method of managing the risk from coastal flooding.

The MR scheme at Medmerry was designed not only to provide a sustainable and cost effective method of coastal flood and erosion risk management, but also to compensate for the loss of saltmarsh and mudflat habitat elsewhere in the Solent. Over 80% of the Solent's coastline is designated for its nature conservation interest (Foster et al., 2014) yet 40% (approximately 670 hectares) of saltmarsh in the region were lost through erosion between 1971 and 2001 (Cope et al., 2008). It was estimated that up to 184 hectares of new intertidal habitat would be created over the hundred years following construction of the Medmerry site (Pearce et al., 2011). The surrounding land drains through four drainage outlets into the realignment area, which consists of previously reclaimed land formerly used for both arable and pastoral agriculture. Construction of 7 km of new defences, reaching 3 km in land, began in autumn 2011. The site was breached on 9th September 2013 through a single opening in the shingle bank, forming a semi-diurnal, mesotidal estuarine system.

3. Materials and methods

Five monitoring sites were initially investigated at Medmerry and described by Burgess et al. (2016). In this study measurements were taken at Sites 3 and 5 (Figure 2), two sites of similar design and construction but contrasting in spatial position within the Medmerry site. Both of these sites were heavily disturbed and altered by heavy plant machinery during site construction as material was extracted to construct the new defences creating borrow pits; areas of lowered elevation designed to encourage the development of a range of different intertidal habitats.

Site 3 (Figure 2a), situated at the centre of the inundated site, historically was an area of pastoral land with vegetation growth increasing during the 20th century. The site is located in an excavated channel that gently slopes up to the borrow pit behind the remnants of a row of trees. The channel was cut through the eastern bank of a pre-existing terrestrial drainage channel which now forms the main drainage network through the site, draining both tidal waters and freshwater from the wider catchment flowing from upstream through two tidal gates. Up to 1.5 m of soil was excavated during construction of the borrow pit and access channel exposing soils compacted by the removed large overburden, with the heavy construction machinery causing additional compaction. The monitoring site is inundated at high water during every tide.

Site 5 (Figure 2b) is located towards the back of a borrow pit in a remnant barley field near the breach area, which is inundated during every tide and is exposed to the prevailing wind from the south west. The barley field was harvested the week before the site was breached and had previously been used consistently for agricultural purposes.

3.1 Hydrodynamic analysis

Hydrodynamic variations at both sites were measured by YSI EXO2 Sondes fitted with conductivity, temperature, depth and turbidity probes, deployed in near bed scaffolding rigs (Figure 2) at 0.46 mOD (Ordnance Datum Newlyn) at Site 3 and -0.31 mOD at Site 5. Measurements were analysed for a one year period from 1st November 2014 to 31st October 2015 to identify conditions related to high sediment supply, and to assess sediment sources and periods of sediment erosion. Turbidity probes were calibrated for suspended sediment concentration (SSC) in the laboratory using re-suspended sediment samples and filtered water samples taken *in situ*.

To quantify temporal variations in the hydrodynamics at different time scales, data were classified into:

1. Spring and neap tidal data, divided using the mean tidal range at each site during the measurement period. Tides where the change in water level (low to high) was greater than the average tidal range were classified as spring tides, whereas tides with a change in water level less than the average range were classified as neap tides. At Site 3 the average tidal range was 1.92 m, whereas at Site 5 the range was 1.5 m. This classification divided the measurements into two, approximately equal, groups which were visually examined against the predicted semi-lunar and observed high water variability.
2. Summer and winter periods. Winter measurements defined as the period between November and April and summer measurements as the period May to October.

Relationships between parameters were assessed relative to high water tidal cyclicity (for each high water measurement and each pre- and proceeding measurement time point throughout the tidal cycle) using Pearson's Linear Correlation Coefficients, after confirming the normality of the data via a quantile-quantile probability plot.

3.2 Sedimentation rhythms and mechanisms

High frequency bed elevation measurements were taken at both sites over the same one year period (1st November 2014 to 31st October 2015) using NKE ALTUS altimeter systems (Figure 2) 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 the acoustic signal to return from the sediment surface to the transducer (Jestin et al., 1998). The ALTUS systems were deployed in the areas excavated during site construction at each site and bed elevations (± 2 mm) were logged every 10 minutes. The initial bed elevation was 0.60 mOD at Site 3 and 0.17 mOD at Site 5.

3.3 Sediment analysis

Surface sediments were sampled at low water in the vicinity of the ALTUS altimeters, at the same elevation, during regular site visits to assess the changes in physical characteristics of the sediment in relation to the rhythms of sedimentation, determined using standard sedimentological procedures. The water content was measured as a percentage of the dry mass (water content = water weight / dry sediment weight x 100) after samples had been oven dried at 105 °C for 48 hours. The organic content of the samples was measured by a six hour loss on ignition test at 450 °C. A Malvern Instruments Mastersizer Hydro 2000G Laser Diffraction Particle Size Analyser was used to determine the grain size distribution, following hydrogen peroxide treatment and dispersion with sodium hexametaphosphate.

4. Results

4.1 Hydrodynamic analysis

4.1.1 Site 3

Tidal averaged (12 hour running mean) hydrodynamic measurements are presented for each study site in Figure 3. Missing data is due to equipment failure or has been considered to an anomaly (e.g. weed wrapped around sensor). At Site 3, the maximum high water depth measured was 3.57 mOD in October 2015 and the lowest recorded low water was 0.49 mOD in June 2015. Differences in the tidal range were predominantly controlled by the semi-lunar tidal cycle, with spring tidal ranges being around 14% larger than neap tidal ranges. A maximum salinity value of 38.03 PSU was measured in August 2015 and a minimum value of 6.28 PSU was recorded in January 2015. Salinities were almost 30% higher during the summer than the winter, whilst spring tides tended to be 15% more saline than neap tides. Differences between the maximum and minimum salinity during a tidal cycle appeared to be predominantly seasonal, although semi-lunar variations were also present. Temperature values decreased during the winter and increased during the summer before beginning to fall again during September and October and showed very little semi-diurnal variance.

Initially, the average SSC per tide at Site 3 was highly variable before remaining relatively constant from February until October, when concentrations became variable again (Figure 3a). Depth had the strongest relationship with SSC during winter spring tides, when positive correlations were found during the flood tide and negative correlations were found during the ebb, with a statistically insignificant relationship two hours either side of high water. Generally, a negative relationship was found between salinity and SSC with statistically significant correlation coefficients tending to occur either side of high water (Figure 4). The relationship between salinity and SSC was most prominent during winter ebb neap tides (Figure 4f) and was usually stronger during neap tides compared to springs. The relationship between spring tide salinities and SSCs was weaker during the summer months (Figure 4h).

