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Sun, J.

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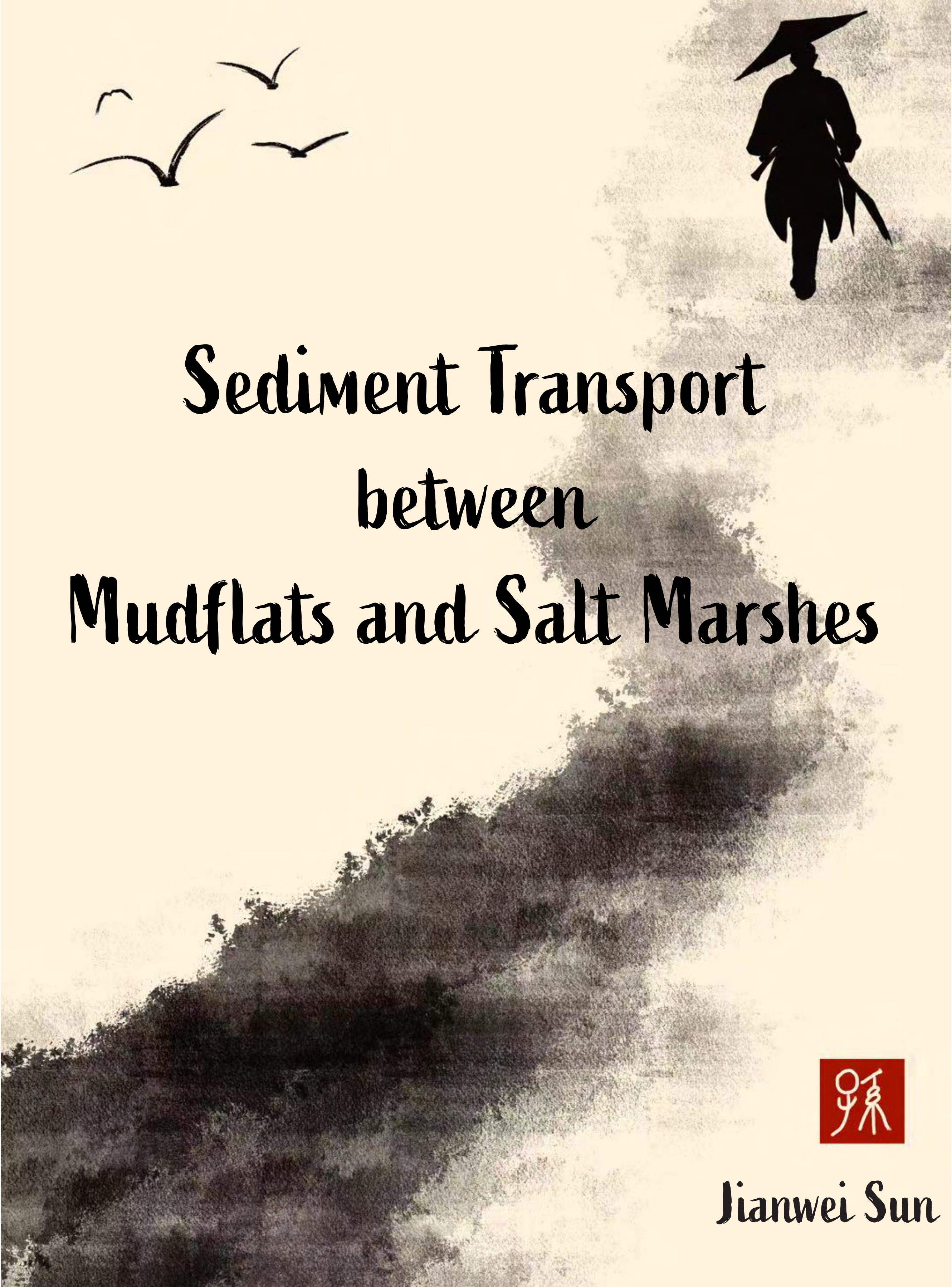

Sediment Transport between Mudflats and Salt Marshes

Jianwei Sun

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Proefschrift

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aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus Prof. dr. ir. T.H.J.J. van der Hagen,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op vrijdag 28 februari 2025 om 10:00 uur

door

Jianwei Sun

Dit proefschrift is goedgekeurd door de promotoren.

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Keywords: sediment flux, marsh creeks, marsh edges, mudflats, salt marshes

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Contents

Summary

Salt marshes are complex and highly productive ecosystems in coastal areas. They play crucial roles in providing habitats for diverse species, sequestering carbon, and serving as natural buffers against storms. However, salt marshes have been threatened by human activities (e.g. reduced sediment supply) and climate change (e.g. sea-level rise), leading to a potential loss. This loss of salt marshes highlights the importance of an influx of sediment to salt marshes for maintaining their structure and resilience. Mudflats, located adjacent to salt marshes, facilitate sediment transport to these marshes under certain conditions. Therefore, advancing our understanding of sediment transport between mudflats and salt marshes is important, as it can provide valuable insights into effective salt marsh management.

This research aims to unravel the varying sediment transport processes between mudflats and salt marshes under different hydrodynamic and sediment dynamic conditions. Chongming Saltmarsh from the Yangtze Estuary and Paulina Saltmarsh from the Western Scheldt Estuary have been selected as study cases. The distinct differences in hydrodynamic forcing and sediment availability between these two estuaries contribute to differing environments and states of their intertidal systems. These differences enable us to compare the sediment transport processes across divergent systems and explore the mechanisms governing the long-term evolution of salt marshes.

Saltmarsh creeks are recognized as efficient conduits that actively facilitate the exchange of water and sediment between mudflats and salt marshes. To identify the role of marsh creeks in sediment transport between two different intertidal systems, the sediment transport processes in a main creek and on the adjacent mudflat in Chongming Saltmarsh (China) and Paulina Saltmarsh (the Netherlands) have been investigated (Chapter 2). Our findings revealed notable differences and common patterns in sediment transport between the two systems. In Chongming, SSC exhibited significant asymmetry between flood and ebb tides, with large SSC peaks occurring during most flood periods. This asymmetry in SSC caused the marsh creek in Chongming to function as a conduit for sediment import. Furthermore, distinct overbank and underbank tides were observed in Chongming. During underbank tides, sediment was trapped and retained within the creeks, only to be eroded and transported to the marsh during subsequent overbank tides. Additionally, the mudflats in Chongming showed a relatively rapid recovery after erosion events. These mechanisms were not observed in Paulina Saltmarsh, where a net export of sediment through the marsh creek was recorded during calm weather. In both systems, the SSC in marsh creeks showed a slight increase due to local erosion of the creek bed but responded more significantly to the erosion of mudflats, indicating that the main sediment sources of the high SSC result from the sediment advection rather than local erosion. These comparative findings suggest that the role of marsh creeks in sediment import and export is closely linked to the availability of sediment from adjacent mudflats, highlighting the importance of mudflats for the growth of salt marshes.

After recognizing the role of main creeks in sediment transport within turbid systems, the role of creek tributaries in sediment delivery still remains poorly understood. Therefore, field measurements were conducted in a main creek and in a secondary creek within Chongming Saltmarsh. These measurements revealed the dual roles of saltmarsh creek systems in drainage and sediment transport, as well as the mechanisms driving residual sediment flux within saltmarsh creeks (Chapter 3). The results indicated that the main creek played a dominant role in sediment delivery, while the secondary creek, influenced by the presence of vegetation, was more effective as a drainage conduit and contributed less to sediment transport. Additionally, the direction and magnitude of residual sediment flux are influenced by the relative importance of asymmetries in net discharge and sediment concentration. Overbank tides primarily result in an ebb-dominant flow asymmetry, which tends to drive sediment export along with the net outflow. However, the abundance of sediment during flood tides can occasionally counteract this export tendency, mitigating the impact of flow asymmetry on sediment export.

