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Morphological evolution of a non-engineered managed realignment site following tidal inundation

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Sedimentation rates; coastal geomorphology; coastal wetlands: small-Unmanned Aerial System

Abstract

There is growing evidence that managed realignment (MR) sites have lower biodiversity than natural saltmarshes, which has been associated with differences in the physical function and morphological evolution following site breaching. This evidence has been derived from MR sites previously used for intensive arable agriculture or modified during site construction. Therefore, the development of these sites may not be representative of the sedimentological evolution that would have otherwise occurred. This paper presents analysis of high spatial resolution digital surface models derived from the images collected using a small-unmanned aerial system from a non-engineered MR site at Cwm Ivy Marsh, Gower Peninsula, Wales. These models are examined alongside a novel combination of high frequency measurements of the rate and patterns of sedimentation, suspended sediment concentration (SSC), and the sub-surface structure and geochemical profiles. Results indicated that although the site became topographically less variable over a four year period, the intertidal morphology developed through an increase in the abundance of higher order creek systems and sediment being deposited at a rate of between 3 to 7 cm / year. The SSC followed an inverse pattern to water depth, with bed elevation increasing and then decreasing during both the flood and ebb tidal phases. Analysis of the sediment subsurface geochemical composition indicated redox profiles similar to natural intertidal environments; evidence of a fluctuating water table was found at a saltmarsh site, in comparison to waterlogging identified at an anoxic mudflat site. These findings provide a new insight to the sedimentological processes in a MR site without the influence of landscaping or site engineering prior to site-breaching, which can be used to inform the design of future MR sites.

1 Introduction

Coastal wetlands, such as saltmarshes and mudflats, provide a number of important ecosystem services including habitats for juvenile fish species, water quality regulation and wave attenuation (Barbier et al., 2011). However, there has been a global decline in the extent of these habitats (Adam, 2002; Barbier et al., 2011) as a result of loss and degradation caused by pollution, urbanisation, land claim, changes in sediment supply, and erosion driven by sea level rise. Subsequently, there are a number of schemes that have been implemented to restore and compensate for the loss of intertidal saltmarsh habitat (Callaway, 2005). One approach, which has become the preferred option in Europe and North America, is managed realignment (MR); where sea defences are deliberately breached allowing tidal inundation of the previously defended terrestrial land. MR is usually performed on low lying land that has previously been reclaimed for agricultural purposes (French, 2006), and is often of lower economic value than the cost of maintaining the external flood defence and protection schemes.

Following tidal inundation, saltmarsh plants and invertebrate species have been found to colonise relatively quickly (Garbutt et al., 2006; Mazik et al., 2010; Wolters et al., 2005). However, at multiple sites, the diversity of key plant species has been recognised to not be equivalent to natural saltmarsh communities (Mossman et al., 2012). This has been associated with differences in sub-surface sediment structure due to agricultural activities, such as ploughing, leading to poor drainage and anoxic conditions (Spencer et al., 2017; Tempest et al., 2015). As a result, these sites may not be delivering the targeted level of ecosystem services such as carbon storage (Moreno-Mateos et al., 2012) or wave attenuation (Moller et al., 2014; Moller and Spencer, 2002; Rupprecht et al., 2017). Site design often includes a mosaic of morphological features including channels, raised areas and lowered sections to encourage a range of intertidal habitat, utilising the distinct elevational niches of different saltmarsh species (e.g. Masselink et al., 2017; Sullivan et al., 2017). Consequently, elevation is considered to be the key physical parameter in the design of MR sites (Howe et al., 2010). However, this approach does not consider post-site breaching changes and the rate of sedimentation. For example, at Paull Holme Strays (Humber estuary, UK) rapid accretion of sediment occurred due to the high suspended sediment load in the Humber estuary (Mazik et al., 2010; Wolanski and Elliott, 2016). Furthermore, at the Medmerry Managed Realignment Site (West Sussex, UK) artificially lowered areas accreted at a faster rate than anticipated due to the internal re-distribution of sediment following site breaching (Dale et al., 2017). In both of these cases, accretion of sediment resulted in the loss of lower elevation environments targeted by the scheme, and did not result in the creation of the range of intertidal habitat to the extent intended.

Predictions of a site's morphological evolution following inundation tend to be derived from theoretical models based on observations of established saltmarshes (e.g. Allen, 2000), or post-site breaching measurements of the rate of accretion (e.g. Dale et al., 2017; Spencer et al., 2017; Spencer et al., 2008). However, empirical measurements from MR sites tend to be focused on sites that have undergone a considerable amount of landscaping and engineering works during site construction prior to site breaching, such as the creation of artificial drainage channels and changes in elevation to encourage a range of habitat types (e.g. Burgess et al., 2014; Dale et al., 2017). As a result of the changes to the elevation, morphology and drainage systems caused by the pre-breach landscaping, these sites may not provide a realistic representation of the natural patterns and rates of sedimentation following intertidal inundation. Furthermore, these studies have relied on traditional surveying techniques, such as differential GPS and LiDAR (e.g. Chirol et al., 2018; Lawrence et al., 2018). As a result, small (but important) changes in morphology such as embryonic creek formation and the availability of distinct elevation niches, which are important for topography variability and therefore plant diversity (e.g. Morzaria-Luna et al., 2004), are likely to have been missed. To address these shortcomings, Dale et al. (2020) demonstrated the benefits of using repeat high resolution digital surface models (DSMs) to examine morphological change in MR sites and intertidal wetlands more widely. These authors produced DSMs using the emerging low-cost photogrammetric method Structure-from-Motion, on images collected using a small-unmanned aerial system (sUAS), in order to identify the morphological evolution. Nonetheless, their study focused on a specific area under 2000 m^2 and known to be developing morphologically, and failed to provide a holistic evaluation of morphological changes across the entire site as it developed.

Therefore, there is a need for inclusive high resolution, *full-site* studies of recently breached non-engineered MR sites to assess the morphological evolution without the influence of extensive (and costly) site design and engineering works. To address this requirement, this study presents a whole site analysis of a recently breached non-engineered MR site at Cwm Ivy Marsh, Gower Peninsula, Wales. Specifically, the rate and spatial variability of the morphological evolution through measurements of the morphological change, drainage network development and sediment accretion and erosion across the site are evaluated via topographic surveys collecting using a sUAS. These measurements are combined with analysis of the suspended sediment concentration (SSC) in relation to the pattern of sedimentation (Dale et al., 2017), to evaluate the variability in the deposition and supply of sediment over a tidal cycle. In addition, the preservation of the terrestrial surface, and its influence on the physio-chemical evolution of the sediment sub-surface, is assessed through sediment core analysis.