4.1.2 Site 5

The maximum water depth measured at Site 5 was 2.23 mOD recorded in October 2015. During large tides the site drained below the position of the depth sensor. At Site 5 the maximum measured salinity was 37.33 PSU in September 2015. In contrast, the lowest recorded salinity was 4.64 PSU in December 2014. In contrast to Site 3, variations in salinity were minimal over a tidal cycle. Temperature variations matched those at Site 3.

SSCs varied throughout the measurement period at Site 5 (Figure 3b). Unlike Site 3, no overall relationships between depth and SSC were detected on a semi-diurnal scale. Low correlation coefficients were found between salinity and SSC at Site 5 during the 12 month measurement period that were not significant at the 95% confidence level (Figure 5), with the exception of during winter spring tides (Figure 5e). During these tides a statistically significant negative correlation was found regularly between salinity and SSC during the tidal cycle.

4.2 Sedimentation rhythms and mechanisms

4.2.1 Site 3

A net increase in bed elevation of 2.7 cm over the 12 month period was measured at Site 3, with sedimentation mainly controlled by the semi-lunar tidal cycle. On an annual scale (Figure 6), these changes are slight in comparison to the net elevation change with the exception of a period between January and March 2015. On a monthly scale (Figure 7a) however a broad pattern of bed level increasing during the spring tide and decreasing or stabilising during neap tides can be identified. Nonetheless, there is some disturbance to this pattern during high SSC events, during which bed elevation initially lowers and then increases for a number of tides with SSC following a similar pattern (Figure 7a).

On a semi-diurnal scale a similar pattern is observed (Figure 8a), with particles settling during the flood tide and experiencing resuspension during ebb periods. Deposition continued during high tide slack water, reaching a maximum approximately one hour after high water. Bed elevation then decreases as sediment is eroded by the outgoing tide. This is also reflected by the SSC data, with low levels of suspended sediment corresponding with the high bed elevations.

4.2.2 Site 5

During the measurement period, Site 5 received a greater net deposition of 15.2 cm (Figure 6). In contrast to Site 3 near-constant sediment deposition was observed, with enhanced rates of deposition associated with higher levels of suspended sediment and deceleration in the rate of deposition related to lower SSCs. However, unlike Site 3, there is very little relationship between the semi-lunar tidal cycle and bed elevation (Figure 7b). On a semi-diurnal scale, deposition of sediment occurred during the flood tide with most sediment deposited during high tide slack water (Figure 8b); with further deposition occurring once water level had decreased. In the case of Figure 8b this resulted in a 0.5 cm thick sediment deposit. SSC showed some relation to bed elevation changes, decreasing as sedimentation occurred and remaining relatively stable once sediment had been deposited.

4.3 Surface sediment analysis

Moisture content (Figure 9a) at Site 3 decreased over time, ranging from 156% to 87%. In contrast there was little temporal variation in moisture content at Site 5 which was also lower than Site 3, varying from 32% to 47%. Organic content measured in proxy by the percentage loss on ignition (Figure 9b) initially increased at Site 3 then showed a general decrease during the study period, ranging from 4.9% to 2.7%. Site 5 yielded lower loss on ignition values than Site 3, between 2.7% and 1.6%, and showed little temporal variation. The mud concentration (clay + silt) (Figure 9c) at Site 3 increased during the winter before decreasing and remaining relatively constant during the summer whereas sediments at Site 5 were coarser, decreasing from 88% to 15% mud content over the measurement period.

5. Discussion

Hydrodynamic and bed elevation measurements were taken during the second year of site inundation at Medmerry in an investigation of the sedimentary rhythmites and ETDC cycle to evaluate patterns of sediment accumulation, differences in the rates of sedimentation and erosion and the sediment source in this newly inundated intertidal environment. Measurements were taken over a 12 month period from two sites substantially landscaped and engineered during the site construction phase of the scheme.

5.1 Sedimentary rhythmites

Despite altimetry measurements indicating net accretion at each site, different sediment rhythms were detected at the two sites. This is despite both sites being designed to locally create a range of intertidal saltmarsh and mudflat habitat through re-profiling and lowering of the pre-breach terrestrial elevation. The different sedimentation rhythms are a product of spatial and temporal variations in sedimentary processes resulting from the complex relationship between the hydrodynamics and SSCs measured and the surface sediment properties (and site morphological characteristics). The preservation of sedimentary rhythmites can be calculated from the altimetry measurements as percentage sediment preserved from each depositional event (after Deloffre et al., 2007):

Preservation rate (%)=(Σ(thickness of deposit episodes during one year)(cm))/(Annual Sedimentation rate (cm))

At Site 3 the preservation rate was 28% owing to the periodic accretion and subsequent erosion of sediment, whereas at Site 5 the preservation rate was much higher at 65% due to less significant periods of erosion.

At Site 3, which consists of waterlogged sediment in a sheltered central site area, sedimentation corresponded to a semi-lunar rhythm typical of a sheltered natural mudflat (Deloffre et al., 2007) with a superimposed rhythm of deposition during the flood tide and resuspension during the ebb. Deposition of sediment matched a decrease in near-bed SSC and following erosion the SSC increased. Rates of sedimentation were greater at the more exposed and lower in elevation Site 5 where generally 1 to 2 mm of coarse grained sediment were accreted regardless of the hydrodynamic conditions during each tidal cycle, predominantly during the flood tidal phase. The main period of sedimentation on the flood tide matched a decrease in SSC and decelerated rates of sedimentation occurred during periods of low SSC. Rates of accretion overall showed no evidence of deceleration however during the measurement period.

Medmerry is a large open coast site, and is exposed to a range of forces and processes resulting in different sedimentation patterns in different parts of the site. At present, there is no evidence of hydro-geomorphic equilibrium having been attained, with sediment remaining to be redistributed around the site. It remains to be seen how the sediment regime will evolve as the site approaches equilibrium and all sediment has been redistributed, particularly in response to rising sea levels, at a site where (in contrast to many previous MR sites) there are no surrounding intertidal saltmarsh or mudflat habitat to act as a potential fine sediment source (discussed further below).

