Pannozzo, N, Leonardi, N, Carnacina, I and Smedley, RK

Storm sediment contribution to salt marsh accretion and expansion

Geomorphology 430 (2023) 108670

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.journals.elsevier.com/geomorphology

Storm sediment contribution to salt marsh accretion and expansion

Natascia Pannozzo [a,*], Nicoletta Leonardi [a], Iacopo Carnacina [b], Rachel K. Smedley [a]

[a] Department of Geography and Planning, School of Environmental Sciences, University of Liverpool, Chatham Street, Liverpool L69 7ZT, UK
[b] Department of Civil Engineering, School of Civil Engineering and Built Environment, Liverpool John Moores University, Byrom Street, Liverpool L3 3AF, UK

ARTICLE INFO

Keywords:
Salt marshes
Storms
Suspended sediments
Sediment provenance

ABSTRACT

Salt marshes are ecosystems with significant economic and environmental value. However, the accelerating rate of sea-level rise is a significant threat to these ecosystems. Storms significantly contribute to the sediment budget of salt marshes, playing a critical role in salt marsh survival to sea-level rise. There are, however, uncertainties on the extent to which storms contribute sediments to different areas of marsh platforms (e.g., outer marsh vs marsh interior) and on the sediment sources that storms draw on (e.g., offshore vs nearshore). This study uses field analyses from an eight-month field campaign in the Ribble Estuary, North-West England, to understand storms' influence on the sediment supply to different marsh areas and whether storms can deliver new material onto the salt marsh platform which would otherwise not be sourced in fair-weather conditions. Field data from sediment traps indicate that storm activity caused an increase in inorganic sediment supply to the whole salt marsh platform, especially benefitting the marsh interior. Geochemistry and particle size distribution analysis indicate that the majority of the sediment supplied to the salt marsh platform during the stormy periods was generated by an increase in erosion and resuspension of mudflat and tidal creek sediments, while only a minimal contribution was given by the sediments transported from outside the intertidal system. This suggests that, in the long term, storms will promote salt marsh vertical accretion but might simultaneously reduce the overall larger-scale sediment availability with implications for the marsh lateral retreat.

1. Introduction

Salt marshes are environments of significant value, as they provide numerous ecosystem services (Zedler and Kercher, 2005; Barbier et al., 2011). Salt marshes are also effective nature-based solutions for coastal protection against flooding and erosion (Temmerman et al., 2013), as they can buffer storm waves and stabilise sediments (e.g., Möller et al., 1999; Feagin et al., 2009). However, increasing rates of salt marsh loss have been recorded worldwide (e.g., Bakker et al., 1993; Environment Agency, 2011), despite the global effort in creating new vegetated intertidal areas and/or restoring wetlands previously reclaimed for anthropogenic purposes (Temmerman et al., 2013). Understanding the geomorphic processes that promote salt marsh resilience is, therefore, necessary for the effective management of these ecosystems.

Salt marshes form when the input of sediments from rivers and the sea to estuarine accommodation space allows tidal flats to reach a threshold elevation relative to sea level that permits vegetation growth (Morris et al., 2002). Encroachment and survival of salt marshes are possible if vertical accretion and lateral expansion of the salt marsh can keep pace with sea-level rise (Ma et al., 2014; Mariotti and Carr, 2014; Mitchell et al., 2017). Increasing rates of sea-level rise can lead to marsh drowning and lateral retreat, as sea-level rise creates new accommodation space, increasing the amount of sediment input required to guarantee marsh stability (FitzGerald et al., 2008; Kirwan et al., 2010; Ganju et al., 2017; Fagherazzi et al., 2020; Leonardi et al., 2018), and promotes near-shore ebb dominance, enhancing sediment export from the intertidal system (Carrasco et al., 2018; Zhang et al., 2020; Pannozzo et al., 2021b). Vertical accretion and lateral expansion are determined by sediment supply and organogenic production (Kirwan et al., 2010, 2016; Donatelli et al., 2020). However, the ongoing decrease in sediment supply to the coastlines, caused seawards by river dredging and damming and landwards by the enhanced sediment export, is currently exacerbating the vulnerability of salt marshes to increasing sea levels (Ganju et al., 2017; Donatelli et al., 2018).

Field and numerical investigations have shown that storms play a significant role in salt marsh accretion, as overwash by storm surges delivers a considerable amount of sediment to marsh platforms supporting marsh growth (Turner et al., 2006; Castagno et al., 2018; Tognin

* Corresponding author.
E-mail address: sgnpanno@liverpool.ac.uk (N. Pannozzo).

https://doi.org/10.1016/j.geomorph.2023.108670
Received 24 November 2022; Received in revised form 17 March 2023; Accepted 17 March 2023
Available online 23 March 2023

et al., 2021). Further studies have shown that the contribution of storm sedimentation to the salt marsh sediment budget allows salt marshes to keep pace with sea-level rise and is therefore critical for marsh survival (Schuerch et al., 2013; Pannozzo et al., 2021b). Despite the numerous studies that have investigated the roles of storm surges in salt marsh resilience, there are still uncertainties on the degree to which storms enhance the accretion of salt marsh platforms – i.e., to what extent storm sediment supply benefits different areas of marsh platforms (e.g., outer marsh vs marsh interior) and what are the sediment sources that storms draw on (e.g., offshore vs nearshore).

Sediment supply to the marsh platform depends on the hydroperiod (duration and frequency of tidal inundation), which decreases with distance from the water sources (i.e., sea and tidal creeks) (Reed, 1990). Therefore, while the outer marsh experiences marine sediment inputs regularly, the inner marsh areas only experience marine sediment inputs when they are inundated by high spring tides and/or storm surges (Roberts and Plater, 2005). Determining how storm sediment supply affects different areas of the marsh platform is, therefore, crucial for understanding to what extent salt marsh vertical accretion can benefit from storm activity. Nonetheless, vertical accretion must be compensated by lateral expansion to avoid the collapse of the platform edge (Fagherazzi et al., 2013; Mariotti and Fagherazzi, 2013). Marine sediments delivered to marsh platforms, however, originate mostly from the erosion of the adjacent intertidal areas, thus promoting vertical accretion but enhancing the lateral retreat of the salt marsh (Roner et al., 2021). Hence, understanding if storms can deliver to the marsh platform sediments from outside the intertidal system allows for determining whether these sediments can also benefit marsh lateral expansion.

This study uses field analyses conducted during the 2021–2022 storm season in the Ribble Estuary, North-West England, to understand: i) how storm activity affects sediment supply to different areas of the marsh platform; and ii) whether storm sediment supply has a different origin than sediment delivered to the marsh platform in fair-weather conditions. The Ribble Estuary was chosen as a case study due to its ecological and economic value (Tovey et al., 2009) and because of the critical role that storm deposits have on the survival of its salt marshes and intertidal flats (Lyons, 1997; Pannozzo et al., 2021a, 2021b). The concentration of suspended sediments collected from Hesketh Out Marsh after stormy and non-stormy periods was analysed to assess how storm activity changes the spatial variability of sediment supply across the marsh platform. The geochemistry and particle size distributions of the salt marsh sediments collected after stormy and non-stormy periods were then compared with each other and to the geochemistry and particle size distributions of surface sediments collected onshore, nearshore, and offshore to determine the sources of sediment supply in stormy and fair-weather conditions.

2. Study site

The Ribble Estuary is located on the Lancashire coast of North-West England (Fig. 2a). It is a funnel-shaped, tidally dominated and macrotidal estuary (Wakefield et al., 2011) with an ordinary tidal range of 8.0 m at spring tide and 4.4 m at neap tide (UKHO, 2001). It only experiences moderate wave energy, owing to waves generated in the Irish Sea basin predominantly by southerly and westerly winds (Pye and Neal, 1994). The average marsh platform elevation is approximately 3.5 m above mean sea level at Ordinance Datum. The formation of the extensive intertidal sand-silt flats and salt marshes lying along the riverbanks (Fig. 2b) resulted from the combination of infilling of sandy sediments from the bed of the Irish Sea and the deposition of silt and clay-sized sediments coming from the River Ribble (van der Wal et al., 2002). The accretion of the intertidal flat and salt marsh platform might have been further aided by the moderate wave climate characterising the estuary, which is insufficient to cause significant lateral erosion (van der Wal et al., 2002). The majority of the sediment supplied to the marsh platform is marine in provenance (Wright et al., 1971; Pannozzo et al., 2022b), with tidal pumping being the main process introducing sediments into the estuary (Lyons, 1997). Sediment supplied by storm surges has a crucial role in the accretion and expansion of the salt marsh and tidal flats, increasing the sediment budget of the system with increasing storm surge intensity and duration (Pannozzo et al., 2021a, 2021b). Between 2007 and 2017, a two-phase scheme was implemented to restore the intertidal habitat, previously reclaimed for agricultural purposes, to enhance the protection of coastal infrastructures against flooding (Tovey et al., 2009).

3. Methods

3.1. Detection of storm activity

Sediments were collected approximately every 30 days from Hesketh Out Marsh from 15th November 2021 to 5th July 2022, with the same frequency both during stormy and non-stormy periods, with the exception of the first period (15th November 2021 to 12th January 2022) as sediments were collected after approximately 60 days for logistics reasons. For the identification of storm events, water level and significant wave height records, measured respectively at the Liverpool Gladstone Dock tide gauge station (Fig. 1a; BODC, 2022) and at the Liverpool Bay WaveNet Site wave buoy (Fig. 1c; Cefas, 2022), were collected for the period studied. BODC and Cefas perform regular checks on the performance of the gauges and data are routinely processed and quality controlled. The water level data has been adjusted to Ordinance Datum (OD) using the conversion parameters provided by the National Tidal and Sea Level Facility and the values flagged as unreliable by BODC were removed from the time series. The residual water level (Fig. 1b) was calculated by subtracting the predicted tide for the period studied from the total water level, and the predicted tide was calculated by combining the tidal constituents derived from the total water level of the period studied, using the MATLAB package T-Tide (Pawlowicz et al., 2002). Stormy periods were identified as periods in which residual water level and significant wave height increased above the 95th percentile (Fig. 1). This is a threshold commonly associated with storm activity (e.g., Matulla et al., 2008; Lyddon et al., 2018). Only periods in which both residual water level and significant wave height increased above the 95th percentile were associated with storm activity.

