Conditional Effects of Tides and Waves on Sediment Supply to Salt Marshes

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Key Points:

- Tidal ranges determine the direction of residual sediment flux in the marsh creek, while wave intensity determines the magnitude
- Wave intensity determines the direction of residual sediment flux over the marsh edge, whereas tidal ranges determine the magnitude
- Unlike mudflats, waves cause erosion in marsh creeks only during tides with large tidal ranges

Supporting Information:

Supporting Information may be found in the online version of this article.

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Conditional Effects of Tides and Waves on Sediment Supply to Salt Marshes

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Abstract The survival of salt marshes, especially facing future sea-level rise, requires sediment supply. Sediment can be supplied to salt marshes via two routes: through marsh creeks and over marsh edges. However, the conditions of tides and waves that facilitate sediment import through these two routes remain unclear. To understand when and how sediment is imported into salt marshes, 2-month measurements were conducted to monitor tides, waves, and suspended sediment concentration (SSC) in Paulina Saltmarsh, a meso-macrotidal system. The results show that the marsh creek tends to import sediment during neap tides with waves. A tidal cycle with a small tidal range result in weaker flow in the marsh creek during ebb tides, reducing the export of sediment. Waves enhance sediment supply to the marsh creek by eroding mudflats. However, strong waves can directly resuspend sediment in marsh creeks during spring tides when the water level is above the marsh canopy, enhancing sediment export through creeks. Net sediment import over marsh edges requires the opposite tidal and wave conditions: spring tides with weak waves. Spring tides provide stronger hydrodynamics, facilitating sediment import over the marsh edge. Increased SSC during the ebb phase can occur with strong waves over the marsh edge, resulting in net sediment export. Therefore, the net import or export of sediment, through the creek and over the marsh edge, depends on the combination of tidal and wave conditions. These conditions can vary between estuaries and even individual marshes. Understanding these conditions is crucial for better management of salt marshes.

Plain Language Summary The future of salt marshes greatly depends on receiving enough sediment, especially in the face of rising sea-level. This sediment can reach salt marshes via two routes: through marsh channels or over the seaside boundary of the marsh. It is not fully understood under what tidal and wave conditions sediment can be supplied to salt marshes, either through marsh channels or over the marsh boundary. Therefore, 2-month data sets on hydrodynamics and sediment dynamics were collected in Paulina Saltmarsh to investigate the optimal conditions of tides and waves for importing sediment into salt marshes. We found that sediment supply along marsh channels and over the marsh boundary requires contrasting tidal and wave conditions. Strong waves and small tidal ranges are favorable conditions for marsh channels to bring sediment into salt marshes. Conversely, sediment tends to be brought into salt marshes during tidal cycles with large tidal ranges and weak waves. This work highlights when and how sediment can be transported into the marsh, contributing to better salt marsh management.

1. Introduction

Salt marshes are ubiquitous on the upper parts of intertidal areas in coastal systems, which are regularly flooded and drained by tides. They are widely recognized for providing an array of crucial ecosystem services, functioning as habitats for species, a sink of organic carbon, and storm buffers (Kelleway et al., 2017; Rountree & Able, 2007; Temmerman et al., 2023). However, salt marshes are challenged by coastal squeeze due to human interventions and accelerating sea-level rise (Alizad et al., 2022; Crosby et al., 2016; Kirwan et al., 2010; Osland et al., 2017). To keep pace with sea-level rise, sufficient sediment supply is needed for the vertical accretion and lateral expansion of salt marshes (Fagherazzi et al., 2020; Ladd et al., 2019).

The sediment budget of salt marshes is affected by the sediment flux between marshes and the adjacent mud flats together with channels. To quantify the net exchange of sediment between mudflats and salt marshes, net sediment flux is introduced. Sediment flux is recognized as an indicator of the growth or decay of salt marshes (Ganju et al., 2013; Nowacki & Ganju, 2019). The total sediment flux results from the residual effects of nonlinear interactions between the temporal variations in depth, flow velocity, and concentration, as well as from spatial non-uniformities in velocity and concentration (Dyer, 1974). It serves as a key indicator of sediment transport within intertidal areas, reflecting the redistribution of sediment across these dynamic environments (Wang et al., 2012; Xie et al., 2018).

Tidal asymmetry is an important factor in causing residual sediment transport within salt marsh creeks. There are two types of tidal asymmetry that serve as indicators of residual sediment transport: the asymmetry in peak velocity and the asymmetry in acceleration/deceleration duration (Dronkers, 1986; Gatto et al., 2017). A net discharge export is generally observed during overbank tides, as some of the water that enters via the marsh edge subsequently drains through the creek during ebb. This pattern is evident only during tidal cycles when the maximum tidal elevation is above the marsh platform (Lacy et al., 2018). The asymmetry in discharge is caused by the different travel paths through the marsh creek and across the marsh platform (Fagherazzi et al., 2013), resulting in unbalanced discharge and an ebb-dominant velocity asymmetry within the creeks. This is a potential mechanism for sediment export, if there is sufficient sediment during the ebb phase. Sediment import, on the other hand, can be caused by an asymmetry in sediment availability. In a turbid system, the abundance of sediment during flood tides can sometimes counteract the tendency to export sediment caused by the asymmetry in flow (Sun, van Prooijen, Wang, Zhao, et al., 2024). Nowacki and Ganju (2019) also found that the direction of sediment flux can be inferred from the flood-ebb differential of suspended sediment concentration (SSC), highlighting the importance of the asymmetry in sediment abundance.

Mudflats serve as an important sediment source for salt marshes by supplying sediment to the marsh through marsh creeks (Sun, van Prooijen, Wang, Hanssen, et al., 2024). Waves play a crucial role in resuspending sediment from mudflats, thereby facilitating sediment transport toward salt marshes. Recent observations indicate that during storms, considerable sediment can be deposited on the marsh platform (Pannozzo et al., 2023; Willemsen et al., 2022). Considering that mudflats would generally be eroded during such events (Fan et al., 2006; Xie et al., 2017), there is a potential for an increase in sediment supply from mudflats to marshes (Rosencranz et al., 2016; Schuerch et al., 2014). However, when waves coincide with tides where the peak tidal elevation is too low to flood marshes, sediment delivery to marshes may be constrained (Duvall et al., 2019). Furthermore, waves can sometimes cause marsh erosion and enhance sediment export (Fagherazzi et al., 2006; Lacy et al., 2018). These observations highlight the variability in sediment transport between mudflats and salt marshes, which is influenced by the interactions between different tidal and wave conditions. The processes responsible for sediment remobilization between mudflats and salt marshes under various tidal and wave conditions require further investigation and sufficiently long measurement periods.

In this paper, we aim to unravel the sediment transport mechanisms driven by the interaction between waves and tides, considering transport through the marsh creek and over the marsh edge. Therefore, we analyzed sediment fluxes in the marsh creek and over the marsh edge based on the 2-month field observations in the Paulina Saltmarsh. We aim to explore (a) whether the marsh creek facilitates or impedes sediment import to salt marshes during wave events, (b) how different conditions of tides and waves may influence the sediment transport via the marsh creek and marsh edge, and (c) what the optimal conditions are for sediment import into salt marshes. By unraveling the various conditions, we can better understand the impact of future changes, such as human interventions and sea-level rise, on salt marsh development.