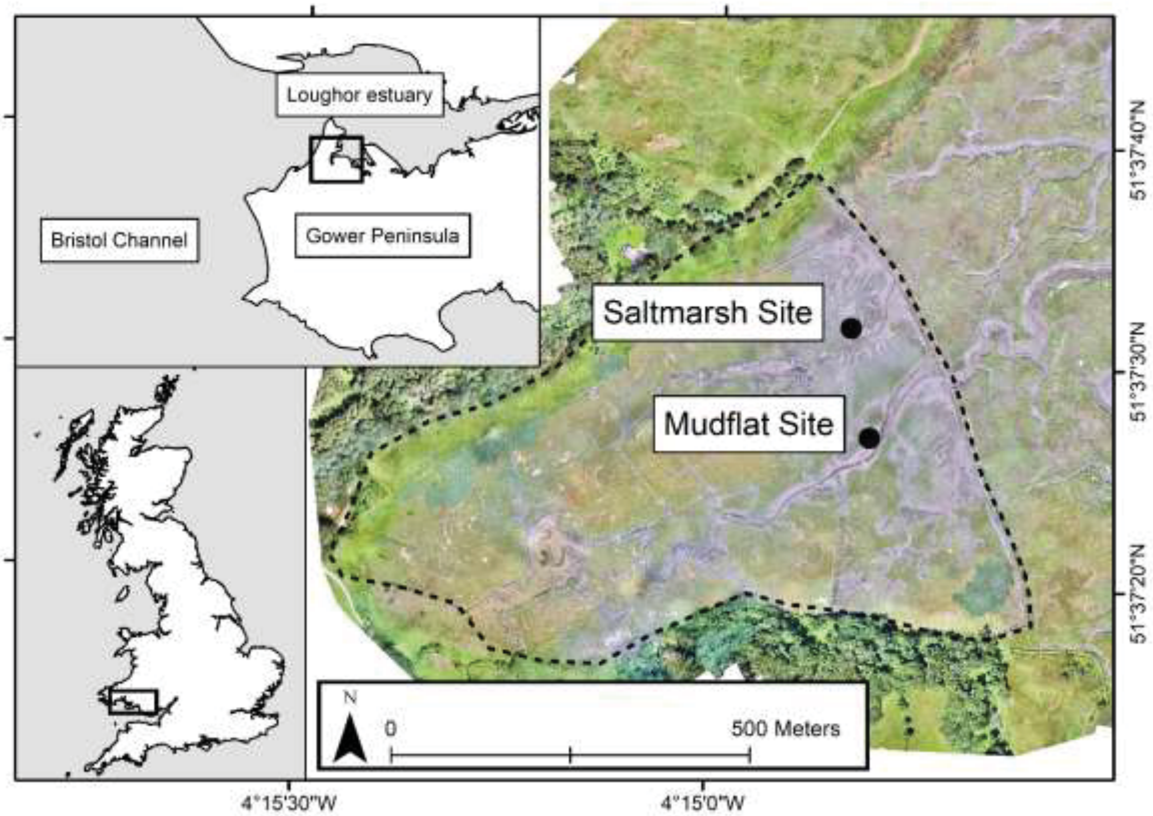

Figure 1: Orthophotography of Cwm Ivy Marsh derived from the July 2019 small-Unmanned Aerial System survey, the location of the saltmarsh and mudflat sites, and the regional and national setting (*both insert*). The site outline is marked by the dashed black line, with the external saltmarsh visible to the northeast and the sand dunes to the north and northwest.

2 Methods

2.1 Study Site

Cwm Ivy Marsh is situated on the Gower Peninsula (Figure 1), on the northern coast of the Bristol Channel; a major inlet on the south west coast of the UK which separate south Wales from southern

England. The site, which is located in the Loughor estuary, is banked by sand dunes and the open coast to the north and northwest, and an expansive area of saltmarsh to the northeast. Tidal waters are fed to the site through external marsh's dendritic creek network; there is limited freshwater input from springs from the cliffs behind the site. The site, which had previously been reclaimed in a number of stages, was formerly protected by a sea wall and drained into the surrounding marsh through a small sluice gate. To compensate for intertidal habitat loss elsewhere and reduce expenditure on unnecessarily maintaining flood defences of grazing land, Natural Resources Wales opted to stop maintaining the seawall. The site was naturally breached during a storm in August 2014, creating a new macrotidal semi-diurnal intertidal system in the approximately 383,000 m^2 of previously defended grazing land. Consequently, no engineering or design works were performed prior to site breaching.

2.2 Spatial variability in the accretion and erosion of sediment

2.2.1 sUAS image acquisition

To assess the spatial variability in sediment accretion and the resulting morphology and topography, an eBee Plus Real-Time Kinematic (RTK) fixed-wing small-unmanned aerial system (sUAS) was used to collect repeat aerial imagery. An initial survey was conducted on 10^{th} March 2015, commissioned by Natural Resources Wales and carried out by Future Aerial Innovations on behalf JBA Consulting. In the 2015 survey, 655 images were collected at a pixel resolution of 3.9 cm / pixel. A second survey was conducted by the authors (also commissioned by Natural Resources Wales) on 3^{rd} July 2019. Flight lines were completed on a grid pattern with an 80% lateral and longitudinal image overlap, and a total of 1047 images captured. Such large overlap values were selected to facilitate increased pixel matching and optimal orthomosaic production; analysis indicated an overlap of over 5+ images for every pixel, and an average of 950 matched 2D key points between image pairs. Multiple flights were flown at 90 m altitude and provided imagery at a pixel resolution of 2.2 cm / pixel. For the purpose of model accuracy, six ground control points (GCPs) were recorded using differential global positioning system (dGPS); measurements taken by a Leica AS19 GNSS antenna, a Leica Viva GS10 GPS receiver and a Leica CS15 controller. Raw GPS measurements were imported into Leica Geo Office (version 8.3). Network Receiver Independent Exchange Format (RINEX) correction data were obtained from Leica Smart Net UK & Ireland (http://uk.smartnet-eu.com/rinex-download_148.htm), and used for post processing of eBee Plus flight data and to correct the raw GPS data. Leica Geo Office reported the positional quality (XYZ) for all dGPS points as <0.02 m. In addition to the GCPs, nine independent check points were collected using dGPS to act as an assessment of model quality (see Supplementary Material for the sUAS properties used in this study).

2.2.2 sUAS image processing and morphological analysis

Dense point clouds were produced from optimised camera locations using mild-depth filtering to ensure small and important details were preserved using Pix4D mapper (version 4.2.27). The 2019 orthophotograph and DSM were compared to the previous survey (Future Aerial Innovations on behalf JBA Consulting) taken in 2015 in ArcMap (version 10.5.1). DSMs of Difference (DoD) analysis was performed to compare differences between the two modelled surfaces. It is important to consider the uncertainties and potential error propagation when comparing two different DSMs. Therefore, a specified level of detection (LoD) was applied, with any changes smaller than the LoD omitted from the analysis (James et al., 2017). The LoD was defined as:

$$LoD = \pm\, t\, (\sigma_{z1}^2 + \sigma_{z2}^2)^{1/2} \qquad \text{[Equation 1]}$$

where σ_{z1} and σ_{z2} are measures of the vertical error of the two DSMs (Lane et al., 2003), in this case the vertical standard deviations of error, and t is the required level of confidence (95 % used here).

Whilst comparing DSM may introduce error due to the inclusion of vegetation, the vegetated area of the site has been colonised by species with a low 'canopy' height such *Salicornia sp.*, *Puccinellia maritima*, and *Suaeda maritima*. Consequently, any error introduced is likely to be within the error of the elevation reconstruction (Hladik and Alber, 2012) particularly once the LoD has been applied, which in this instance was calculated to be ± 15 cm.

Morphological changes were assessed through analysis of the rugosity, an assessment of the surface heterogeneity, derived from the standard deviation of the elevation in a 3 x 3 pixel moving window (Lawrence et al., 2018). Prior to analysis of the 2019 DSM, which originally had a higher pixel resolution, the model was aggregated to coarsen the resolution in order to ensure consistency between the two models. Stream order analysis (Strahler, 1957) was conducted to evaluate the development of the sites drainage network morphology, following the calculation of the flow direction and accumulation, and visually confirmed through a comparison with the orthophotograph (Dale et al., 2020). The difference in total number of creeks in each order between the two surveys was assessed using a Pearson Chi^2 test. In addition, differences in creek length between the two surveys were assessed for each order using a Mann-Whitney U test as data were not normally distributed (assessed via a quantile-quantile plot), with the median, maximum, minimum, and total creek length also calculated for each order. Analysis was conducted using ArcMap (version 10.5.1) and Minitab (version 19).