Sediment can be imported from mudflats to salt marshes through marsh creeks and marsh edges. To address how varying tidal and wave conditions affect sediment transport within marsh creeks and over marsh edges (Chapter 4), a two-month field campaign was conducted in Paulina Saltmarsh. Field data revealed that tidal ranges determine the direction of residual sediment flux in the marsh creek, while wave intensity determines its magnitude. Conversely, wave intensity determines the direction of residual sediment flux over the marsh edge, whereas tidal ranges determine the magnitude. Specifically, sediment was imported through the marsh creek during tidal cycles with small tidal ranges and strong waves, whereas sediment was imported through the marsh edge during tidal cycles with large tidal ranges and weak waves. These findings offer deeper insights into sediment transport through marsh creeks and marsh edges under different tidal and wave conditions, which is crucial for effective salt marsh management.

This dissertation explores sediment transport between mudflats and salt marshes in two different systems, providing insights into the roles of marsh creeks and marsh edges in facilitating or impeding sediment import to salt marshes under varying conditions. The findings offer guidance for developing conservation and management strategies to support salt marsh growth in response to decreasing sediment supply and accelerating sea-level rise.

Samenvatting

Kwelders zijn complexe en uiterst productieve ecosystemen in kustgebieden. Ze spelen cruciale rollen bij het bieden van leefgebieden aan diverse soorten, het vastleggen van koolstof en het fungeren als natuurlijke buffers tegen stormen. Echter, kwelders worden bedreigd door menselijke activiteiten (bijvoorbeeld verminderde sedimentaanvoer) en klimaatverandering (bijvoorbeeld zeespiegelstijging), wat kan leiden tot een mogelijk verlies. Dit verlies van kwelders benadrukt het belang van sedimentaanvoer naar kwelders om hun structuur en veerkracht te behouden. Slikken, gelegen naast kwelders, faciliteren onder bepaalde omstandigheden sedimenttransport naar deze kwelders. Daarom is het van groot belang om ons begrip van sedimenttransport tussen slikken en kwelders te vergroten, omdat dit waardevolle inzichten kan bieden voor effectief beheer van kwelders.

Dit onderzoek heeft als doel de variërende sedimenttransportprocessen tussen slikken en kwelders te ontrafelen onder verschillende hydrodynamische en sedimentdynamische omstandigheden. Chongming Kwelder in de Yangtze-estuarium en Paulina Kwelder in de Westerschelde-estuarium zijn geselecteerd als casestudies. De duidelijke verschillen in hydrodynamische krachten en sedimentbeschikbaarheid tussen deze twee estuaria dragen bij aan uiteenlopende omgevingen en toestanden van hun intergetijdengebieden. Deze verschillen stellen ons in staat om de sedimenttransportprocessen in uiteenlopende systemen te vergelijken en de mechanismen te onderzoeken die de langetermijnevolutie van kwelders bepalen.

Kwelderkreken worden erkend als efficiënte kanalen die actief de uitwisseling van water en sediment tussen slikken en kwelders faciliteren. Om de rol van kreken in sedimenttransport tussen twee verschillende intergetijdengebieden te identificeren, zijn de sedimenttransportprocessen in een hoofdkreek en op het aangrenzende slik in Chongming Kwelder (China) en Paulina Kwelder (Nederland) onderzocht (Hoofdstuk 2). Onze bevindingen toonden opmerkelijke verschillen en gemeenschappelijke patronen in sedimenttransport tussen de twee systemen. In Chongming vertoonden SSC (suspensed sediment concentrations) een significante asymmetrie tussen vloed- en ebstromen, met grote SSC-pieken tijdens de meeste vloedperioden. Deze SSC-asymmetrie zorgt ervoor dat de kreek in Chongming fungeert als een kanaal voor sedimentimport. Daarnaast werden in Chongming duidelijke overbank- en onderbanktijden waargenomen. Tijdens onderbanktijden wordt sediment gevangen en vastgehouden in de kreken, om vervolgens tijdens daaropvolgende overbanktijden naar de kwelder te worden getransporteerd. Bovendien herstelden de slikken in Chongming relatief snel na erosie-evenementen. Deze mechanismen werden niet waargenomen in Paulina Kwelder, waar netto sedimentexport via de kreek werd geregistreerd tijdens rustig weer. In beide systemen nam SSC in de kreken enigszins toe door lokale erosie van de kreekbodem, maar reageerde sterker op erosie van de slikken. Dit geeft aan dat de belangrijkste sedimentbronnen van hoge SSC voortkomen uit sedimentadvectie in plaats van lokale erosie. Deze vergelijkende bevindingen suggereren dat de rol van kreken in sedimentimport en -export nauw verbonden is met de beschikbaarheid van sediment van aangrenzende slikken, wat het belang van slikken voor de groei van kwelders benadrukt.

Na het erkennen van de rol van hoofdkreken in sedimenttransport binnen troebele systemen, blijft de rol van zijtakken in sedimentaanvoer nog steeds onderbelicht. Daarom zijn veldmetingen uitgevoerd in een hoofdkreek en een secundaire kreek binnen Chongming Kwelder. Deze metingen onthulden de dubbele rollen van kwelderkreeksystemen in drainage en sedimenttransport, evenals de mechanismen die de residuele sedimentflux binnen kreken aandrijven (Hoofdstuk 3). De resultaten wijzen erop dat de hoofdkreek een dominante rol speelt in sedimentaanvoer, terwijl de secundaire kreek, beïnvloed door de aanwezigheid van vegetatie, effectiever is als drainagesysteem en minder bijdraagt aan sedimenttransport. Daarnaast worden de richting en omvang van residuele sedimentflux beïnvloed door de relatieve belangrijkheid van asymmetrieën in netto debiet en sedimentconcentratie. Overbanktijden resulteren voornamelijk in een eb-dominante stroomasymmetrie, die sedimentexport aandrijft samen met de netto uitstroom. Echter, de overvloed aan sediment tijdens vloed kan deze exporttendens soms tegengaan, waardoor de invloed van stroomasymmetrie op sedimentexport wordt gemitigeerd.

Sediment kan vanuit slikken naar kwelders worden geïmporteerd via kreken en kwelderranden. Om te onderzoeken hoe variërende getijden- en golfomstandigheden het sedimenttransport binnen kreken en over kwelderranden beïnvloeden (Hoofdstuk 4), is een twee maanden durende veldcampagne uitgevoerd in Paulina Kwelder. Veldgegevens suggereren dat het getijbereik de richting van residuele sedimentflux in de kreek bepaalt, terwijl de golfintensiteit de omvang bepaalt. Omgekeerd bepaalt de golfintensiteit de richting van residuele sedimentflux over de kwelderrand, terwijl het getijbereik de omvang bepaalt. Specifiek werd sediment geïmporteerd via de kreek tijdens getijdencycli met kleine getijbereiken en sterke golven, terwijl sediment via de kwelderrand werd geïmporteerd tijdens getijdencycli met grote getijbereiken en zwakke golven. Deze bevindingen bieden diepere inzichten in sedimenttransport via kreken en kwelderranden onder verschillende getijden- en golfomstandigheden, wat cruciaal is voor effectief beheer van kwelders.

Dit proefschrift verkent sedimenttransport tussen slikken en kwelders in twee verschillende systemen en biedt inzichten in de rollen van kreken en kwelderranden bij het faciliteren of belemmeren van sedimentimport naar kwelders onder variërende omstandigheden. De bevindingen bieden richtlijnen voor het ontwikkelen van behouds- en beheerstrategieën ter ondersteuning van de groei van kwelders in reactie op een afnemende sedimentaanvoer en een versnelde zeespiegelstijging.