3.2. Sediment supply

There is evidence that sediment supply to salt marshes is strongly controlled by the concentration of suspended sediment in the source water (Temmerman et al., 2004; Willemsen et al., 2021). Hence, to assess how storm activity affects sediment supply over the marsh platform, suspended sediments were collected across Hesketh Out Marsh (Fig. 2e) during stormy and non-stormy periods, using sediment traps. Two transects 100 m in length were set up on the salt marsh with traps placed at 15 m intervals, one orthogonal to the marsh edge and one orthogonal to the bank of one of the biggest tidal creeks (Fig. 2f). To ensure that there were no significant topographic constraints on the sediment supply to the sediment traps, transects profiles were produced using a TOPCON HIPER II RTK GPS with ~10 mm + 1 ppm horizontal accuracy and ~ 15 mm + 1 ppm vertical accuracy. The overall transects elevation has been adjusted to Ordnance Datum (OD) using the LiDAR-derived Digital Elevation Model (DEM) relative to the RTK base-station position as the reference point (Fig. 2g). The traps consisted of 50 mL plastic tubes which were placed at ground level and at 30 cm from the ground to capture the SSC vertical profile and to compare the trends at different levels to ensure internal consistency (Fig. 2h). Multiple stormy and non-stormy periods were assessed to further ensure consistency between trends relative to periods with similar hydrodynamic conditions (Figs. 3 and S3). The samples were centrifuged to remove excess water and freeze-dried to remove any moisture before being weighed.

The availability of suspended sediment in the water column is

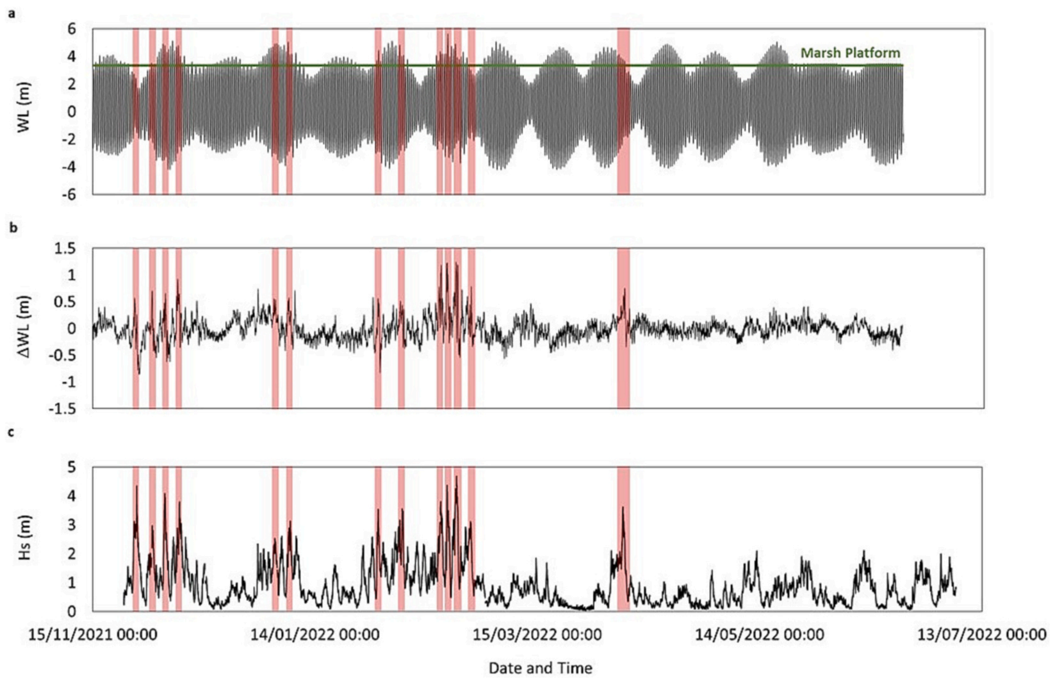

Fig. 1. Total water level (WL) (a), residual water level (ΔWL) (b) and significant wave height (Hs) (c) measured from 15th November 2021 to 5th July 2022. The red bands highlight periods in which both residual water level and significant wave height are higher than the 95th percentile (i.e., stormy periods). The water level data has been adjusted to Ordnance Datum (OD).

controlled by current velocities and wave energy, responsible for sediment resuspension and transport (Rose and Thorne, 2001; Zhang et al., 2019). Storms cause an increase in water level and wave height, enhancing current velocities and wave energy (Bertin et al., 2017), thus increasing the availability of suspended sediment within the system (Duvall et al., 2019). As the storm period increases, the availability of suspended sediment also increases (Pannozzo et al., 2021a, 2021b). Hence, to assess how storms control the sediment delivery to different areas of the marsh platform, a linear regression analysis was performed between the suspended sediment concentration measured across both transects over stormy and non-stormy periods and the hydrodynamic variables estimated for the same periods – i.e., mean residual water level and significant wave height above the 95th percentile (representative of storm intensity) and total period during which residual water level and significant wave height are above the 95th percentile (representative of the total period of storminess). To facilitate comparison between all stormy and non-stormy periods, the total suspended sediment concentration measured at the end of each period was normalized to daily rates and the total period of storminess was measured in days per month with one month being defined as 30 days. The linear regression was then used to calculate coefficients of determination (R^2) to investigate how the control of each hydrodynamic parameter on the SSC varies spatially across the marsh platform.

3.3. Sediment composition and provenance

Pannozzo et al. (2022b) showed that the inorganic sediment input to Hesketh Out Marsh is predominantly marine in provenance, while the riverine influence is minimal. As the marine provenance of the inorganic sediments was ascertained, to assess the spatial extent of the marine sediment supply to the marsh platform during stormy and fair-weather conditions, the geochemical composition of the sediments collected from the salt marsh after stormy and non-stormy periods and the geochemical composition of the sediments collected from the potential marine sources were determined using X-Ray Fluorescence (XRF) analysis and compared. Geochemistry is, indeed, widely used as a proxy to reconstruct the composition of marshland sediments (e.g., Kolditz et al., 2012; Hazermoshar et al., 2016).

As the estuary is infilled with marine sediments, the nearshore and offshore areas of the estuary are expected to be similar in sediment composition; thus, geochemical analysis is insufficient to discern which marine source the inorganic sediments are transported from. Particle size distributions (PSDs) analysis, on the other hand, can detect differential modes of sediment deposition, indicative of different levels of energy that characterise the salt marsh in different hydrodynamic conditions, and can be used to speculate on the distance travelled by sediments before deposition (Rahman and Plater, 2014; Pannozzo et al., 2023). Fine-skewed to near-symmetrical distributions characterised by well-sorted, sand-sized sediment are typical of traction load delivered by the fast tidal flow velocities (i.e., during the flood phase) and are found in substrates with low elevation and high energy levels (e.g., sandflats). Near-symmetrical distributions characterised by fine to very fine, poorly sorted silts are typical of the suspension load that settles during the turn of the tide (i.e., during the ebb phase) and are found in substrates with high elevation and low energy levels (e.g., salt marsh platforms). Mudflats, which are transitional environments, typically have a mixed distribution. As salt marshes are low energy environments, the suspension load that dominates their PSDs is mostly eroded and transported by tidal currents and waves from adjacent mudflats and tidal creeks (Zhang et al., 2019; Roner et al., 2021). If storm flooding significantly enhances the energy levels over the marsh platform, the PSD of the salt marsh sediments are expected to change and resemble the PSD of the mudflat sediments, as higher energy levels allow sediment supply to the marsh platform through infilling as well as settling. A significant increase in energy levels would further imply that sediments can be transported over longer distances, thus suggesting that storms could transport significant amount of sediments from further marine sources (i.e., sandflat, sand dunes and offshore region) in addition to eroding the adjacent mudflat areas and tidal creeks (Cahoon et al., 1995). On the contrary, if storm flooding does not cause a significant increase in the energy level over the marsh platform, it would be unlikely that sediments are transported from sources further than the adjacent mudflat and tidal creeks, and the PSD of the sediments supplied to the salt marsh by storms are expected to be similar to the PSD of the sediments supplied in fair-