2. Materials and Methods

2.1. Study Site

The Western Scheldt is the Dutch part of the Scheldt estuary. It has significant economic value as a shipping lane to the Ports of Antwerp, Vlissingen, and Terneuzen. Furthermore, it holds high ecological value as a foraging area for wading birds. The Western Scheldt consists of ebb and flood channels and many intertidal areas (Bolle et al., 2010), and is connected to the Scheldt river (Figure 1a). The average tidal range varies from 3.8 m in Vlissingen to 5.2 m in Antwerp, with a maximum tidal range reaching 5.4 m (Schepers et al., 2018). Thus, it can be considered as meso to macrotidal system. The freshwater discharge from the Scheldt river is about 100 m^3/s, which is 0.1% of the tidal prism (De Vriend et al., 2011). Therefore, the Western Scheldt is well-mixed and the fluvial sediment supply is limited (Dam et al., 2016).

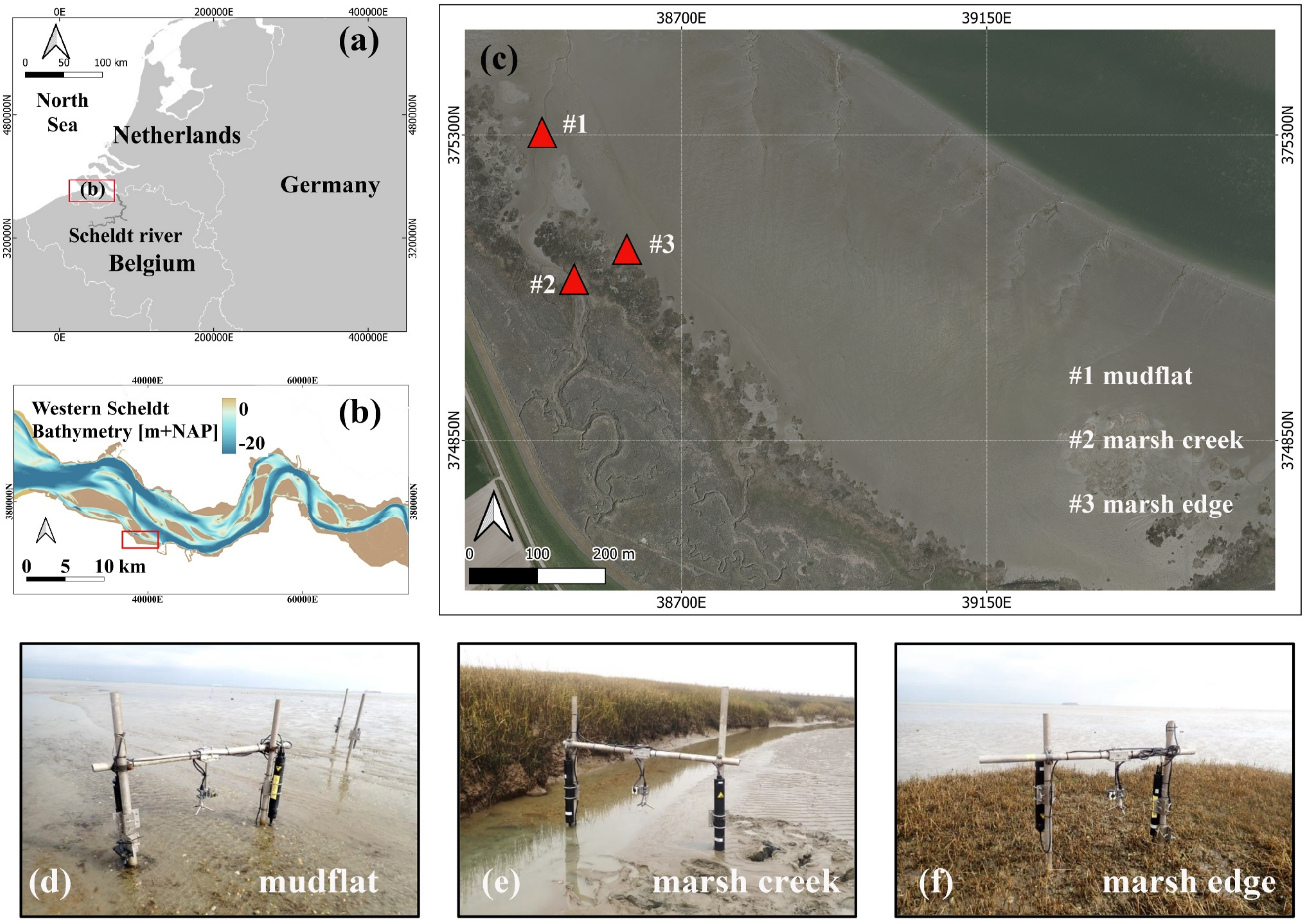

Figure 1. Study area and measuring locations. (a) Location of the Netherlands and the red rectangle indicates the Western Scheldt Estuary. (b) The Western Schelde Estuary in the Netherlands and the red rectangle indicates the location of Paulina Saltmarsh. Bathymetry data source: Rijkswaterstaat. (c) The aerial photo showcasing measuring sites in Paulina Saltmarsh (Red triangles indicate measuring locations). Source aerial imagery: Beeldmateriaal Nederland. (d) Photos of instruments and frames on the mudflat, (e) in the marsh creek, and (f) at the marsh edge.

Paulina Saltmarsh is a marsh of approximately 0.6 km^2 and is located on the southern border of the Western Scheldt (Figure 1b). A creek system is present with creeks varying in width from 0.3 to 7 m and in depth from 0.3 to 1.5 m (Figure 1c). Paulina Saltmarsh exhibits a semi-diurnal tidal regime with an average tidal range of 3.9 m (van Belzen et al., 2017; Willemsen et al., 2022). Spartina anglica is the dominant pioneering species (Oteman et al., 2019). The system is perceived as a low-turbidity environment (Temmerman et al., 2003). The SSC in the marsh creek remains relatively low during calm weather (less than 0.1 g/L). Seasonal impacts primarily stem from the contrast between the calm summer season and the stormy winter season. Measurements conducted in summer by Sun, van Prooijen, Wang, Hanssen, et al. (2024) revealed that the creek generally acts as a conduit for sediment export during this season, especially when there is limited sediment supply from mudflats. Storms mainly occur during autumn/winter (October–March).

2.2. Data Collection and Processing

To explore the impacts of storms or large wave events, measurements were conducted over a 2-month period from January 26 to 29 March 2023. We captured some moderate wave events and one storm event during our measurements. More information about wind conditions (speed and direction) and wave heights during the measurement period is provided in Figure S4 in Supporting Information S1. To investigate the sediment transport to salt marshes, tides, waves, and sediment concentration were measured simultaneously on the mudflat (Figure 1d), in the marsh creek (Figure 1e), and at the marsh edge (Figure 1f).

