

Research article

Hydrodynamic and sedimentary processes in sedimentation fields: the requirement for continued maintenance to preserve restored intertidal habitat

Jonathan Dale ^{a,*}, Cai J.T. Ladd ^b, Michelle Farrell ^c, Michael P. Kennedy ^{c,d}, Gabriela Ciappara ^a, Chloe James ^{e,f}, Iain Fairley ^e

^a Department of Geography and Environmental Science, University of Reading, Reading, RG6 6DW, UK

^b Department of Geography, Swansea University, Swansea, UK

^c Centre for Agroecology, Water and Resilience, Coventry University, Coventry, CV1 5FB, UK

^d Environmental & Geographical Sciences, University of Northampton, NN1 5PH, UK

^e Natural Resources Wales, Maes Newydd, Llandarcy, Neath, SA10 6JQ, UK

^f Cornwall Wildlife Trust, Five Acres, Allet, Truro, TR4 9DJ, UK

ARTICLE INFO

Keywords:

Saltmarsh
Restoration
Sedimentation fields
Sedimentary processes
Sediment properties
Hydrodynamics

ABSTRACT

Globally, approximately 46.4% of saltmarsh has been lost or degraded. Sedimentation fields are one method of restoring and creating compensatory intertidal habitat, by enclosing mudflat to reduce hydrological forcing, trap sediment, and encourage saltmarsh establishment. To date, sedimentation fields have predominantly been studied using numerical models or with a focus on the initial deposition of sediment and plant colonisation. Consequently, it remains unknown whether the created habitat in sedimentation fields can become self-sustaining or whether there is a need for continued maintenance to prevent subsequent erosion. Here, we present a novel empirical investigation of Rumney Great Wharf, Wales, where sedimentation fields were constructed between 1989 and 2005 but no maintenance has been carried out since 2010. Hydrodynamic measurements indicate greater spatial differences in current velocity during the summer, and that suspended particulate matter was higher outside the sedimentation fields in comparison to inside the enclosed area during the summer but not during the winter. Between May 2023 and 2024, 87% of the surface area of the sedimentation fields experienced erosion resulting in the net loss of 9531 m³ of sediment. This loss occurred despite indications from on-site sediment trap data that there is the potential for sediment to accrete at more than 10 cm/year at mudflat sites and up to 9 cm/year at saltmarsh sites. These results suggest that the created marsh is not self-sustaining, and continued maintenance of the sedimentation fields might be required. Further research is required into sedimentary processes in sedimentation fields, both to inform the management of such schemes and to identify suitable locations for future sedimentation field construction. Assessments of marsh functioning and ecosystem service delivery in sedimentation fields are also needed to provide justification for future implementations of this restoration method.

1. Introduction

Approximately 5.1 to 5.3 Mha of the Earth's surface is occupied by saltmarsh habitat (Pendleton et al., 2012; Worthington et al., 2024). These environments provide important ecosystem services such as flood defence, carbon sequestration, and water quality regulation (e.g. Barbier et al., 2011; Costanza et al., 1997). Despite the importance of this habitat, it is estimated that 46.4% of saltmarsh globally has been lost or

degraded (Brook et al., 2025). These losses are largely due to the influence of human activity such as land claim, erosion caused by rising sea levels, and reductions in sediment supply (e.g. Doody, 2004; Gedan et al., 2009; Schuerch et al., 2018). Consequently, several nature-based solutions have been employed to restore and create habitat to compensate for the loss of saltmarsh (Pontee et al., 2021). These methods either restore marsh that is eroding, degrading or has been lost through, for example, land claim, or create marsh in new locations

* Corresponding author.

E-mail address: j.j.dale@reading.ac.uk (J. Dale).

<https://doi.org/10.1016/j.jenvman.2026.129798>

Received 11 November 2025; Received in revised form 16 April 2026; Accepted 24 April 2026

Available online 4 May 2026

0301-4797/© 2026 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

where it is currently not present. Approaches to marsh restoration and creation can be divided into three broad categories: (1) reintroduction of tidal inundation, (2) transplanting vegetation, (3) enhanced sediment deposition.

Reintroduction of tidal inundation to restore saltmarsh involves the breaching, lowering or removal of coastal flood defences such as sea walls and dykes, usually to reinstate tidal inundation to areas which have previously been embanked and drained through land claim. This can be achieved through either managed or unmanaged realignment, or regulated tidal exchange. However, it is not possible to allow tidal inundation in all previously reclaimed areas due to concerns such as soil contamination, infrastructure, and site elevation (e.g. Dale and Arnall, 2024). Furthermore, issues such as poor drainage and reduced topographic variability in these sites have been associated with anoxia and inhibited saltmarsh development (e.g. Lawrence et al., 2018; Mossman et al., 2012; Spencer et al., 2017; Tempest et al., 2015).

In areas where reintroduction of tidal inundation is not possible, marsh is already present, or restoration is envisioned without breaching defences, transplanting of vegetation has been carried out to stabilise marshes and reduce marsh recession (e.g. Liu et al., 2024). For example, species of *Spartina* have historically been used globally to stabilise marshes (Cao et al., 2018; Ladd, 2021), although there are now concerns in some regions that *Spartina* has become invasive and is impacting ecosystem functioning (e.g. Zhao et al., 2020). Recent attempts to transplant other marsh species that are more appropriate for the local environment have demonstrated some evidence of successfully restoring marsh biogeomorphic processes. This includes the transplanting of *Bolboschoenus maritimus* in the Eden estuary of Scotland, although assessments of this scheme have indicated that the restored marsh did not provide comparable rates of sediment retention to naturally vegetated areas (Taylor et al., 2019).

As an alternative method to compensate for saltmarsh loss, the bed elevation can be increased to a position within the tidal frame which is more suitable for saltmarsh growth by enhancing the deposition of sediment. This can be achieved using three approaches: (1) sediment can be deposited artificially, for example through the beneficial use and disposal of dredge material (e.g. Baptist et al., 2019); (2) artificial structures can be erected to retain deposited material and enhance sedimentation rates by reducing current velocity and wave height (e.g. Siemes et al., 2020); (3) a combination of both structures and dredge material (Baptist et al., 2021). Sedimentation enhancing structures can either be constructed within or outside of areas of pre-existing saltmarsh. For example, coir rolls can be installed in channels within the saltmarsh to create a partial dam and encourage sediment accumulation in smaller creeks to restore the marsh (e.g. Pontee et al., 2021). Alternatively, structures can be built to create saltmarsh in areas of mudflat, including small-scale interventions such as sandbags (e.g. Gonçalves et al., 2025) or larger scale features including breakwaters (e.g. Vona et al., 2020), net structures such as the 'derosion lattice' (Hung et al., 2025), and sedimentation fields (Scarton et al., 2000; Siegersma et al., 2023).

This study focuses on sedimentation fields, which are typically constructed using brushwood groynes and fencing to (partially) enclose an area of intertidal mudflat with the intention of trapping sediment and encouraging saltmarsh to grow (e.g. Boumans et al., 1997; Reeder et al., 2021). Historically, they have been used extensively in areas of the Danish, Dutch and German Wadden Sea for agricultural land claim, where approximately 50% of the saltmarsh has been created or managed in this way (Pontee et al., 2021). More recently, similar schemes have been used to create and stabilise eroding saltmarsh (Scarton et al., 2000; Siegersma et al., 2023). Whilst creating saltmarsh in areas that are already tidally connected may mitigate issues associated with re-inundating agricultural land, the use of sedimentation fields for saltmarsh creation is not without limitations. For example, it might be necessary to maintain fencing until saltmarsh has become established, or permanently if a marsh would not otherwise have established at a given

location without human intervention (e.g. Reed et al., 2018). This is dependent on the created marsh becoming self-sustaining and resilient to storms, erosion and sea level rise (e.g. Ganju, 2019; Kirwan et al., 2010) by crossing a vegetation cover threshold (e.g. D'Alpaos, 2011) and through biophysical feedback processes accelerating vertical marsh buildup (e.g. Kirwan et al., 2016). Ensuring sediment accretion to increase the bed elevation and enable saltmarsh vegetation to become established is, therefore, one of the key factors in determining the success of sedimentation fields.

Despite the importance of sedimentation, investigations into the sedimentary processes associated with saltmarsh created in sedimentation fields have predominantly been modelling studies or have focused on the initial sediment deposition and early saltmarsh development (e.g. Hung et al., 2025; Scarton et al., 2000; Siegersma et al., 2023; Siemes et al., 2020). Consequently, there is a need for empirical assessments of the stability of the created marsh and the sources, mechanisms, and timescales of sediment delivery and accretion once saltmarsh has become established. Through these assessments, the appropriateness of the design and location, the influences on the stability of the created marsh, and the requirement for continued maintenance can then be evaluated. This understanding is urgently needed to inform the management of future sedimentation field sites to ensure maximum saltmarsh development and ecosystem service delivery, and to maintain saltmarsh growth and prevent erosion at locations already created using this method. This is particularly important for relatively exposed sites, where large tidal ranges and high exposure to storm surges may make maintaining sedimentation fields especially challenging.