5.2 Source of sediment

SSCs were found to relate to differences in water depth on a semi-diurnal scale at Site 3 and at both sites lower salinities were related to high levels of suspended sediment. This is probably the result of wave induced erosion within the site during wet and windy conditions. At both sites lower salinities typically occurred during the winter most probably as a result of high rainfall and therefore more freshwater draining through the system. A higher input of freshwater is often associated with transporting greater levels of eroded sediment from elsewhere in the catchment and influencing the position of the turbidity maximum, whilst the transportation of eroded terrestrial sediment from runoff within the site may also occur (e.g. Fettweis et al., 1998).

Previous studies have suggested that material transported and accreting in estuarine MR sites has come from externally eroding saltmarshes (e.g. Rotman et al., 2008; Symonds and Collins, 2005). However, the Medmerry MR scheme is located on an open coast, a considerable distance (approximately 7.5 km eastwards from Chichester Harbour entrance and on the opposite side of the peninsular from Pagham Harbour) from any external pre-existing saltmarshes, and is banked by a shingle beach. It is therefore likely that the majority of suspended sediment within the site has originated internally and is being redistributed around the site. A fraction of the suspended sediment may be sourced from the eroding offshore relic Mixon barrier islands, although the extent of this requires further investigation.

At Site 3 a supply of sediment to the channel has been observed by the authors during water run-off from the surrounding newly created intertidal floodplain, which still maintains some resemblance to the terrestrial fields present prior to site inundation. Sediment has been seen to be flushed off the banks during the ebb tide as water levels fall to below the bank-full level, represented by the steepening of the tidal curve and resulting in an increase in the SSC observed in Figure 8a. Variations in the levels of suspended sediment were found to negatively relate to the salinity, indicating that terrestrial inputs of freshwater may provide a source of sediment and increase the levels of erosion within the site, but further consideration of up and downstream sediment supply at Site 3 is needed.

Changes in the position of the turbidity maximum also need to be considered, to account for changes in available sediment supply and the evolution of the sediment regime within the site. Small, locally induced wind waves (< 50 cm) have been observed at Site 3. Waves originating over the former agricultural field on the opposite bank have been observed by the authors, which refract through the pre-existing channel and travel up the cut channel during periods of inundation. The effect of wind induced erosion is related not only to the properties of the waves, but also to the cohesion of the surface sediment (Deloffre et al., 2007). Despite sedimentary rhythmites at this site being more typical of a natural intertidal mudflat, compared to Site 5, the sediment remains heavily waterlogged due to the high levels of sub-surface sediment compaction generated during site construction. Compact sediment reduces the efficiency of sediment drainage in frequently inundated areas due to poor vertical hydrological connectivity. Poor drainage could, in turn, hinder the physical, chemical and ecological development of the site and have negative implications for the ecosystem services that it may eventually provide (e.g. Tempest et al., 2015).

At Site 5 sedimentation trends showed less relationship with hydrodynamic differences and high accretion rates of typically sandy sediment are indicative of a shift towards hydro-geomorphic equilibrium. The sediment source at this site originates from sand deposits in local collapsed banks and former hedgerows and is washed landward by locally induced wind waves. Relic banks and hedgerows are positioned seawards of Site 5, are orientated in line with the prevailing wind from the southwest and are the only features which remain exposed during high water, but are gradually diminishing in extent over time. Some sediment has also been provided from the surrounding intertidal floodplain, a former barley field prior to site inundation, which has been experiencing erosion via embryonic creek formation and a decrease in elevation from its level during site construction. This has implications for future site design, in that account has to be taken of the availability of large local sediment sources which may erode or reprofile and cause rapid infilling impacting the type of intertidal environment which develops.

5.3 Rates of sedimentation

Predictive models (e.g. Allen, 2000) and measurement data (e.g. Clapp, 2009; Dixon et al., 2008) of the evolution of intertidal environments suggest high sedimentation rates would initially be expected following inundation, particularly in areas of lower elevation. Lower rates of accretion were measured at Site 3, which could be due to the site being positioned towards the lower energy centre of the MR site away from a readily available source of sediment. Furthermore, lower rates of accretion at Site 3 may be caused by the relatively high elevation of the site at the time of initial inundation compared with areas nearer the breach, a reason given for the relatively low rates of sedimentation observed by Cundy et al. (2002) at neighbouring Pagham Harbour following its natural breaching in 1910. Cundy et al. (2002) presented evidence of a near-constant sediment accretion rate of ca. 5 mm/year, significantly lower than those measured at either site at Medmerry, although these authors note that the calculated errors on the historic (immediate post-breaching) sedimentation rates were greater than in more recent sediments. The low rate of sediment accretion at Site 3 might result in the heavily disturbed sediment remaining at the surface and influencing the ecological development of the new intertidal habitat, having negative implications for the ecosystem services provided by the site.

Rapid, near-constant accretion was observed at Site 5 throughout the measurement period. This site is located nearer the breach, at lower elevation in a former borrow pit, and is exposed to the prevailing wind from the southwest and therefore locally induced wind waves. Despite the pattern of sedimentation matching the models of Allen (2000) and others the rates of sedimentation measured at Site 5 were half those reported by Dixon et al. (2008) at the

Wallasea Managed Realignment (MR) site, an estuarine based scheme that is also considerably smaller than Medmerry. It remains to be seen whether these high sedimentation rates will be maintained, presuming there is a sufficient sediment supply. This is particularly the case if the bed elevation in the borrow pit reaches the level of the surrounding bank and intertidal floodplain. It is likely that the rates of sedimentation will decrease as the site elevation increases relative to the tidal frame, but further monitoring is required in order to evaluate whether this will be the case. Nonetheless, the high rate of accretion observed at Site 5 could have significant consequences for the range of ecosystem services provided at this site due to the loss of the lower elevation intertidal habitat.

The sedimentation patterns at other realignment sites show varying levels and styles of accretion. Some sites, such as Tollesbury in Essex (UK), have maintained high levels of accretion following site inundation (e.g. Chang et al., 2001). Other sites, for example the abandoned and subsequently inundated reclaimed agricultural land on the Blyth estuary in Suffolk (UK), failed to accrete sufficient levels of sediment to form saltmarsh and remained as mudflat habitat (French et al., 2000). In sediment-rich estuarine MR sites, rapid rates of accretion have resulted in the establishment of extensive saltmarsh at the expense of mudflat as elevation has increased relative to the tidal frame (e.g. Pontee, 2014).