2.3 Hydrodynamics, suspended sediment concentration and patterns of sedimentation

To assess the supply and movement of sediment, YSI EXO2 Sondes fitted with conductivity, temperature, depth and turbidity probes were deployed on scaffolding rigs over two spring tidal cycles between 13th and 14th June 2018. Measurements were logged every 10 seconds from an area of colonising saltmarsh and a mudflat environment, 0.39 m lower in elevation than the saltmarsh, and adjacent to the main drainage channels (Figure 1). The Sondes were deployed at 2.75 mOD (Ordnance Datum Newlyn) at the saltmarsh site and 2.73 mOD at the mudflat site. Turbidity probes were calibrated for SSC in the laboratory using filtered water samples taken *in situ*. To measure the pattern of sediment accretion and erosion over a typical tidal cycle at the mudflat site, high frequency bed elevation measurements were taken over the same period using an NKE ALTUS altimeter system. The altimeter consists of a 2 MHz acoustic transducer, supported above the sediment surface on a tripod, which measures the time required for the acoustic signal to return to the transducer from the sediment surface (Jestin et al., 1998), and was also set to measure every 10 seconds. Given that the site is fetch and depth limited, and wind levels were low during the measurement period, the impact of wave activity on the deposition and re-suspension of sediment was presumed to be negligible.

2.4 Sub-surface geochemistry and preservation of the terrestrial surface

Sediment cores were collected from both the saltmarsh site and the mudflat site at Cwm Ivy Marsh for analysis of the sub-surface geochemical profiles and the preservation of the terrestrial surface following site breaching and the accretion of intertidal sediment. Following extraction, samples were wrapped in film, transported back to the University of Brighton Geochemistry Laboratory, and refrigerated at 3.6 °C until analysis. Each core was logged and divided into 2 cm increments to measure a variety of sediment physicochemical characteristics. Specifically, the moisture content, organic content, particle grain size, and a suite of elements (Al, Fe, Mn, S, Ca and Na) were assessed, selected as these parameters have been used at sites such as Orplands Farm (e.g. Spencer et al., 2008), Medmerry (Dale et al., 2019) and Pagham Harbour (Cundy et al., 2002) to identify the terrestrial surface. Moisture content was measured following drying at 105 °C for 48 hours and calculated as the percentage weight loss. Loss of ignition, measured via combustion at 450 °C for six hours, was used as a proxy for organic matter. Particle grain size distribution was analysed using a Malvern Instruments Mastersizer Hydro 2000G Laser Diffraction Particle Size Analyser following treatment in hydrogen peroxide to remove organic matter and dispersion with sodium hexametaphosphate on a rotary shaker at 300 rpm for 2 hours to facilitate disaggregation. For each sample, three replicates were measured for all parameters.

To support identification of the terrestrial surface, the geochemical composition of the samples was examined. Samples were digested in aqua-regia (1:3 molar ratio of $HCl:HNO_3$) for three hours in a dry heat block at 80 °C. Samples were filtered through a 0.2 µm syringe filter before dilution in distilled water at 1:10. Samples were analysed for a suit of elements using a Perkin Elmer Optima 2100 DV ICP-OES. Samples were analysed alongside the Mess-4 Marine Sediment Certified Reference Material (National Research Council Canada) and process blanks to assess the accuracy of extraction. Recovery values were generally within ± 20 % (see Supplementary Material) and process blanks were below the detection limits. Repeat samples were run in triplicate every 10 samples and were typically within ±10 % throughout.

3 Results

3.1 Morphological Development

Analysis of the two small-Unmanned Aerial System (sUAS) topographic surveys showed that, over the four-year period, 55.24 % of the 383,000 m^2 new intertidal area experienced a change in elevation above the level of detection (LoD). Of this area, 22 % (12 % of the entire site) experienced erosion, with sediment accreting in the other 78 % (43 % of the entire site). Erosion was limited to the areas around the main channels running through the site, apart from in the south-western corner of the site where the surface elevation decreased by between 0.2 and 0.3 m between the surveys (Figure 2). The majority of the accretion above the LoD occurred through the centre of the site, to the north of the main channel. Between 15 and 30 cm of sediment was accreted in these areas, giving an average annual accretion rate of 3.75 to 7.5 cm / year. Along the northern side of the site a larger increase in surface elevation of approximately 50 cm was detected. However, given the distance from the main creek network, the relatively high elevation, and the comparably large change in elevation, this area may well consist of transitional or freshwater vegetation; with this change reflective of vegetation growth rather than the accretion of sediment (e.g. Enwright et al., 2018).

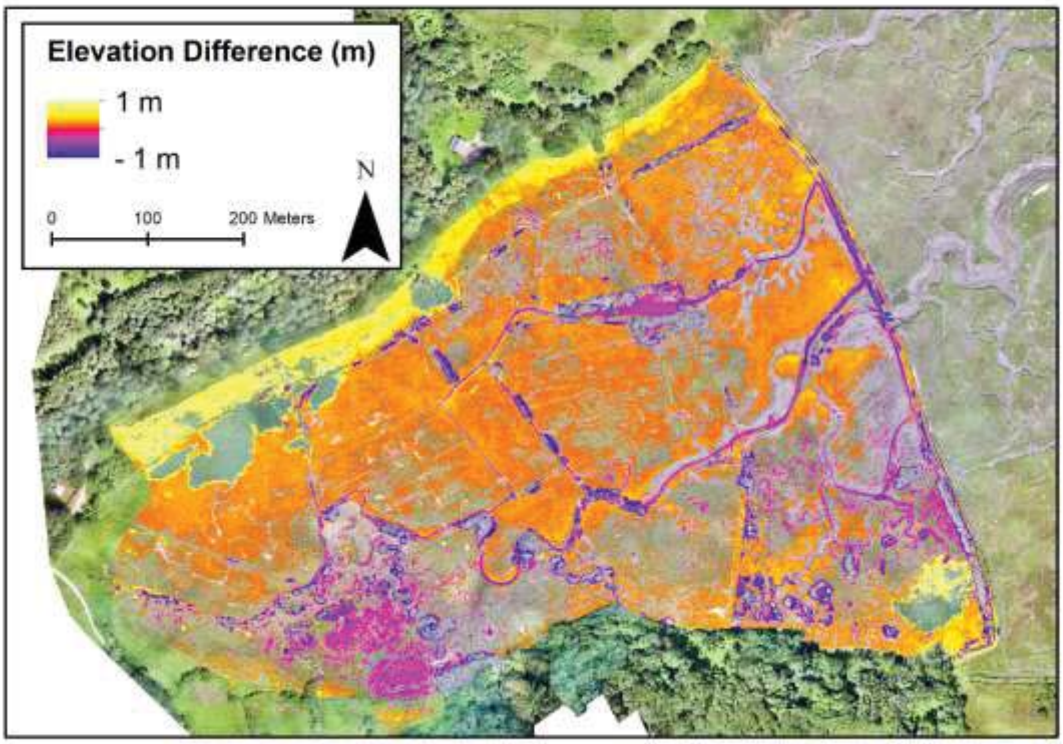

Figure 2: DSM of Difference (DoD) analysis of the change in elevation between the 2015 and 2019 sUAS surveys at Cwm Ivy Marsh, Wales.