To address these knowledge gaps, this study presents a novel combination of measurements of hydrodynamics, sediment properties and accumulation, and elevation change. These measurements were taken from an area where saltmarsh has developed following sedimentation field construction between 1989 and 2005 at Rumney Great Wharf (Fig. 1) in the macrotidal Severn Estuary, Wales, to:

1. Assess spatial and temporal variations in the hydrodynamics, and the movement and availability of sediment.
2. Determine the composition of the sediment that has accumulated following sedimentation field construction.
3. Examine spatial patterns in the accretion and erosion of sediment to evaluate whether the created marsh is self-sustaining.
4. Evaluate the potential for further saltmarsh development at Rumney, and the requirements for successful future saltmarsh creation using sedimentation fields at other locations.

2. Methods

2.1. Study site

The geology of the site comprises a series of early to mid-Holocene estuarine and peat sediment deposits, known collectively as the Wentlooge Formation (Bell et al., 2000). Sediment has accreted in intertidal areas, and saltmarsh has developed on top of the Wentlooge Formation. On exposed mudflats, the Formation is topped by a fine silt layer, with a peat shelf dating from 6000 to 2500 BP (Allen, 1997) exposed in some locations (Supplementary Fig. 1). The site has a long history of human influence with evidence of small-scale human activity at the site during the Bronze Age (Bell, 2013) and early land reclamation during the Roman period (Allen and Fulford, 1986). The site is backed by an embankment (Supplementary Fig. 1) constructed prior to the 13th century AD (Fulford et al., 1994), which protects the Wentlooge Levels from tidal inundation, with a spring tidal range of over 11 m.

The upper marsh is separated from the lower marsh by a pronounced cliff, or wharf, which is over 3m high in places (Ladd, 2021). In 2005, boulders were added to create a revetment and stabilise the cliff between the upper and lower marsh (Supplementary Fig. 1). The boulders were also used to infill the channels which dissected the upper marsh and

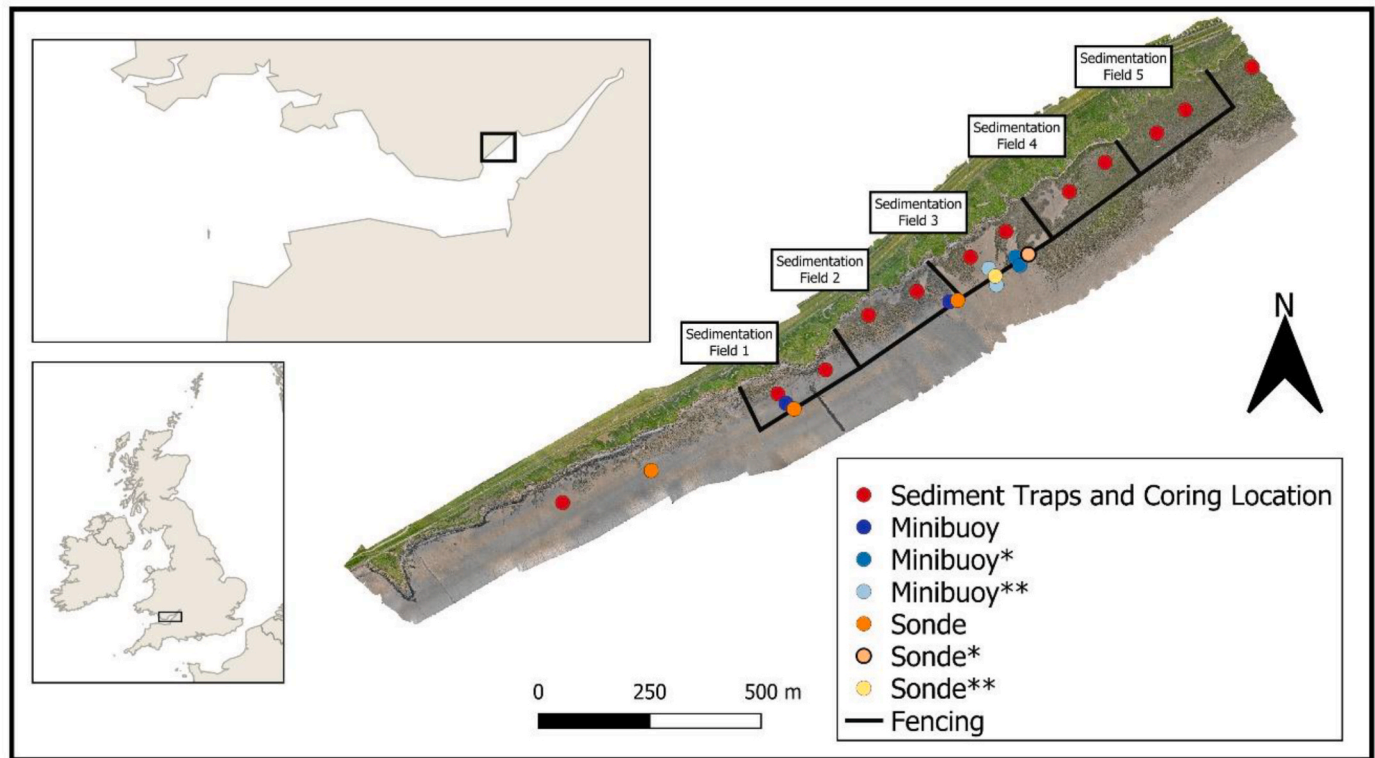


Fig. 1. Location of Rumney Great Wharf and equipment deployed during two measurement periods (*summer deployment only, **winter deployment only). Sedimentation fields 1 to 4 were constructed in 2005, and sedimentation field 5 was constructed in 1989.

connected the lower and upper marsh. The site is relatively exposed to the prevailing wind from the southwest, though is sheltered from the Atlantic swell (Armstrong et al., 2021). The site is inundated during most tides apart from during lower neap tides, with the wharf marking the position of mean high water. This study focuses on the lower marsh and tidal flat seawards of the revetment where sedimentation fields have been constructed.

To decelerate and reverse the loss of lower saltmarsh, five sedimentation fields numbered one to five in a west to east direction (Fig. 1) were constructed at Rumney Great Wharf. Initially, a single sedimentation field was constructed to the west of an area of pre-existing marsh in 1989 (Ferns, 1990). This sedimentation field is now known as Sedimentation Field 5 (SF5). In 2005, the fencing was extended to the west (Burgess-Gamble et al., 2017) through the construction of Sedimentation Fields 1 to 4 (SF1 to SF4). Brushwood fencing was constructed through the erection of two rows of larch stakes driven into the mudflat with willow bundles woven between the rows. Sediment has accreted and marsh has developed following sedimentation field construction, predominantly in the eastern sedimentation fields (SF3, SF4 and SF5; Fig. 1) where elevation has increased by over 0.5 m (Armstrong et al., 2021). Most of the created marsh has formed with a ridges and groove morphology, similar to other sites in the Severn Estuary (Allen, 2000). Some saltmarsh vegetation has also colonised in SF2, although this is mainly establishing on the exposed peat shelf. The fencing has not been maintained since 2010 and, as a result, the willow bundles have washed away leaving only the larch stakes *in situ*.

2.2. Field measurements

Variations in hydrodynamics across the site were assessed during two monitoring periods: a summer deployment from 18th May to 30th June 2023 and a winter deployment from 31st October to 15th December 2023. Four YSI EXO2 Sondes were deployed, three along the front fencing of SF1, SF2 and SF3 and one to the west outside of the

sedimentation fields (Fig. 1). Each Sonde measured water depth, salinity and turbidity at a 10-min logging frequency, with turbidity later calibrated for suspended particulate matter (SPM) in the laboratory using filtered local water samples. To assess variations in current and wave orbital velocity during each measurement period, Mini Buoys measuring at 2 s logging frequency were deployed. Mini Buoys are battery-powered accelerometer data loggers, contained in a sealed centrifuge tube float tethered to the bed. Mini Buoys float upright whilst inundated and move freely, with the acceleration motion used to measure inundation, current velocity and wave orbital velocity. Details of the Mini Buoys calibration and validation, including differentiation between current and wave orbital velocity, were reported by Ladd and Balke (2024) and Ladd et al. (2024). In our study, the B4+ design with MSR145W B4 accelerometers (accuracy = ± 0.15 G at 25 °C; resolution = 0.004 G; range = ± 2 G) was used. Three Mini Buoys were deployed inside the sedimentation fields, in SF1, SF2 and SF3, and two were deployed outside of the sedimentation fields: one alongside the Sonde to the west, and one in front of the fencing at SF3 (Fig. 1). Each Sonde and Mini Buoy were deployed at the same location for the duration of the two monitoring periods, except for the Sonde and Mini Buoys inside and outside of SF3 which were moved 80 m to the west for the winter deployment.

To determine the rate of sediment accumulation, sediment traps were deployed during both measurement periods following the method of Baranes et al. (2022). Sediment traps are a method of indicating the available sediment that could potentially be accreted and do not account for the tidal pattern of accretion and erosion or the overall trend of accretion or erosion. Five sediment traps were deployed at each of 12 locations (Fig. 1), along a shore parallel transect which extended from the mudflat outside of the sedimentation fields to the west, used as a control site, moving through the unvegetated areas inside SF1 and onto the marsh that has developed following fence construction. The transect continued across the marsh platform to the east, to a second control site on the marsh that existed outside the sedimentation fields prior to site construction. Sediment traps were deployed at two locations within each

sedimentation field, and each trap was named according to sedimentation field number and the position of the traps within the sedimentation field (west or east). On retrieval, sediment traps were capped and stored in a cold store at 3.5 °C prior to laboratory analysis.