摘要

潮滩湿地是沿海地区复杂且高生产力的生态系统，它们在为多物种提供栖息地、生物多样性、固碳增汇以及作为风暴的天然缓冲区方面发挥着重要作用。然而，盐沼正面临人类活动（如泥沙供给减少）和气候变化（如海平面上升）的威胁，可能导致盐沼的退化甚至丧失。盐沼的侵蚀退化凸显了泥沙输入对维持其结构和生态韧性的关键作用。潮滩（光滩），潮沟与盐沼在不同条件下泥沙的输送存在差异。因此，深入理解光滩与盐沼之间的泥沙输运过程，对盐沼的有效管理具有重要意义。

本研究旨在揭示不同水动力与泥沙动力条件下，潮滩与盐沼之间泥沙输运过程的差异性及其控制机制。研究选取了长江口的崇明东滩盐沼和西斯凯尔特（Western Scheldt）河口的 Paulina 盐沼作为主要研究区域进行案例研究。两个河口系统在水动力和泥沙供给能力上的显著差异，导致了其潮间带系统的环境和状态迥异。这些差别使得我们能够比较不同系统中的泥沙输运过程，并探索影响盐沼长期演化的主要机制。

1. 不同潮间带系统中盐沼潮沟内悬浮泥沙的输运
盐沼潮沟被认为是有效的水沙交换通道，能够促进潮滩与盐沼之间水体和泥沙的交换。为了探究盐沼潮沟在两个不同潮间带系统中的泥沙输运作用，本研究分析了崇明盐沼（中国）和 Paulina 盐沼（荷兰）的主潮沟及其相邻潮滩之间的泥沙输运过程（第2章）。研究结果揭示了两个系统中泥沙输运的显著差异与共同特征。在崇明盐沼，悬沙浓度（SSC）在涨潮和落潮之间表现出明显的不对称性，大多数涨潮期间出现了高 SSC 峰值。这种 SSC 的不对称性使得崇明盐沼潮沟成为泥沙输入的通道。此外，在崇明观测到了显著的漫滩潮（overbank tide）和非漫滩潮（underbank tide）。在非漫滩潮周期期间，由于潮位较低，潮沟无法与盐沼进行泥沙交换，泥沙滞留在潮沟中，并在随后的漫滩潮周期中被侵蚀并输送到盐沼中。另外，崇明的潮滩在侵蚀事件后表现出相对较快的恢复能力。这些机制在 Paulina 盐沼中未被观察到，在常态天气条件下，Paulina 盐沼通过潮沟向盐沼系统外输出泥沙。在两个系统中，共性规律是盐沼潮沟中的 SSC 都能因为潮沟床面的局部侵蚀而增加，但对潮滩侵蚀的响应更为显著，这表明潮沟中高 SSC 峰值的主要来源是潮滩泥沙平流输送，而非局部侵蚀。对比研究结果表明，盐沼潮沟泥沙输入或输出的功能与相邻潮滩的泥沙可供给能力密切相关，凸显了潮滩对盐沼生长的重要性。

2. 盐沼潮沟主支系统内的泥沙通量
在认识到主潮沟在高含沙量系统中泥沙输运的作用后，支潮沟在泥沙输送中的作用了解仍然有限。因此，本研究在崇明盐沼的一条主潮沟和一条次级潮沟内进行了野外实地观测。观测结果揭示了盐沼潮沟系统在排水和泥沙输运中的双重作用，以及影响盐沼潮沟中泥沙通量的机制（第3章）。研究结果表明，主潮沟在泥沙输送中起重要作用，而次级潮沟由于受潮沟内植被存在的影响，更有效地作为排水通道，而对泥沙输送的贡献较小。此外，潮沟内泥沙通量的方向和大小受净水流

通量和涨落潮泥沙浓度不对称性的影响。漫滩潮周期会导致落潮占优的净水流通量不对称，从而导致泥沙有向外输出的趋势。然而，涨潮期间的高沙含量可以抵消这种向外输出趋势，减轻落潮占优的净水流通量的不对称性对泥沙输出的影响。

3. 潮汐和波浪对盐沼泥沙补给的条件效应
为了探究不同潮汐和波浪动力条件如何影响盐沼潮沟和盐沼边界的泥沙输运（第4章），在 Paulina 盐沼进行了为期两个月的野外实地观测。现场数据研究表明，潮差决定了盐沼潮沟中泥沙通量的方向，而波浪强度决定了其大小。相反，波浪强度决定了盐沼边界泥沙通量的方向，而潮差决定了其大小。具体而言，在小潮差和强波浪的潮周期中，泥沙通过盐沼潮沟输入，而在大潮差和弱波浪的潮周期中，泥沙通过盐沼边界输入。这些研究结果为理解不同潮汐和波浪条件下盐沼潮沟和盐沼边界的泥沙输运提供了更深入的认识，这对海岸带盐沼的有效管理至关重要。

本论文探讨了两个不同系统中潮滩与盐沼之间的泥沙输运，揭示了盐沼潮沟和盐沼边界在不同条件下对泥沙输入盐沼的作用。研究结果为制定保护和管理策略以应对泥沙供给减少和海平面加速上升下的盐沼生长提供了指导。

1

Introduction

1

1.1. The Yangtze Estuary and the Western Scheldt Estuary

Estuaries are water systems where a river meets the ocean (Potter et al., 2010). Due to their strategic locations at the confluence of rivers and oceans, estuaries have become significant spots for major shipping-trade ports. As a result, cities situated in these regions, i.e. Shanghai, Hong Kong, New York and Rotterdam, have experienced rapid urbanization, transforming them into some of the world's most densely populated areas (Syvitski et al., 2022). Estuaries are shaped by the river flow and tidal currents. However, due to increasing pressures from anthropogenic interventions (dam construction, land reclamation, and channel deepening, etc.) and climate change (accelerating sea-level rise), estuaries are undergoing transitions, altering the hydrology and sediment transport, and thereby reshaping the morphology of the estuary. (Syvitski et al., 2009; Wang et al., 2015; Nienhuis et al., 2020). The extent of these transitions varies between estuaries, depending on differences in local environments and the types of projects implemented. Comparing various estuaries allows for deeper insights into the mechanisms driving these transitions.

The Yangtze Estuary (China) and the Western Scheldt Estuary (the Netherlands) are two examples of estuaries that were and are undergoing a transition due to extensive human interventions and engineering modifications (Figure 1.1). Large-scale infrastructural developments, such as dam constructions, dredging for navigation, and land reclamation, were conducted in the estuaries to support economic growth and enhance human safety (Eelkema et al., 2012; Luan et al., 2018; Yang et al., 2018; van Dijk et al., 2021; Zhang et al., 2022). However, these projects have shifted the estuaries from the natural state to a anthropogenically altered state, substantially altering their physical dynamics and ecosystems. Nowadays, land reclamation stopped in both systems. There is even an increasing number of restoration and depoldering projects to mitigate the impacts of human activities and enhance resilience to climate change (Eertman et al., 2002; Zhao et al., 2020; De Knegt et al., 2024; Lepesant, 2024).

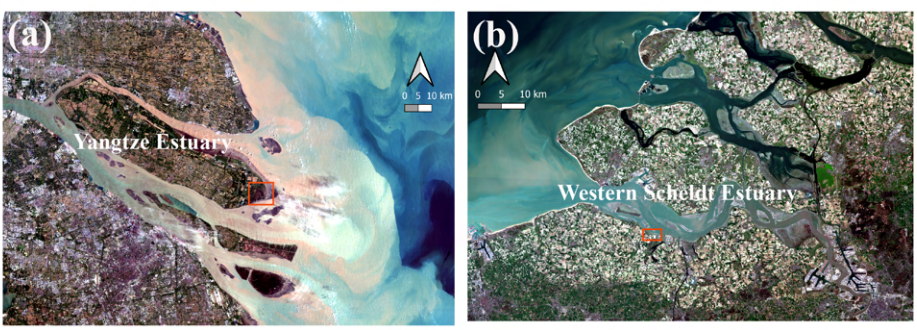

Figure 1.1: Satellite images of (a) the Yangtze Estuary and (b) the Western Scheldt Estuary located in the Scheldt Estuary. The orange rectangles indicate the locations of Chongming Saltmarsh and Paulina Saltmarsh, respectively. Source aerial imagery: Landsat 9 & Sentinel-2.