Analysis of the resulting morphological change indicated that the topography within the site became less variable between the two surveys, with the rugosity decreasing from 0.034 to 0.029. Strahler stream order analysis (Figure 3) detected 1047 creeks in 2015 and 1007 creeks in 2019, categorised into six orders. Pearson Chi^2 analysis indicated a significant difference ($\chi^2 = 39.95$, $p < 0.01$) in the number of creeks in each order between the two surveys, with fewer lower order and increased higher order creeks being detected in 2019 (Table 2). However, only first order creeks were found to be significantly different in length ($p < 0.01$), with differences in total length due to changes in the number rather than characteristics of the creeks themselves.

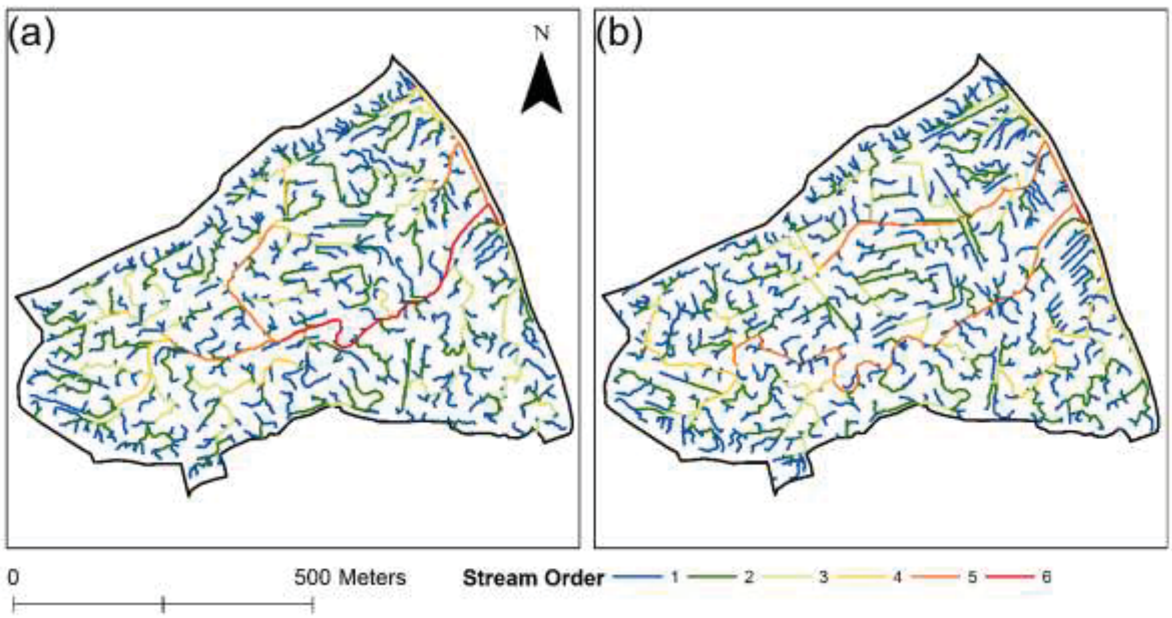

Figure 3: Strahler Stream Order analysis of the creek networks in Cwm Ivy Marsh, Wales in (a) 2015 and (b) 2019.

Table 2: Number of creeks and median, maximum, minimum and total creek length (m) for each order determined by Strahler Stream Order analysis of the 2015 and 2019 digital surface models from Cwm Ivy Marsh, Wales.

		First Order	Second Order	Third Order	Fourth Order	Fifth Order	Sixth Order
Number of Creeks	2015	531	278	131	52	32	23
	2019	511	247	108	58	80	3
Median Length (m)	2015	14.30	15.48	17.46	13.35	16.71	24.30
	2019	16.24	16.76	18.60	16.16	15.97	12.79
Maximum Length (m)	2015	111.87	110.80	111.63	95.06	85.29	103.50
	2019	80.33	148.33	75.48	97.61	98.12	37.78
Minimum Length (m)	2015	0.30	0.28	0.28	0.28	0.28	1.28
	2019	0.20	0.28	0.28	0.28	1.57	1.80
Total Length (m)	2015	10168.07	5782.77	2916.36	966.03	685.35	562.24
	2019	11018.47	5403.70	2255.97	1153.20	1554.26	14.59

3.2 Patterns of sedimentation

The maximum recorded water depth was 4.34 m OD at the saltmarsh site and 4.39 m OD at the mudflat site, with the water level falling below the sensor during low water at both sites. Peaks in the SSC (Figure 4) occurred at the onset of the flood tide and towards the end of the ebb tide at both sites when, typically, the current velocity would be at a maxima; suggesting both the landward and seaward movement of sediment. Average SSCs per tidal phase were marginally greater during the flood tide than the ebb at both the saltmarsh site (Tide 1: 0.12 g/l vs 0.06 g/l, Tide 2: 0.19 g/l vs 0.08 g/l) and the mudflat site (Tide 1: 0.15 vs 0.11 g/l, Tide 2: 0.21 vs 0.14 g/l). As no current velocity measurements were collected during this study the sediment flux and net direction of sediment transport could not be calculated. However, some variability was detected in the SSC at the saltmarsh site during the flood tide, which is probably related to the flooding pattern and drainage system characteristics within the site. Changes in bed elevation at the mudflat site (Figure 4e-f) followed a pattern of sedimentation then erosion during both the flood and ebb tidal phases, with a net increase in bed elevation of 0.1 cm during Tide 1 and 0.3 cm during Tide 2.

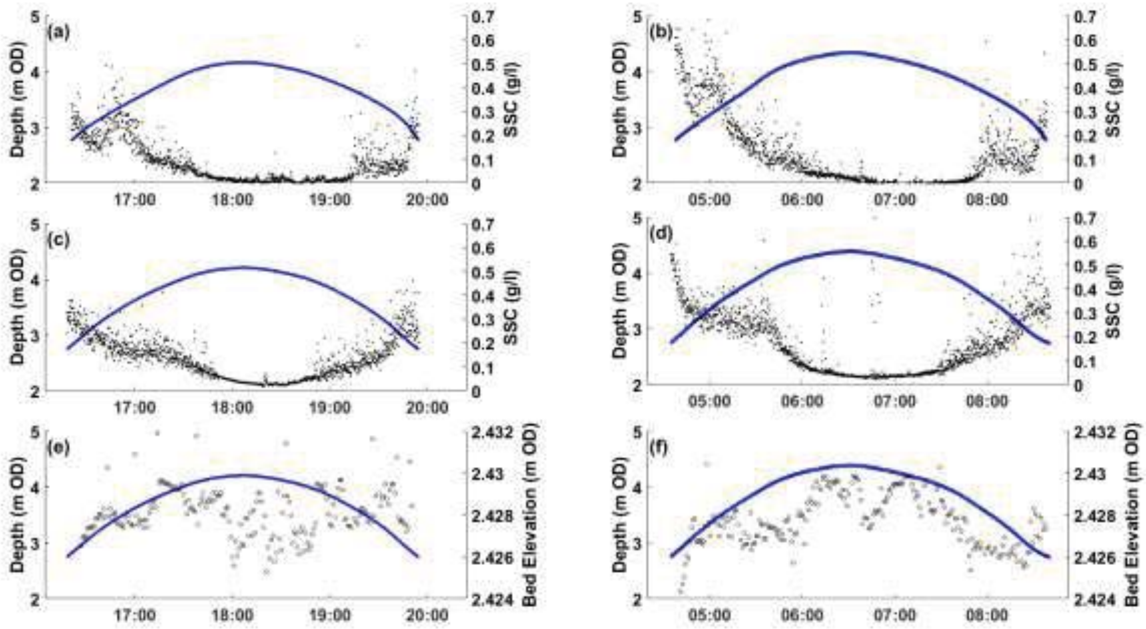

Figure 4: Changes in depth (blue solid line) and suspended sediment concentration (SSC, dots) for Tide 1 (left side) and Tide 2 (right side) at (a-b) the saltmarsh site (c-d) the mudflat site, and changes in bed elevation (averaged every minute for presentation purposes, circles) at (e-f) the mudflat site at Cwm Ivy Marsh, Wales. The time period for sampling (24H) is indicated by the x-axis.