In May 2023, sediment cores were taken at each location to a depth of between 40 and 80 cm using a 5 cm diameter gouge auger to assess the properties of the created marsh. Each core was visually examined, logged stratigraphically and sub-sampled at 2 cm intervals in the field. Each sub-sample was placed in a polythene bag and stored in a cold store at 3.5 °C prior to laboratory analysis.

To determine spatial patterns in sediment accretion and erosion, a DJI Mavic 3e with Real-Time Kinematic (RTK) uncrewed aerial system (UAS) was used to survey the site in May 2023 and May 2024. RGB images were collected from an altitude of 45 m, giving a ground sampling resolution of 1.16 cm/pixel. For the purposes of model accuracy, three ground control points were recorded using a Trimble Catalyst DA2. Three additional independent points were recorded to be used as check points to assess model quality. All points had a reported horizontal and vertical positional quality of <0.02m.

2.3. Laboratory analysis

Subsamples from sediment cores were analysed in the laboratory for dry bulk density, moisture content and organic content. A known volume of sediment was extracted from each sub-sample and dried at 105 °C for 48 h. Dry bulk density was calculated as the dry mass per unit volume, and moisture content as the percentage weight lost following drying. Loss on ignition was used as a proxy for organic content, measured following combustion of the dry sediment at 450 °C for 6 h. Sediment accumulation rates were calculated following Baranes et al. (2022). Materials that had accumulated within the sediment traps were decanted, rinsed to remove salt, and dried at 105 °C for 48 h. Accumulation rates were calculated by dividing the dry mass of sediment by the sediment trap cross-sectional area, divided by the deployment time.

2.4. Data analysis

Average SPM, current velocities, and wave orbital velocities were calculated for each flood and ebb tide. Differences between sites were assessed for current velocity and suspended sediment concentration during the flood and ebb tidal phases separately using a Kruskal-Wallis test suitable for non-parametric data (Anderson-Darling test, $p < 0.05$). Differences between the flood and ebb tide SPM and current velocity at each site were also assessed via a Mann-Whitney U test. Differences in wave orbital velocity between the flood and ebb tide were not assessed as it was assumed wave activity would be a product of extrinsic conditions such as wind strength and direction rather than flood/ebb tidal variations. Instead, the daily average wave orbital velocity was used to evaluate variations in waves, with differences between sites assessed using a Kruskal-Wallis test. The correlation between SPM and both current and wave orbital velocity during flood and ebb tidal phases was assessed through a Spearman's Rank test to determine the relationship between site hydrodynamics and SPM.

Differences in sediment properties between areas where saltmarsh has become established and sites which have remained mudflat were confirmed through Principal Component Analysis (PCA) of the parameters measured from the sediment cores. PCA was used as the technique has previously been shown to (partially) discriminate differences in intertidal sediments (Cundy et al., 2006; Dale et al., 2019, 2021). All statistical analysis was conducted in Minitab (21.2.0).

UAS imagery was processed using Agisoft Metashape Professional (1.8.4). For each survey, a dense point cloud was produced using mild-depth filtering from which an orthophoto and digital surface model (DSM) were constructed. Root mean square error values of 0.04 m and 0.03 m were calculated for 2023 and 2024 DSMs respectively using the independent check points recorded in the field (see Section 2.2). DEMs

of Difference (DoD) analysis provides a method of identifying and quantifying areas experiencing either erosion or accretion (Dale et al., 2020, 2021; Strick et al., 2019; Williams, 2012) and was performed in this study for the two DSMs using QGIS (3.34.14). When conducting DoD analysis, it is important to consider the potential propagation of error. Therefore, a specified level of detection (LoD) was calculated using the independent check points (Lane et al., 2003), with any change smaller than the LoD not included in the analysis (James et al., 2017). In this study, we calculated the LoD to be 0.01 m. We recognise that comparing DSMs containing vegetation may introduce error into the calculation, although this is expected to be minimal given that surveying took place in May before the growth of any tall canopied annual species such as *Spartina*. Furthermore, any error introduced is likely to be within the error of the reconstruction (e.g. Hladik and Alber, 2014) and removed once the LoD has been applied.

3. Results

3.1. Hydrodynamics

SPM was significantly greater (Mann-Whitney U test, $p < 0.05$) on the flood tide than the ebb at all sites (Fig. 2), both in and outside of the sedimentation fields, except for SF3 during the winter measurement period where the difference was not statistically significant. At this site, the deployment location was changed for the winter measurement period due to the considerably higher SPM values observed in the summer deployment. These are likely the result of the proximity of the summer deployment site to the marsh platform and localised variations in hydrodynamics, resulting in the decision to move the instrument 80 m to the west for the winter deployment.

Significant differences in SPM were detected during the summer measurement period between SF1, SF2, and the deployment sites outside to the west of the sedimentation fields (Kruskal-Wallis test, $p < 0.05$) on both the flood and on the ebb tides. Post-hoc testing indicated this difference was between the deployment site outside to the west of the sedimentation fields and the other two sites, with higher SPM concentrations detected outside of the fields in comparison to inside. Summer SPM data from SF3 was not included in comparisons between sites due to concerns regarding the influence of localised hydrodynamics and the data not being representative of the whole sediment field. SPM did not differ significantly between sites on either the flood or the ebb tides during the winter measurement period.

Current velocity was significantly greater (Mann-Whitney U test, $p < 0.05$) on the ebb tide than the flood inside SF1, SF3, and outside to the west of the site, during the summer measurement period (Fig. 2). Current velocities did not differ significantly between the flood and ebb tide inside SF2 and outside in front of SF3, where lower current velocities were typically measured. In contrast, significant differences in current velocity were only detected between the flood and ebb tides at the site to the west outside of the sedimentation fields and at SF1 in the winter measurement period (Mann-Whitney U test, $p < 0.05$), when current velocities were typically higher across the sites. At both locations the current velocity was greater on the ebb tide than the flood. Kruskal-Wallis tests indicated significant differences ($p < 0.05$) between sites on both the flood and ebb tides across both measurement periods. Post-hoc testing suggested more similarity between sites (fewer groups) during the winter measurements (Supplementary Table 1).

Wave orbital velocity differed significantly between sites during the summer measurement period (Kruskal-Wallis test, $p = 0.02$). This difference was the result of typically lower wave orbital velocities outside of SF3, the most seaward site, with no significant differences detected between the other four sites. In comparison, higher wave orbital velocities were measured in the winter (Fig. 2) with no significant differences detected. Spearman's rank correlation coefficients indicated that during the summer measurement period wave orbital velocity generally had the strongest relationship with SPM across the site (Table 1). During

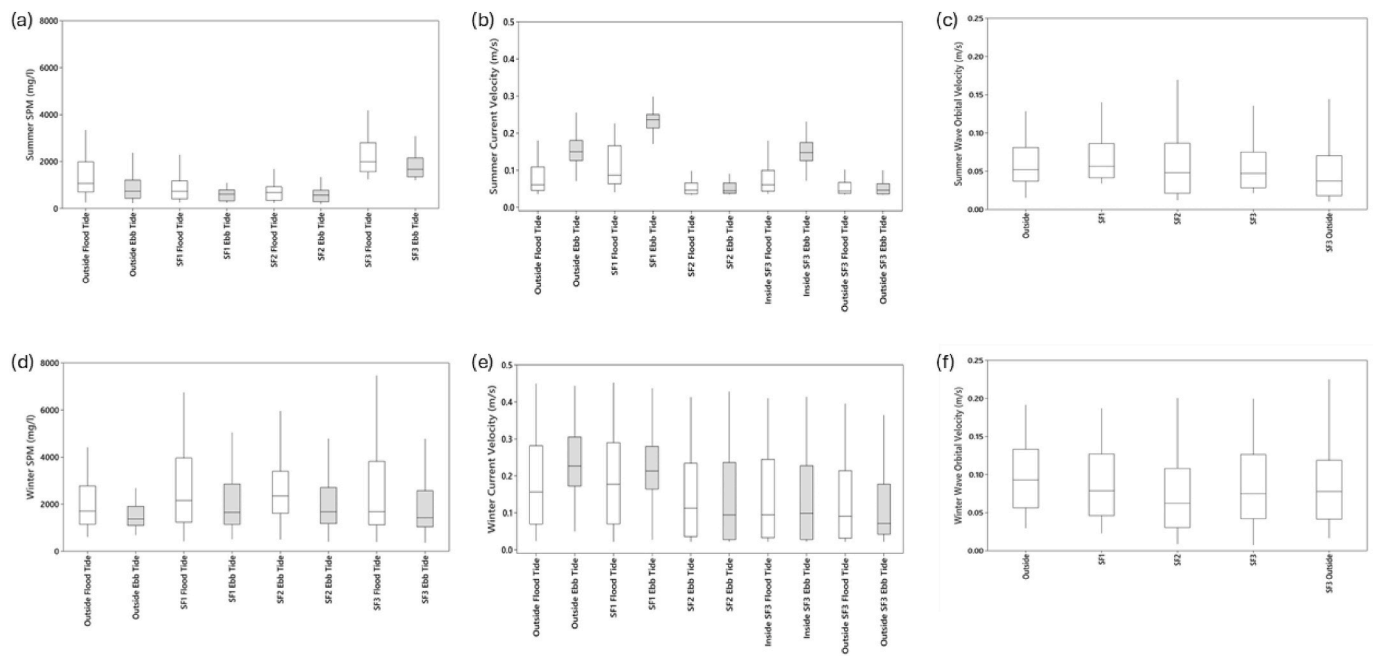


Fig. 2. Variations in summer (a) suspended particulate matter (SPM), (b) current velocity, and (c) wave orbital velocity and winter (d) SPM, (e) current velocity, and (f) wave orbital velocity (SF = sedimentation field). Average flood (clear bars) and ebb (filled bars) tide values were used for SPM and current velocity measurements. Average daily values were used for wave orbital velocity. Error bars represent the standard deviation.