Though both the Yangtze Estuary and the Western Scheldt Estuary have been modified by anthropogenic interventions, they differ significantly in hydrodynamic conditions and sediment availability. Both estuaries are meso-macrotidal systems, exhibiting a semi-diurnal tidal regime. However, the Yangtze Estuary has an average tidal range from 2.0 to 3.1 m (Yang et al., 2001), while the Western Scheldt Estuary features a larger average tidal range varing from 3.8 to 5.2 m (Schepers et al., 2018). In addition, the Yangtze Estuary is a mixed fluvial-tidal estuary. It is significantly influenced by the Yangtze River upstream, which supplies a substantial amount of water and sediment (Yang et al., 2015). On the other hand, the Western Scheldt Estuary connects to the Scheldt River, whose freshwater discharge is relatively small compared to the tidal discharge at the mouth (De Vriend et al., 2011). Therefore, the Western Scheldt is well-mixed and the fluvial sediment supply is limited (Dam et al., 2016).

Both estuaries consist of multi-channel systems with numerous intertidal systems (De Vriend et al., 2011). Intertidal areas are exposed to the air at low tide and submerged at high tide. They can be categorized into rocky, sandy, and muddy systems based on sediment types. This dissertation specifically focuses on muddy intertidal systems characterized by fine-grained sediment. Muddy intertidal systems generally consist of mudflats and salt marshes (Figure 1.2). Mudflats are unvegetated muddy areas (see Figure1.2a), whereas salt marshes are located on the upper intertidal zones and are characterized by the presence of salt-tolerant plants (see Figure1.2b, c and d). In this dissertation, we select Chongming Saltmarsh from the Yangtze Estuary and Paulina Saltmarsh from the Western Scheldt Estuary as study areas. They are both meso-macro tidal system with the semi-diurnal tidal regime. However, variations in external forcing and sediment availability of the Yangtze Estuary and the Western Scheldt Estuary contribute to different states and structures of their intertidal systems. Paulina Saltmarsh is much smaller, more frequently inundated, and has lower sediment concentrations compared to Chongming Saltmarsh. Moreover, Chongming Saltmarsh is a semi-open system, more exposed to wave action, while Paulina Saltmarsh is a semi-closed system, relatively less affected by waves. Comparing these systems enables us to better understand the sediment transport processes in different systems and explore the mechanisms that govern the long-term evolution of salt marshes.

1.2. Significance of Salt Marshes

Salt marshes provide essential functions and offer numerous benefits to both wildlife and human beings. Intertidal areas can be alternatively submerged and exposed by the rise and fall of tides. This extraordinary environment functions as habitats for diverse species to thrive (Wanner et al., 2014). In addition, salt marshes can act as carbon sinks, sequestering carbon dioxide (CO_2) as ”blue carbon” (Mason et al., 2023), which reduces the greenhouse gases in the atmosphere. Beyond their ecological significance, with the dense vegetation and intricate root systems, they also serve as natural buffers against storm events (Temmerman et al., 2023).

The existence of salt marshes has been threatened by human intervention (e.g. decreasing sediment supply) and climate change (e.g. sea-level rise) (Fagherazzi et al., 2020).

Sediment accumulation plays a crucial role in the survival of salt marshes. Salt marshes require the establishment of plants to persist, especially under the conditions of low sediment supply (Kirwan et al., 2011), as plants can attenuate waves and trap sediment (Temmerman et al., 2005a). This explains why salt marshes can still survive under the low-turbidity environment once saltmarsh plants have been established. However, when facing the accelerating sea-level rise, the resilience of marshes with low sediment supply is limited (Kirwan et al., 2010; Grandjean et al., 2024). Limited sediment availability hinders salt marshes from undergoing vertical accretion and lateral expansion. As a result, salt marshes struggle to withstand prolonged inundation caused by accelerating sea-level rise. Conversely, the positive sediment budget could shift salt marshes from erosion to accretion (Willemsen et al., 2022), which emphasizes the importance of sediment supply for the survival of salt marshes.

Mudflats and salt marshes are often adjacent coastal ecosystems (Figure 1.3a), and sediment can be supplied from mudflats to salt marshes. Therefore, advancing our understanding of sediment transport between mudflats and salt marshes provides valuable insights into better management strategies for maintaining the development and functionality of salt marshes.

Figure 1.2: Photos showcasing elements of intertidal systems. (a) Photos of mudflats and mudflat creeks in Paulina Saltmarsh, the Netherlands; (b) mudflats and saltmarsh creeks emerging from the water in Paulina saltmarsh; (c) lower marshes in Chongming; and (d) higher marshes in Chongming.

1

1.3. Challenges in Exploring Sediment Transport to Salt Marshes

The resilience of salt marshes under the pressure of human intervention and climate change depends on three pivotal factors: (i) sufficient sediment availability in the system outside the marsh; (ii) an effective mechanism for transporting sediment towards the marsh (i.e. sediment import); and (iii) favorable conditions that guarantee the retention of sediment within the marsh. Intrinsically linked to these factors are the three processes of sediment dynamics: erosion, transport, and deposition (Figure1.3b).

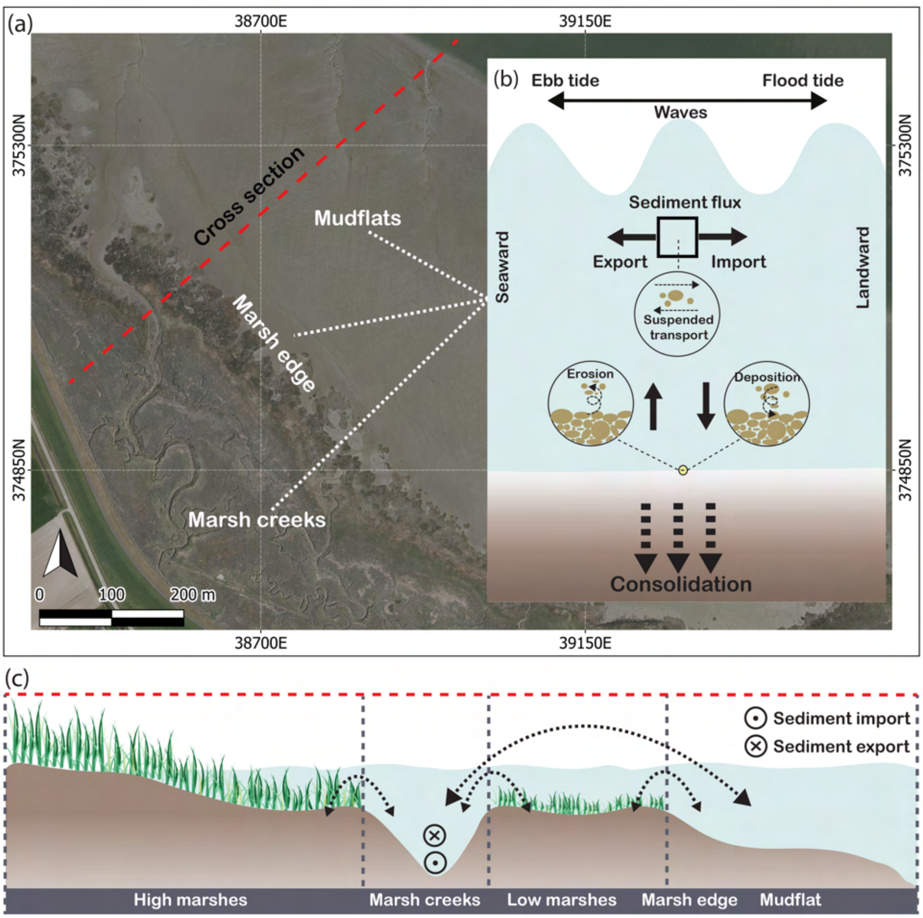

Figure 1.3: Conceptual visualization of sediment transport within muddy intertidal zones. (a) The aerial photo showcasing an example of an intertidal area: Paulina Saltmarsh in the Netherlands. Image source: Beeldmateriaal Nedeland. (b) A conceptual overview of sediment dynamics. (c) A schematic cross-section view of the potential sediment transport pathways.