Differences in accretion rates between Medmerry and other MR sites highlight the site specific nature of the ETDC cycle in these environments, whilst the results presented here demonstrate additional internal spatial complexity within MR sites. This is demonstrated by the different patterns and rates of sedimentation which have evolved following site inundation at the two sites within the Medmerry MR site, despite both experiencing similar disturbances and engineering during site construction. This generates difficulty in designing and engineering MR schemes. Analysis of the mechanisms and rates of sedimentation and erosion presented in this paper provides new insights into the preservation of deposited sediment and therefore the rate of accretion in a newly inundated intertidal environment, and enhances the understanding of the ETDC processes in these environments. Although the long term influence of these initial (post-inundation) sedimentation patterns on habitat creation and the resulting ecosystem services at Medmerry remains to be seen, this allows greater consideration of the role of sedimentary processes in the development and likely success (in terms of their habitat creation and coastal protection goals) of MR sites and other newly inundated intertidal environments.

6. Conclusion

This paper demonstrates that high resolution and frequency altimeter and hydrodynamic measurements can be used to enhance the understanding of the ETDC cycle in newly inundated intertidal environments, an area that has received little attention in previous studies (e.g. French et al., 2000; Rotman et al., 2008). High resolution data are provided on site hydrodynamics, and the preservation and occurrence of sedimentation rhythms for two infilling sites heavily altered during site construction in an open coast MR site. Clear differences in sedimentation patterns were identified at each site. At Site 3 SSCs related to salinity and, to some extent, depth. The suspended sediments were deposited during the flood tide and re-suspended during the ebb, whilst overall bed elevation related to the lunar cycle. The SSC at Site 5 had some relation to salinity during low water, but there was a near constant increase in bed elevation with sediment being deposited during the flood tide and consolidating during the ebb.

Sediment altimeter data highlighted different sedimentation patterns at the two sites; near constant deposition of sediment occurred near the breach resulting in 15.2 cm of sediment being accreted over the one year monitoring period (at Site 5), whereas periodic accretion and erosion of sediment occurred inland leading to 2.7 cm of net accretion (at Site 3). Accumulated sediment is largely derived from internal site reworking, with inputs also likely from terrestrial (catchment) sources.

Further monitoring is required to identify whether sedimentation continues at the measured rates, but differences between the two sites has long term implications for the evolution of the sediment regime and the ecosystem services provided by the Medmerry MR site. There is a need for wider consideration of the hydrodynamics and sedimentation rhythms in the construction of future MR schemes to ensure they are a success, especially as restoration techniques become an increasingly significant component in coastal management strategies. Further field measurements and knowledge are required to support theoretical and numerical models for these environments, which can only be accomplished through consistent, long term post-breach monitoring of the sedimentation rhythms and hydrodynamic controls.

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Figure 1: Location of study sites and the Medmerry Managed Realignment Site in the wider Solent region (insert). Cross-hatched areas show location of borrow pits (see text for discussion).

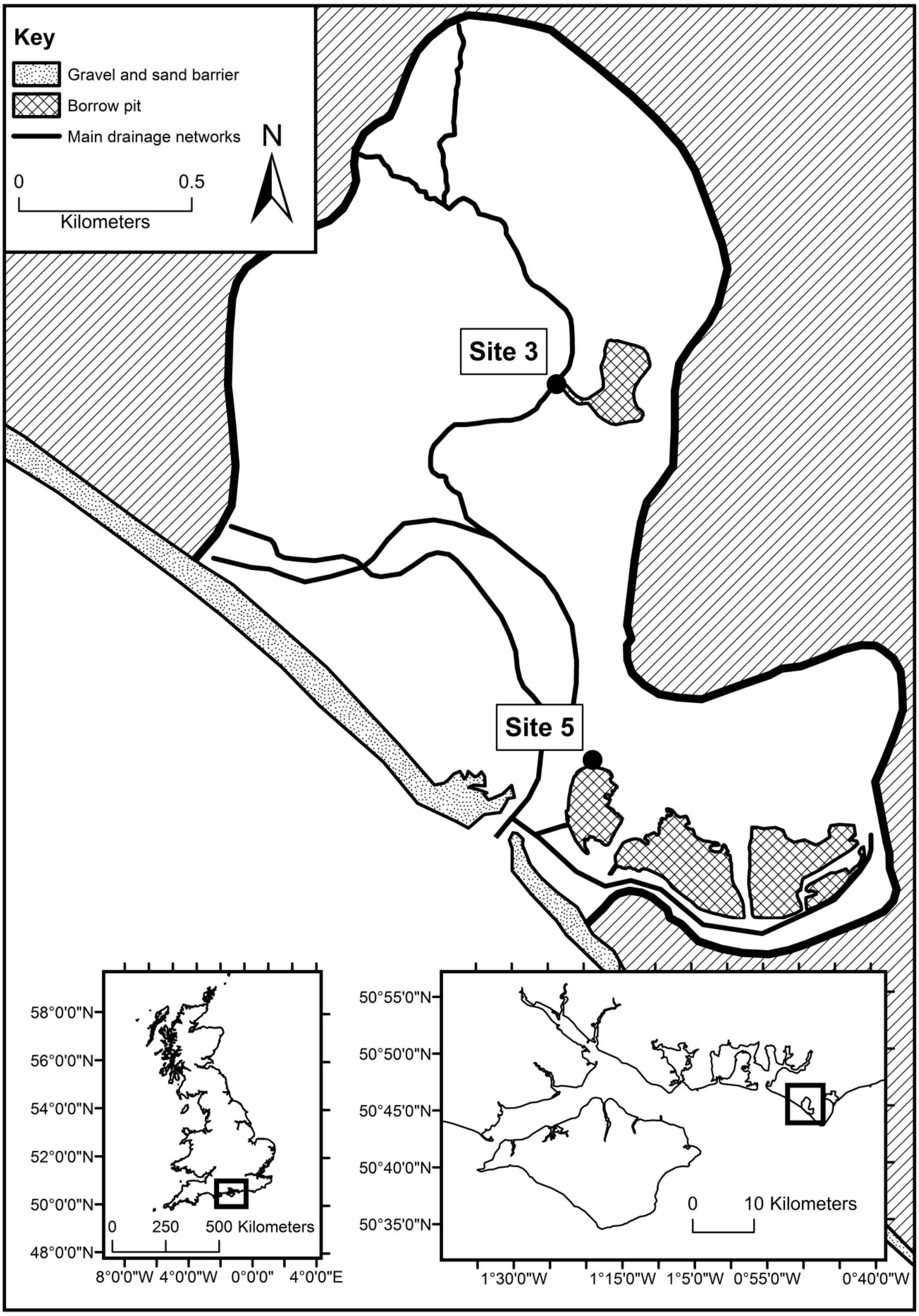

Figure 2: View of (a) Site 3 on towards the northwest 15th January 2015 and (b) Site 5 towards the southwest on 1st December 2014 at the Medmerry Managed Realignment Site annotated to show location of instruments deployed (photography: J.Dale).