Table 1

Spearman's rank correlation coefficients between flood and ebb tide average suspended particulate matter (SPM) and current and wave orbital velocity during the summer and winter measurement periods (SF = sedimentation field). All correlations were statistically significant ($P < 0.05$). Summer SPM data from SF3 was not included due to concerns that the data were not representative of the sedimentation field as a whole.

		Outside		SF1		SF2		Inside SF3		Outside SF3	
		SPM Flood	SPM Ebb	SPM Flood	SPM Ebb	SPM Flood	SPM Ebb	SPM Flood	SPM Ebb	SPM Flood	SPM Ebb
Summer	Current Velocity	0.48	0.50	0.40	0.45	0.80	0.69	-	-	-	-
	Wave Orbital Velocity	0.66	0.70	0.56	0.81	0.80	0.70	-	-	-	-
Winter	Current Velocity	0.77	0.79	0.78	0.85	0.77	0.85	0.91	0.90	0.92	0.86
	Wave Orbital Velocity	0.74	0.76	0.75	0.92	0.76	0.87	0.92	0.90	0.91	0.93

the winter measurement period, current velocity had a stronger relationship with SPM in comparison to the summer measurement period, although wave orbital velocity also maintained a strong relationship during the winter.

3.2. Sediment properties and accumulation

Sediment cores, in general, indicated a typical profile for both the vegetated saltmarsh and non-vegetated mudflat sites. Charcoal fragments were identified in some cores, as found in other Severn Estuary sediment records (French, 1998), and in deeper cores larger wood fragments were found at depths greater than 68 cm. Fig. 3 presents the average bulk density, moisture content and organic content for each sediment core. PCA analysis demonstrated clear segregation in the first component (Fig. 4), which explained 91% of the variability (eigenvalue = 2.7) between the saltmarsh and the mudflat sites. Each variable made even contributions to Component 1, demonstrated by the calculated eigenvectors (bulk density = -0.6, moisture content = 0.6, organic content = 0.6). The second component explained 6% of the variability (eigenvalue = 0.2) and was associated with moisture content (eigenvalue = -0.79) and organic content (eigenvalue = 0.58).

Sediment trap measurements detected greater accumulation rates (Fig. 5) in the unvegetated mudflat sites compared to the vegetated saltmarsh sites in both the summer and winter measurement periods. Average accumulation was 0.05 g/cm²/day higher in the summer and

0.02 g/cm²/day higher in the winter at mudflat sites compared to saltmarsh sites. During both the summer and winter deployments, a greater sediment accumulation rate was also generally detected at mudflat sites within the sedimentation fields in comparison to the mudflat outside of the fields. To calculate the equivalent potential accretion rate, the average bulk density measured from the equivalent sediment core was divided by the summer and winter sediment accumulation rates. Findings suggest that there is potential for sediment accretion of greater than 10 cm per year at some unvegetated mudflat sites and up to 9 cm per year at vegetated saltmarsh sites (Fig. 6).

3.3. Spatial sedimentary processes

In the 12 months between the 2023 and 2024 UAS surveys, a net loss of 9531 m³ of sediment was eroded from inside the sedimentation fields (Fig. 7). In total, 87% of the surface area of the sedimentation fields experienced erosion with an average erosion depth of 8.61 cm. Accretion occurred across 7% of the sedimentation fields and the remaining 6% experienced change below the LoD (0.01 m). The average accretion depth was 5.38 cm. The greatest erosion occurred in the unvegetated mudflat areas, particularly in the centre of SF3. The rest of the erosion typically occurred on the marsh platform in SF4 and SF5 and along the edge of the peat shelf, particularly in SF2 and the northeast corner of SF1.

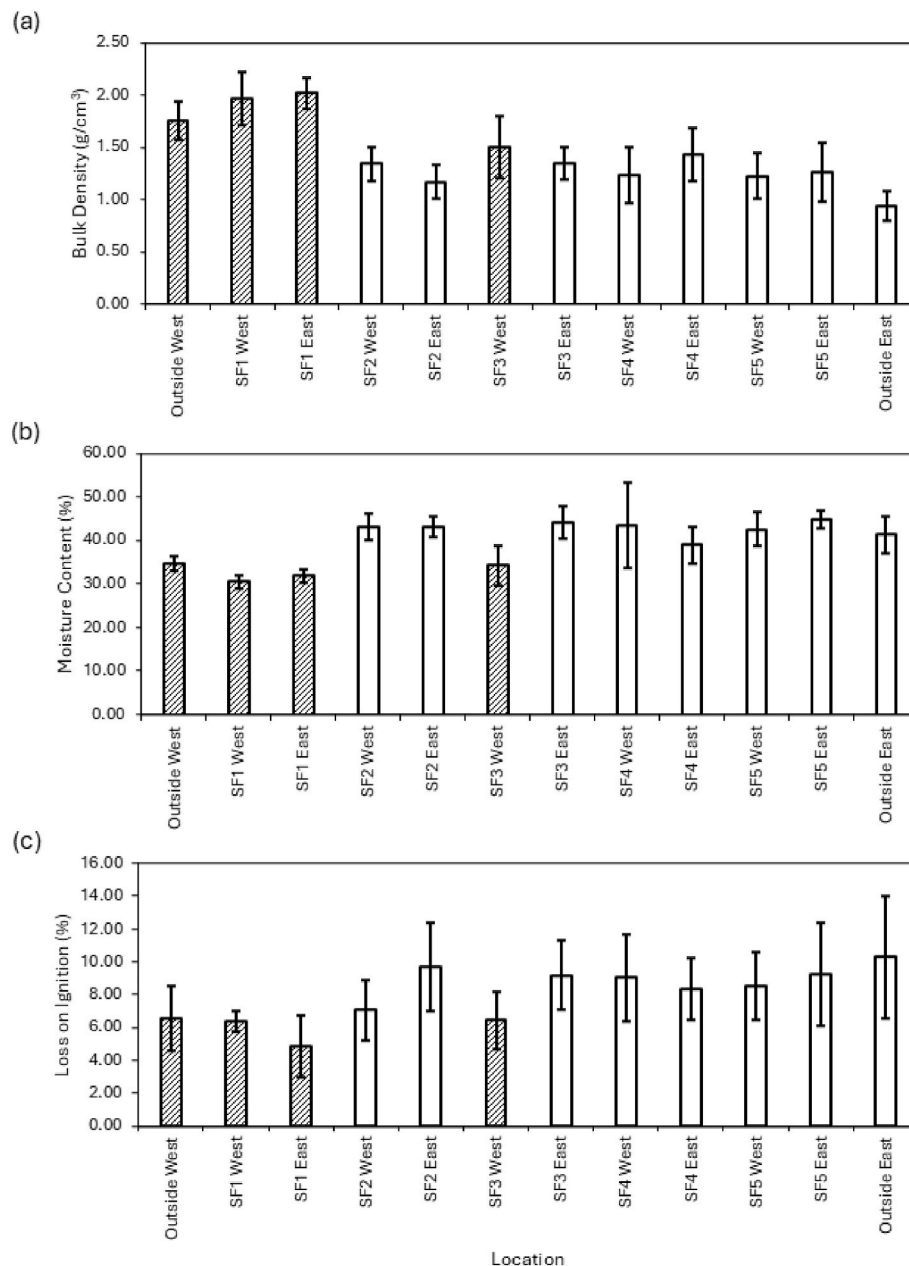


Fig. 3. Average bulk density (a), moisture content (b), and organic content (c) for each site sampled within and outside (control sites) the sedimentation fields (SF) at Rumney Great Wharf. Filled bars represent unvegetated mudflat sites and clear bars represent vegetated saltmarsh sites.

4. Discussion

The sedimentation fields at Rumney Great Wharf were not maintained beyond 2010, with the brushwood lost and only stakes remaining at the time of this study. Given the lack of maintenance, the level of current reduction and wave sheltering is likely to have been reduced from the ‘as-built’ protection, allowing for assessments to be made of the functioning, stability and resilience of the created marsh without continued human intervention.

4.1. Hydrodynamics and sediment movement

Our findings suggest greater heterogeneity between sites at Rumney Great Wharf during the summer in terms of the current velocity and sediment accumulation, although wave orbital velocity had the strongest relationship with SPM during the summer. In contrast, higher SPM concentrations, current velocities and wave orbital velocities were

detected during the winter measurement period, with more consistency between sites. We acknowledge that Ladd et al. (2024) only found a reasonable relationship between wave orbital velocity measurements collected by the B4+ Mini Buoy and measurements taken using industry-standard sensors. However, Mini Buoys still provide an informative indication of the wave climate and its influence on the supply of sediment to, and stability of, the created marsh. This is demonstrated by the seasonal differences detected at Rumney Great Wharf, as well as the relationship between wave orbital velocity and SPM. Hydrodynamic forcing by tidal currents and wave action play an important role in the movement and accumulation of sediment, and the potential for marsh vegetation to become established (e.g. Bouma et al., 2016; Cao et al., 2018; Möller and Christie, 2019). Consequently, an understanding of the hydrodynamics is required to ensure sedimentation fields are designed to capture and consolidate deposited sediment when it is available (Oosterlee et al., 2020).