Sediment availability: Sediment availability is crucial for the fate of salt marshes (Ladd et al., 2019), as sediment acts as the building material of salt marshes. At smaller spatial and temporal scales, sediment availability for salt marshes primarily originates from the surroundings, such as the adjacent mudflat. However, on broader scales, sediment supplied from rivers and seas determines sediment availability for both mudflats and salt marshes. Because of the intensive human interference, i.e. dam constructions, dredging and dumping, sediment availability can be dramatically altered (Besset et al., 2017, 2019). The impact of the transition from abundant sediment supply to limited sediment supply, and vice versa, on sediment transport within salt marshes remains unclear. Comparing the sediment dynamics within sediment-abundant systems and sediment-limited systems is crucial for predicting the long-term evolution of salt marshes, providing guidance for conservation strategies, and informing climate change adaptions.

Sediment transport: Tides drive the movement of sediment in and out of salt marshes (see Figure 1.3b). However, the amount of sediment transported during the flood tide is usually not equal to that transported during the ebb tide. This results in a net movement of sediment over a tidal cycle, a phenomenon known as residual sediment transport. Tidal asymmetries (e.g. the asymmetry in slack water duration and in peak velocity) and Lag effects (e.g. settling and scour lag) are important factors in causing residual sediment transport (Van Straaten & Kuenen, 1957; Dronkers, 1986; Friedrichs & Aubrey, 1988; Gatto et al., 2017). Flow velocities and suspended sediment concentration (SSC) are not always proportional in practice, because of limited sediment availability. For example, erosion can be affected by varying erodibility over depths due to sediment consolidation (Choi et al., 2023; Colosimo et al., 2023), potentially making the deep layers more resistant to erosion. This could lead to low SSC along with large tidal velocities, thereby affecting residual sediment flux. Additionally, sediment transport is also affected by wind wave forcing, especially in the intertidal zone (Green & Coco, 2014). The SSC differential (difference between SSC during flood and during ebb) is therefore found to be a good indicator for the sediment flux in creek (Nowacki & Ganju, 2019).

Sediment from mudflats can be imported into salt marshes via two routes: through the marsh creek and over marsh edge (Figure 1.3c). Saltmarsh creeks, which dissect salt marshes and connect to mudflat, actively facilitate the exchange of water, nutrients, and sediment between mudflats and salt marshes. On the other hand, marsh edges represent the transition zones between bare mudflats and salt marshes, characterized by patches of sparser vegetation. During shallow inundation tidal cycles, the transport of water and sediment over the marsh edge is obviously limited (Temmerman et al., 2005a). However, an increasing amount of water and sediment can be delivered over the marsh edge during high inundation tidal cycles, while sediment transport through the marsh edge, especially to inner marshes, remains limited. This limitation is due to the impacts of vegetation, which enhances deposition by dissipating energy of tides (Bouma et al., 2005). Therefore, the limited energy is insufficient to keep sediment suspended and to carry sediment further into the marsh (Temmerman et al., 2003). Conversely, the flow velocities in marsh creeks are larger than those in salt marshes (Ashall et al., 2016), making these creeks potentially more efficient conduits for sediment transport. This efficiency is particularly notable in higher marsh areas, which are less frequently inundated by tides. Therefore, the role of marsh creeks in water and sediment transport is investigated in this study.

The fact that marsh creeks act as effective channel for water and sediment transport offers a potential solution to mitigating impacts associated with sea-level rise. Specifically, marsh creeks play major roles in efficient drainage(Fagherazzi et al., 2008), preventing saltmarsh plants from being inundated for prolonged periods. Substantial amounts of water from salt marshes drain through marsh creeks during ebb tides, accelerating the draining process and preventing plants from prolonged submersion. Secondly, marsh creeks have the potential to import sediment and contribute to expanding salt marshes (Reed et al., 1999; Murphy & Voulgaris, 2006). However, their roles in delivering sediment are complex and not fully understood. Marsh creeks can serve dual roles: they may function as pathways for sediment to be either imported into the marsh or exported out of the marsh.

Identifying the functions of marsh creeks is challenging due to the structural complexity of marsh creek systems. Typically, a marsh creek system comprises a main creek and numerous interconnected tributary creeks. In this dissertation, the main creek is defined as the widest creek section connected to mudflats, whereas tributaries are generally considered as smaller creeks that are connected to the main creek. Thus, the main creek act as the primary channel for direct sediment and water exchange between mudflats and salt marshes. In contrast, tributary creeks, which branch further into salt marshes, may contribute more to local sediment exchange within specific marsh areas (Ortals et al., 2021). These differences result in different water discharge and sediment flux, potentially leading to distinct functions for the main creek and the tributary creeks. The mechanisms that determine the role of the main creek and tributaries in water and sediment transport requires further investigation.

Direct sediment delivery to high marshes through marsh edges may be limited by vegetation impacts, yet the role of marsh edges in sediment accumulation at low marshes could be significant, given their extensive length. The existence of vegetation and topography affect sediment transport over marsh edges, creating the mechanisms that differ from those in marsh creeks (Reed et al., 1999; Christiansen et al., 2000; Leonard & Reed, 2002). In addition, sediment transport processes in intertidal areas are influenced not only by tidal flow but also by wind and wave forcing. Varing tidal and wave conditions can redistribute sediment differently across salt marshes (van Proosdij et al., 2006; Mariotti & Carr, 2014). Therefore, the different physical structures of marsh creeks and marsh edges, combined with varying tidal and wave conditions, create complex sediment transport mechanisms for these two pathways. This complexity poses challenges in predicting how and when sediment is transported to marsh systems. Consequently, it is crucial to investigate the tidal and wave conditions that induce sediment import through these routes. Understanding the timing and pathways of sediment delivery to salt marshes is essential for effective marsh management.

Sediment retention: Effective sediment retention within salt marshes can be enhanced by low-energy environments and less-erodible conditions. Salt marshes can benefit from natural barriers and sheltered locations, such as barrier islands, sheltered bay, and offshore reefs, that reduce wave energy before it reaches the marsh (Pedersen & Bartholdy, 2007; Schuerch et al., 2012; Chowdhury et al., 2019). Vegetation in salt marshes can attenuate tidal and wave energy to some extent, thereby enhancing sediment retention (Möller et al., 2014). However, the occurrence of sediment retention depends on local conditions, including plant height, type, density, as well as tidal and wave conditions (Rupprecht et al., 2017; Schulze et al., 2019). Additionally, the cohesive features of clay and silt facilitate flocculation, a process that can be enhanced by biological effects, i.e. the presence of algae (Schwarz et al., 2017; Deng et al., 2021). Flocculation contributes to the aggregation of sediment particles, promoting sediment deposition. After being deposited, sediment can be consolidated, especially during the period when sediment beds are exposed to the air, enhancing the resistance to erosion (van Rees et al., 2024). The conditions above play a role in maintaining salt marsh resilience. Yet, this dissertation does not focus on exploring the favorable conditions that ensure sediment retention within the marsh.