Table 1
An Overview of the Instruments Set Up

Location	Instrument	Sampling frequency (Hz)	Measuring intervals (s)	Length of burst (s)
Mudflat	ADV + STM	8	300	60
	OSSI	10	1	1
Marsh creek	ADV + STM	8	300	60
Marsh edge	ADV + STM	8	300	60

We collected time-series data on the water depth, velocity, and bed level changes with an ADV (Acoustic Doppler Velocimeter, Nortek AS, Norway). The sensors of the ADVs were 34 cm, 30 cm, and 47 cm above the bed on the mudflat, in the creek, and at the marsh edge, respectively, while the pressure sensors of these three ADVs were deployed close to the bed (approximately 10 cm above the bed). Instrument settings are indicated in Table 1.

To remove the invalid data from the ADV, specific criteria for amplitude data (less than 100 counts) and correlation data (less than 70%) were applied (Xie et al., 2018). Amplitude data and correlation data of the ADV represent signal strengths and data accuracy, respectively. Spike noise from ADV data was detected and excluded using the phase-space method (Goring & Nikora, 2002). Velocities in this work were considered only in the along-creek direction for the ADV located in the marsh creek and in the cross-shore direction for the ADVs located on the mudflat and at the marsh edge. This approach allows us to investigate the exchange of water and sediment between mudflats and salt marshes.

Turbidity signals were collected with STMs (Seapoint Turbidity Meter, Seapoint Sensors, Inc., USA), which were synced with the ADVs. The STMs were positioned at 42 cm, 39 cm, and 57 cm above the bed on the mudflat, in the creek, and at the marsh edge, respectively. Sediment concentration data were derived from the turbidity signals using sediment calibration experiments in the laboratory following the procedure as described in Hoitink and Hoekstra (2005) with in situ sediment samples. The calibration curves are provided in Figure S3 in Supporting Information S1.

One pressure sensor OSSI (The Ocean Sensor Systems Wave Gauge Blue, Wave Sensor Company, USA) for wave measurements was deployed 5 cm above the mudflat bed. More details about the instrument setup are presented in Table 1.

In this work, wave shear stress measured on the mudflat serves as an indicator for assessing the intensity of wave events (Fagherazzi & Wiberg, 2009). Wave shear stress (τ_w (Pa)) obtained from OSSI was calculated using the method described by Zhu et al. (2016). Significant wave heights (Hs (m)) at three locations were obtained from the ADV pressure data.

The wave shear stress (τ_w) is calculated based on the significant bottom orbital velocity U_δ and wave friction coefficient f_w:

$$\tau_w = \frac{1}{4}\rho_w f_w U_\delta^2 \tag{1}$$

where ρ_w = 1,025 kg/m^3, which corresponds to the sea water density at 21°C and 35 ppt salinity (Newton & Mudge, 2003). The significant orbital excursion (m), A_δ, and the significant orbital velocity (m/s), U_δ, are defined as follows:

$$A_\delta = \frac{H}{2\sinh(kh)} \tag{2}$$

$$U_\delta = \omega A_\delta = \frac{\pi H}{T\sinh(kh)} \tag{3}$$

where H is the wave height (m), k is wave number, given by $k = 2\pi/L$ (m^{-1}), L is wave length, defined as $L = (gT^2/2\pi)\tanh(kh)$ (m), h is the water depth (m), T is wave period (s), and ω is angular velocity (s^{-1}). The wave friction varies depending on the hydraulic regime (Soulsby, 1997):

$$f_w = \begin{cases} 2Re_w^{-0.5}, Re_w \ll 10^5 \text{ (laminar)} \\ 0.0521 Re_w^{-0.187}, Re_w \gg 10^5 \text{ (smooth turbulent)} \\ 0.237 r^{-0.52} \text{ (rough turbulent)} \end{cases} \tag{4}$$

where Re_w is wave Reynolds number ($Re_w = \frac{U_\delta A_\delta}{\nu}$) and r is relative roughness ($r = \frac{A_\delta}{k_s}$). k_s is Nikuradse roughness, which is related to the median grain size of bed sediment (d_{50}), and ν is the kinematic viscosity of water. Mudflats are assumed to be a smooth bed (Zhu et al., 2019). Therefore, the rough turbulent regime is excluded when calculating wave friction.

To compare sediment transport through the marsh creek and the marsh edge, the residual sediment flux per unit width, ΔF (kg/m), was utilized (van Weerdenburg et al., 2021; Wang et al., 2012). This single-point residual sediment flux is obtained using the instantaneous burst-averaged data of velocity (v (m/s)), water depth (h (m)), and SSC (c (g/L)). We assumed that the measured velocity represents a depth-averaged velocity and the measured sediment concentration is uniform over the depth. The impacts of the variations in cross-sectional areas of the creek have been discussed in Sun, van Prooijen, Wang, Zhao, et al. (2024), where the point sediment flux was found to be sufficiently accurate to indicate the role of marsh creeks in sediment delivery.

This residual sediment flux is only considered as the sediment exchange toward or away from the marsh system in this work. Therefore, we focused on the total constituent flux without investigating different flux components.

$$\Delta F = \sum_{i=1}^{n} (v_i\, h_i\, c_i)\, \Delta t \tag{5}$$

where $\Delta t = 300$ (s), which is the measuring interval of ADVs and STMs in this work. n is the number of the valid data we measured for each tidal cycle. Positive values of ΔF indicate sediment import into the marsh, and vice versa, negative values represent sediment export out of the marsh.

Similar to the residual sediment flux, we also focus on the residual discharge per unit width (ΔQ (m^3/m)) towards or away from the marsh system.

$$\Delta Q = \sum_{i=1}^{n} (v_i\, h_i)\, \Delta t \tag{6}$$

The SSC differential between flood and ebb tides (ΔC (g/L)) can be obtained by the difference in the average SSC between the flood and ebb tides (Nowacki & Ganju, 2019).

$$\Delta C = \frac{1}{n_{\text{flood}}} \sum_{i=1}^{n_{\text{flood}}} c_i - \frac{1}{n_{\text{ebb}}} \sum_{i=1}^{n_{\text{ebb}}} c_i \tag{7}$$

Where n_{flood} and n_{ebb} are the number of SSC data for the flood tide and the ebb tide, respectively.

Time-series data sets measured at three locations are included in Figures S1 and S2 in Supporting Information S1.

3. Results

To explore the conditional effects of tides and waves on the role of creeks and marsh edges in sediment transport, the relationships between the tidally averaged wave shear stress, maximum tidal elevation per tide, and residual sediment flux have been explored (Figures 2b and 2f). The tidally averaged wave shear stress indicates wave intensity during each tidal cycle. Additionally, the maximum tidal elevation indicates the tidal range for each tidal cycle.