Understanding site hydrodynamics is also important when

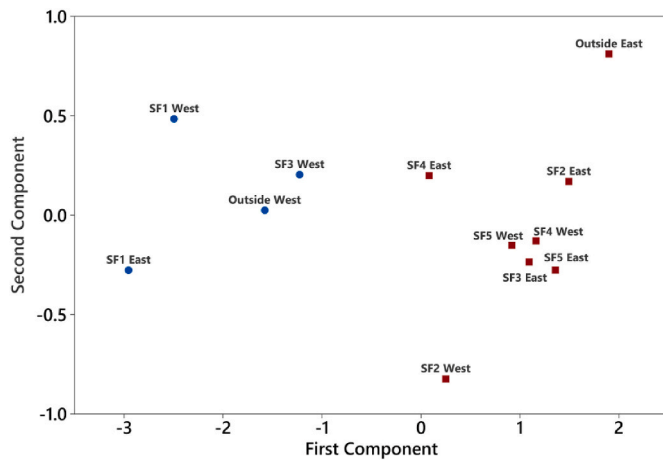


Fig. 4. Score plot for the first and second component calculated through Principal Component Analysis. Collectively, the first and second components explained 97% of the variability. Each site is labelled (SF = sedimentation field) with red squares indicating the saltmarsh and blue circles the mudflat sites. Outside East was the only site that was saltmarsh prior to sedimentation field construction.

evaluating the stability of the created marsh and the need for continued intervention until the marsh is established and able to sustain itself. Between May 2023 and May 2024, we observed a net loss of sediment at Rumney Great Wharf (Fig. 7), suggesting that the marsh is not self-sustaining and might have reverted to having an erosive trend. Appropriate sedimentation field design is needed to ensure sites are resilient and to encourage the created marsh to become self-sustaining. This typically occurs once a threshold in vegetation cover is crossed (e.g. D'Alpaos, 2011), although how this threshold is determined and

detected for sedimentation fields requires further investigation. Sedimentation field design can differ considerably. The traditional design, which was used at Rumney Great Wharf, involves the construction of cross-shore brushwood groynes fronted by a shore-parallel fence, which can contain a tidal opening (Pontee et al., 2021). Numerical modelling simulations by Siemes et al. (2020) found this design to be the most effective for stimulating saltmarsh growth. There does, however, remain a need to consider height, width, and spacing between groynes, depending on the local processes and environment (Pontee et al., 2021) to maximise sediment accretion for saltmarsh establishment. Sediment accumulation rates measured at Rumney Great Wharf indicated increased sediment delivery to the marsh platform during the winter in comparison to the summer. However, lower accumulation rates were measured on the mudflat in the winter, likely due to higher hydrodynamic forcing preventing the sediment from settling. Without continued maintenance of the fencing to reduce current velocity and wave heights during the winter, and to encourage sediment deposition in the summer, it is likely that the erosive trend will continue.

Predictive models (e.g. Allen, 2000) and empirical measurements from other saltmarsh restoration schemes (e.g. Clapp, 2009; Dale et al., 2021; Dale et al., 2017; McMahon et al., 2023; Mossman et al., 2022) suggest that rapid accretion would be expected following sedimentation field construction. Similar observations have been made by studies on sedimentation-enhancing structures (e.g. Gonçalves et al., 2025; Van Loon-Steensma and Slim, 2013), including the few studies on sedimentation fields (e.g. Scarton et al., 2000; Siegersma et al., 2023; Winterwerp et al., 2020). However, further research into the initial accretion of sediment, the time required for saltmarsh to become established, and the resilience of the created marsh is needed. This is of particular importance in settings with high sediment availability such as the Severn Estuary, where high accretion rates may bury deposited sediment before it has consolidated, resulting in lower resistance to erosion (Oosterlee et al., 2020; Stoorvogel et al., 2024).

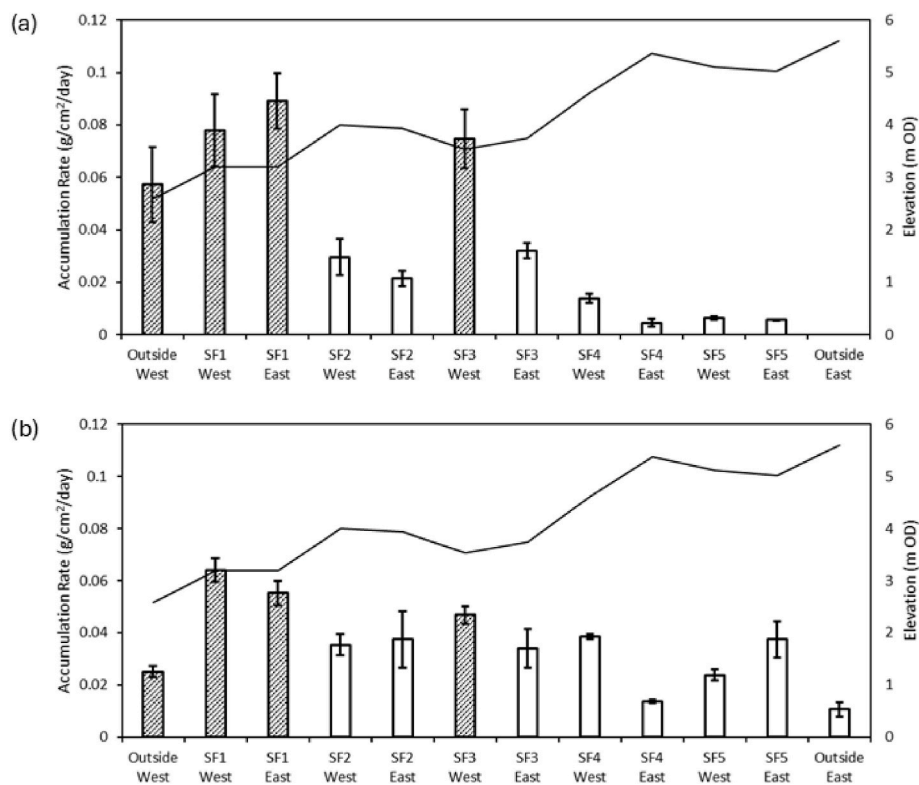


Fig. 5. Sediment accumulation rates measured at each site (SF = sedimentation field) during (a) summer and (b) winter measurement periods. Filled bars represent unvegetated mudflat sites and clear bars represent vegetated saltmarsh sites. The elevation of each site is also indicated. No sediment traps were recovered from the Outside East site following the summer measurement period. Outside East was also the only site that was saltmarsh prior to sedimentation field construction.

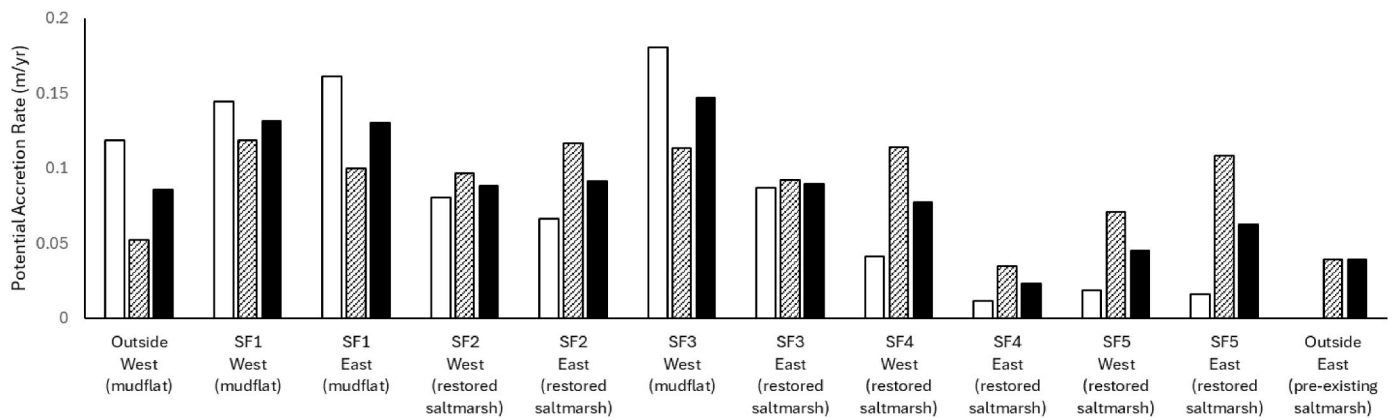


Fig. 6. Potential summer (clear bars), winter (dash filled bars) and average (block filled bars) accretion rates based on the measured sediment accumulation and average bulk density measurements at each site (SF = sedimentation field). No sediment traps were recovered from the Outside East site following the summer measurement period.