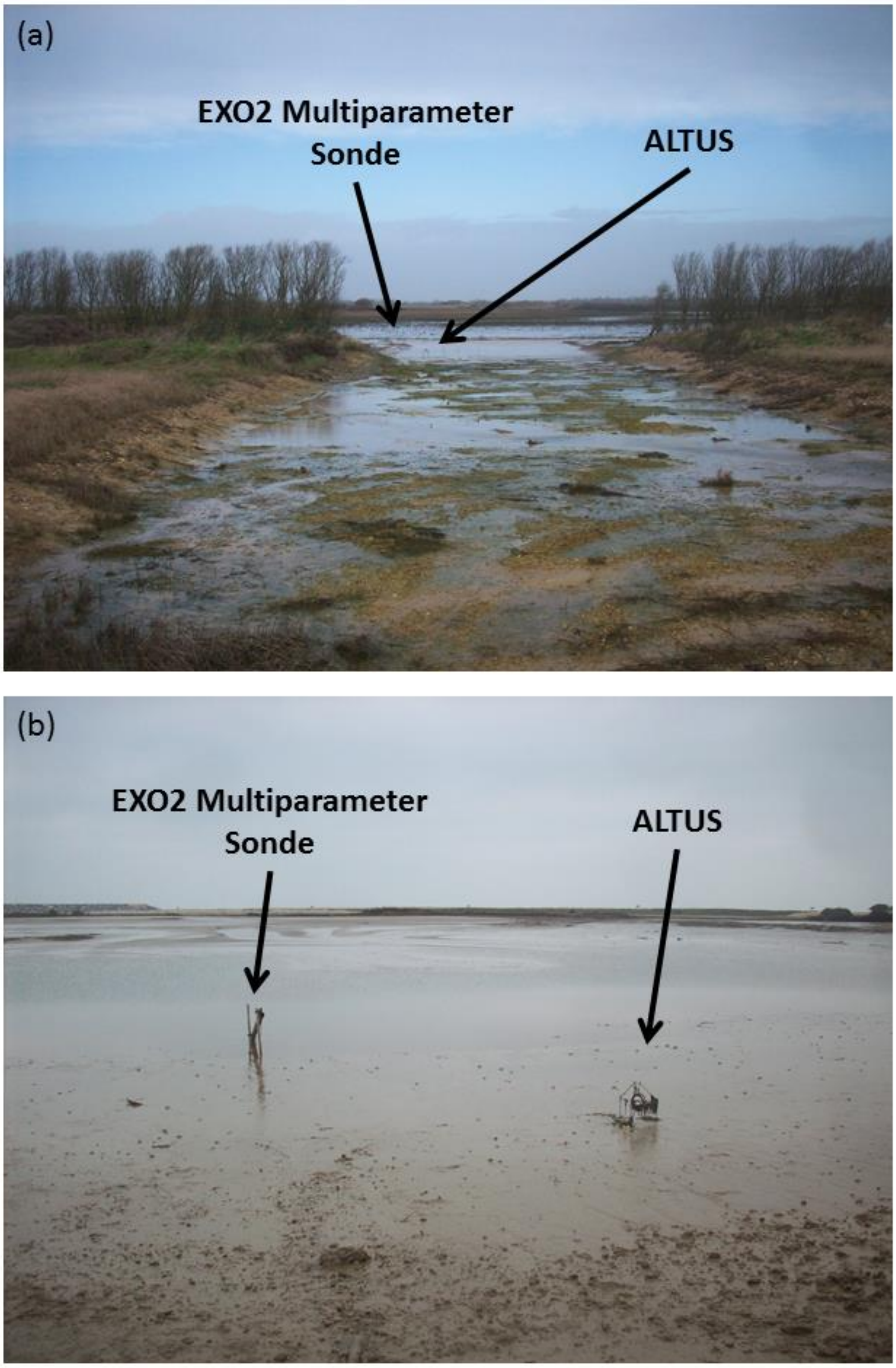

Figure 3: Tidal averaged hydrodynamics data, calculated by applying a 12 hour running mean, for (a) Site 3 and (b) Site 5, Medmerry Managed Realignment Site.