In the marsh creek, the direction of residual sediment flux is determined by tidal ranges, while the magnitude of sediment flux is influenced by wave intensities (Figure 2b). When the maximum tidal elevation exceeds 2.74 m, the residual sediment flux is generally negative, indicating sediment export. Conversely, when the maximum tidal

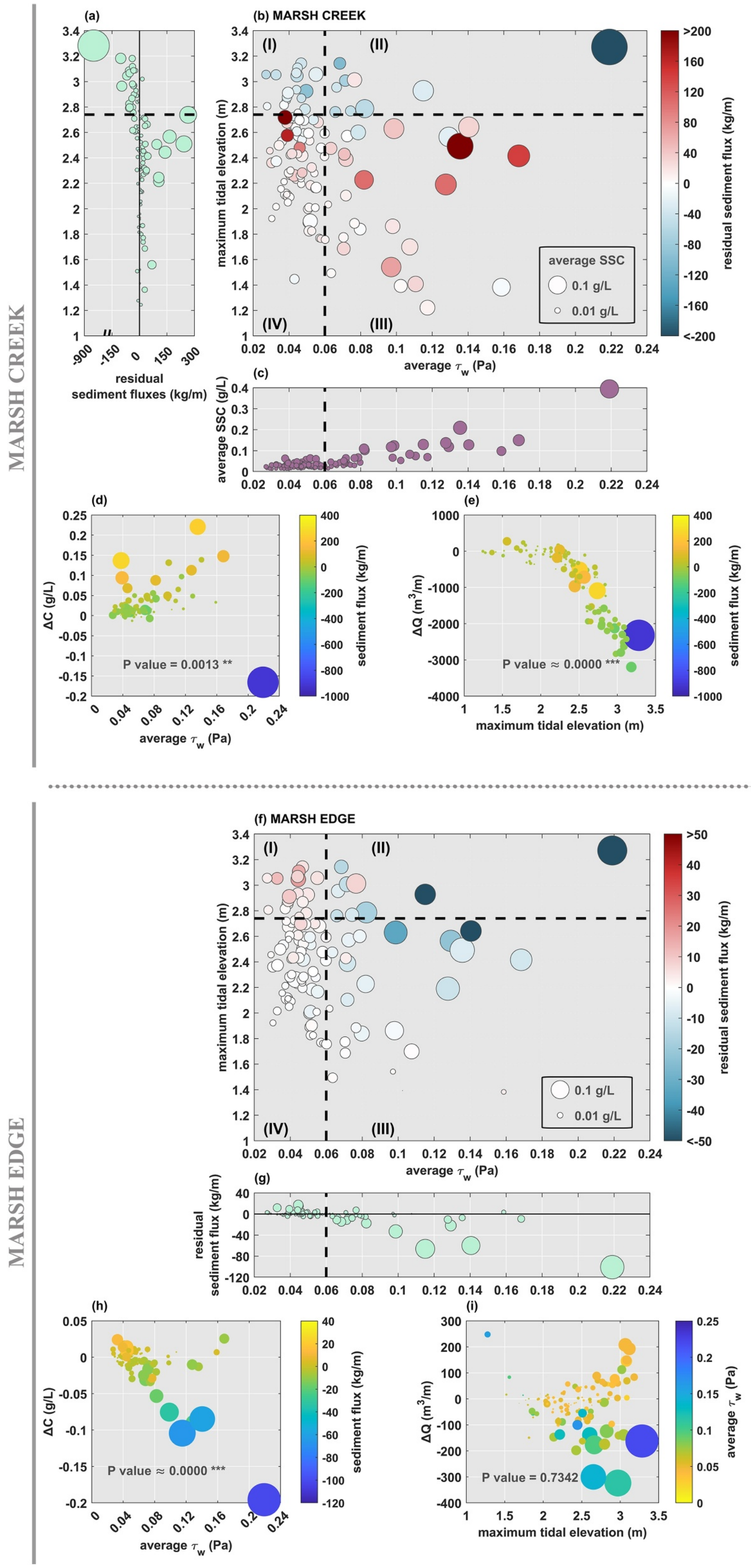
MARSH CREEK
(a)
residual sediment fluxes (kg/m)
(b) MARSH CREEK
(I)
(II)
(III)
(IV)
maximum tidal elevation (m)
average τ_w (Pa)
average SSC
0.1 g/L
0.01 g/L
residual sediment flux (kg/m)
>200
<-200
(c)
average SSC (g/L)
(d)
ΔC (g/L)
P value = 0.0013 **
sediment flux (kg/m)
(e)
ΔQ (m^3/m)
P value ≈ 0.0000 ***
maximum tidal elevation (m)
MARSH EDGE
(f) MARSH EDGE
>50
<-50
(g)
residual sediment flux (kg/m)
(h)
P value ≈ 0.0000 ***
(i)
P value = 0.7342
average τ_w (Pa)

Figure 2.

elevation is less than 2.74 m, the residual sediment flux is generally positive (Figure 2a). The increase in wave shear stress ($\tau_w > 0.06$ Pa) leads to an increase in SSC (Figure 2c). The SSC in the creek during strong wave events ($\tau_w > 0.06$ Pa) is, on average, 4 times larger than during weak wave periods ($\tau_w < 0.06$ Pa).

On the contrary, over the marsh edge, waves determine the direction of residual sediment flux, whereas tides influence the magnitude of sediment import (Figure 2f). When the wave shear stress becomes relatively strong ($\tau_w > 0.06$ Pa), sediment export occurs regardless of the magnitude of the tidal range (Figure 2g). However, sediment import is relatively large during large tidal range and weak wave conditions. Sediment exchange at the marsh edge was negligible when both the tidal range and wave intensities were low (Quadrant IV in Figure 2f).

To better understand how tides and waves influence residual sediment flux in the creek, we introduce the relative importance of asymmetries in water discharge (ΔQ) and sediment concentration (ΔC). These two parameters determine the direction and magnitude of residual sediment flux. The SSC differential between flood and ebb tides (ΔC) shows a good correlation with the average wave shear stress (Figure 2d). When wave shear stresses are larger, a larger ΔC is generally observed, indicating that waves cause an increase in SSC during flood tides. On the other hand, a large tidal range causes a large negative net discharge (ΔQ) (Figure 2e), as more water from the marsh drains through the creek during ebb tides. This ebb dominant tidal current results in a higher tendency to export sediment if there is insufficient sediment supply during flood tides. It is noteworthy that an extreme wave event triggers a peak in SSC during ebb, leading to sediment export (the dark blue dot in Figure 2d). In such a case, waves function differently than merely supplying sediment to the creek; they may also promote sediment export.

We further investigate why strong waves consistently lead to sediment export over the marsh edge. As shown in Figure 2h, a larger negative ΔC is associated with an increase in the wave intensity, indicating that waves cause a larger ebb SSC over the marsh edge. This large ebb SSC results in the export of sediment. The potential reasons for this large ebb SSC will be discussed in the following section. Furthermore, there is no linear relationship between tidal ranges and the net discharge (ΔQ) over the marsh edge (Figure 2i). However, the positive ΔQ generally appears with weak waves, whereas negative ΔQ occurs with strong waves. It is crucial to point out that the net discharge over the marsh edge is relatively small compared to that in the marsh creek. Consequently, the impacts of ΔQ on residual sediment flux over the marsh edge are less significant than the impacts of ΔC.