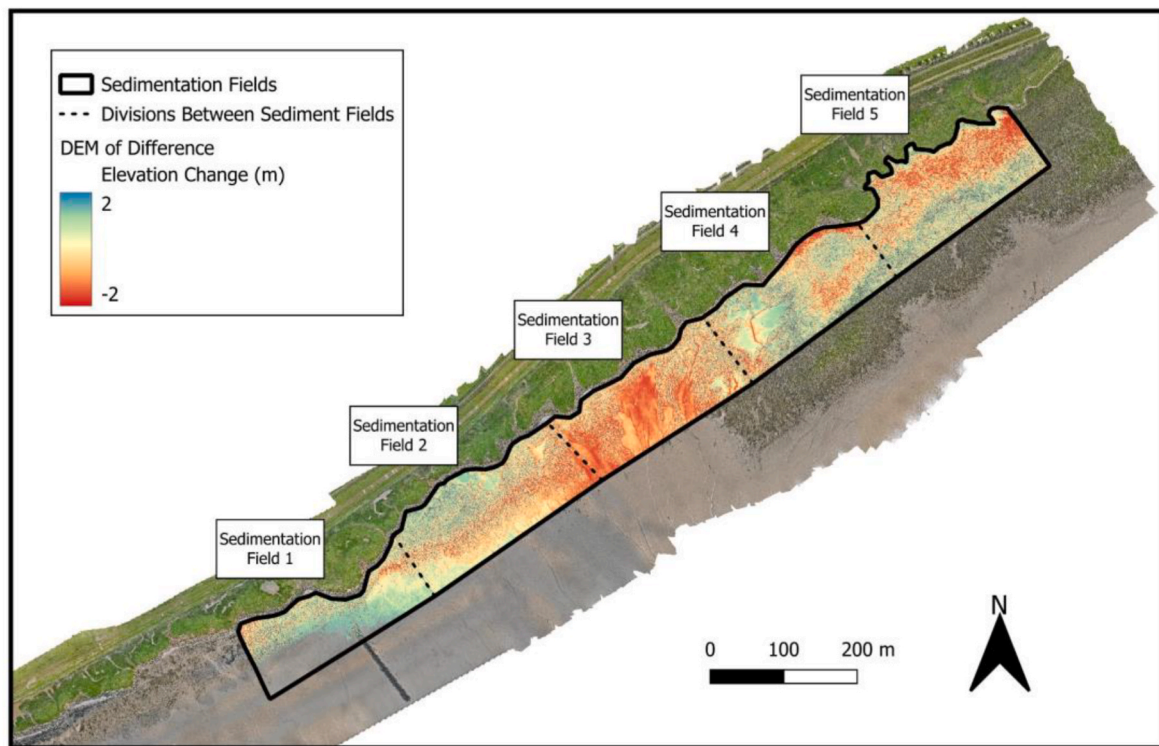


Fig. 7. DEM of Difference analysis of digital surface models produced in May 2023 and May 2024.

The spatial and temporal variability in the rate of sediment deposition in sedimentation fields needs to be assessed not only to ensure that the bed elevation reaches the level required for saltmarsh to colonise, but also to outpace the rate of sea level rise. The longer-term biogeomorphic evolution of the site should also be considered, as the mechanism of sediment accumulation (trapping vs bioaccumulation) may change over time as the site develops. There is, therefore, a requirement for investigations of changes in vegetation structure and composition, and the associated influence on hydrodynamics, sediment transport pathways and the success of the scheme (e.g. Silliman et al., 2015). Implementing monitoring programmes such as these will help to ensure the dynamic adaptive capacity of the developing marsh to erosion and sea level rise (Ganju, 2019) and maintain the provision of important ecosystem services (Schuerch et al., 2022).

4.2. Sediment composition

Principle Component Analysis of sediment cores from Rumney Great Wharf suggested clear segregation between sites where saltmarsh has developed and sites that have remained mudflat (Fig. 4). These findings support suggestions that the use of sedimentation fields for saltmarsh creation might mitigate some of the limitations associated with other approaches (Dale and Farrell, 2026). For example, managed realignment sites have been shown to have lower diversity and abundance of key plant species than pre-existing reference sites due to reduced topographic complexity and decreased sub-surface hydrological connectivity, leading to anoxia (Lawrence et al., 2018; Mossman et al., 2012; Tempest et al., 2015). This has been associated with alterations to the sediment structure caused by former (terrestrial) land use (e.g. Spencer et al., 2017).

Despite the limited evidence of any segregation between the pre-existing and the created marsh, further research should still consider the sedimentological differences between pre-existing marshes and those created using sedimentation fields, especially as sediment accumulates and saltmarsh starts to become established. Specifically, the composition and properties of the accreted sediment should be investigated in future assessments of sedimentation schemes. For example, sedimentation fields could store contaminated sediment (Henry et al., 1999), delivering benefits such as water quality improvements and providing additional justification for the expense associated with their continued maintenance. Any elevation changes caused by subsidence as the deposited sediment consolidates (Saintilan et al., 2022) should also be considered.

4.3. Future use of sedimentation fields

Sedimentation fields should be viewed as the artificial manipulation of hydrological functioning and sedimentary processes to encourage saltmarsh growth (e.g. Dale and Farrell, 2026). However, for sedimentation fields to be used more widely to compensate for saltmarsh loss, it is important that sites reach the required threshold (e.g. D'Alpaos, 2011) beyond which continued manipulation is no longer required. The sedimentary and hydrodynamic processes in newly constructed sedimentation fields need to be investigated to understand the required frequency and duration of maintenance until this threshold is reached. Further assessments of the suitability of potential locations for future schemes, including locations where other methods of saltmarsh restoration are not possible, are also needed. For example, the presence of infrastructure, urban development or other designated habitat types means that in some locations, flood defences either cannot be breached through managed realignment or be allowed to fail due to a policy of not maintaining defences, resulting in the formation of an unmanaged realignment site (Dale and Arnall, 2024). This is particularly pertinent given that only a comparatively small amount of the area where realignment is possible has so far been realised (Williams and Dale, 2023), partially due to unfavourable public perceptions of realigning defences (Esteves, 2014).

Consideration of the ecological functioning and ecosystem service provision of newly created saltmarsh is required more widely. For example, it is possible that constructing sedimentation fields in front of coastal flood defences could create a buffer zone and reduce pressure on the defences through attenuation of high-water levels (e.g. Kiesel et al., 2022; Wamsley et al., 2010) and waves (e.g. Moller et al., 2014; Rupprecht et al., 2017). It is also likely that the anticipated high sedimentation rates could result in rapid carbon accumulation, as seen in some managed realignment sites (McMahon et al., 2023; Mossman et al., 2022). If this is confirmed, it could lead to increased availability of funding for future site construction through the move towards integrating saltmarshes into carbon markets (Friess et al., 2022; Mason et al., 2022). However, caution must be applied whilst the understanding of sedimentary processes in sedimentation fields remains under-studied.

Since this research was conducted, Natural Resources Wales have installed new sedimentation fields at Rumney Great Wharf (Dale and Farrell, 2026). The new sedimentation fields were constructed in summer 2024, covering the longshore extent of the previous scheme and extending further west. This new scheme will provide the opportunity to answer some of the outstanding questions relating to the hydrodynamic and sedimentary processes operating in sedimentation fields through additional morphological surveys, and further hydrodynamic and sedimentary measurements. Findings from the research reported here will provide an important baseline to assess the effectiveness of the new scheme when evaluating changes in site hydrodynamics, the subsequent deposition and transportation of sediment, and whether the current erosive trend can be reversed.

5. Conclusion

This study presents a novel assessment of the hydrodynamics, sedimentation patterns, and sediment properties in sedimentation fields which have not been maintained since 2010. Sediment accumulation was greater in areas of unvegetated mudflat in comparison to vegetated saltmarsh sites, although the difference between saltmarsh and mudflat was lower in the winter; during the winter more sediment accumulated in vegetated areas and less accumulated at mudflat locations. This is despite higher concentrations of SPM being measured during the winter, when higher current and wave orbital velocities were also measured which likely reduced the deposition of sediment from suspension. Despite the potential for there to be more than 10 cm per year of sediment accretion at unvegetated mudflat sites and up to 9 cm at vegetated saltmarsh sites, 87% of the sedimentation field area at Rumney Great Wharf experienced erosion over a 12-month period, resulting in the removal of 9531 m³ of sediment. It is postulated that the amount of erosion would have been lower if the fences had been adequately maintained.

These findings suggest that the created saltmarsh is not self-sustaining, highlighting the importance of maintenance to ensure saltmarsh can successfully become established following sedimentation field construction. However, uncertainty remains regarding the sedimentary processes that are in operation immediately following sedimentation field construction and the longer-term processes required for saltmarsh to become self-sustaining (if at all). Addressing these shortcomings in understanding by monitoring the newly repaired and extended sedimentation fields at Rumney Great Wharf, and elsewhere, will help coastal managers to identify suitable locations for future sedimentation field construction. This will potentially mitigate some of the limitations associated with other restoration approaches. In addition to further research into the sedimentary processes, there is also a need to evaluate the ecological functioning and ecosystem service delivery provided by sedimentation fields. This includes the level of coastal flood defence and carbon storage which, once quantified, could provide justification for wider sedimentation field construction globally.

CRediT authorship contribution statement

Jonathan Dale: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Cai J.T. Ladd:** Writing – review & editing, Methodology, Formal analysis, Data curation, Conceptualization. **Michelle Farrell:** Writing – review & editing, Methodology, Data curation. **Michael P. Kennedy:** Writing – review & editing, Investigation, Data curation. **Gabriela Ciappara:** Investigation, Formal analysis. **Chloe James:** Methodology, Investigation, Funding acquisition, Conceptualization. **Iain Fairley:** Writing – review & editing, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank Natural Resources Wales who provided financial support for the research and the technical services staff at the University of Reading who provided laboratory support.