3.3 Subsurface structure and geochemistry

At both sites clear vertical zonation was exhibited visually, with the cores divided into a lower terrestrial unit and an upper post-breach intertidal unit dating from August 2014. At both sites, this horizon occurred at 12 cm depth. The upper section of the 28 cm core retrieved from the saltmarsh site consisted of compact, grey, clay rich sediment with vertical root material. Following a sharp boundary at the horizon between the two units, the lower section of the core was more friable with evidence of red mottling and organic root material. At the mudflat site, where a 38 cm core was retrieved, the upper 12 cm consisted of dark, black clay and silt rich sediment. Below a sharp boundary at the horizon, the lower terrestrial unit was more friable and contained a higher proportion of silt and sand. A large amount of root and organic material was found at, and below, the horizon.

Confirmation of the location of the pre-breach terrestrial surface was assessed through analysis of the sub-surface physicochemical profiles. At the saltmarsh site (Figure 5a), moisture content and loss on ignition decreased with depth. Both of these parameters were greater at the mudflat site (Figure 5b), where a similar trend was observed with both parameters peaking at the terrestrial / intertidal sub-surface horizon. Median grain size was relatively similar at both sites in the intertidal units, although more variability was observed at the mudflat site. In the terrestrial sections, median grain size increased at 26 cm at the saltmarsh site and 22 cm at the mudflat site, possibly the result of aeolian sediment transport from sand dunes located to the north and northwest of the site.

Figure 6 presents the major element data (Al, Fe, Mn, S, Ca and Na) for both sites. As grain size varied with depth, concentrations of Fe, Mn, S, Ca and Na have been geochemically normalised to Al (after Spencer et al., 2008). The diagenetic enhancement of Fe and Mn in oxic saltmarsh sediments has been recognised and described in depth elsewhere (e.g. Cundy and Croudace, 1995; Spencer et al., 2003; Zwolsman et al., 1993). Concentrations of Fe and Mn fluctuated throughout the sediment at the saltmarsh site, with no major peaks or trends. This, along with the evidence of red mottling caused by the presence of Fe-oxyhydroxides (Zwolsman et al., 1993) indicates a fluctuating water table, and periodic shifts from oxidising to reducing conditions during tidal inundation. The saltmarsh site showed a depletion of S except in the upper 6 cm, probably due to the introduction, percolation and evaporation of sea water, rather than the bacterial reduction of sulphate. Both Ca and Na fluctuated with Ca, decreasing slightly with depth.

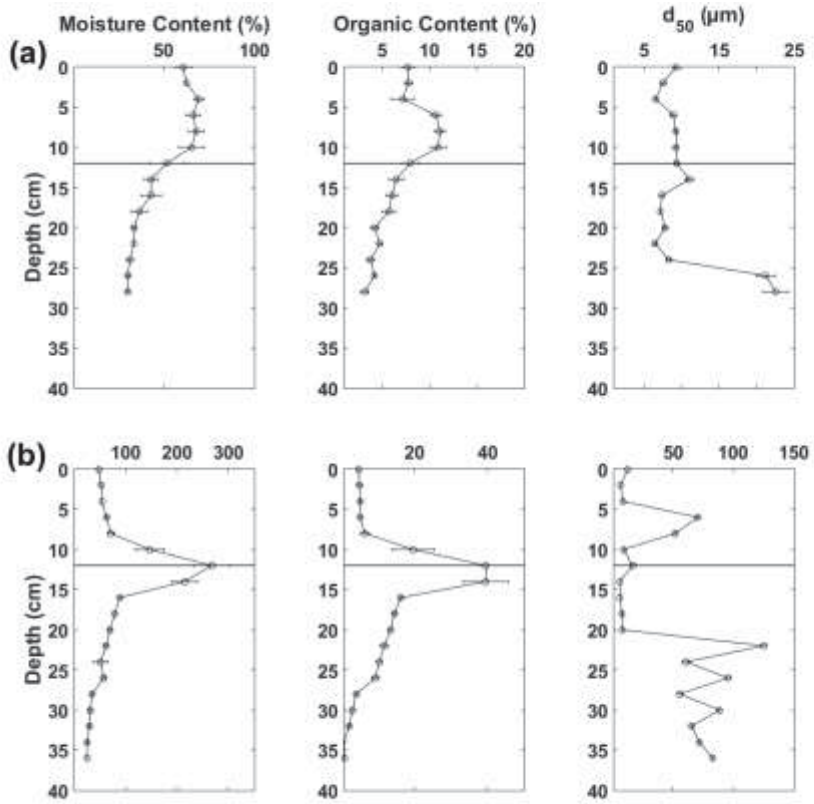

Figure 5: Moisture content, loss on ignition and median grain size (d_{50}) with depth (n = 3) for (a) the saltmarsh site and (b) the mudflat site at Cwm Ivy Marsh, Wales. The solid line marks the position of the solid boundary between the two units.

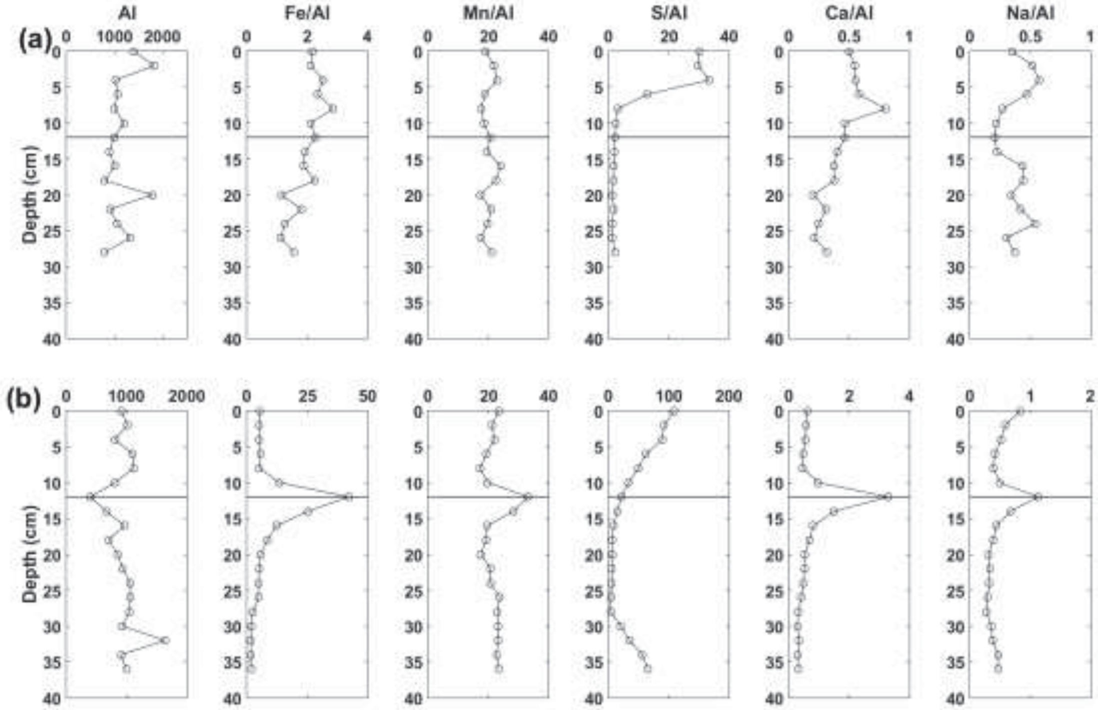

Figure 6: Variations in Al, Fe, Mn, S, Ca and Na with depth (n = 3) for (a) the saltmarsh site and (b) the mudflat site at Cwm Ivy Marsh, Wales. The solid line marks the position of the solid boundary between the two units.