4. Discussions

4.1. Different Wave Impacts on Sediment Transport Regimes

Waves have different impacts on sediment transport over the marsh edge than through the marsh creek. To explore the differences, five representative tidal cycles with various tidal and wave conditions are selected and presented in Figure 3. These tidal cycles are also highlighted in the overall time-series data in Figure S1 and S2 in Supporting Information S1.

Figure 2. Residual sediment flux under varying tidal and wave conditions in the marsh creek and over the marsh edge. (a) The relationship between the maximum tidal elevation and residual sediment flux in the marsh creek. The size of each circle represents the magnitude of the residual sediment flux; (b) Effects of tides and waves on residual sediment flux in the marsh creek. The size of the circle shows the tidally averaged suspended sediment concentration (SSC). The color of the circle represents the residual sediment flux, where the warm color indicates sediment import and the cold color indicates sediment export. (c) The relationship between tidally averaged SSC and tidally averaged wave shear stress in the marsh creek. The size of each circle represents the magnitude of tidally averaged SSC. (d) The relationship among the tidally averaged wave shear stress, the SSC differential between flood and ebb tides (ΔC) and residual sediment flux in the marsh creek. The size of each circle represents the magnitude of the residual sediment flux. (e) The relationship among the maximum tidal elevation, net discharge (ΔQ), and residual sediment flux in the marsh creek. The size of each circle represents the magnitude of the residual sediment flux. (f) Effects of tides and waves on residual sediment flux over the marsh edge. The size of the circle shows the tidally averaged SSC. The color of the circle represents the residual sediment flux, where the warm color indicates sediment import and the cold color indicates sediment export. (g) The relationship between tidally averaged SSC and tidally averaged wave shear stress over the marsh edge. The size of each circle represents the magnitude of tidally averaged SSC. (h) The relationship among the tidally averaged wave shear stress, the SSC differential between flood and ebb tides (ΔC) and residual sediment flux over the marsh edge. The size of each circle represents the magnitude of the residual sediment flux. (i) The relationship among the maximum tidal elevation, net discharge (ΔQ), tidally averaged wave shear stress, and residual sediment flux over the marsh edge. The size of each circle represents the magnitude of the residual sediment flux.

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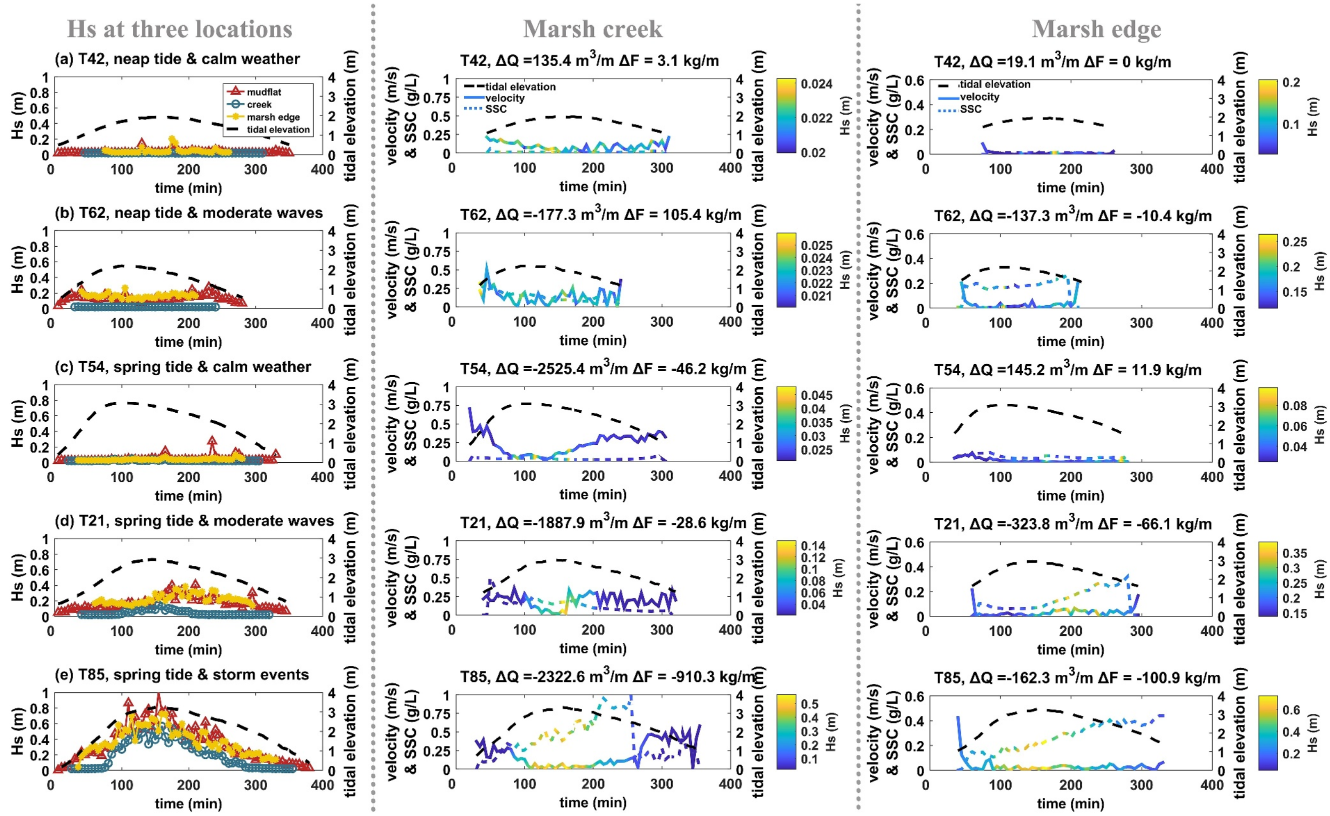

Figure 3. Wave impacts on sediment transport regimes in the marsh creek and on the marsh edge under five representative tidal and wave conditions.

There are two different effects of waves on the sediment transport regimes in marsh creeks. First, waves can stir up sediment on mudflats with a consequent increase in SSC in marsh creeks. This indirect wave impact leads to an increase in sediment import of 105.4 kg/m during neap tides with moderate waves (Figure 3b) compared to the sediment import of 3.1 kg/m during neap tides without waves (Figure 3a). Second, waves can erode marsh creek beds during the periods when the water level exceeds the marsh canopy. Large significant wave heights were observed in the marsh creek during spring tides (Figures 3d and 3e). These strong waves in the creek are observed as the creek is relatively close to the marsh edge. The waves were apparently not attenuated by vegetation yet. Therefore, waves were able to mobilize sediment, potentially from the creek bed and surrounding vegetated areas. The erosion led to an increase in SSC in the marsh creek during ebb (Figure 3e). The large tidal range during spring tides resulted in a negative net discharge (water export) in the creek. Consequently, the combination of tides and waves resulted in a substantial sediment export of approximately 910 kg/m in the marsh creek, represented by the dark blue dot in Figure 2d. Conversely, when the water level was below the marsh canopy, the creek was minimally affected by waves (Figure 3b), potentially due to the sheltering effects of elevated marshes. We emphasize here that the measurement location in the creek is relatively close to the marsh edge, where waves did not have sufficient space to attenuate. Further into the marsh, waves will likely be attenuated by the vegetation (Foster-Martinez et al., 2018). This mechanism of stirring up sediment in the creek and/or marsh and transporting sediment during ebb, thereby depends not only on the wave intensity but also on the tidal range. A larger tidal range will reduce wave attenuation and lead to a stronger ebb flow.