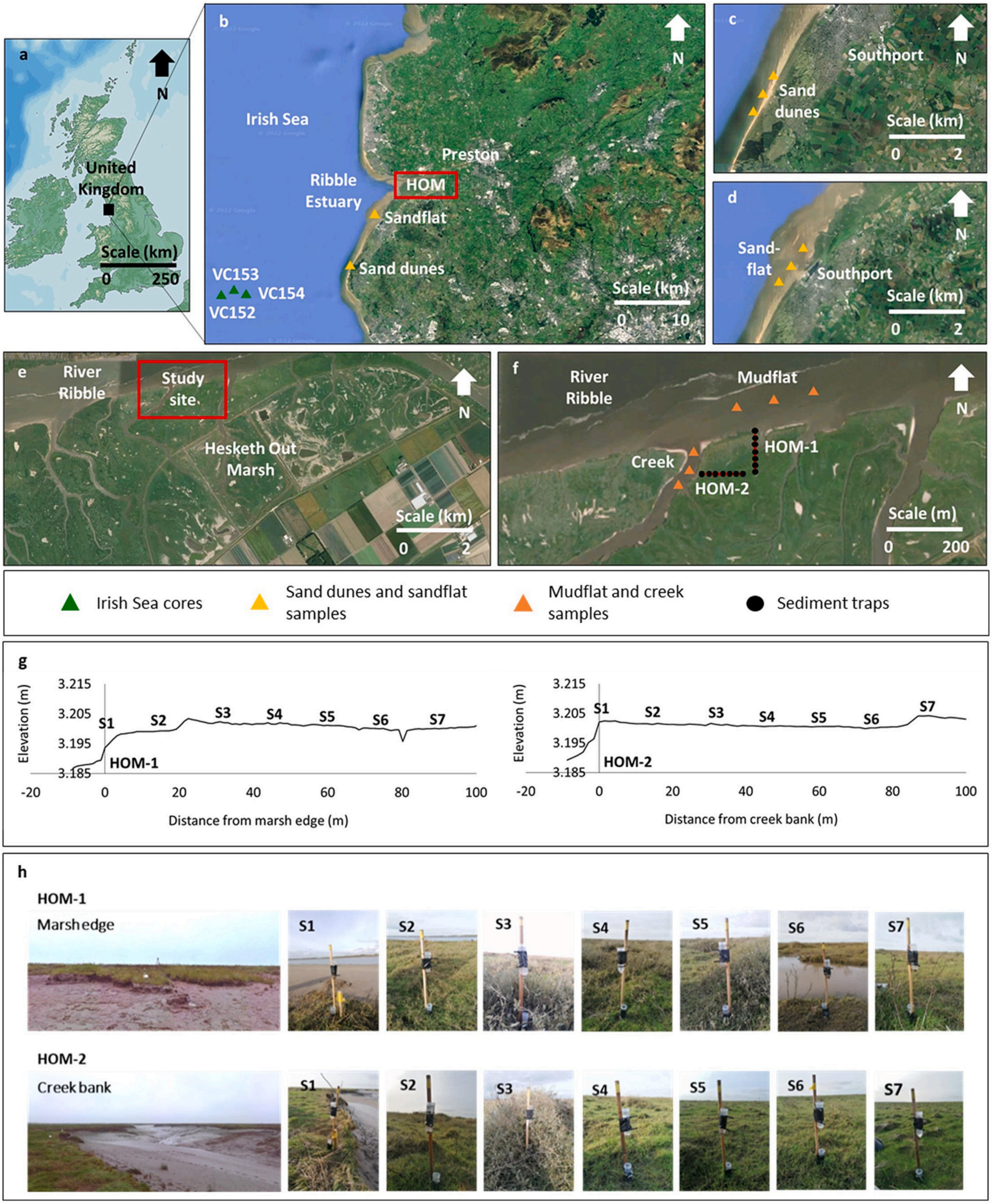

Fig. 2. Location of the Ribble Estuary (a); location of Hesketh Out Marsh (HOM), the Irish Sea coring sites (VC153, VC154, VC152), and the sand dunes and sandflat sampling sites (© Google Earth Pro, 2022) (b); high-resolution view of the sand dunes (c) and sandflat (d) sampling sites (© Google Earth Pro, 2022); high-resolution view of Hesketh Out Marsh and location of the study site (© Google Earth Pro, 2022) (e); high-resolution view of the mudflat and creek sampling sites and transects location (© Google Earth Pro, 2022) (f); transects profiles and location of the sediment traps (g); panoramic of the starting points of the transects HOM-1 (marsh edge) and HOM-2 (creek bank) obtained with a FARO 3D laser scanner Focus X330 and photos displaying the locations of the sediment traps along each transect (h).

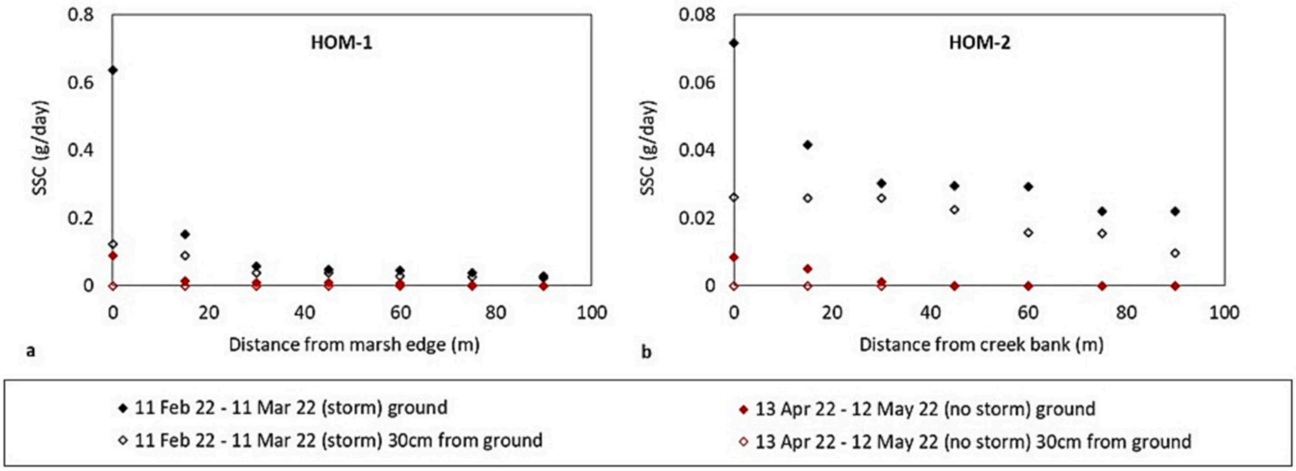

Fig. 3. SSC (g/day) profile with distance from the marsh edge (a) and the creek bank (b), at ground level and at 30 cm from the ground, relative to a stormy and a non-stormy period (see Fig. S3 for the profiles relative to the other periods studied).

weather conditions.

To show how PSDs can detect differential modes of sediment deposition, PSD analysis was first performed on the sediments collected from the potential onshore, nearshore and offshore sources, to characterise the landward change in energy levels. The same analysis was then performed on the sediments collected from the salt marsh platform during stormy and non-stormy periods to assess any change in energy levels caused by storm activity and relative change in sediment transport pathways. To characterise the onshore sediments, three samples were collected from the coastal aeolian dunes near Southport (Fig. 2c). To characterise the nearshore sediments, a set of nine samples (three per location) were collected from the mudflat and tidal creek adjacent to the marsh platform (Fig. 2f), and the sandflat at the south of the Ribble Estuary (Fig. 2d). The offshore sediments were characterised by analysing three sediment cores collected at 2 km spacing across the Irish Sea ~20 km offshore in 28–30 m water depths (Pearce et al., 2011); only the top 1 m of the cores (originally 6 m long) was subsampled (at 0.1 m intervals, resulting in 30 samples in total), with these depths characterising the more mobile surface sediments of the eastern Irish Sea (Fig. 2b).

3.3.1. *Sediment composition*

The geochemical composition of the sediments collected from Hesketh Out Marsh and potential marine sediment sources was measured by X-Ray fluorescence (XRF) using a XEPOS 3 Energy-dispersive XRF. All samples were hand ground, pressed and then measured under a He atmosphere under combined Pd and Co excitation radiation and using a high resolution, low spectral interference silicon drift detector. The XEPOS 3 undergoes daily standardisation procedure and has accuracies verified routinely using 18 certified reference materials (Boyle et al., 2015). Light elements were corrected for organic content, using loss-on-ignition (LOI) values measured by heating the samples at 105 °C overnight to evaporate all moisture content and then igniting them in a furnace at 450 °C for 4.5 h to combust all organic matter (Boyle, 2000).

Principal component analysis was performed using PAST3 (Hammer, 2019) to explore the geochemical compositions of the samples and to assess any association between the salt marsh sediments and the potential marine sources. The parameters selected for this PCA were: coarse mineral (Si (mg/g), Zr (μg/g)) and shell content (Ca (mg/g), Sr (μg/g)) indicators, salt water (Na (mg/g)) and organic content (LOI (%), S (mg/g), Br (μg/g)) indicators, fine mineral indicators (K (mg/g), Al (mg/g), Ti (μg/g), Rb (μg/g), Nb (μg/g)), post-depositional diagenesis indicators (Fe (mg/g), Mn (μg/g)), pollutants (Mg (mg/g), P (mg/g), As (μg/g), Pb (μg/g), Zn (μg/g), Ni (μg/g), Cu (μg/g), V (μg/g), Cr (μg/g), Ga (μg/g), Ge (μg/g), Ba (μg/g), I (μg/g)) and the rare elements (Y (μg/g), La (μg/g), Ce (μg/g)) (Boyle, 2000; Plater et al., 2000).

3.3.2. *Particle size distribution analysis*

Particle size distributions (PSDs) were measured for the sediments collected at the marsh edge and from the potential sources using a Coulter LS 13320 Single-Wavelength Laser Diffraction Particle Size Analyser that determines the dimensions of individual particles 0.375–2000 μm. Only the sediments trapped at marsh edge at ground level were used for the PSD analysis, as they are the most likely to show a mixed distribution if any infilling has occurred (Rahman and Plater, 2014). Subsamples were digested in 6 % concentrated H_2O_2 (50 mL of H_2O_2 per 10 mL of sample) to remove any organic component, with the samples then dispersed and sonicated in $Na_6O_{18}P_6$ and analysed under sonicating measurement conditions. The resulting PSDs are the average of three repeats after the elimination of outliers. The Coulter LS 13320 undergoes regular calibration checks using samples with known size distributions. End-member modelling analysis (EMMA) was conducted using the EMMAgeo R package to statistically derive the dominant modes in the PSDs of the marsh and potential marine source sediments (Dietze et al., 2012). The maximum number of end-members that the model could detect was set as seven, as identified by Clarke et al. (2013) and Clarke et al. (2014). Particle size categories with several zero values were combined to enable an end-member analysis of the entire data set. A robustness test was performed to check on each end-member (Fig. S2a). The model showed that 85 % of the variance in the PSDs could be explained by two PSD end-members (Fig. S2b). The loading of the end-members explaining most of the variance was plotted to characterise the dominant modes in the PSDs of the marsh edge and potential marine source sediments. The end-members scores relative to the salt marsh and potential sources were then plotted to observe any similarities between the modes characterising the salt marsh sediments during stormy and non-stormy periods and the modes characterising the potential marine sources.

4. Results

4.1. *Sediment supply*

Both at ground level and at 30 cm from the ground, suspended sediment concentration (SSC) decayed non-linearly with distance from the marsh edge and the creek bank, similarly during stormy and fair-weather periods, but was overall higher across both transects during stormy periods (Figs. 3 and S3).

Close to the marsh edge, SSC reached up to 0.2 g/day at ground level and up to 0.04 g/day at 30 cm from the ground in fair-weather conditions, while it reached up to 0.7 g/day at ground level and up to 0.2 g/day at 30 cm from the ground in stormy conditions (Fig. 4 c, d). Close to the creek bank and at 30 m from the marsh edge and creek bank, SSC was consistently lower than 0.01 g/day in fair-weather conditions, both at ground level and at 30 cm from the ground, while it reached up to 0.07 g/day at ground level and up to 0.04 g/day at 30 cm from the ground in stormy conditions (Fig. 4 c, d, e, f). Thus, in stormy periods, SSC at the marsh edge increased by up to 250 % at ground level and by up to 400 % at 30 cm from the ground; in the marsh interior, however, it increased up to 600 % at ground level and up to 300 % at 30 cm from the ground. Hence, in relative terms, the increase in SSC caused by storm activity was more significant for the interior of the marsh than it was for the marsh edge.