At the mudflat site a greater concentration of S was found, suggesting conditions are permanently reducing and the supply of oxygen limited. A peak in Fe and Mn concentration was found at the terrestrial / intertidal boundary, indicative of the remobilisation of Fe and Mn from the reducing sediments. This may well be caused by poor hydrological connectivity resulting in water being unable to penetrate through the terrestrial surface and flowing along the interface between the two units, explaining the high moisture content found at this depth. Evidence of vertical inhabitation of saline water is supported by peaks in the Ca and Na concentrations at the interface between the two units.

Further confirmation of the location of the pre-breach terrestrial surface is possible through Principal Component Analysis (PCA) of the sediment physicochemical properties. PCA is a technique used to reduce the dimensionality of data through the calculation of a series of new variables, or principle components, through linear combinations of the original parameters (Reid and Spencer, 2009). This multivariate technique has previously been used successfully elsewhere in coastal sediments to (partially) discriminate physiochemical datasets (e.g. Cundy et al., 2006; Dale et al., 2019), and was used here to group different depths based on their variability in sediment physicochemical properties. Results indicated that, at the saltmarsh site (Figure 7a), the first component accounted for the greatest variability (PC1 = 46%, Eigenvalue = 4.10) and described a clear separation in the sediment physicochemical properties between identified intertidal and terrestrial units (Figure 7a). Limited discrimination was found in the subsequent principal components (e.g. PC2 = 22%, Eigenvalue = 1.98). Conversely, the mudflat site (Figure 7b) showed the clearest separation between terrestrial and intertidal sediment physicochemical properties through the second component scores (PC1 = 64%, Eigenvalue = 5.76; PC2 =16%, Eigenvalue = 1.47). The first component showed the greatest variability was between the samples at 12 and 14 cm depth, the horizon between the intertidal and terrestrial layers, likely to be the result of peaks in the moisture content, organic content and Fe, Mn, Ca and Na.

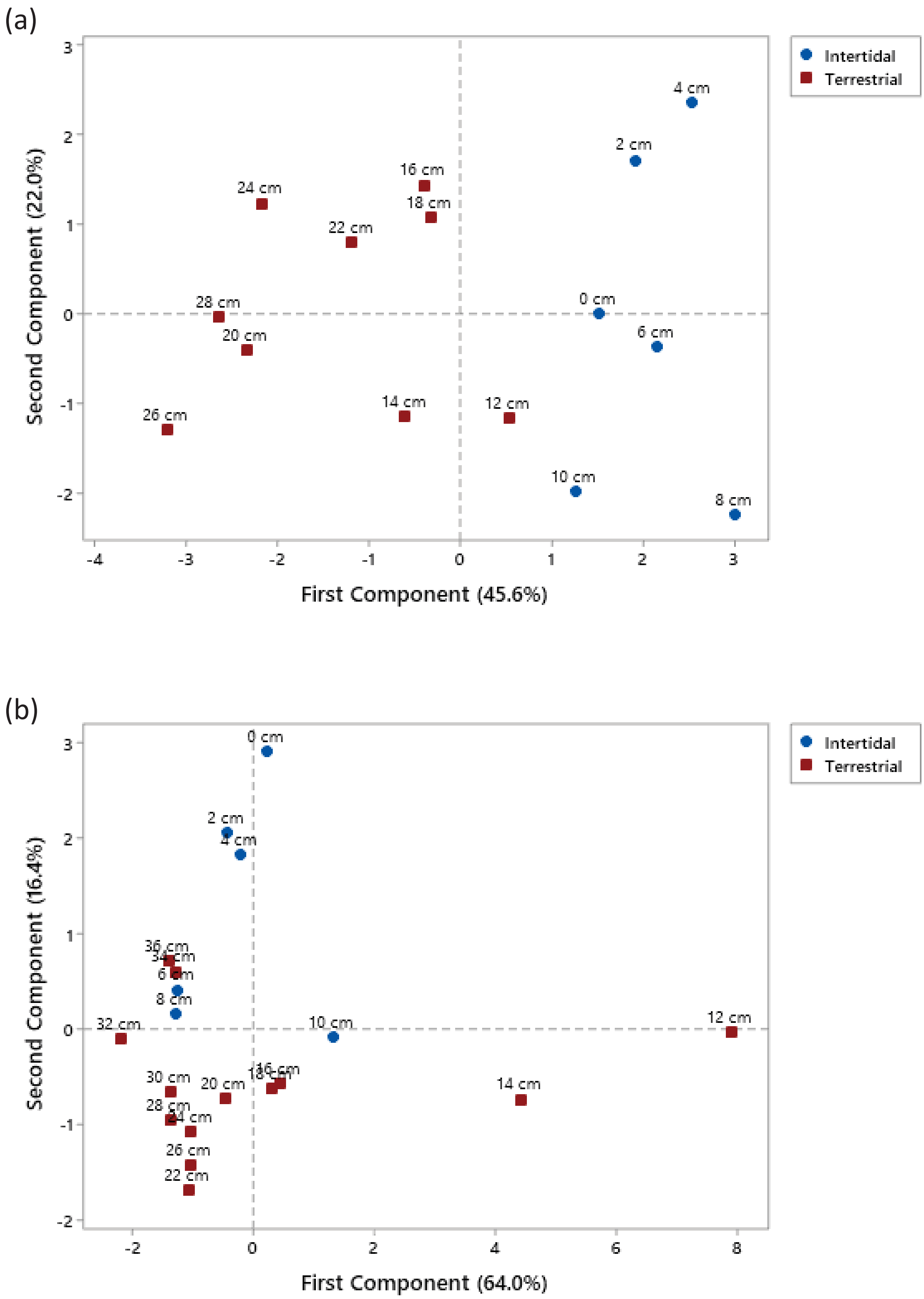

Figure 7: Principal component analysis for (a) the saltmarsh site and (b) the mudflat site of the physicochemical properties for different depths at Cwm Ivy Marsh, Wales. Blue circles represent depths identified visually as being the post-site breaching intertidal unit, and red squares are the

terrestrial unit. Collectively, components 1 and 2 accounted for 67.5% of the variability at the saltmarsh site and 80.3% of the variability at the mudflat site.

4 Discussion

4.1 Surface Morphological Evolution

Examination of the spatial and temporal pattern of erosion and accretion at Cwm Ivy Marsh, presented via an innovative combination of sUAS derived topographic and morphological, hydrological and geochemical analysis, provides a new insight into the development of newly inundated intertidal wetlands. Evaluation of whole site topographic variability, assessed through analysis of the DSM rugosity, indicated a decrease in surface heterogeneity between the two surveys; and highlights the importance of full-site assessment. Elsewhere, rugosity has been demonstrated to correlate positively with number of creeks (Lawrence et al., 2018) with analysis of the creek network at Cwm Ivy Marsh corroborating this finding; the number of creeks also decreased between the two surveys. These findings are also similar to those of Dale et al. (2020) who observed a reduction in the number of creeks, albeit within a much smaller study area, which the authors associated with an increase in the prominence of some of the channels in terms of site drainage.