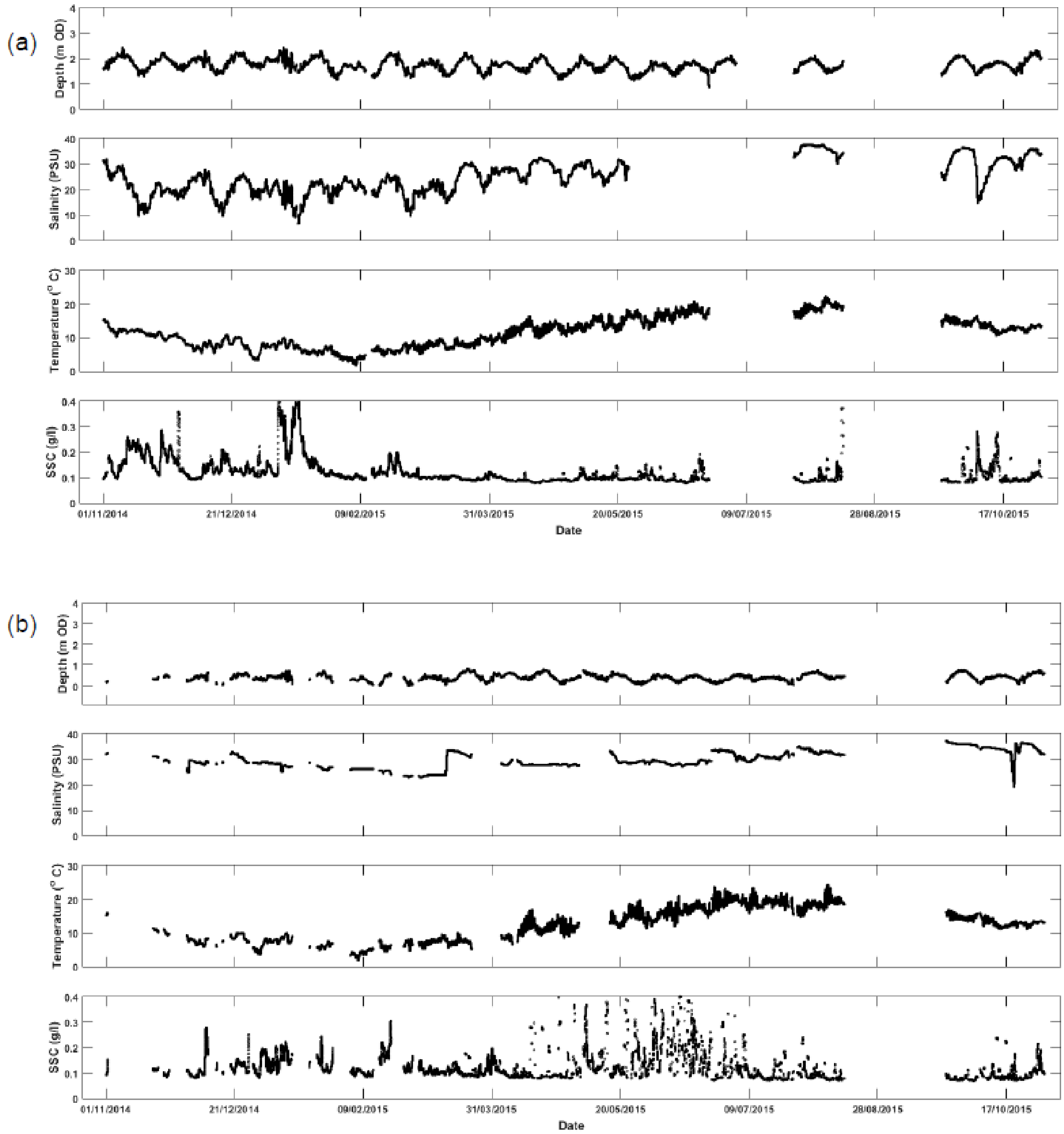

Figure 4: Pearson's Correlation Coefficients for the relationship between salinity and suspended sediment concentration for each point in the tidal cycle during (a) all tides over a year, (b) all spring tides over a year, (c) all neap tides over a year, (d) all winter tides, (e) winter spring tides, (f) winter neap tides, (g) all summer tides, (h) summer spring tides, (i) summer neap tides at Site 3, Medmerry Managed Realignment Site. Filled circles are statistically significant at the 95% confidence interval.

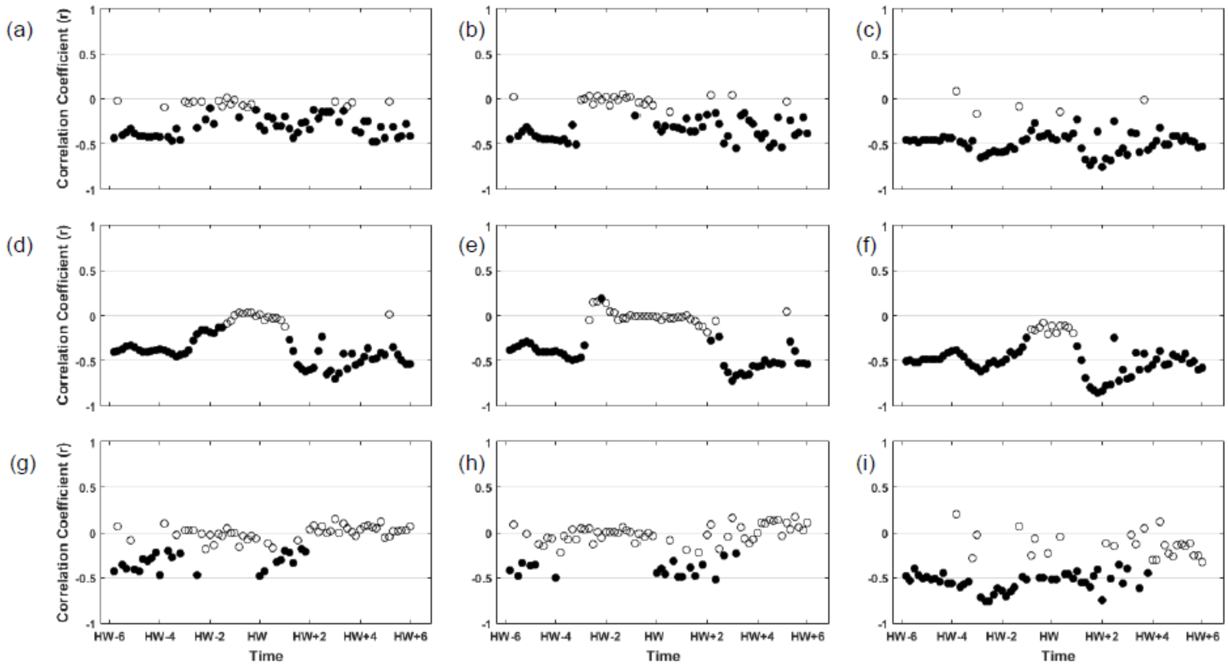

Figure 5: Pearson's Correlation Coefficients for the relationship between salinity and suspended sediment concentration for each point in the tidal cycle during (a) all tides over a year, (b) all spring tides over a year, (c) all neap tides over a year, (d) all winter tides, (e) winter spring tides, (f) winter neap tides, (g) all summer tides, (h) summer spring tides, (i) summer neap tides at Site 5, Medmerry Managed Realignment Site. Filled circles are statistically significant at the 95% confidence interval.