The increase in SSC during stormy periods corresponds to an increase in the residual water level and significant wave height, both of which consistently increased above the 95th percentile; the mean residual water level above the 95th percentile ranged between 0.35 m and 0.53 m, while the significant wave height above the 95th percentile ranged between 2.8 m and 3.2 m (Fig. 4a, b). Overall, across both transects, SSC shows a positive correlation with all three hydrodynamic variables, increasing with an increase in storm intensity (i.e., mean residual water level and significant wave height above the 95th percentile) and storm duration (i.e., total period during which residual water level and significant wave height are above the 95th percentile), similarly at ground level and at 30 cm from the ground (Fig. 5). The control of the hydrodynamic variables on the SSC, however, is not uniform across the salt marsh platform (Fig. 6). Results show that variations in water level and wave height cause the greatest changes in SSC at the marsh edge, while their influence decreases with distance from marsh edge and creek bank. Nevertheless, wave height has a stronger control on SSC compared to water level. Storm duration, on the other hand, is more influential over the marsh interior and has, overall, the strongest control on the total sediment availability above the marsh platform.

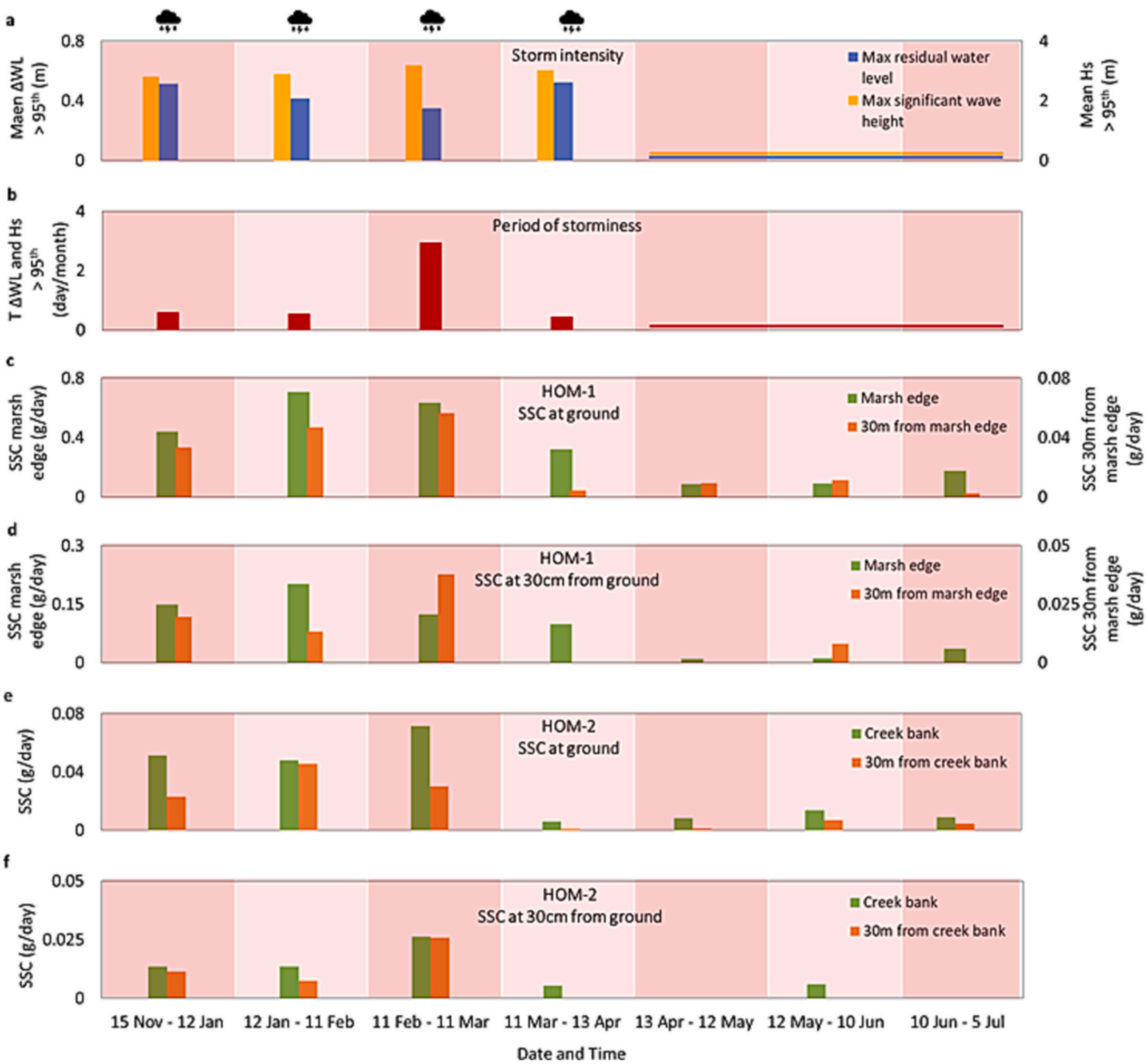

Fig. 4. Mean residual water level (ΔWL) (m) and significant wave height (Hs) (m) above the 95th percentile (a); total period (T) during which residual water level (ΔWL) and significant wave height (Hs) are above the 95th percentile (b); SSC (g/day) at ground level, at the marsh edge and at 30 m from the marsh edge (c); SSC (g/day) at 30 cm from the ground, at the marsh edge and at 30 m from the marsh edge (d); SSC (g/day) at ground level, at the creek bank and at 30 m from the creek bank (e); SSC (g/day) at 30 cm from the ground, at the creek bank and at 30 m from the creek bank (f); for each period studied between 15th November 2021 and 5th July 2022. The cloud symbols indicate the periods characterised by storm activity.

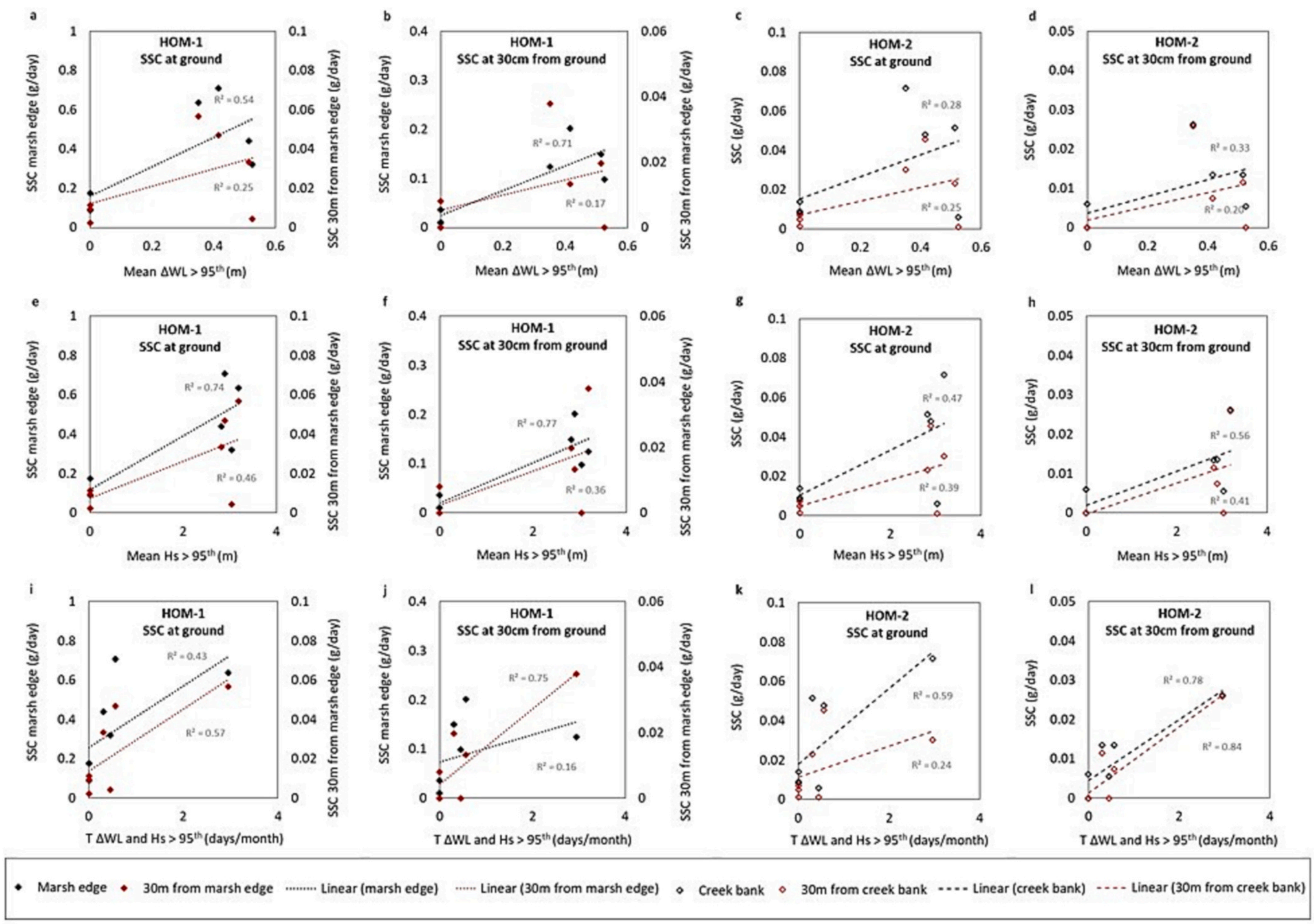

Fig. 5. Linear regression analysis performed between SSC (g/day), mean residual water level (ΔWL) (m) and significant wave height (Hs) (m) above the 95th percentile, and the total period (T) during which residual water level (ΔWL) and significant wave height (Hs) are above the 95th percentile (days/month); at ground level at the marsh edge and at 30 m from the marsh edge (a, e, i), at 30 cm from the ground at the marsh edge and at 30 m from the marsh edge (b, f, j), at ground level at the creek bank and at 30 m from the creek bank (c, g, k), and at 30 cm from the ground at the creek bank and at 30 m from the creek bank (d, h, l).

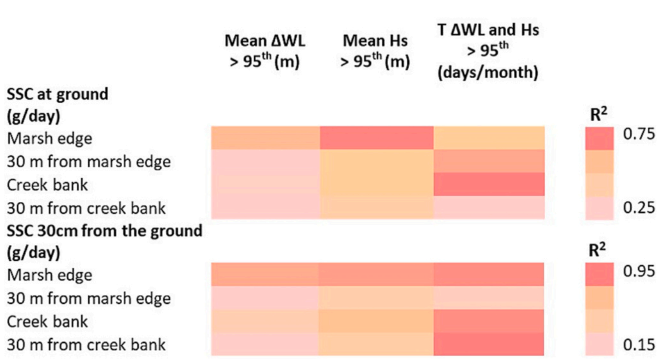

Fig. 6. Coefficients of determination (R^2) relative to the regression analysis performed between SSC (g/day), mean residual water level (ΔWL) (m) and significant wave height (Hs) (m) above the 95th percentile, and the total period (T) during which residual water level (ΔWL) and significant wave height (Hs) are above the 95th percentile (days/month); at ground level at the marsh edge and at 30 m from the marsh edge, at 30 cm from the ground at the marsh edge and at 30 m from the marsh edge, at ground level at the creek bank and at 30 m from the creek bank, and at 30 cm from the ground at the creek bank and at 30 m from the creek bank.