To further explore the mechanisms behind sediment export over the marsh edge during wave events, the responses of velocities and SSC to waves over the marsh edge were analyzed. The contributions of waves to the export of sediment over the marsh edge can be split up into two parts: (a) Waves significantly increased SSC, especially during ebb tides. This phenomenon was attributed to the occurrence of strong waves primarily during the late flood tide and the ebb tide (Figures 3b, 3d, and 3e). Consequently, the average SSC during ebb tides was considerably higher than that during flood tides over the marsh edge. (b) Wave-generated flow caused fluctuations in velocities over the marsh edge, resulting in relatively minor negative net discharge. Because of the energy-dissipating effect of vegetation (Leonardi et al., 2018), flow velocities over the marsh edge remained low. Even during spring tides, they were typically below 0.1 m/s. Therefore, small fluctuations in velocities induced by waves can affect net discharge, switching the net discharge over the marsh edge from positive values (inflow) to negative values (outflow) (Figures 3c and 3d). Given the above, the combination of higher ebb SSC and minor outflow contributed to the export of sediment over the marsh edge.

It is important to note that the further interpretation of the single-point residual sediment flux over the marsh edge requires the understanding of the source of the measured SSC. There are three potential sediment sources contributing to the increased SSC during ebb over the marsh edge: marsh surface erosion, marsh edge scouring, or longshore sediment transport on mudflats (Callaghan et al., 2010; Choi et al., 2021; Finotello et al., 2020; Shi et al., 2016). Many studies have suggested that storm waves can cause scouring and damage to the marsh surface and edges (Fagherazzi et al., 2006; Feagin et al., 2009; Marani et al., 2011). Significant wave heights at the marsh edge exhibited comparable magnitudes and patterns to those observed on mudflats (Figures 3b, 3d, and 3e). This suggests that wave action may be a driving force behind marsh edge erosion. In such cases, a negative sediment flux (sediment export) over the marsh edge may indicate sediment loss and erosion of the marsh surface. On the other hand, in contrast to the marginal cross-channel velocities observed in the marsh creek, the longshore velocities on mudflats and over the marsh edge can be more evident. If the source of SSC during ebb originates from longshore transport, a negative residual sediment flux does not necessarily imply marsh loss. Sediment can be transported to the marsh during flood without being eroded during ebb due to the presence of vegetation. Consequently, the marsh may receive sediment and experience vertical accretion, even with a negative sediment flux over the marsh edge. These align well with the findings of Mariotti and Carr (2014), who discovered that waves may enhance horizontal marsh retreat while simultaneously reducing the tendency for vertical marsh drowning. Nevertheless, the single-point residual sediment flux can be used as an indicator for identifying the role of the marsh edge in sediment import or export under different tidal and wave conditions. We lack data on bed-level changes at the marsh edge. Further research is required to investigate the source of ebb SSC during wave events.

4.2. Effects of Tides and Waves on Sediment Transport in Chongming Saltmarsh Creeks

To investigate whether the effects of tides and waves on sediment transport in Paulina Saltmarsh remain consistent with those in other systems, we take Chongming Saltmarsh as an example. Chongming Saltmarsh, located in the Yangtze Estuary, is perceived as a turbid system (Shi et al., 2014). Chongming Saltmarsh is a mesotidal salt marsh with an area of approximately 18 km^2 (Ge et al., 2021), where the tidal range is 2.6 m on average and the extreme tidal range can reach 4.6 m (Ding & Hu, 2020). Compared to Paulina Saltmarsh, Chongming is larger, experiences flooding less frequently, and has higher turbidity in the water column. In addition, most storm events in Chongming occur in summer (June-September), whereas the storm season in Paulina is in winter (November-March). We compared the data between calm weather and two successive storm events in a main creek in Chongming. These data sets were obtained from Fan et al. (2019).

Even in the turbid system, the conditional effects of tides and waves still play an important role in the function of marsh creeks in transporting sediment. During calm weather, a slight import of sediment is observed in the creek during neap tides (maximum water depth less than 2 m), but an export of sediment is observed during spring tides (water depth larger than 2 m) (Figure 4). During storm events, waves have two different effects on sediment transport depending on the tidal range. On the one hand, waves shift the role of marsh creeks from exporting sediment to importing sediment during tides with relatively large tidal ranges (larger than 2m) by supplying additional sediment from mudflats to marsh creeks during flood tides. On the other hand, when the tidal range continues to increase, the combined effects of tides and waves enhance sediment export through the creek. These patterns are consistent with our findings in Paulina Saltmarsh.

Apparently, even with data from the Yangtze Estuary, our analysis does not cover all possible scenarios. However, the underlying patterns observed, such as the interaction among tidal ranges, waves, and sediment dynamics, appear to be broadly applicable. This is because the residual sediment flux under varying tidal and wave conditions can actually be explained by the relative importance of the asymmetry in flow and in sediment concentration between flood and ebb tides (Sun, van Prooijen, Wang, Zhao, et al., 2024). The asymmetry in flow is determined by tidal ranges. A large tidal range leads to larger ebb velocities and net water export in the marsh creeks, as water from the marsh can drain through marsh creeks during ebb tides (Fagherazzi et al., 2013). This