1.4. The Aim and Research Questions

The aim of this dissertation is:

To improve the understanding of sediment transport between mudflats and salt marshes.

Advancing our understanding of sediment transport between mudflats and salt marshes is important for effective management of salt marshes. To bridge the knowledge gaps addressed in Section 1.3 and achieve the aim of this dissertation, we will explore the following research questions:

Research Question 1

What are the mechanisms behind sediment transport in marsh creeks?

Research Question 2

What are the mechanisms behind sediment transport over the marsh edge?

Research Question 3

How does sediment transport between mudflats and salt marshes differ across different systems?

1.5. Structure of the Dissertation

The three research questions were the guidance for chapters 2, 3 and 4. Using field measurements, we explored the mechanisms behind sediment transport in marsh creeks and over marsh edges, and also investigated the intricate interplay of tides, waves, vegetation, and sediment. The findings allow us to advance our understanding of sediment transport between mudflats and salt marshes. It should be mentioned that each chapter does not address a single question; Instead, the questions are answered collectively by the three chapters. Additionally, the content of these chapters aligns with journal articles. Therefore, each chapter follows the format of its publication.

In **Chapter 2**, a comparative analysis of sediment transport in the marsh creek in two distinct intertidal systems is conducted. These systems differ in sediment availability: Chongming, China (high-turbidity environment) and Paulina Saltmarsh, the Netherlands (low-turbidity environment). This study sheds lights on distinct roles of marsh creeks in sediment delivery in different systems. Additionally, the sources and ultimate sink of suspended sediment in marsh creeks are identified.

In **Chapter 3**, the dual role of saltmarsh creek systems in drainage and sediment transport is explored, with the objective of unraveling the mechanisms behind residual sediment fluxes. To achieve this, we analyze field data collected in a main creek and a secondary creek in Chongming, China over different months. This work unravels how the sediment differential and residual discharge contribute to the residual sediment flux, providing a better understanding of sediment transport in marsh creek systems.

In **Chapter 4**, the processes of sediment transport through saltmarsh creeks and over marsh edges under varying tidal and wave conditions is investigated, using field measurements that spanned two months during winter in Paulina Saltmarsh. The aim to identify the optimal tidal and wave conditions for sediment import through these two routes. These findings offer deeper insights into when sediment is supplied to salt marshes, through the marsh creek and over the marsh edge.

In **Chapter 5**, answers to the three research questions are presented. Our findings are synthesized into practical applications, emphasizing on their implications for the management of salt marshes. Essential topics, including the excavation of marsh creeks and optimal conditions for dredging disposal, are covered. Recommendations for future research are also provided.

Photograph of a main creek in Chongming Saltmarsh

2

Sources of Suspended Sediments in Saltmarsh Creeks: Field Measurements in China and the Netherlands

Key Points

- High SSC during flood tides in the studied marsh creeks is attributed to advection of sediment rather than local erosion.
- Ebb tides were limited in suspended sediment by various mechanisms, reducing the export of sediment via marsh creeks.
- Roles of marsh creeks in sediment delivery depend on the sediment supply from mudflats and hydrodynamic forcing in creeks.

This chapter has been published in *Geomorphology*:

Sun, J., van Prooijen, B., Wang, X., Hanssen, J., Xie, W., Lin, J., Xu, Y., He, Q., & Wang, Z.B. (2024). Sources of suspended sediments in salt marsh creeks: Field measurements in China and the Netherlands. *Geomorphology*, 456, 109206, https://doi.org/10.1016/j.margeo.2021.106544.

Abstract

Marsh creeks are perceived as important conduits for transporting water and sediment between mudflats and marshes. In order to advance the understanding of the transport mechanisms in creeks, the source and ultimate sink of sediment which moves between mudflats and marshes through creek channels need further investigation. Therefore, two field campaigns were conducted in two intertidal systems with varying sediment availability. The water depth, flow velocity, suspended sediment concentration, and bed level change were measured simultaneously in a marsh creek and on the adjacent mudflat in Chongming Island (China) and in Paulina Saltmarsh (the Netherlands). Paulina Saltmarsh is much smaller, more frequently flooded, and has lower sediment concentration than Chongming. These contrasting conditions allow for a comparison of transport mechanisms and functioning of the creek. Both systems first show that the high suspended sediment concentration (SSC) measured in marsh creeks is mainly the consequence of sediment advection rather than local erosion. In addition, erosion in marsh creeks is usually limited during ebb tides, reducing the export of sediment through these creeks. However, differences have been observed between two systems. The measured SSC was highly asymmetric between flood and ebb tides in Chongming. Large peaks in SSC during the flood period can be observed for most tidal cycles. The marsh creeks in Chongming therefore function as conduits for sediment import. Additionally, there are distinct overbank and underbank tides in Chongming. Sediment was trapped and retained in creeks during underbank tides, which can then be eroded and transported to the marsh during subsequent overbank tides. We also observed that mudflats in Chongming quickly recovered after erosion. These mechanisms have not been observed in Paulina Saltmarsh, where net sediment export via the marsh creek was observed due to a lack of abundant sediment in suspension during flood tides. Furthermore, the remaining bed surface of mudflats after an erosion event was stronger than before, limiting further erosion in Paulina Saltmarsh. These findings from the two systems indicate that the role of creeks in sediment import/export depends on the availability of sediment from mudflats, shedding light on nourishment strategies for salt marshes.

Keywords

Saltmarsh creeks; Sediment concentration; Sediment transport

2.1. Introduction

Salt marshes are highly productive ecosystems that provide valuable functions, such as serving as habitats, acting as natural buffers against storms, and enhancing carbon sequestration (Benoit & Askins, 2002; Fagherazzi et al., 2012; Lockwood & Drakeford, 2021). These marsh systems are characterized by low relief. They expand vertically through accretion and horizontally via vegetation propagation. The capability of salt marshes to keep pace with accelerated sea level rise (SLR) largely depends on their accretion rates (Morris et al., 2002; Kirwan et al., 2010; Carrasco et al., 2021). This implies a need for sufficient sediment in the system outside the marsh, a transport mechanism to move sediment towards the marsh (i.e., sediment import), and conditions that ensure the sediment remains on the marsh.

The three-dimensional structure of salt marshes underscores the fact that their evolution is not only a result of internal factors but also closely linked with the co-evolution of adjacent mudflats. Mudflats are an important sediment reservoir for marshes, especially during storms when erosion in the former leads to deposition in the latter (Hache et al., 2021; Pannozzo et al., 2021). Sediment transported over the marsh edge is often trapped in the frontal area of marshes due to vegetation (Li & Yang, 2009; Lacy et al., 2020). Marsh creeks are the conduits connecting mudflats and salt marshes, serving as effective routes for sediment transport (Voulgaris & Meyers, 2004; Ganju et al., 2015; Ortals et al., 2021), and contributing to the growth of marsh surfaces, especially for the inner marshes. They deliver sediment onto the salt marsh during overbank tides, which leads to the accretion of salt marshes (Temmerman et al., 2005b; Roner et al., 2016). Therefore, it is necessary to enhance our understanding of sediment transport regimes in salt marsh creeks.

Several field measurements have been carried out to unravel the complex hydrodynamics and sediment dynamics within the inter-tidal area (Ly & Huang, 2022; Carrasco et al., 2023). Particularly, dynamics of suspended sediment concentration (SSC) exhibit spatial and temporal variability, as erosion can be space and time dependent (Carniello et al., 2016). High SSC is occasionally observed in association with large tidal velocities. However, SSC does not always scale with local hydrodynamic forcings. High SSC values can also be found in association with relatively low tidal velocities (Green & Coco, 2007; Wang et al., 2012; Zhang et al., 2021). In such cases, the measured high sediment concentration may originate from erosion at other locations rather than from local erosion. To better understand the sediment transport regimes in marsh creeks, it is essential to determine the source of the measured suspended sediment concentration.