4.2. Sediment composition and provenance

The first two components of the PCA performed on the XRF measurements of the sediments collected from Hesketh Out Marsh, the Irish Sea floor, Southport sand dunes, and the intertidal areas summarise 76 % of the variance in the data, respectively 43 % and 33 % (Fig. 7). Component 2 separates samples rich in shells (Ca and Sr) and silt-sand sized minerals (Si and Zr) from those rich in organic content (LOI, S and Br). Component 1 separates samples rich in organic content from those rich in minerals and pollutants. The marsh sediments collected after stormy periods are mostly characterised by shells and silt-sand sized minerals, with some contribution from finer minerals, and have similar composition to some of the marine samples. The sediments collected after non-stormy periods are mostly characterised by organic content with minimal contribution from finer minerals, with the exception of the sediments collected at the edge of the marsh platform, which are richer in shells and silt-sand sized minerals and have stronger association with the stormy sediments and some of the marine samples.

The EMMA analysis (Fig. 8) shows two dominant end-members characterising the PSDs variance: EM1 is characterised by a mixed near-symmetrical to fine-skewed distribution of silt to fine sand with a secondary near-symmetrical mode dominantly clay to silt and EM2 is characterised by a fine-skewed to near-symmetrical distribution of fine to coarse sand. The Irish Sea, sand dunes and sandflat sediments have PSDs dominated by EM2, with only minimal contribution (up to 30 %) from EM1. Progressing landwards, however, the EM1 mode becomes

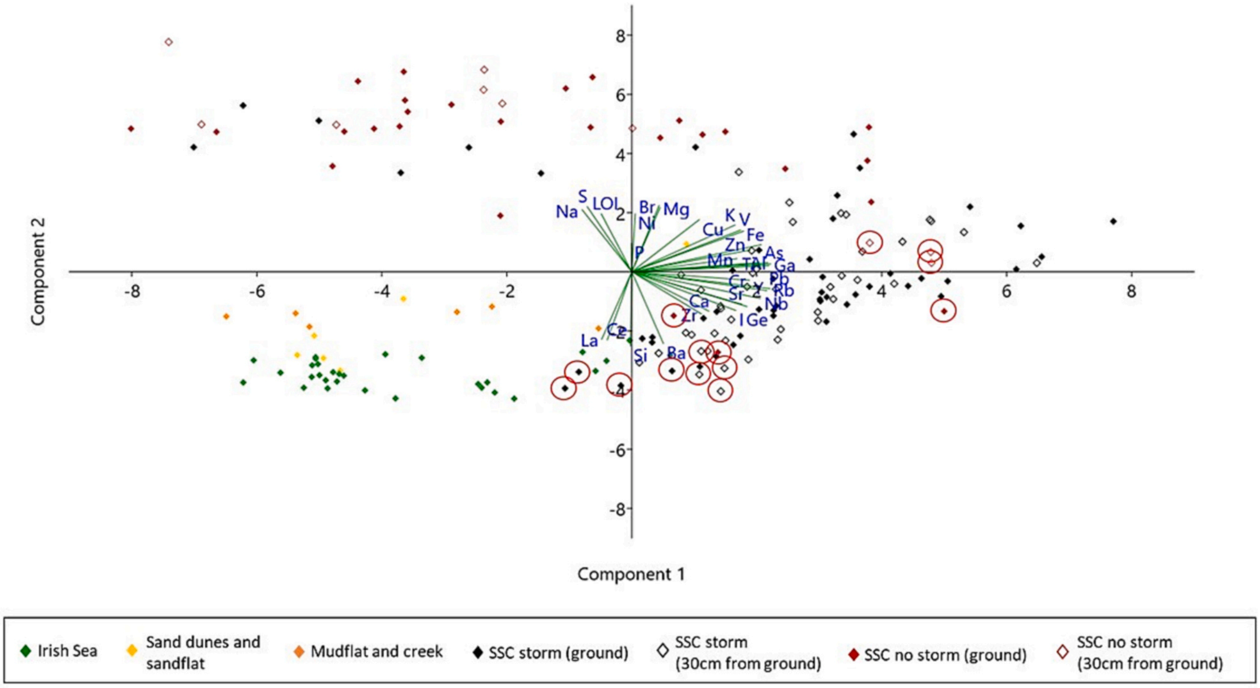

Fig. 7. Principal component analysis between samples collected from Hesketh Out Marsh, sand dunes and sandflat, mudflat and creek adjacent to the salt marsh, and the Irish Sea cores. Component 1 and component 2 summarise 76 % of the variance in the data, respectively 43 % and 33 %. The figure shows the parameters used by each component to separate the samples and the clusters formed by the samples that correlate with each other. The red circles highlight the samples collected at the marsh edge.

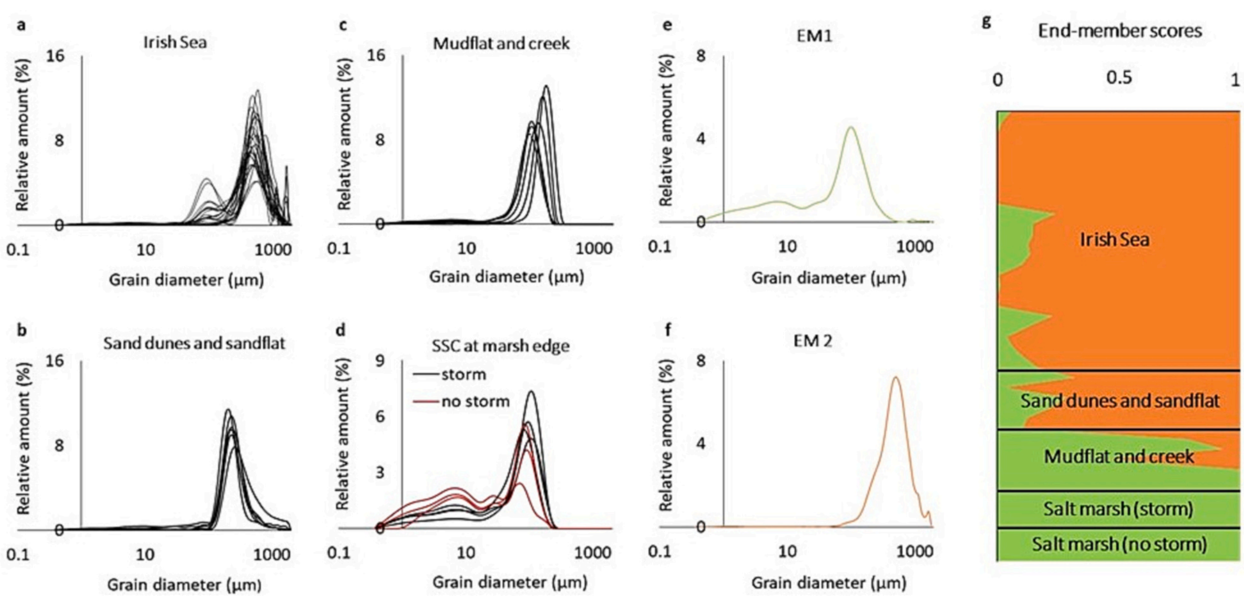

Fig. 8. PSDs of sediments from Irish Sea (a), sand dunes and sandflat (b), mudflat and creek (c) and Hesketh Out Marsh (d); end-member loading for EM1 (e) and EM2 (f); end-member scores for salt marsh and potential sediment sources (g).

dominant, characterising between 40 % and 100 % of the mudflat and creek PSDs. The samples collected from the salt marsh edge after the stormy periods do not differ statistically from the samples collected after non-stormy periods; their PSDs are both dominated by the EM1 mode.

5. Discussion

5.1. Sediment supply

Sediment supply decreased with distance from the marsh edge and the creek bank, similarly during stormy and fair-weather periods (Figs. 3 and S3). This non-linear decrease resembles trends already showed for other sites by modelling (Zhang et al., 2019; Zhu and Wiberg, 2022) and field (Temmerman et al., 2003; Duvall et al., 2019) studies. Sediments are resuspended from the tidal creeks and the mudflats and transported over the marsh platform by flood currents and waves (Zhang et al., 2019; Roner et al., 2021). Therefore, the areas closest to tidal water (i.e., marsh edge and creek bank), which are flooded first and experience more frequent inundations, are supplied with most of the sediments present in the source water, while the inner marsh areas, which are flooded later and experience less frequent inundations, are only reached by minimum amounts of sediment.