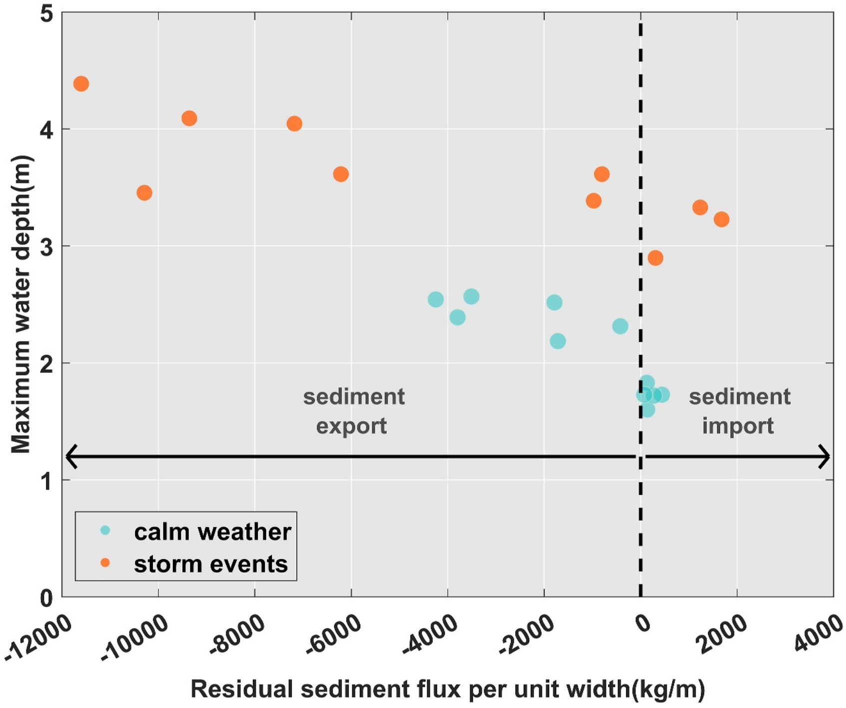

Figure 4. Residual sediment flux per unit width under various tidal conditions during calm weather (blue circles) and during storm events (orange circles) in Chongming (Data adapted from the tables and figures of Fan et al. (2019)).

asymmetry in flow tends to export sediment through marsh creeks, especially when there is insufficient sediment supply during floods. On the other hand, waves enhance mudflat erosion, thereby supplying more sediment to marsh creeks (Fagherazzi & Priestas, 2010). The net import or export of sediment in marsh creeks depends on the extent to which sediment brought in during flood tides, facilitated by wave action, can counteract the export of sediment and water driven by large tidal ranges. Local variations, such as local morphology, vegetation impacts, and regional climate, might influence sediment transport regimes (Ortals et al., 2021; Poirier et al., 2017; Zhu & Wiberg, 2022). Future research is essential for further verifying these findings to enrich our knowledge of these complex ecosystems.

4.3. Potential Sediment Transport Regimes in Meso-Macrotidal Salt Marshes

Marsh creeks are recognized as dynamic channels that convey water and sediment to the marsh systems (Ortals et al., 2021), especially during neap tides (small inundation tidal cycles), when more water is conveyed through the marsh creek than the marsh edge (Temmerman, Bouma, Govers, & Lauwaet, 2005). However, due to the low tidal elevation, sediment exchange between creeks and marshes is limited. This characteristic is typical, especially during neap tides or in a microtidal system, where the flow and sediment are forced to pass via creek systems with minimal lateral exchange (Bonometto et al., 2019). Consequently, sediment primarily accumulates in marsh creeks with sufficient sediment supply during floods (Figure 5a). Waves during neap tides enhance this sediment accumulation in the marsh creek but can cause sediment export over the marsh edge (Figure 5c).

During spring tides (large inundation tidal cycles), a substantial amount of water and sediment can be delivered directly through the marsh edge as well (Temmerman, Bouma, Govers, Wang, et al., 2005). This allows marsh edges to receive an increased supply of water and sediment under calm or weak wave conditions (Figure 5b) but leads to a greater sediment export under strong wave conditions (Figure 5d). For the marsh creek, overbank flow provides the potential for sediment deposited in the creek during the previous neap tides to be transported to the marsh. Meanwhile, an ebb-dominant current appears because water from the marsh would drain through the creek during ebb tides, resulting in net sediment export in the creek (Figure 5b). Strong waves intensify the erosion of marsh creek beds and may also erode the marsh creek bank (Howes et al., 2010; Ma et al., 2018; Mariotti &

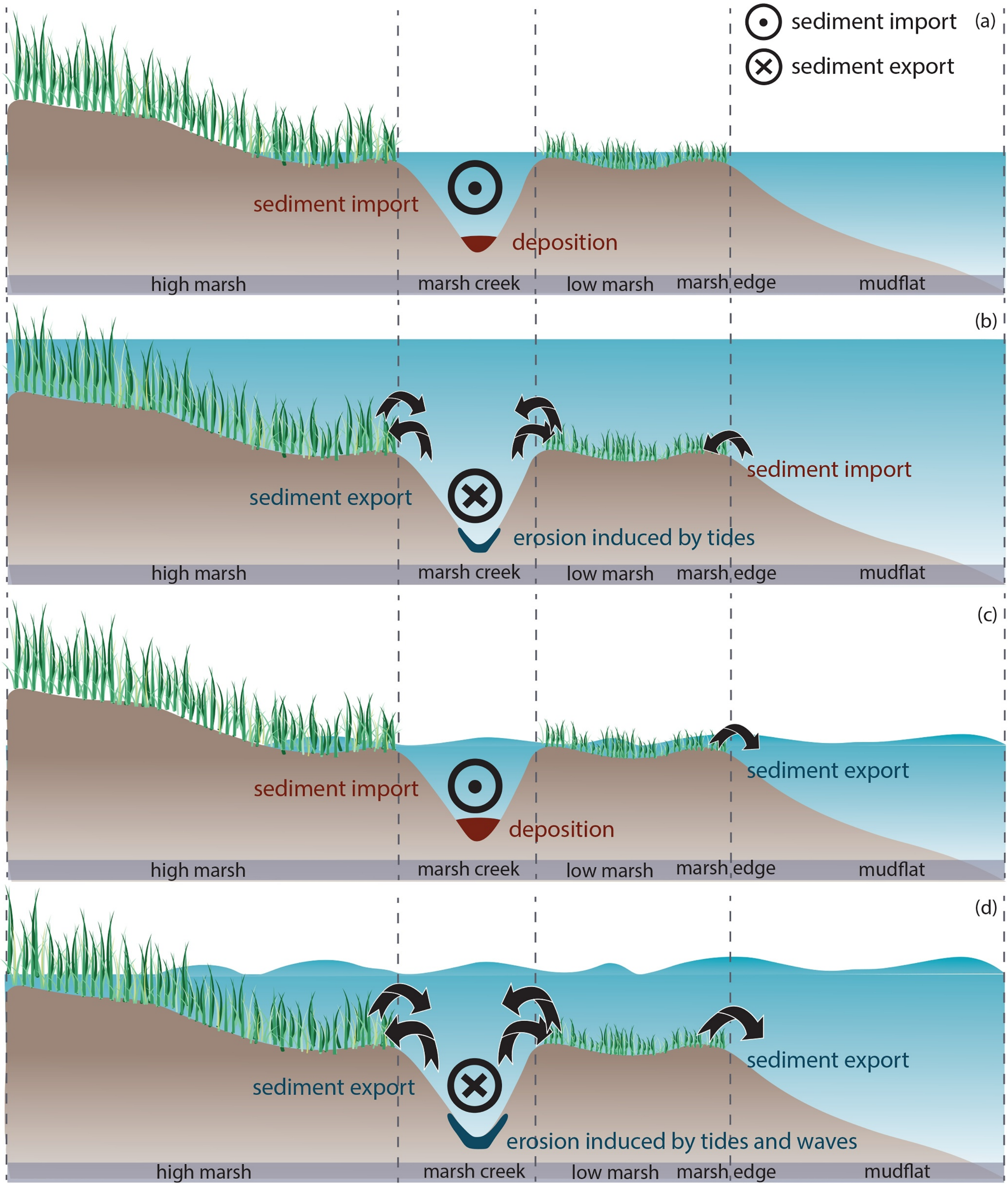

Figure 5. Conceptual schemes for the potential residual sediment flux within salt marshes under different tidal and wave conditions: (a) a scenario of small inundation tidal cycles with weak waves; (b) a scenario of large inundation tidal cycles with weak waves; (c) a scenario of small inundation tidal cycles with strong waves; and (d) a scenario of large inundation tidal cycles with strong waves.