As a non-engineered site, Cwm Ivy Marsh did not experience any artificial channel creation, excavation or re-profiling, which is common practice in large engineered sites (Burgess et al., 2014; Dale et al., 2018b). Previous studies have also identified pre-existing terrestrial features such as relic plough lines as a major influence on creek development in MR sites (Dale et al., 2020; French and Stoddart, 1992). However, the Cwm Ivy site was used predominantly for grazing and is not known to have experienced intensive arable agricultural activity. Nonetheless, the site is still developing a functioning drainage system utilising the pre-existing areas of lower elevation, remnant pre-reclamation creeks and artificial drainage networks. This is evident from the combination of both dendritic channels and straighter channels running parallel to the old sea wall, perpendicular to the direction of higher order creeks, and in some cases away from the breach area. Consequently, these results indicate that, providing some form of drainage systems exist, MR sites are still capable of developing functioning intertidal morphology without the need to extensive site landscaping. The site is also appearing to decrease in topographical variability. This may inhibit the formation of the distinct elevational niches required by saltmarsh plants (Masselink et al., 2017; Sullivan et al., 2017), although further research is required to assess the relationship between saltmarsh coverage, colonisation and morphology in non-engineered MR sites, and restored saltmarshes more widely.

Analysis of the spatial pattern of accretion and erosion was performed via DoD analysis of the DSMs, recognising the limitations of LoD factors. Results indicated that erosion was limited to the area around the channels with accretion occurring across the majority of site, particularly to the north of the main channel. In these areas sediment accreted at a rate of 3.75 to 7.5 cm / year. This rate of accretion is slightly higher than that calculated through analysis of the accretion above the terrestrial surface recorded in the sediment cores retrieved from Cwm Ivy Marsh, which indicated that an accretion rate of 3 cm / year. However, it is worth to note that 3 cm / year, equivalent to 12 cm of accretion, would have returned a change in elevation below the LoD (± 15 cm) for these surveys.

These results highlight the importance for continuing to advance high resolution, site-wide, empirical studies of this nature through a combination of repeat high spatial resolution remote sensing or sUAS approaches, alongside high temporal resolution analysis using equipment such as the ALTUS used in this study.

Sediment was accreted and eroded during both the flood and ebb tides were measured by the ALTUS system deployed at Cwm Ivy Marsh, which differs from the patterns found elsewhere within natural intertidal sites. For example, Deloffre et al. (2007) detected a pattern of accretion during the flood tide and dewatering and erosion during the ebb in the Seine estuaries, which has a similar rate of sediment accumulation to those measures here for Cwm Ivy Marsh. Furthermore, a pattern of sedimentation on the flood tide and stability during the ebb was measured for the Authie estuaries by Deloffre et al. (2007). A similar pattern to the Authie was found at the Medmerry Managed Realignment Site, at a near breach site, by Dale et al. (2017), whilst in the centre of the site the pattern followed a trend of accretion on the flood and erosion on the ebb (Dale et al., 2017; Dale et al., 2018b). However, Cwm Ivy marsh differs from these three sites as, unlike the Seine and the Authie, there is negligible fluvial input and there is a much larger tidal range than Medmerry. This, therefore, highlights the importance of the internal and external hydrodynamics (such as the current velocity, tidal input and fluvial input) on the deposition and accretion of sediment, which in turn influences the physical functioning post-site breaching and morphological evolution of the site.

The pattern of sedimentation is also determined by the post site breaching supply and internal redistribution of sediment. Peaks in the SSC were observed on the flood and ebb tide at both sites, although the source of the sediment remains unknown. Some of this sediment may be material internally redistributed around the site as the sediment regime adjusts to intertidal conditions.

However, previous studies from MR sites in sediment rich estuaries, fronted by natural saltmarshes, have suggested that the transported and accreted sediment has originated from external sources (e.g. Rotman et al., 2008; Symonds and Collins, 2005). Whilst no measurements of the fluxes of SSC were recorded in the breach for this study, it is highly likely that the channel feeding into Cwm Ivy Marsh has been the major source of sediment. An examination of the two orthophotographs and DSMs, collected as part of the sUAS analysis, indicated that from the channel immediately flowing into the site 29392 m^3 of sediment were eroded from a 2424 m^2 area of saltmarsh between March 2015 and July 2019 (Figure 8). In addition, the breach has widened from 9.96 m (2015) to 14.79 m (2019) during this time. This erosion and channel widening will have been caused by an increase in discharge and velocity within the channel owing to the increased transfer of water following site breaching, providing a readily available source of sediment to the Cwm Ivy site.

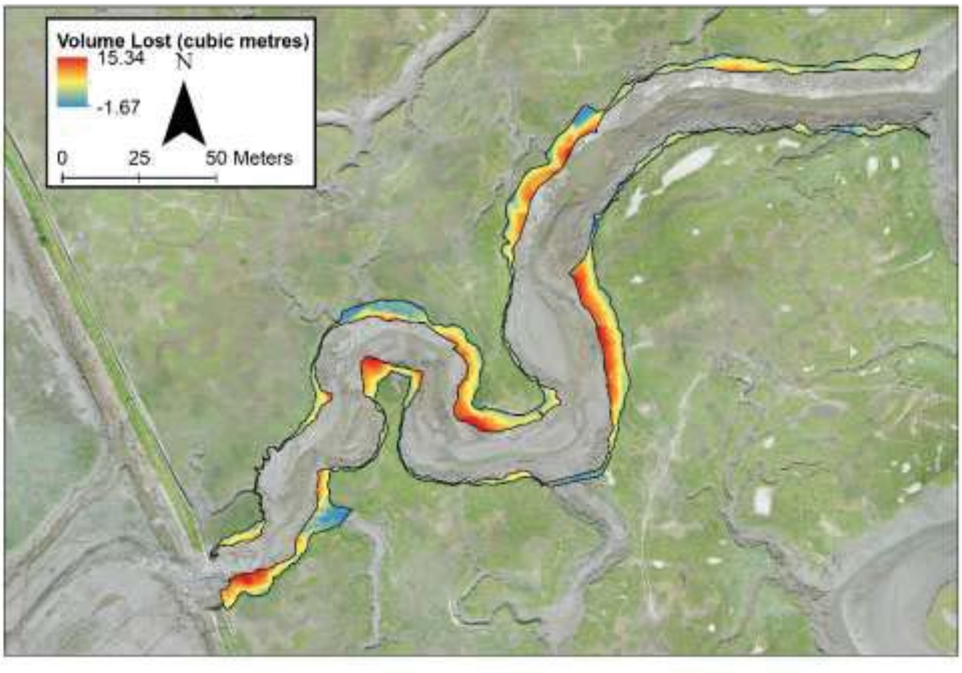

Figure 8: Volume of sediment lost (m^3) per 4 m^2 pixel from the channel leading into Cwm Ivy Marsh, Wales.

The previous understanding of the morphological evolution of recently inundated saltmarsh sites is largely derived from theoretical models (e.g. Allen, 2000), which suggest that initially high rates of sedimentation should be expected following site breaching. In addition, some field-based measurements (e.g. Dixon et al., 2008; Virgin et al., 2020) do exist, however most empirical measurements of the morphological development post-site breaching have been calculated from heavily engineered sites, using either sediment cores or traditional remote surveying techniques such as LiDAR or GPS (Chirol et al., 2018; Cundy et al., 2002; Dale et al., 2018a; Lawrence et al., 2018; van Proosdij et al., 2010; Virgin et al., 2020). As a result of the lack of full site, high resolution spatial analysis, combined with specific high-frequency field measurements of the sedimentological processes important morphological changes that are smaller than the surveying resolution are likely to have been missed.