Sediment supply over the marsh platform, however, was overall higher across both transects during stormy periods (Figs. 3 and S3). Storms cause an increase in both water level and wave height (Fig. 4a; Bertin et al., 2017). When a storm causes an increase in water level (i.e., positive surge), the water depth increases and enhances the propagation speed of the tidal wave, leading to an increase in the speed of the flood currents (Bertin et al., 2017). Simultaneously, storms also cause an increase in wave height, which is responsible for an increase in wave energy (Bertin et al., 2017). This increase in current velocities and wave energy contributes to higher bottom shear stress resulting in higher sediment resuspension and enhances sediment transport within the system (Mariotti et al., 2010; Carniello et al., 2012), also affecting areas of the inner marsh platform which are not flooded in fair-weather conditions (D'Alpaos et al., 2007; Kirwan and Murray, 2007). As showed by the regression analysis (Fig. 5), this resulted in a positive correlation between SSC and the hydrodynamic parameters, with SSC increasing with increasing storm intensity (i.e., mean residual water level and significant wave height above the 95th percentile) and storm duration (i.e., period during which mean residual water level and significant wave height are above the 95th percentile). The uneven influence of the hydrodynamic parameters on the spatial distribution of sediment supply across the salt marsh platform observed in Fig. 6 is due partially to the increase of vegetation and topographic constraints with increasing distance from marsh edge (Neumeier and Ciavola, 2004; Mudd et al., 2010; Yang et al., 2012) and partially to the differential increase in settling time over different marsh areas (Temmerman et al., 2003; Duvall et al., 2019; Zhang et al., 2019). Water level and wave height cause the greatest changes at the marsh edge, while their influence decreases with distance from marsh edge and creek bank. While above the outer marsh an increase in water level and wave height directly corresponds to an increase in tidal current velocities and wave energy, with increasing distance from the marsh edge and creek bank, the increased friction caused by vegetation and topographic variations buffers tidal currents and waves, hence inhibiting their influence above the inner marsh areas (Neumeier and Ciavola, 2004; Mudd et al., 2010; Yang et al., 2012). Wave height, however, seems to have a stronger control on sediment supply than water level, in agreement with results from other field (Duvall et al., 2019) and modelling (Zhu and Wiberg, 2022) studies. Duvall et al. (2019) observed that water level is responsible for the regulation of marsh inundation, which influences sediment delivery, while waves are responsible for most of the sediment resuspension on tidal flats, which controls sediment availability; hence, waves are ultimately responsible for the amount of sediments that can be transported from the mudflat to the salt marsh platform. Storm duration, on the other hand, is more influential over the marsh interior and has, overall, the strongest control on the total sediment availability above the marsh platform. Although an increase in storm duration is responsible for longer inundation of the marsh platform and consequent higher overall sediment supply (Pannozzo et al., 2021a, 2021b), close to the marsh edge, where water depths are already high, the increase in settling time caused by increased water levels is higher than in the marsh interior (Temmerman et al., 2003; Duvall et al., 2019; Zhang et al., 2019); hence, an increase in storm duration has lower control on the sediment deposition closer to the water sources. The higher settling time (due to increased water depth) at the marsh edge compared to the marsh interior is also responsible for the lower rates of change in sediment supply that characterise the outer marsh, as observed in Fig. 4. Indeed, although sediment supply was overall higher at the marsh edge than it was in the marsh interior, the increase in sediment supply at ground level during stormy periods was more significant for the inner marsh (up to 600 %) than it was for the marsh edge (up to 400 %). This differential increase in settling time was also detected by the SSC vertical profile. At the marsh edge, the storm-driven increase in SSC at ground level was lower than the increase at 30 cm from the ground; however, over the marsh interior, the increase at ground level was higher than the increase at 30 cm from the ground (Fig. 4).

Overall, results showed that storm activity causes an increase in sediment supply to the whole salt marsh platform, and that this increase is especially significant for the marsh interior.

5.2. Sediment composition and provenance

The PCA analysis (Fig. 7) suggests that, in fair-weather conditions, inorganic sediments transported from marine sources only reach the outer portion of the marsh platform up to 30 m from the marsh edge; most of the sediment supply beyond that point was characterised by locally resuspended organic sediment, produced through in-situ organogenic processes (Boyle, 2000; Plater et al., 2000), as those areas of the marsh are flooded with less frequency (D'Alpaos et al., 2007; Kirwan and Murray, 2007). During storm events, on the other hand, as water level and wave height increase (Bertin et al., 2017) and further inland portions of the salt marsh experience flooding (D'Alpaos et al., 2007; Kirwan and Murray, 2007), marine sediments reach both outer and inner marsh areas covering, in the majority of the cases, the whole extent of the transects (Boyle, 2000; Plater et al., 2000). Similar trends have been observed in other sites (Stumpf, 1983; Marani et al., 2013; Morris et al., 2016; Tognin et al., 2021).

The EMMA analysis (Fig. 8) shows, as expected (Rahman and Plater, 2014; Pannozzo et al., 2023), that the particle size distributions (PSDs) of the sediments collected from the Irish Sea basin, sand dunes and sandflat are dominated by the EM2 mode (fine-skewed to near-symmetrical distribution of fine to coarse sand typical of energetic environments where sedimentation occurs through infilling), with only minimal contribution from EM1, while the mudflat and tidal creeks have PSDs which progressively become dominated by the EM1 mode (mixed near-symmetrical to fine-skewed distribution of silt to fine sand with a secondary near-symmetrical mode dominantly clay to silt typical of low energy environments where sedimentation occurs through settling). Interestingly, the EMMA analysis also shows that the PSDs of the sediments collected from the salt marsh edge after the stormy periods do not differ statistically from the PSDs of the sediments collected after non-stormy periods, as they are both dominated by the EM1 mode. The sediment supplied to salt marshes is mostly suspension load that is transported by flood tides from adjacent mudflats and tidal creeks and settles on the marsh platforms during the turn of the tide (Rahman and Plater, 2014; Zhang et al., 2019; Roner et al., 2021; Pannozzo et al., 2023). The lack of significant change in the PSDs of the salt marsh sediments between fair-weather and stormy periods suggests that the increase in energy levels caused by the storms was not high enough to change the mode of sediment deposition (Rahman and Plater, 2014); hence, even in stormy conditions, the majority of the sediments supplied to the salt marsh platform are likely to be resuspended from the tidal creeks and the mudflats adjacent to the marsh (Zhang et al., 2019; Roner et al., 2021). It is indeed reasonable that, since sediment availability is strongly dependent on resuspension (Fig. 6; Duvall et al., 2019), the majority of the sediments are transported from shallow areas, where waves and currents can generate shear stresses (Mariotti et al., 2010; Carniello et al., 2012). This interpretation also agrees with the trends observed by Pannozzo et al. (2021b), which modelled the effects of increasing storm intensity on the sediment budget of the Ribble Estuary. The model showed that even the most intense storms (surges up to 4 m) would increase the sediment budget of the salt marsh platform by up to 67 % but would only contribute to an increase in the sediment budget of the inner estuary by up to 7 %. Such a difference in rates suggests that, although a minimal contribution from further sources is probable, the majority of the sediments transported by storms onto the salt marsh platform must come from within the inner estuary, thus confirming our interpretation of the PSDs results.

5.3. Implications

With the ongoing decrease in sediment supply to the coastlines (Darby et al., 2020; Tamura et al., 2020; Wei et al., 2020), the contribution of storm sedimentation to the salt marsh sediment budget is thought to be critical for marsh survival to sea-level rise (Schuerch et al., 2013; Pannozzo et al., 2021b). Salt marsh resilience to sea-level rise depends on their ability to accrete vertically and expand laterally (Ma et al., 2014; Mariotti and Carr, 2014; Mitchell et al., 2017). While vertical accretion prevents salt marshes from drowning, lateral expansion is crucial to avoid collapse of the platform edge (Fagherazzi et al., 2013; Mariotti and Fagherazzi, 2013).

Results showed that storm activity causes an overall increase in inorganic sediment supply to the salt marsh platform, and that this increase is especially significant for the marsh interior. This suggests that storms are especially beneficial to the vertical accretion of the inner marsh areas, which rarely experience minerogenic supply (Stumpf, 1983; Marani et al., 2013; Morris et al., 2016; Tognin et al., 2021). Nonetheless, results also showed that the majority of the sediment supplied to the salt marsh platform by storms is likely generated by an increase in erosion and resuspension of mudflat and tidal creek sediments (Zhang et al., 2019; Roner et al., 2021), while only a minimal contribution is given by sediment transported from outside the system (Cahoon et al., 1995). This suggests that, in the long-term, storms will promote salt marsh vertical accretion, but might simultaneously reduce the overall larger-scale sediment availability with implications for the lateral retreat of the marsh platform (Roner et al., 2021).

6. Conclusions

This study aimed at understanding how storm activity affects sediment supply to different marsh areas and whether storm sediment supply has different origin to the marine sediment delivered to marsh platforms during fair-weather conditions. Suspended sediment concentrations were analysed across Hesketh Out Marsh, North-West England, during the 2021–2022 storm season, during stormy and non-stormy periods to assess how storm activity changes the spatial variability of sediment supply across the marsh platform. Geochemical and particle size distribution analyses were then conducted on sediments from the salt marsh and potential onshore, nearshore and offshore sources of sediments to determine whether storms deliver any new material onto the salt marsh platform which would not be delivered in fair-weather conditions. Results showed that storm activity causes an increase in inorganic sediment supply to the whole salt marsh platform and that this increase is especially significant for the marsh interior. However, the majority of the sediment supplied to the salt marsh platform by storms is produced by an increase in erosion and resuspension of mudflat and tidal creek sediments, while the sediments transported from outside the intertidal system only contribute minimally. This suggests that, in the long-term, storms will promote salt marsh vertical accretion but might simultaneously reduce the overall larger-scale sediment availability with implications for the marsh lateral retreat.

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.

Data availability

Data related to this article can be found in the following repository (Pannozzo et al., 2022a): doi: https://doi.org/10.5281/zenodo.7590233.

Acknowledgments

We acknowledge support from the School of Environmental Sciences, University of Liverpool, which is funding the PhD project of the first author, the RGS-IBG for funding the field campaign and the first author time on this project (project title: Building coastal resilience one sediment grain at the time: field measurements and community engagement on nature-based solutions for coastal protection, PI Prof. Nicoletta Leonardi, RGS-IBG Environment and Sustainability Research Grant) and EPSRC support to Prof. Nicoletta Leonardi (EP/V056042/1). We also acknowledge Prof. Chiverrell R. for providing us with the Irish Sea cores. We further acknowledge the support of the RSPB for allowing the fieldwork campaign in the Ribble Estuary and the Geography laboratories and their technicians and students (Jennifer Bradley, Luke Glascott, Mike O'Connor, Richard Clark, Joshua Hicks, and Molly Spater) for their support with equipment, fieldwork and laboratory analyses. We ultimately thank Dr. Kirwan M. and Dr. Hein C. for the insightful discussions held at the early stages of this study during an AGU conference and two anonymous reviewers for their constructive feedback on the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2023.108670.

References

Bakker, J.P., de Leeuw, J., Dijkema, K.S., Leendertse, P.C., Prins, H.H., Rozema, J., 1993. Salt marshes along the coast of the Netherlands. Hydrobiologia 265, 73. https://doi.org/10.1007/BF00007263.

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 (2), 169–193. https://doi.org/10.1890/10-1510.1.

Bertin, X., Olabarrieta, M., McCall, R., 2017. Hydrodynamics under storm conditions. In: Ciavola, P., Coco, G. (Eds.), Coastal Storms: Processes and Impacts. https://doi.org/10.1002/9781118937099.ch2.

BODC, n.d.BODC (British Oceanographic Data Centre) (n.d.): https://www.bodc.ac.uk, last access: 1 September 2022.

Boyle, J.F., Chiverrell, R.C., Schillereff, D., 2015. In: Croudace, I.W., Guy Rothwell, R. (Eds.), Approaches to Water Content Correction and Calibration for μXRF Core Scanning: Comparing X-ray Scattering With Simple Regression of Elemental Concentrations, in: Micro-XRF Studies of Sediment Cores. Springer, Netherlands, pp. 373–390. https://doi.org/10.1007/978-94-017-9849-5_14.