Fagherazzi, 2013), enhancing the sediment export in the creek and the sediment exchange between creeks and the marsh platform (Figure 5d).

Considering the wider expanse of marsh edges, the amount of sediment transported over the marsh edge could exceed the amount transported through the marsh creek. This suggests that the role of marsh creeks in transporting sediment might be overestimated during large inundation tidal cycles. Nevertheless, due to the impact of plants hindering energy flow, sediment tends to be deposited near the marsh edge (Temmerman et al., 2003), and cannot easily reach the inner marsh through the marsh edge. As a result, the contribution of marsh creeks to vertical accretion, especially for the inner marsh, is highlighted.

The resilience of salt marshes to accelerated sea-level rise depends on sediment supply (Alizad et al., 2018; Fagherazzi et al., 2020; Ladd et al., 2019). Marsh loss facing sea-level rise is generally due to the failure of sediment accumulation and thereby the marsh eventually drowns (Best et al., 2018). Consequently, sediment availability is crucial for the survival of salt marshes. Combining with our findings, sea-level rise prolongs inundation periods and promotes ebb dominance. Hence, more scenarios similar to Figure 5b can occur, resulting in fewer occurrences of small inundation tidal cycles (scenarios depicted in Figure 5a). Sediments that would have accumulated in the marsh creek during small inundation tidal cycles cannot be replenished in time, and more erosion occurs in creeks. This aligns well with the findings of Mariotti (2018), where creek widening was observed due to accelerated sea-level rise. Therefore, creek widening leads to the erosion of salt marshes in the face of sea-level rise. On the other hand, we found that the marsh edge imports sediment during large inundation tidal cycles (Figure 5b), potentially benefiting from sea-level rise in the short term. This is possible because marshes can keep up with sea-level rise up to a certain limit (Alizad et al., 2016; Horton et al., 2018; Kirwan et al., 2010). Storm-induced waves have been identified as a significant contributor to salt marsh erosion (Leonardi et al., 2016; Marani et al., 2011). However, research has also found that storms can enhance salt marsh accretion and thereby increase the capacity of marshes to cope with rising sea-levels (Schuerch et al., 2013). Marsh evolution is closely linked with rates of sea-level rise, estuary types, and the characteristics of marshes and storms.

To explore the possible impacts of residual sediment flux on the long-term evolution of salt marshes, we compare our findings with studies that have investigated the impacts of tides and waves on marsh evolution using numerical modeling. Willemsen et al. (2022) found that low wave forcing causes seaward extension of salt marshes, while high wave forcing leads to landward retreat. In the work of Mariotti and Carr (2014), they found that elevated wind waves increase marsh edge erosion but promote vertical accretion of salt marshes. These phenomena can be explained by the observed patterns of residual sediment flux in Figures 5c and 5d. Waves cause sediment export over the marsh edge, potentially indicating marsh edge erosion. On the other hand, waves can enhance sediment exchange between creeks and inner marshes, thereby contributing to vertical accretion. Additionally, Mariotti and Carr (2014) discovered that an increased tidal range enhances the capacity of marshes to prevent drowning. This phenomenon can be attributed to the pattern of residual sediment flux shown in Figure 5b, where both creeks and the marsh edge contribute to vertical accretion.

The sediment transport processes through the two routes shown in Figure 5 are summarized based on the four quadrant-based patterns of sediment transport for the marsh creek and marsh edge in Figure 2. These findings provide valuable insights into sediment transport under varying tidal and wave conditions in marsh systems similar to Paulina Saltmarsh, a meso-macrotidal and low-turbidity marsh system (Temmerman et al., 2003). Although tidal and wave conditions vary between different marsh systems, we expect similar quadrant-related patterns of sediment transport to be observed in other systems, as the mechanisms behind the interplay between tides, waves, and sediment dynamics remain consistent. The general applicability of sediment transport shown in Figure 5 undoubtedly requires further investigation in other systems. It requires measurements of fluxes as well as bed shear stresses by waves. However, the analysis could also be explored with numerical models.

5. Conclusions

Residual sediment flux in the marsh creek and over the marsh edge varies depending on different tidal and wave conditions. We identified four quadrants in the parameter space defined by the wave forcing and tidal range. In the creek, the direction of sediment flux is determined by the tidal range, and the magnitude is influenced by wave action. Marsh creeks tend to export sediment during tidal cycles with a large tidal range and import sediment during tidal cycles with a small tidal range. Larger tidal ranges facilitate a greater ebb-dominant asymmetry in flow within the marsh creek, as water from the marsh drains through the marsh creek. This likely results in the erosion of marsh creeks during ebb tides, causing the export of sediment. During the tidal cycle with a small tidal range, marsh creeks function as conduits for importing sediment. The occurrence of waves enhances both sediment import and export processes. Waves have two different impacts on sediment transport depending on the tidal range. During neap tides, waves contribute to sediment supply by transporting sediment from mudflats to the marsh creek, increasing SSC and promoting sediment import. However, strong waves, coupled with large tidal ranges, can intensify the erosion of marsh creek beds, leading to sediment export.

The residual sediment flux over the marsh edge is determined by contrasting conditions: the sediment flux direction is governed by wave action, while the magnitude of flux is influenced by the tidal range. Waves contribute to sediment export over the marsh edge. Waves primarily occurred during the late flood tide and the ebb tide within our measurements. This resulted in an increase in SSC during the ebb tide over the marsh edge, with minor fluctuations in velocities during this period. Sediment import over the marsh edge exclusively occurs under the conditions of large tidal ranges and calm weather. During neap tides, the tidal prism is too small to result in substantial sediment fluxes.

The net import or export of sediment, through the creek and over the marsh edge, is determined by the specific combination of tidal and wave conditions. Whether a salt marsh will keep pace with sea-level rise depends on how frequently each combination occurs. These four quadrant-based patterns of sediment transport for the marsh creek and marsh edge, shown in Figure 2, were observed in Paulina Saltmarsh, a meso-macrotidal marsh system. Thus, the findings can be applied to similar marsh systems. However, tidal and wave conditions vary between estuaries and even among individual marshes. Whether similar quadrant-related patterns of sediment transport can also be observed in other systems requires further investigation.

Data Availability Statement

Field data collected in Paulina Saltmarsh on the mudflat, in the marsh creek, and at the marsh edge between 26 January and 29 March 2023 were used in this manuscript. These velocities, pressure, bed level change at measuring points, SSC data sets are available in Sun (2024).

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