Erosion stands as an important factor which adds suspended sediment to the water column. It is a dynamic process shaped by the interplay of hydrodynamic forcings and the sediment bed characteristics (Winterwerp et al., 2018). While detailed erosion formulations, such as the Partheniades' erosion equation, offer insights into the quantifiable aspects of erosion. The parameters governing erosion, such as the critical shear stress, are often taken as constant and uniform values especially in numerical modes (van Leeuwen et al., 2010; Best et al., 2018; Wang et al., 2019). However, Sanford (2008), Mengual et al. (2016), and Zhu et al. (2019) and Colosimo et al. (2020) had shown that the values of the critical shear stress are far from uniform across different spatial dimensions. The influence of such variations in critical shear stress, or in other words, availability of sediment, on the net sediment flux in creeks requires further investigation.

In this work, we analyzed the fieldwork data collected in two intertidal systems (Chongming Saltmarsh in China and Paulina Saltmarsh in the Netherlands). These two systems differ in suspended sediment concentration: the SSC in Chongming is substantially higher than in Paulina Saltmarsh. The data in Chongming was already partly presented in Xie et al. (2018a). Here, we re-used the data for additional analysis and comparison with the Paulina dataset. This allows comparisons of different sediment transport regimes in marsh creeks across systems that differ in size, hydrodynamic conditions, and SSC levels, shedding light on the role of marsh creeks in delivering sediment under different conditions. In this work, we aim to (i) identify when the high SSC occurs in marsh creeks; (ii) interpret the source of this high SSC in the marsh creek; and (iii) compare sediment transport regimes within marsh creeks between two systems with very different sediment availability. With the comparison of sediment transport regimes between the two systems, the significance of sediment availability is highlighted. Our work enhances the understanding of the sediment sources and transport processes in marsh creeks, giving insights into management strategies that are essential for the resilience and development of salt marshes.

2.2. Materials and methods

2.2.1. Study area and field campaigns

Chongming is located in the Yangtze Estuary, China (Fig. 2.1a and b). The eastern part of Chongming Island consists of a wide salt marsh and multiple branched marsh creek systems. The salt marsh is approximately 18 km^2 and consists of many large creeks of 20–50 m in width and 0.1–3 m in depth (Jing et al., 2007; Ge et al., 2021). The slope of the marsh area is between 0.2 % and 0.5 %. According to the statistical data at Datong station, the annual runoff of the Yangtze River is 1.045×10^12 m^3 and the sediment flux was 1.52×10^11 kg in 2016 (CWRC, 2016)). The annual averaged tidal range is approximately 2.6 m (Ding & Hu, 2020) and the extreme tidal range can reach up till 4.6 m. Because the Yangtze Estuary is very turbid, the sediment concentration in marsh creeks in Chongming can range between 0.1 g/L and 18 g/L (Wang et al., 2020). In addition, most precipitation and storm events occur in summer (June–September) in Chongming. Wave events during neap tides were captured in our measurements in Chongming.

Paulina Saltmarsh is located in the Western Scheldt Estuary, the Netherlands (Fig. 2.1c and d). Compared to the salt marsh in Chongming, Paulina Saltmarsh is much smaller with an area of approximately 0.6 km^2. It contains an old high marsh and a young low marsh. The marsh is dissected by a well-developed creek system of 0.3–7 m in width and 0.3–1.5 m in depth (Temmerman et al., 2005b). The tidal range is 3.9 m on average, while spring tides can reach to 4.5 m (Oteman et al., 2019). Due to the relatively low-turbidity environment, the average SSC is around 0.05 g/L (Temmerman et al., 2003). Storm events generally occur in winter (November–March) in Paulina. There were no evident storm events in our measurements in Paulina.

To compare the two systems with different sediment availability, two summer field cam-

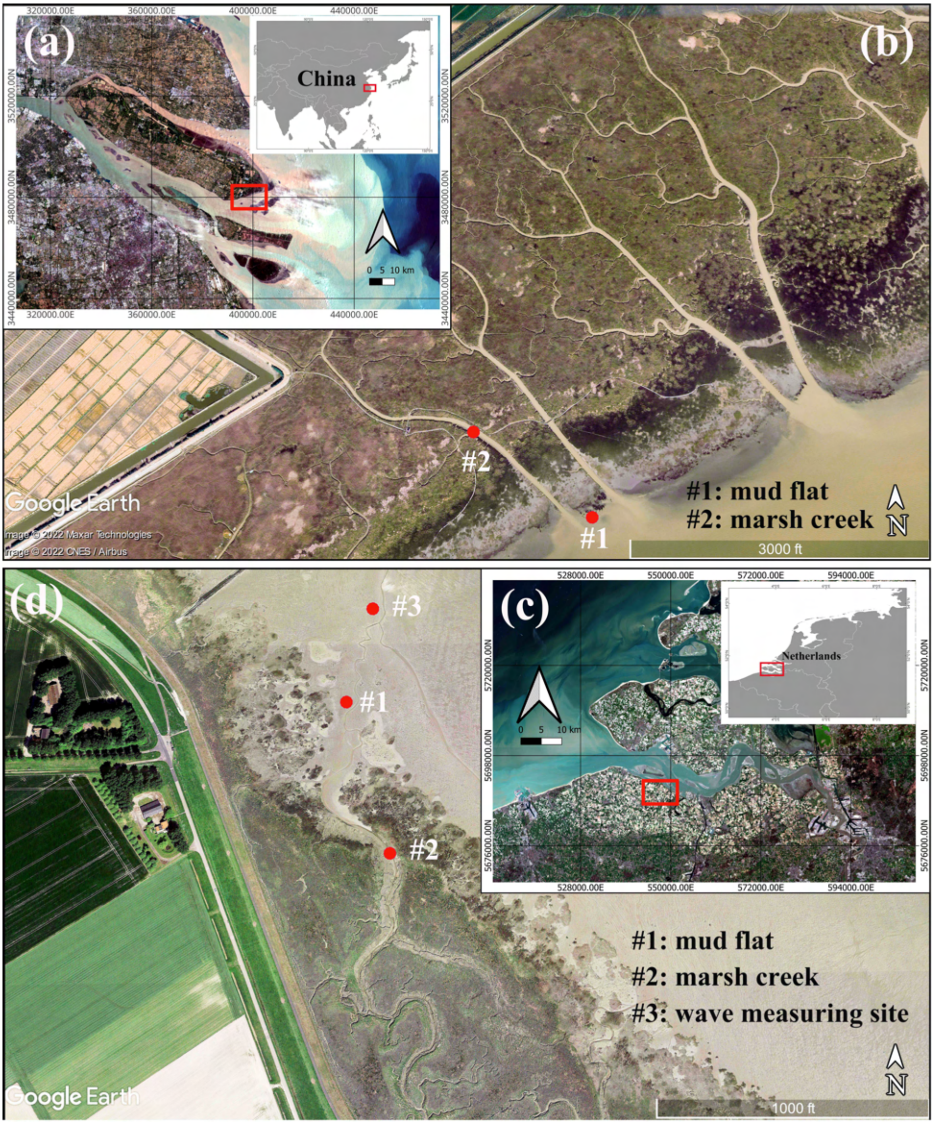

Figure 2.1: (a) The Yangtze Estuary in China. Source aerial imagery: Landsat 9; (b) measuring sites in Chongming. Source aerial imagery: Google Earth; (c) the Westerschelde Estuary in the Netherlands. Source aerial imagery: Sentinel-2; (d) measuring sites in Paulina Saltmarsh. Source aerial imagery: Google Earth (Red circles indicate measuring locations).

paigns were conducted in Chongming from 2nd of August to 12th of August in 2016, and in Paulina Saltmarsh from 22nd of July to 31st of August in 2021.