Boyle, J.F., 2000. Rapid elemental analysis of sediment samples by isotope source XRF. J. Paleolimnol. 23, 213–221. https://doi.org/10.1023/A:1008053503694.

Cahoon, D.R., Reed, D.J., Day, J.W., Steyer, G.D., Boumans, R.M., Lynch, J.C., McNally, D., Latif, N., 1995. The Influence of Hurricane Andrew on Sediment distribution in Louisiana Coastal Marshes. J. Coast. Res. 21, 280–294. http://www.jstor.org/stable/25736015.

Carniello, L., Defina, A., D'Alpaos, A., 2012. Modeling sand-mud transport induced by tidal currents and wind-waves in shallow microtidal basins: application to the Venice Lagoon (Italy). Estuar. Coast. Shelf Sci. 102-3, 105–115. https://doi.org/10.1016/j.ecss.2012.03.016.

Carrasco, A.R., Plomaritis, T., Reyns, J., Ferreira, Ó., Roelvink, D., 2018. Tide circulation patterns in a coastal lagoon under sea-level rise. Ocean Dyn. 68 (9), 1121–1139. https://doi.org/10.1007/s10236-018-1178-0.

Castagno, K.A., Jimenez-Robles, A.M., Donnelly, J.P., Wiberg, P.L., Fenster, M.S., Fagherazzi, S., 2018. Intense Storms increase the Stability of Tidal Bays. Geophys. Res. Lett. 45 (11), 5491–5500. https://doi.org/10.1029/2018gl078208.

Cefas, n.d.Cefas (Centre for Environment, Fisheries and Aquaculture Science) (n.d.): https://www.cefas.co.uk/, last accessed: 1 September 2022.

Clarke, D.W., Boyle, J.F., Chiverrell, R.C., Lario, J., Plater, A.J., 2014. A sediment record of barrier estuary behaviour at the mesoscale: interpreting high-resolution particle size analysis. Geomorphology 221, 51–68. https://doi.org/10.1016/j.geomorph.2014.05.029.

Clarke, D.W., Boyle, J.F., Lario, J., Plater, A.J., 2013. Meso-scale barrier estuary disturbance, response and recovery behaviour: evidence of system equilibrium and resilience from high-resolution particle size analysis. The Holocene 24 (3), 357–369. https://doi.org/10.1177/0959683613518597.

D'Alpaos, A., Lanzoni, S., Marani, M., Rinaldo, A., 2007. Landscape evolution in tidal embayments: Modeling the interplay of erosion, sedimentation, and vegetation dynamics. J. Geophys. Res. Earth Surf. 112 (F1) https://doi.org/10.1029/2006JF000537.
Darby, S.E., Appeaning Addo, K., Hazra, S., Rahman, M.M., Nicholls, R.J., 2020. Fluvial sediment supply and relative sea-level rise. In: Nicholls, R., Adger, W., Hutton, C., Hanson, S. (Eds.), Deltas in the Anthropocene. Palgrave Macmillan, Cham, pp. 103–126. https://doi.org/10.1007/978-3-030-23517-8_5.
Dietze, E., Hartmann, K., Diekmann, B., IJmker, J., Lehmkuhl, F., Opitz, S., Stauch, G., Wünnemann, B., Borchers, A., 2012. An end-member algorithm for deciphering modern detrital processes from lake sediments of Lake Donggi Cona, NE Tibetan Plateau, China. Sediment. Geol. 243 (244), 169–180. https://doi.org/10.1594/pangaea.894284.
Donatelli, C., Ganju, N.K., Zhang, X., Fagherazzi, S., Leonardi, N., 2018. Salt marsh loss affects tides and the sediment budget in shallow bays. J. Geophys. Res.: Earth Surf. 123 (10), 2647–2662. https://doi.org/10.1029/2018JF004617.
Donatelli, C., Zhang, X., Ganju, N.K., Aretxabaleta, A.L., Fagherazzi, S., Leonardi, N., 2020. A nonlinear relationship between marsh size and sediment trapping capacity compromises salt marshes' stability. Geology 48 (10), 966–970. https://doi.org/10.1130/G47131.1.
Duvall, M.S., Wiberg, P.L., Kirwan, M.L., 2019. Controls on Sediment Suspension, Flux, and Marsh Deposition near a Bay-Marsh Boundary. Estuar. Coasts 42, 403–424. https://doi.org/10.1007/s12237-018-0478-4.
Environment Agency, 2011. The Extent of Saltmarsh in England and Wales: 2006–2009. Environment Agency, Bristol.
Fagherazzi, S., Giulio, M., Wiberg, P.L., McGlathery, K.J., 2013. Marsh collapse does not require sea level rise. Oceanography 26 (3), 70–77. http://www.jstor.org/stable/24862066.
Fagherazzi, S., Mariotti, G., Leonardi, N., Canestrelli, A., Nardin, W., Kearney, W.S., 2020. Salt marsh dynamics in a period of accelerated sea level rise. J. Geophys. Res.: Earth Surf. 125 (8), e2019JF005200 https://doi.org/10.1029/2019JF005200.
Feagin, R.A., Lozada-Bernard, S.M., Ravens, T.M., Möller, I., Yeager, K.M., Baird, A.H., 2009. Does vegetation prevent wave erosion of salt marsh edges? PNAS 106 (25), 10109–10113. https://doi.org/10.1073/pnas.0901297106.
FitzGerald, D.M., Fenster, M.S., Argow, B.A., Buy Nevich, I.V., 2008. Coastal impacts due to sea-level rise. Annu. Rev. Earth Planet. Sci. 36, 601–647. https://doi.org/10.1146/annurev.earth.35.031306.140139.
Ganju, N.K., Defne, Z., Kirwan, M.L., Fagherazzi, S., D'Alpaos, A., Carniello, L., 2017. Spatially integrative metrics reveal hidden vulnerability of microtidal salt marshes. Nat. Commun. 8, 14156. https://doi.org/10.1038/ncomms14156.
Hammer, O., 2019. PAST, Paleontological Statistics Version 3.25, Reference Manual. Natural History Museum, University of Oslo.
Hazermoshar, A., Lak, R., Espahbood, M.R., Ghadimvand, N.K., Farajzadeh, R., 2016. Geochemical, sedimentological and mineralogical characterization of surficial sediments in Eynak Marsh (North of Iran). Open J. Geol. 6, 640–659. https://doi.org/10.4236/ojg.2016.67050.
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 (23) https://doi.org/10.1029/2010GL045489.
Kirwan, M.L., Murray, A.B., 2007. A coupled geomorphic and ecological model of tidal marsh evolution. PNAS 104 (15), 6118–6122. https://doi.org/10.1073/pnas.0700958104.
Kirwan, M.L., Temmerman, S., Skeehan, E.E., Guntenspergen, G.R., Fagherazzi, S., 2016. Overestimation of marsh vulnerability to sea level rise. Nat. Clim. Chang. 6 (3), 253–260. https://doi.org/10.1038/nclimate2909.
Kolditz, K., Dellwig, O., Barkowski, J., Badewien, T.H., Freund, H., Brumsack, H.-J., 2012. Geochemistry of salt marsh sediments deposited during simulated sea-level rise and consequences for recent and Holocene coastal development of NW Germany. Geo-Mar. Lett. 32 (1), 49–60. https://doi.org/10.1007/s00367-011-0250-2.
Leonardi, N., Carnacina, I., Donatelli, C., Ganju, N.K., Plater, A.J., Schuerch, M., Temmerman, S., 2018. Dynamic interactions between coastal storms and salt marshes: a review. Geomorphology 301, 92–107. https://doi.org/10.1016/j.geomorph.2017.11.00.
Lyddon, C., Brown, J.M., Leonardi, N., Plater, A.J., 2018. Flood Hazard Assessment for a Hyper-Tidal Estuary as a Function of Tide-Surge-Morphology Interaction. Estuar. Coasts 41 (6), 1565–1586. https://doi.org/10.1007/s12237-018-0384-9.
Lyons, M.G., 1997. The dynamics of suspended sediment transport in the Ribble Estuary. Wat. Air and Soil Poll. 99 (1–4), 141–148. https://doi.org/10.1023/a:1018388517409.
Ma, Z., Ysebaert, T., van der Wal, D., de Jong, D.J., Li, X., Herman, P.M.J., 2014. Long-term salt marsh vertical accretion in a tidal bay with reduced sediment supply. Estuar. Coast. Shelf Sci. 146, 14–23. https://doi.org/10.1016/j.ecss.2014.05.001.
Marani, M., Da Lio, C., D'Alpaos, A., 2013. Vegetation engineers marsh morphology through multiple competing stable states. PNAS 110 (9), 3259–3263. https://doi.org/10.1073/pnas.1218327110.
Mariotti, G., Carr, J., 2014. Dual role of salt marsh retreat: long-term loss and short-term resilience. Water Resour. Res. 50, 2963–2974. https://doi.org/10.1002/2013WR014676.
Mariotti, G., Fagherazzi, S., 2013. Critical width of tidal flats triggers marsh collapse in the absence of sea-level rise. PNAS 110 (14), 5353–5356. https://doi.org/10.1073/pnas.1219600110.
Mariotti, G., Fagherazzi, S., Wiberg, P.L., McGlathery, K.J., Carniello, L., Defina, A., 2010. Influence of storm surges and sea level on shallow tidal basin erosive processes. J. Geophys. Res. Oceans 115 (C11). https://doi.org/10.1029/2009JC005892.
Matulla, C., Schöner, W., Alexandersson, H., 2008. European storminess: late nineteenth century to present. Clim. Dyn. 31, 125–130. https://doi.org/10.1007/s00382-007-0333-y.
Mitchell, M., Herman, J., Bilkovic, D.M., Hershner, C., 2017. Marsh persistence under sea-level rise is controlled by multiple, geologically variable stressors. Ecosyst. Health Sust. 3, 10. https://doi.org/10.1080/20964129.2017.1396009.
Möller, I., Spencer, T., French, J.R., Leggett, D.J., Dixon, M., 1999. Wave transformation over salt marshes: A field and numerical modelling study from north Norfolk, England. Estuar. Coast. Shelf Sci. 49 (3), 411–426. https://doi.org/10.1006/ecss.1999.0509.
Morris, J.T., Sundareshwar, P.V., Nietch, C.T., Kjerfve, B., Cahoon, D.R., 2002. Responses of coastal wetlands to rising sea level. Ecology 83 (10), 2869–2877. https://doi.org/10.1890/0012-9658(2002)083[2869:ROCWTR]2.0.CO;2.
Morris, J.T., Barber, D.C., Callaway, J.C., Chambers, R., Hagen, S.C., Hopkinson, C.S., Johnson, B.J., Megonigal, P., Neubauer, S.C., Troxler, T., Wigand, C., 2016. Contributions of organic and inorganic matter to sediment volume and accretion in tidal wetlands at steady state. Earth's Future 4, 110–121. https://doi.org/10.1002/2015EF000334.
Mudd, S.M., D'Alpaos, A., Morris, J.T., 2010. How does vegetation affect sedimentation on tidal marshes? Investigating particle capture and hydrodynamic controls on biologically mediated sedimentation. J. Geophys. Res. Earth Surf. 115 (F3) https://doi.org/10.1029/2009jf001566.
Neumeier, U., Ciavola, P., 2004. Flow resistance and associated sedimentary processes in a Spartina maritima salt-marsh. J. Coast. Res. 20 (2), 435–447. https://doi.org/10.2112/1551-5036(2004)020[0435:fraasp]2.0.co;2.
Pawlowicz, R., Beardsley, B., Lentz, S., 2002. Classical tidal harmonic analysis including error estimates in MATLAB using T-TIDE. Comput. Geosci. 28 (8), 929–937. https://doi.org/10.1016/s0098-3004(02)00013-4.
Pannozzo, N., Leonardi, N., Carnacina, I., Smedley, R., 2021a. Dataset of results from numerical simulations of increased storm intensity in an estuarine salt marsh system. Data Brief 38 (6), 107336. https://doi.org/10.1016/j.dib.2021.107336.
Pannozzo, N., Leonardi, N., Carnacina, I., Smedley, R., 2021b. Salt marsh resilience to sea-level rise and increased storm intensity. Geomorphology 389 (4), 107825. https://doi.org/10.1016/j.geomorph.2021.107825.
Pannozzo, N., Leonardi, N., Carnacina, I., Smedley, R., 2022. Storm Sediment Contribution to Salt Marsh Accretion and Expansion [Dataset]. https://doi.org/10.5281/zenodo.7590233.
Pannozzo, N., Smedley, R., Chiverrell, R., Carnacina, I., Leonardi, N., 2022. An integration of numerical modelling and paleoenvironmental analysis reveals the effects of embankment construction on long-term salt marsh accretion. J. Geophys. Res. Earth Surf. 127, e2021JF006524 https://doi.org/10.1029/2021JF006524.
Pannozzo, N., Smedley, R., Plater, A., Carnacina, I., Leonardi, N., 2023. Novel luminescence diagnosis of storm deposition across intertidal environments. Sci. Total Environ. 867, 161461 https://doi.org/10.1016/j.scitotenv.2023.161461.
Pearce, A., Johnson, M., White, J., 2011. Geotechnical Report - Laboratory and in Situ Data Western HVDC Link Marine Cable Route Survey Geotechnical Fieldwork - Shallow Sampling (Vibrocoring) and Continuous Piezocone Penetration Testing (PCPT).
Plater, A.J., Ridgway, J., Rayner, B., Shennan, I., Horton, B.P., Haworth, E.Y., Wright, M. R., Rutherford, M.M., Wintle, A.G., 2000. Sediment provenance and flux in the Tees Estuary: the record from the late Devensian to the present. Geol. Soc. 166, 171–195. https://doi.org/10.1144/GSL.SP.2000.166.01.10.
Pye, K., Neal, A., 1994. Coastal dune erosion at formby point, north merseyside, England - causes and mechanismS. Mar. Geol. 119 (1–2), 39–56. https://doi.org/10.1016/0025-3227(94)90139-2.
Rahman, R., Plater, A.J., 2014. Particle-size evidence of estuary evolution: a rapid and diagnostic tool for determining the nature of recent saltmarsh accretion. Geomorph. 213, 139–152. https://doi.org/10.1016/j.geomorph.2014.01.004.
Reed, D.J., 1990. The impact of sea-level rise on coastal salt marsheS. Prog. Phys. Geogr. 14 (4), 465–481. https://doi.org/10.1177/030913339001400403.
Roberts, H.M., Plater, A.J., 2005. Optically Stimulated Luminescence (OSL) dating of sands underlying the gravel beach ridges of Dungeness and Camber, Southeast England, UK. Historic England 27.
Roner, M., Ghinassi, M., Finotello, A., Bertini, A., Combourieu-Nebout, N., Donnici, S., Gilli, A., Vannacci, M., Vigliotti, L., Bellucci, L.G., Fedi, M., Liccioli, L., Tommasini, L., D'Alpaos, A., 2021. Detecting the delayed Signatures of changing Sediment Supply in Salt-Marsh Landscapes: the Case of the Venice Lagoon (Italy). Front. Mar. Sci. 8 https://doi.org/10.3389/fmars.2021.742603.
Rose, C.P., Thorne, P.D., 2001. Measurements of suspended sediment transport parameters in a tidal estuary. Cont. Shelf Res. 21 (15), 1551–1575. https://doi.org/10.1016/S0278-4343(00)00087-X.
Schuerch, M., Vafeidis, A., Slawig, T., Temmerman, S., 2013. Modeling the influence of changing storm patterns on the ability of a salt marsh to keep pace with sea level rise. J. Geophys. Res. Earth Surf. 118 (1), 84–96. https://doi.org/10.1029/2012jf002471.
Stumpf, R.P., 1983. The process of sedimentation on the surface of a salt marsh. Estuar. Coast. Shelf Sci. 17 (5), 495–508. https://doi.org/10.1016/0272-7714(83)90002-1.
Tamura, T., Nguyen, V.L., Ta, T.K.O., 2020. Long-term sediment decline causes ongoing shrinkage of the Mekong megadelta, Vietnam. Sci. Rep. 10, 8085. https://doi.org/10.1038/s41598-020-64630-z.
Temmerman, S., Govers, G., Wartel, S., Meire, P., 2003. Spatial and temporal factors controlling short-term sedimentation in a salt and freshwater tidal marsh, Scheldt estuary, Belgium, SW Netherlands. Earth Surf. Process. Landf. 28 (7), 739–755. https://doi.org/10.1002/esp.495.
Temmerman, S., Govers, G., Wartel, S., Meire, P., 2004. Modelling estuarine variations in tidal marsh sedimentation: response to changing sea level and suspended sediment