Appendix A Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2026.129798>.

Data availability

Data will be made available on request.

References

- Allen, J., Fulford, M., 1986. The Wentlooge level: a Romano-British saltmarsh reclamation in southeast Wales. *Britannia* 17, 91–117.
- Allen, J.R., 1997. Subfossil mammalian tracks (Flandrian) in the Severn Estuary, SW Britain: mechanics of formation, preservation and distribution. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences* 352, 481–518.
- Allen, J.R.L., 2000. Morphodynamics of Holocene salt marshes: a review sketch from the Atlantic and Southern North Sea coasts of Europe. *Quat. Sci. Rev.* 19, 1155–1231.
- Armstrong, S., Whitehead, P., Scott, C., Hull, S., 2021. Rumney Great Wharf Saltmarsh Restoration/Enhancement Feasibility and Preferred Option Studies, p. 96.
- Baptist, M.J., Dankers, P., Cleveringa, J., Sittoni, L., Willemsen, P.W.J.M., van Puijenbroek, M.E.B., de Vries, B.M.L., Leuven, J.R.F.W., Coumou, L., Kramer, H., Elschot, K., 2021. Salt marsh construction as a nature-based solution in an estuarine social-ecological system. *Nat. Based Solut.* 1, 100005.
- Baptist, M.J., Gerkema, T., van Prooijen, B.C., van Maren, D.S., van Regteren, M., Schulz, K., Colosimo, I., Vroom, J., van Kessel, T., Grasmeijer, B., Willemsen, P., Elschot, K., de Groot, A.V., Cleveringa, J., van Eekelen, E.M.M., Schuurman, F., de Lange, H.J., van Puijenbroek, M.E.B., 2019. Beneficial use of dredged sediment to enhance salt marsh development by applying a 'Mud Motor'. *Ecol. Eng.* 127, 312–323.
- Baranes, H., Woodruff, J., Geyer, W., Yellen, B., Richardson, J., Griswold, F., 2022. Sources, mechanisms, and timescales of sediment delivery to a new England salt marsh. *J. Geophys. Res. Earth Surf.* 127.
- 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. *Ecol. Monogr.* 81, 169–193.
- Bell, M., 2013. The Bronze Age in the Severn Estuary. Council for British Archaeology.
- Bell, M., Caseldine, A., Neumann, H., 2000. Prehistoric Intertidal Archaeology in the Welsh Severn Estuary. Council for British Archaeology.
- Bouma, T.J., van Belzen, J., Balke, T., van Dalen, J., Klaassen, P., Hartog, A.M., Callaghan, D.P., Hu, Z., Stive, M.J.F., Temmerman, S., Herman, P.M.J., 2016. Short-term mudflat dynamics drive long-term cyclic salt marsh dynamics. *Limnol. Oceanogr.* 61, 2261–2275.
- Boumans, R.M.J., Day, J.W., Kemp, G.P., Kilgen, K., 1997. The effect of intertidal sediment fences on wetland surface elevation, wave energy and vegetation establishment in two Louisiana coastal marshes. *Ecol. Eng.* 9, 37–50.
- Brook, T., Millington-Drake, M., Garbutt, A., McGarrigle, A., Rodriguez, K., du Plessis, N., 2025. The State of the Worlds Saltmarshes 2025: a Global Call to Action for Coastal Resilience and Adaptation.
- Burgess-Gamble, L., Ngai, R., Wilkinson, M., Nisbet, T., Pontee, N., Harvey, R., Kipling, K., Addy, S., Rose, S., Maslen, S., 2017. Working with Natural processes—evidence Directory. Environmental Agency. Report No. SC150005.
- Cao, H., Zhu, Z., Balke, T., Zhang, L., Bouma, T.J., 2018. Effects of sediment disturbance regimes on *Spartina* seedling establishment: implications for salt marsh creation and restoration. *Limnol. Oceanogr.* 63, 647–659.
- Clapp, J., 2009. Managed Realignment in the Humber Estuary: Factors Influencing Sedimentation. University of Hull.
- 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., Sprague, D., Hopkinson, L., Maroukian, H., Gaki-Papanastassiou, K., Papanastassiou, D., Frogley, M.R., 2006. Geochemical and stratigraphic indicators of late Holocene coastal evolution in the Gythio area, southern Peloponnese, Greece. *Mar. Geol.* 230, 161–177.
- D'Alpaos, A., 2011. The mutual influence of biotic and abiotic components on the long-term ecomorphodynamic evolution of salt-marsh ecosystems. *Geomorphology* 126, 269–278.
- Dale, J., Arnall, A., 2024. Managed and unmanaged realignment as a nature-based solution to saltmarsh habitat loss: a sedimentary perspective. *Nat. Based Solut.* 100166.
- Dale, J., Burgess, H.M., Berg, M.J., Strong, C.J., Burnside, N.G., 2021. Morphological evolution of a non-engineered managed realignment site following tidal inundation. *Estuar. Coast Shelf Sci.* 260, 107510.
- 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.
- Dale, J., Burnside, N.G., Strong, C.J., Burgess, H.M., 2020. The use of small-Unmanned Aerial Systems for high resolution analysis for intertidal wetland restoration schemes. *Ecol. Eng.* 143, 105695.
- Dale, J., Cundy, A.B., Spencer, K.L., Carr, S.J., Croudace, I.W., Burgess, H.M., Nash, D.J., 2019. Sediment structure and physicochemical changes following tidal inundation at a large open coast managed realignment site. *Sci. Total Environ.* 660, 1419–1432.
- Dale, J., Farrell, M., 2026. Sedimentation fields as a method of saltmarsh restoration: continuity of human influence on natural processes. *Cambridge Prisms: Coastal Futures* 4, e1.
- Doody, J.P., 2004. 'Coastal squeeze' - an historical perspective. *J. Coast Conserv.* 10, 129–138.
- Esteves, L.S., 2014. *Managed Realignment : a Viable long-term Coastal Management Strategy?* Springer, Netherlands.
- Ferns, P.N., 1990. Use of a Poldered Area of Mudflats in the Severn Estuary by Shorebirds. Cardiff.
- French, P.W., 1998. The impact of coal production on the sediment record of the Severn Estuary. *Environ. Pollut.* 103, 37–43.
- Friess, D.A., Howard, J., Huxham, M., Macreadie, P.I., Ross, F., 2022. Capitalizing on the global financial interest in blue carbon. *PLOS Climate* 1, e0000061.
- Fulford, M.G., Allen, J., Rippon, S., 1994. The settlement and drainage of the Wentlooge Level, Gwent: excavation and survey at Rumney Great Wharf 1992. *Britannia* 25, 175–211.
- Ganju, N.K., 2019. Marshes are the new beaches: integrating sediment transport into restoration planning. *Estuaries Coasts* 42, 917–926.
- Gedan, K.B., Silliman, B.R., Bertness, M.D., 2009. Centuries of human-driven change in Salt Marsh ecosystems. *Ann. Rev. Mar. Sci.* 1, 117–141.
- Gonçalves, C., Verdelhos, T., Caçador, I., Oliveira, P.J.V., Marques, D., Veríssimo, H., 2025. Effectiveness of eco-engineering structures to promote sediment particles retention in estuarine salt marshes. *Water* 17 (5), 678.
- Henry, K., Walsh, M., Morin, S., 1999. Selection of silt fence filter to retain suspended toxic particles. *Geotext. Geomembranes* 17, 371–387.
- Hladik, C., Alber, M., 2014. Classification of salt marsh vegetation using edaphic and remote sensing-derived variables. *Estuar. Coast Shelf Sci.* 141, 47–57.
- Hung, H.-N., Chen, H.-H., Yang, R.-Y., 2025. Experimental Study on the sediment-trapping performance of different coastal protection structures in a high-tidal range area. *J. Mar. Sci. Eng.* 13, 1022.
- James, M.R., Robson, S., Smith, M.W., 2017. 3-D uncertainty-based topographic change detection with structure-from-motion photogrammetry: precision maps for ground control and directly georeferenced surveys. *Earth Surf. Process. Landf.* 42, 1769–1788.
- Kiesel, J., MacPherson, L.R., Schuerch, M., Vafeidis, A.T., 2022. Can managed realignment buffer extreme surges? The relationship between marsh width, vegetation cover and surge attenuation. *Estuaries Coasts* 45, 345–362.
- Kirwan, M.L., Guntenspergen, G.R., D'Alpaos, A., Morris, J.T., Mudd, S.M., Temmerman, S., 2010. Limits on the adaptability of coastal marshes to rising sea level. *Geophys. Res. Lett.* 37.
- Kirwan, M.L., Temmerman, S., Skeehean, E.E., Guntenspergen, G.R., Fagherazzi, S., 2016. Overestimation of marsh vulnerability to sea level rise. *Nat. Clim. Change* 6, 253–260.
- Ladd, C., Balke, T., 2024. Development of the B4+ Mini Buoy Design. Newcastle University.
- Ladd, C.J.T., 2021. Review on processes and management of saltmarshes across Great Britain. *Proc. Geologists' Assoc.* 132, 269–283.
- Ladd, C.J.T., Vovides, A.G., Wimpler, M.-C., Schwarz, C., Balke, T., 2024. Monitoring tides, currents, and waves along coastal habitats using the Mini Buoy. *Limnol. Oceanogr. Methods* 22, 619–633.
- Lane, S.N., Westaway, R.M., Hicks, D.M., 2003. Estimation of erosion and deposition volumes in a large, gravel-bed, braided river using synoptic remote sensing. *Earth Surf. Process. Landf.* 28, 249–271.
- Lawrence, P.J., Smith, G.R., Sullivan, M.J.P., Mossman, H.L., 2018. Restored saltmarshes lack the topographic diversity found in natural habitat. *Ecol. Eng.* 115, 58–66.
- Liu, Z., Fagherazzi, S., He, Q., Gourgue, O., Bai, J., Liu, X., Miao, C., Hu, Z., Cui, B., 2024. A global meta-analysis on the drivers of salt marsh planting success and implications for ecosystem services. *Nat. Commun.* 15, 3643.
- Mason, G.V., Wood, K.A., Jupe, L.L., Burden, A., Skov, M.W., 2022. Saltmarsh Blue Carbon in UK and NW Europe—evidence Synthesis for a UK Saltmarsh Carbon Code.
- McMahon, L., Ladd, C.J.T., Burden, A., Garrett, E., Redeker, K.R., Lawrence, P., Gehrels, R., 2023. Maximizing blue carbon stocks through saltmarsh restoration. *Front. Mar. Sci.* 10.
- Möller, I., Christie, E., 2019. Chapter 8 - hydrodynamics and modeling of water flow in coastal wetlands. In: Perillo, G.M.E., Wolanski, E., Cahoon, D.R., Hopkinson, C.S. (Eds.), *Coastal Wetlands*, second ed. Elsevier, pp. 289–323.
- 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? *J. Appl. Ecol.* 49, 1446–1456.
- Mossman, H.L., Pontee, N., Born, K., Hill, C., Lawrence, P.J., Rae, S., Scott, J., Serato, B., Sparkes, R.B., Sullivan, M.J.P., Dunk, R.M., 2022. Rapid carbon accumulation at a saltmarsh restored by managed realignment exceeded carbon emitted in direct site construction. *PLoS One* 17, e0259033.
- Oosterlee, L., Cox, T.J.S., Temmerman, S., Meire, P., 2020. Effects of tidal re-introduction design on sedimentation rates in previously embanked tidal marshes. *Estuar. Coast Shelf Sci.* 244, 106428.
- Pendleton, L., Donato, D.C., Murray, B.C., Crooks, S., Jenkins, W.A., Sifleet, S., Craft, C., Fourqurean, J.W., Kauffman, J.B., Marba, N., Megonigal, P., Pidgeon, E., Herr, D., Gordon, D., Baldera, A., 2012. Estimating global "Blue Carbon" emissions from conversion and degradation of vegetated coastal ecosystems. *PLoS One* 7.
- Pontee, N., Mossman, H., Burgess, H., Schuerch, M., Charman, R., Hudson, R., Dale, J., Austin, W., Burden, A., Balke, T., 2021. *Saltmarsh Restoration Methods*, Saltmarsh Restoration Handbook: UK & Ireland. Environment Agency, pp. 65–102.
- Reed, D., van Wesenbeeck, B., Herman, P.M.J., Meselhe, E., 2018. Tidal flat-wetland systems as flood defenses: understanding biogeomorphic controls. *Estuar. Coast Shelf Sci.* 213, 269–282.