In addition to limitations resulting from the resolution of previous studies, the evolution of the sites examined in these investigations may have been influenced by site design and landscaping processes. Therefore, the development of these sites may not be representative of the morphological evolution resulting from the introduction of tidal inundation. For example, Dale et al. (2017) measured a similar rate of accretion at the centre of the Medmerry Managed Realignment Site to those measured in this study, regardless of the temporal variability. Conversely, the accretion rates at Cwm Ivy were considerably lower than those observed in an area of lower elevation near the breach at the Medmerry site by Dale et al. (2017). However, these measurements were taken at locations which had been artificially lowered during site construction to encourage a range of intertidal habitat, creating accommodation space for sediment to be accreted. In contrast, no engineering works took place at Cwm Ivy Marsh prior to site breaching, and therefore allows for the rate of accretion to be assessed without the influence of engineering and site landscaping, which is often carried out on the basis that it would enhance site development.

Further work is required to assess the external and internal sources of sediment, and to determine the areas of deposition, to calculate the changes in sediment volume and the sediment budget as sites develop following the introduction of intertidal inundation. This is particularly the case for non-engineered sites to further the understanding of influence site design and pre-breach landscape have on the functioning and evolution of the sediment regime. This will, in turn, inform analysis of the physical functioning and the morphological evolution of MR sites which has been recognised to differ between MR sites and equivalent natural marshes (Lawrence et al., 2018). Many sites are subject to extensive engineering based on numerically modelled site designs derived simply on the hydroperiod (frequency and duration of inundation) and the elevation. These parameters are often considered equal to parameters such as the aesthetics, and other factors which may not be most suitable for a natural system. For example, Steart Managed Realignment Site was designed with a herringbone channel pattern, rather than a natural dendritic creek network, due to concerns of the safety of cattle grazing the marsh during the rising flood tide (Burgess et al., 2014). As a result, it is possible that the site design and landscaping may hinder the hydrological evolution and physical functioning of engineered MR sites.

Analysis of non-engineered MR sites will also validate predictions of future non-engineered MR sites (e.g. Krolik-Root et al., 2015), breached following policies no active intervention and the decision to no long maintain defences in selected located. In addition, non-engineered MR sites provide a modern analogue for historically breached sites, such as Pagham Harbour, West Sussex, UK, and locations around the Essex (southeast England) coastline (Cundy et al., 2002; Spencer et al., 2017). These sites have often been identified as natural field laboratories for assessing the potential longer-term outcome for modern day MR sites. Comparisons of the processes in modern engineered and non-engineered MR sites will allow for the evaluation of the suitability of this approach, and validate the use of older naturally breached sites to estimate the evolution of future MR schemes.

4.2 Evolution of the sediment sub-surface and the preservation of the terrestrial surface

Analysis of the rate of accretion following site breaching was possible via visual detection of terrestrial surface, and confirmed through PCA of the sediment physicochemical properties. Visual detection of the terrestrial surface has been performed elsewhere at similarly aged sites such as the Medmerry Managed Realignment Site (Dale, 2018), although considerably more intertidal sediment has been accreted at Cwm Ivy Marsh following site breaching. At older accidently breached and MR sites, including Pagham Harbour and Orplands Farm (Cundy et al., 2002; Spencer et al., 2008), the terrestrial surface could not be detected visually. The interface between the terrestrial and intertidal units could only be identified through analysis of the physicochemical properties, and detailed three-dimensional analysis of the sediment structure (Spencer et al., 2017), highlighting the transient nature of analysis of developing intertidal sites. Nonetheless the findings this study, compared to these observations from elsewhere, indicate that the ability to detect the terrestrial surface is a function of time since intertidal inundation, and not the result of changes to the sediment sub-surface.

Analysis of the sub-surface geochemical properties at Cwm Ivy Marsh indicate a fluctuating water table in the freely draining sediment of the saltmarsh site. This is consistent with the redox profiles typically found in natural intertidal environments (e.g. Cundy and Croudace, 1995), suggesting that reduced hydrological connectivity and an aquaclude-like horizon, found in other, older MR sites (e.g. Boorman, 1992; Hazelden and Boorman, 2001; Tempest et al., 2015), is not present. As would be expected, anoxic conditions were found at the mudflat site. However, some evidence of the remobilisation of Fe and Mn, potentially caused by an aquaclude horizon, was also found, although given the peak in organic content at this depth the increase in Fe and Mn may also be caused by the decay of freshwater vegetation buried under the accreted sediment (Macleod et al., 1999). Reduced hydrolological connectivity has been associated with modifications to the sediment structure due to dewatering and organic matter mineralisation, as a result of the agricultural activity (e.g. Crooks and Pye, 2000; Crooks et al., 2002). Given that the terrestrial land use of Cwm Ivy Marsh was predominantly sheep grazing land, and the site was not subject to any pre-inundation landscaping, it is unlikely to have experienced the same level of disturbance (compaction, collapse of pore-space, construction of artificial drainage features) as other MR sites (Burgess et al., 2014; Spencer et al., 2017). This in turn appears to be allowing for a more natural intertidal system to develop, maximising the potential for ecosystem service provision, such as habitats and nursery grounds for fish species.

5 Conclusion

High spatial resolution topographic models, innovatively combined with short-term high frequency hydrological, bed elevation and sediment core data have been examined to assess the morphological evolution of a non-engineered MR site. During the flood tide SSC decreased, and increased during the ebb, suggesting sediment is transported landwards during the incoming tide and flushed seaward during the outgoing tide. Bed elevation increased and decreased during both the flood and ebb tides, with this pattern resulting in a sedimentation rate of 3 to 7.5 cm / year. Following four years of intertidal inundation the site has developed morphologically, yet the terrestrial surface could still be detected both visibly and via analysis of the physicochemical properties.

Cwm Ivy Marsh had previously been used for sheep grazing, and was not subjected to intensive agricultural activity or extensive site design and landscaping prior to tidal inundation. Nonetheless, as the site has developed pre-existing features such as reclamation drainage channels and areas of lower elevation have contributed to site development. This highlights the importance of evaluating, and utilising where appropriate, the on-site terrestrial morphology during site design and in predictions of site evaluation. Furthermore, whilst differences between the terrestrial and intertidal sediment units could be detected, particularly following PCA of the sediment properties at different depths, the geochemical composition of the sediment subsurface followed the trends expected in a natural intertidal environment. This contrasts with analysis of other (older) MR sites where changes in the sediment structure have been detected as a result of the former agricultural land use, which has been recognised to lower hydrological connectivity leading to reduced biodiversity and abundance of key saltmarsh species.

This paper addresses this shortage of baseline data via a novel combination of high frequency and high spatial resolution datasets. Further analysis of sites like Cwm Ivy Marsh, including longer-term analysis of the erosion, transportation, deposition and consolidation of sediment, is required to further the understanding of evolution of MR sites without the influence of these processes. This can then inform coastal managers and decision makers in terms of the location and design of future MR sites in order to reduce the influence of alterations to the sediment structure and to evaluate the need for costly engineering works prior to site breaching. This will maximise the extent to which the physical functioning of MR sites represents a natural intertidal environment, increasing the delivery of key ecosystem services provided by these sites.

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