concentrations. Mar. Geol. 212 (1–4), 1–19. https://doi.org/10.1016/j.margeo.2004.10.021.
Temmerman, S., Meire, P., Bouma, T.J., Herman, P.M.J., Ysebaert, T., De Vriend, H.J., 2013. Ecosystem-based coastal defence in the face of global change. Nature 504 (7478), 79–83. https://doi.org/10.1038/nature12859.
Tognin, D., D'Alpaos, A., Marani, M., Carniello, L., 2021. Marsh resilience to sea-level rise reduced by storm-surge barriers in the Venice Lagoon. Nat. Geosci. 14 (12), 906–911. https://doi.org/10.1038/s41561-021-00853-7.
Tovey, E.L., Pontee, N.I., Harvey, R., 2009. Managed Realignment at Hesketh out Marsh West. Proc. Inst. Civ. Eng.: Eng. Sustain. 162 (4), 223–228. https://doi.org/10.1680/ensu.2009.162.4.223.
Turner, R.E., Baustian, J.J., Swenson, E.M., Spicer, J.S., 2006. Wetland sedimentation from Hurricanes Katrina and Rita. Science 314 (5798), 449–452. https://doi.org/10.1126/science.1129116.
UKHO, 2001. Admiralty Tide Tables. United Kingdom and Ireland (Including European Channel Ports). UK Hydrographic Office, Taunton.
van der Wal, D., Pye, K., Neal, A., 2002. Long-term morphological change in the Ribble Estuary, Northwest England. Mar. Geol. 189 (3–4), 249–266. https://doi.org/10.1016/s0025-3227(02)00476-0.
Wakefield, R., Tyler, A.N., McDonald, P., Atkin, P.A., Gleizon, P., Gilvear, D., 2011. Estimating sediment and caesium-137 fluxes in the Ribble Estuary through time-series airborne remote sensing. J. Environ. Radioact. 102 (3), 252–261. https://doi.org/10.1016/j.jenvrad.2010.11.016.
Wei, X., Cai, S., Ni, P., Zhan, W., 2020. Impacts of climate change and human activities on the water discharge and sediment load of the Pearl River, southern China. Sci. Rep. 10 (1), 16743. https://doi.org/10.1038/s41598-020-73939-8.
Willemsen, P.W.J.M., Smits, B.P., Borsje, B.W., Herman, P.M.J., Dijkstra, J.T., Bouma, T.J., Hulscheret, S.J.M.H., 2021. Modeling decadal salt marsh development: variability of the salt marsh edge under influence of waves and sediment availability. Water Resour. Res. 58 (1), e2020WR028962 https://doi.org/10.1029/2020WR028962.
Wright, J.E., Hull, J.H., McQuillin, R., Arnold, S.E., 1971. Irish Sea Investigations 1969-71. NERC Institute of Geological Sciences, Report 71/19.
Yang, S.L., Shi, B.W., Bouma, T.J., Ysebaert, T., Luo, X.X., 2012. Wave attenuation at a salt marsh margin: a case study of an exposed coast on the Yangtze Estuary. Estuar. Coasts 35, 169–182. https://doi.org/10.1007/s12237-011-9424-4.
Zedler, J.B., Kercher, S., 2005. Wetland resources: Status, trends, ecosystem services, and restorability. Annu. Rev. Environ. Resour. 30, 39–74. https://doi.org/10.1146/annurev.energy.30.050504.144248.
Zhang, X.H., Leonardi, N., Donatelli, C., Fagherazzi, S., 2020. Divergence of sediment fluxes triggered by sea-level rise will reshape coastal bays. Geophys. Res. Lett. 47 (13) https://doi.org/10.1029/2020gl087862.
Zhang, X., Leonardi, N., Donatelli, C., Fagherazzi, S., 2019. Fate of cohesive sediments in a marsh-dominated estuary. Adv. Water Resour. 125, 32–40. https://doi.org/10.1016/j.advwatres.2019.01.003.
Zhu, Q., Wiberg, P.L., 2022. The importance of storm surge for sediment delivery to microtidal marshes. J. Geophys. Res. Earth Surf. 127 (9), e2022JF006612 https://doi.org/10.1029/2022JF006612.