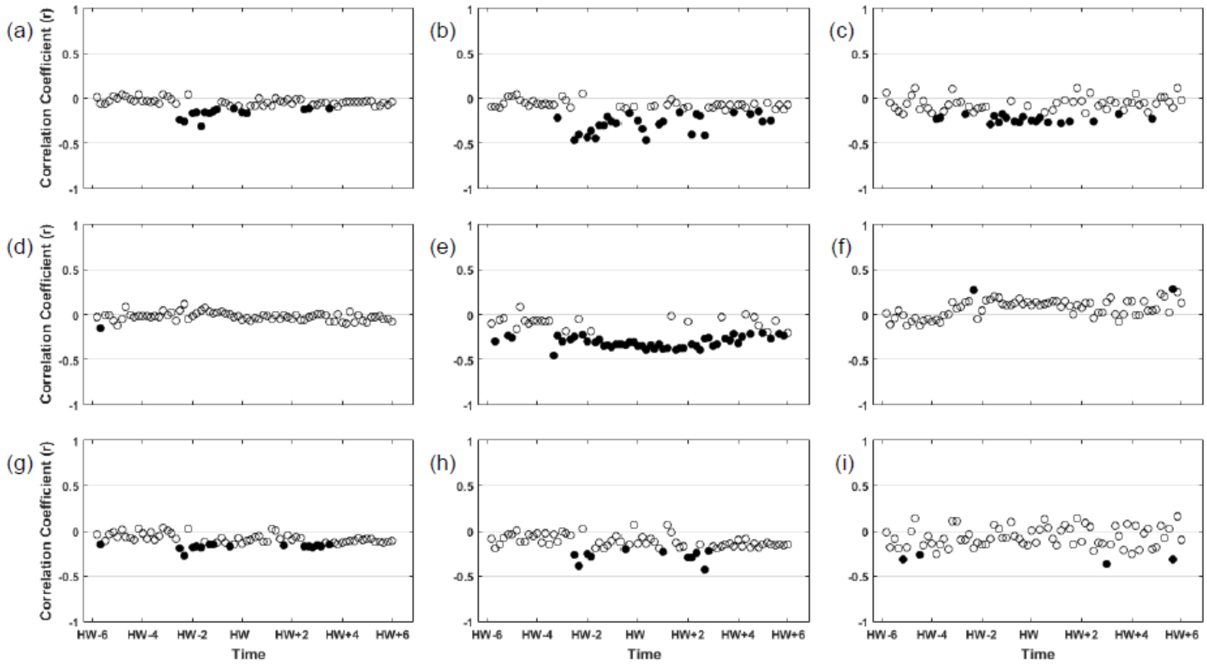

Figure 6: Bed elevation over 12 months at the two study sites (Sites 3 and 5) within the Medmerry Managed Realignment site. See text and Figure 1 for further details of site locations and characteristics.

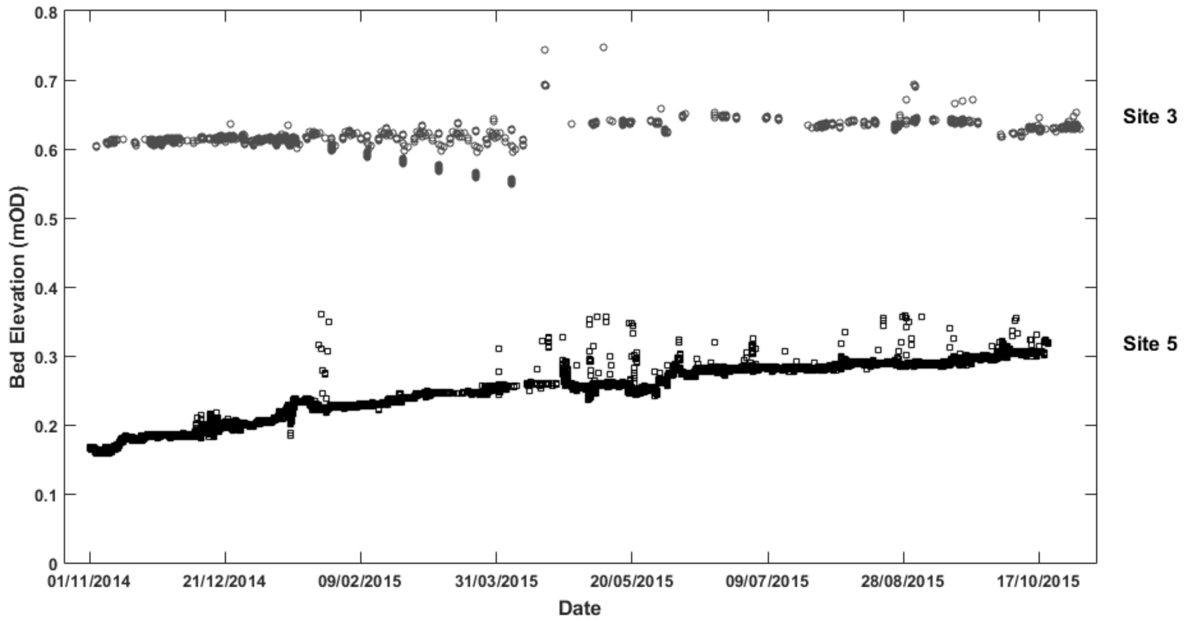

Figure 7: Comparisons between monthly sedimentation rhythms and depth, temperature, salinity and suspended sediment concentration (SSC) at (a) Site 3 and (b) Site 5, Medmerry Managed Realignment Site. Bed level (elevation (mOD)) is shown by open circles (upper dataset) on each graph.