- Reeder, I., Coulet, W., Miko, D., Thomas, J., Hopkins, G., 2021. Advances in saltmarsh restoration. Iran. J. Energy Environ. 12, 45–51.
- Rupprecht, F., Moller, I., Paul, M., Kudella, M., Spencer, T., van Wesenbeeck, B.K., Wolters, G., Jensen, K., Bouma, T.J., Miranda-Lange, M., Schimmels, S., 2017. Vegetation-wave interactions in salt marshes under storm surge conditions. Ecol. Eng. 100, 301–315.
- Saintilan, N., Kovalenko, K.E., Guntenspergen, G., Rogers, K., Lynch, J.C., Cahoon, D.R., Lovelock, C.E., Friess, D.A., Ashe, E., Krauss, K.W., Cormier, N., Spencer, T., Adams, J., Raw, J., Ibanez, C., Scarton, F., Temmerman, S., Meire, P., Maris, T., Thorne, K., Brazner, J., Chmura, G.L., Bowron, T., Gamage, V.P., Cressman, K., Endris, C., Marconi, C., Marcum, P., St Laurent, K., Reay, W., Raposa, K.B., Garwood, J.A., Khan, N., 2022. Constraints on the adjustment of tidal marshes to accelerating sea level rise. Science 377, 523–527.
- Scarton, F., Day, J.W., Rismondo, A., Cecconi, G., Are, D., 2000. Effects of an intertidal sediment fence on sediment elevation and vegetation distribution in a Venice (Italy) lagoon salt marsh. Ecol. Eng. 16, 223–233.
- Schuerch, M., Mossman, H.L., Moore, H.E., Christie, E., Kiesel, J., 2022. Invited perspectives: managed realignment as a solution to mitigate coastal flood risks – optimizing success through knowledge co-production. Nat. Hazards Earth Syst. Sci. 22, 2879–2890.
- Schuerch, M., Spencer, T., Temmerman, S., Kirwan, M.L., Wolff, C., Lincke, D., McOwen, C.J., Pickering, M.D., Reef, R., Vafeidis, A.T., Hinkel, J., Nicholls, R.J., Brown, S., 2018. Future response of global coastal wetlands to sea-level rise. Nature 561, 231–234.
- Siegersma, T.R., Willemsen, P.W.J.M., Horstman, E.M., Hu, Z., Borsje, B.W., 2023. Protective structures as adaptive management strategy in Nature-based Solutions to mitigate sea level rise effects. Ecol. Eng. 196, 107079.
- Siemes, R.W., Borsje, B.W., Daggenvoorde, R.J., Hulscher, S.J., 2020. Artificial structures steer morphological development of salt marshes: a model study. J. Mar. Sci. Eng. 8, 326.
- Silliman, B.R., Schrack, E., He, Q., Cope, R., Santoni, A., van der Heide, T., Jacobi, R., Jacobi, M., van de Koppel, J., 2015. Facilitation shifts paradigms and can amplify coastal restoration efforts. Proc. Natl. Acad. Sci. 112, 14295–14300.
- Spencer, K.L., Carr, S.J., Diggins, L.M., Tempest, J.A., Morris, M.A., Harvey, G.L., 2017. The impact of pre-restoration land-use and disturbance on sediment structure, hydrology and the sediment geochemical environment in restored saltmarshes. Sci. Total Environ. 587–588, 47–58.
- Stoorvogel, M.M., van Belzen, J., Temmerman, S., Wiesebron, L.E., Fivash, G.S., van Ijzerloo, L., van de Koppel, J., Bouma, T.J., 2024. Salt marshes for nature-based flood defense: sediment type, drainage, and vegetation drive the development of strong sediment beds. Ecol. Eng. 207, 107335.
- Strick, R.J.P., Ashworth, P.J., Sambrook Smith, G.H., Nicholas, A.P., Best, J.L., Lane, S. N., Parsons, D.R., Simpson, C.J., Unsworth, C.A., Dale, J., 2019. Quantification of bedform dynamics and bedload sediment flux in sandy braided rivers from airborne and satellite imagery. Earth Surf. Process. Landf. 44, 953–972.
- Tempest, J.A., Harvey, G.L., Spencer, K.L., 2015. Modified sediments and subsurface hydrology in natural and recreated salt marshes and implications for delivery of ecosystem services. Hydrol. Process. 29, 2346–2357.
- Van Loon-Steensma, J.M., Slim, P.A., 2013. The impact of erosion protection by stone dams on salt-marsh vegetation on two Wadden Sea barrier islands. J. Coast Res. 29, 783–796.
- Vona, I., Gray, M.W., Nardin, W., 2020. The impact of submerged breakwaters on sediment distribution along marsh boundaries. Water 12, 1016.
- Wamsley, T.V., Cialone, M.A., Smith, J.M., Atkinson, J.H., Rosati, J.D., 2010. The potential of wetlands in reducing storm surge. Ocean Eng. 37, 59–68.
- Williams, N., Dale, J., 2023. Unmanaged realignment: recent examples and the morphological evolution of naturally breached flood defences. Ocean Coast Manag. 242, 106715.
- Williams, R., 2012. Dams of Difference. Geomorphological Techniques 2.
- Winterwerp, J.C., Albers, T., Anthony, E.J., Friess, D.A., Mancheño, A.G., Moseley, K., Muhari, A., Naipal, S., Noordermeer, J., Oost, A., Saengsupavanich, C., Tas, S.A.J., Tonneijck, F.H., Wilms, T., Van Bijsterveldt, C., Van Eijk, P., Van Lavieren, E., Van Wesenbeeck, B.K., 2020. Managing erosion of mangrove-mud coasts with permeable dams – lessons learned. Ecol. Eng. 158, 106078.
- Worthington, T.A., Spalding, M., Landis, E., Maxwell, T.L., Navarro, A., Smart, L.S., Murray, N.J., 2024. The distribution of global tidal marshes from Earth observation data. Global Ecol. Biogeogr. 33, e13852.