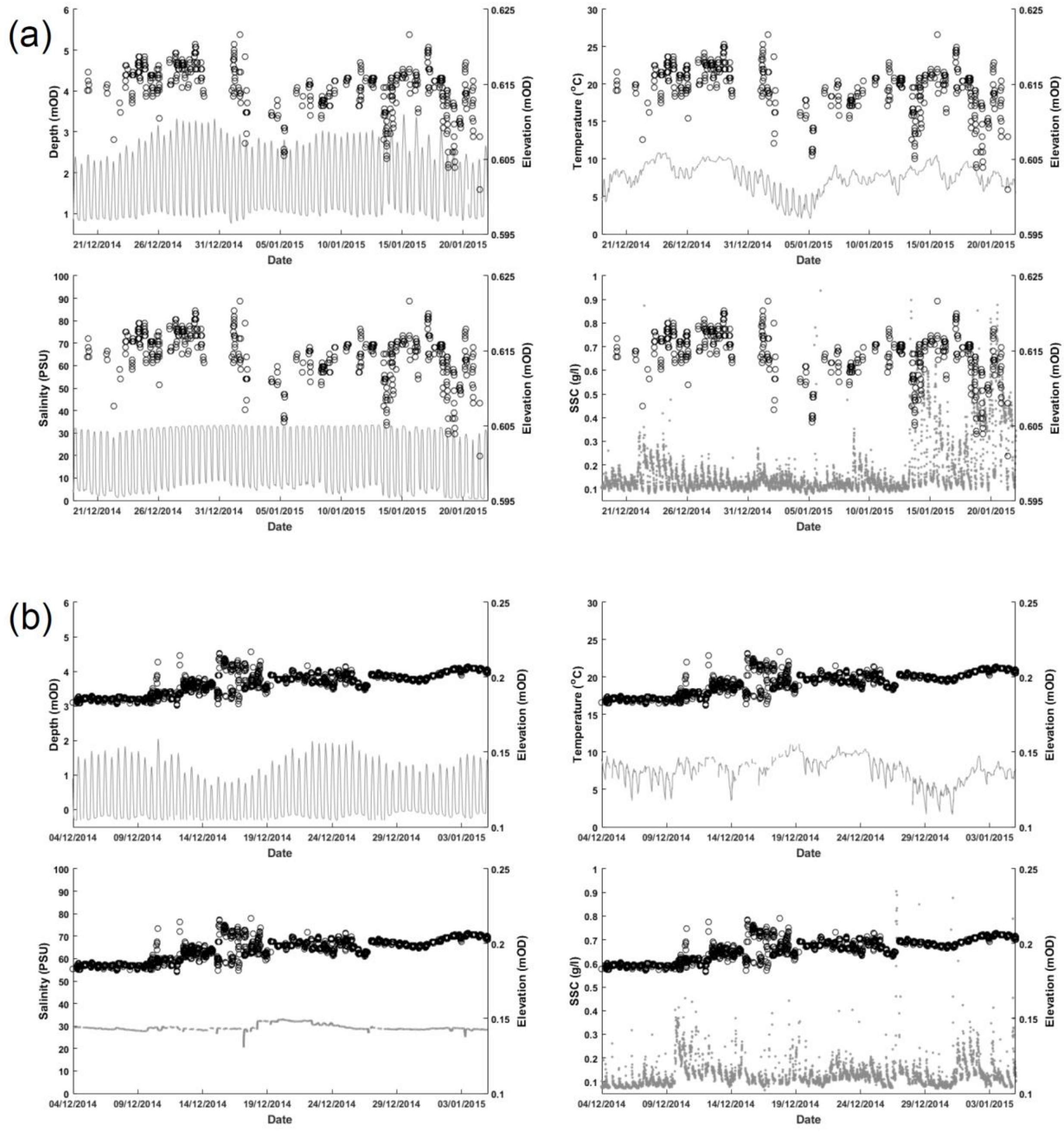

Figure 8: Comparisons between semi-diurnal bed elevation changes and depth, temperature, salinity and suspended sediment concentration (SSC) at (a) Site 3 on 20th and 21st December 2014 and (b) Site 5 on 7th December 2014, Medmerry Managed Realignment Site. Data shown are representative of a typical flood-ebb tidal cycle.

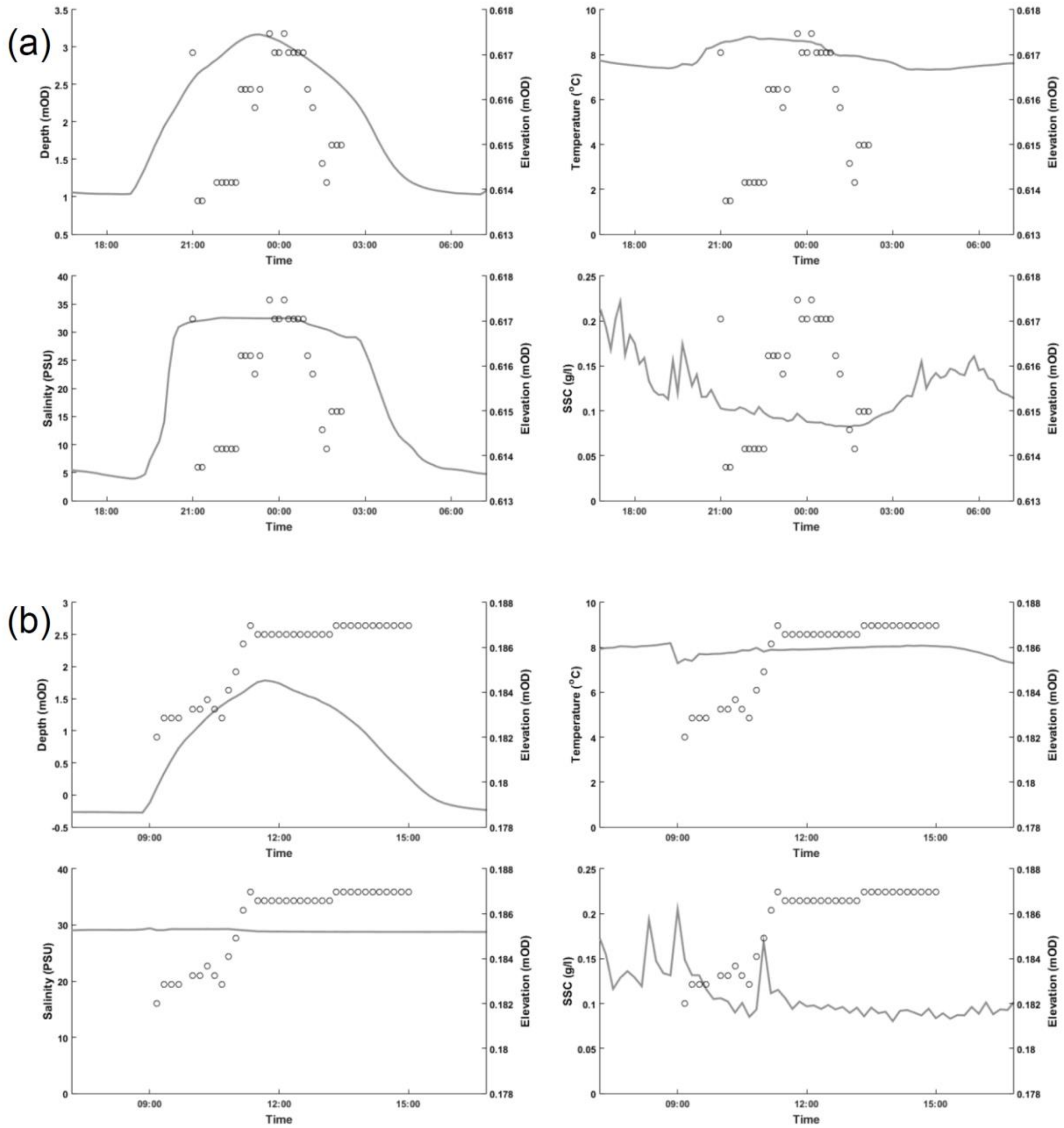

Figure 9: Variations in surface (a) moisture content (n = 5), (b) loss on ignition (n = 5) and (c) mud (sand + silt) content (n = 3) sediment properties at Sites 3 and 5 at the Medmerry Managed Realignment Site.