In Chongming, two tripods with an ADV (Acoustic Doppler Velocimeter, Nortek AS, Norway), an ASM (Argus Surface Meter, ARGUS, Germany), and one RBR (Tide & Wave Loggers, RBR Limited, Canada) were deployed in a marsh creek (Fig. 2.1b #2) and on the adjacent mudflat (Fig. 2.1b #1), respectively. The ADV, ASM, and RBR at the creek site were 25, 25, and 7 cm above the bed, respectively; at the mudflat site, they were deployed 35, 35, and 5 cm above the bed, respectively. The SSC data obtained from the ASM were depth-averaged. Water depth, velocity, bed level change, and SSC were measured at these two sites.

In Paulina, we installed 2 frames with an ADV and an OBS-3+ (Optic Backscatter Sensor, Campbell Scientific, Australia) on the mudflat (Fig. 2.1d #1) and in the marsh creek (Fig. 2.1d #2) in Paulina Saltmarsh. We measured waves with a pressure sensor OSSI (the Ocean Sensor Systems Wave Gauge Blue, Wave Sensor Company, USA), which was deployed at the lower part of the mudflat (Fig. 2.1d #3). The ADV and the OBS at the mudflat were both deployed around 30 cm above the bed. At the marsh creek site, the ADV was also 30 cm above the creek bed, but due to the measurement failures for the OBS near the creek bed, we only acquired data from the OBS deployed 85 cm above the bed. We assume a fully mixed water column in this case. The OBS was synced with the ADV, and thus they measured for the same periods, bursts, and frequencies. More details of the setup for each instrument at all locations are shown in Table 2.1.

Table 2.1: Set-up information of instruments in Chongming and Paulina Saltmarsh

Location	Instrument	Measuring interval (s)	Length of burst (s)	Frequency (Hz)
Chongming	ADV	600	60	64
	ASM	300	25	1
	RBR	300	128	4
Paulina Saltmarsh	ADV	300	60	8
	OBS	300	60	8
	OSSI	1	1	10

2.2.2. Data processing

The acoustic parameters (amplitude and correlation) of ADVs were used to remove erroneous data. Amplitudes larger than 100 and beam correlations higher than 70 were regarded as the valid velocity data (Zhu, 2017; Xie et al., 2018a). To investigate sediment transport into and out of salt marsh systems, we focused on the along-creek component in the creek and cross-shore component of velocities on the mudflat. We substituted the missing points by linear interpolation to get a more complete estimate for sediment flux.

OBS data were converted from the turbidity to sediment concentration, via calibration experiments using in-situ sediment samples. The calibration curves are shown in the supplementary material (Figure A.1).

The cumulative single-point sediment flux per tidal inundation (Fa) was derived from the instantaneous data of velocity, water depth, and SSC (van Weerdenburg et al., 2021). The value of the integration for the entire tidal cycle indicates the import or export of sediment per tide. Positive values represent sediment import into the marsh while negative values represent sediment export out of the marsh.

$$F_a = \int_0^T (v \cdot h \cdot c)dt \tag{2.1}$$

where v represents the velocity (m/s) in along-creek direction within the creek and in the cross-shore direction on the mudflat, h is the water depth (m), c is the suspended sediment concentration (g/L), and T is the tidal period (s). As mudflats and creeks surfaces are drained of water with every tide, the tidal period is defined as the interval between two dry periods.

To better understand whether the erosion results from the current or waves, the shear stress induced by current and by waves were calculated separately (MacVean & Lacy, 2014). We used the same method as Zhu et al. (2016) and Xie et al. (2018a) to obtain the bed shear stress. The wave shear stress was only considered on the mudflat. The bed shear stress induced by waves (τ_w) is normally derived from the significant bottom orbital velocity U_δ and wave friction coefficient f_w:

$$\tau_w = \frac{1}{4}\rho_w f_w U_\delta^2 \tag{2.2}$$

where ρ_w = 1025 kg/m^3, which is the sea water density at the temperature of 21 °C and the salinity of 35 ppt (Newton & Mudge, 2003). A_δ is the significant orbital excursion (m) and U_δ is the significant orbital velocity (m/s). They can be expressed as follows:

$$A_\delta = \frac{H}{2\sinh(kh)} \tag{2.3}$$

$$U_\delta = \omega A_\delta = \frac{\pi H}{T\sinh(kh)} \tag{2.4}$$

where H is the wave height (m), k is wave number defined as $k = 2\pi/L$ (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 from hydraulic regime (Soulsby, 1983):

$$f_w = \begin{cases} 2Re_w^{-0.5}, Re_w \leq 10^5 & (laminar) \\ 0.0521Re_w^{-0.187}, Re_w \geq 10^5 & (smooth\ turbulent) \\ 0.237r^{-0.52}, & (rough\ turbulent) \end{cases} \tag{2.5}$$

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 related to the median grain size of bed sediment (d_{50}), and ν is the kinematic viscosity of water. We consider mudflats as a smooth bed. Therefore, we excluded the rough turbulent regime.

2

The shear stress induced by current (τ_c) was considered both on mudflats and in marsh creeks. We used the logarithmic profile method for the current shear stress (Zhu et al., 2016), directly linking the bed shear stress to the mean flow. It is assumed that the current profile within boundary layers follows a logarithmic distribution.

$$\tau_c = \rho_w C_f \overline{U}^2 \tag{2.6}$$

where C_f is the drag coefficient, which is taken a constant as 0.0025, and $\overline{U}$ is the burst-averaged velocities (m/s) obtained from the ADV.

2.3. Results

2.3.1. Chongmoing

In Chongming, the elevation of the marsh near the creek measuring site lies between mean high water neap (MHWN) and mean high water spring (MHWS), indicating that overbank tides and underbank tides occur. Overbank tides are tidal cycles when water can overtop the banks of a creek, whereas underbank tides refer to those when water levels are contained within the creek. Overbank flow only occurred during spring tides. Because of the diurnal inequality, one overbank tide and one successive underbank tide were observed (Fig. 2.2a, from T1 to T9). The water level did not exceed the bank level during neap tides, resulting in underbank tides (Fig. 2.2a, from T10 to T19). The velocities during the overbank tide, which reached approximately 0.8 m/s in the creek and 0.15 m/s on the mudflat, were higher compared to the velocities during the underbank tide, which were approximately 0.3 m/s in the creek and 0.05 m/s on the mudflat (Fig. 2.2b1 and b2). Larger ebb velocities were observed in the creek during overbank tides as more water from the marsh was concentrated into the creek, while larger flood velocities were observed during underbank tides due to the flood-dominant tidal asymmetry (Fig. 2.2b1).

A significant SSC peak of approximately 4 g/L was observed at the beginning of flood tides for most tidal cycles in the creek (Fig. 2.2c). This high flood SSC led to a slight accretion of the creek bed at the beginning of each overbank tide (Fig. 2.2d1). After the flood peak, the measured SSC in the creek decreased significantly and stayed at a relatively low value of <1 g/L. Local erosion of approximately 20 mm initially occurred in the creek (Fig. 2.2d1), leading to a slight increase in SSC to 0.9 g/L (Fig. 2.2c1). However, this increase in SSC was not as substantial as the flood peak of SSC at the beginning of the tidal cycle. During ebb tides, an additional 10 mm erosion occurred in the creek until the late stage of the ebb tide. After that, a deposition of approximately 7 mm occurred instead. Local erosion from the creek bed can contribute to an increased SSC during overbank tides. During the subsequent underbank tide, a high flood SSC of approximately 3 g/L was also

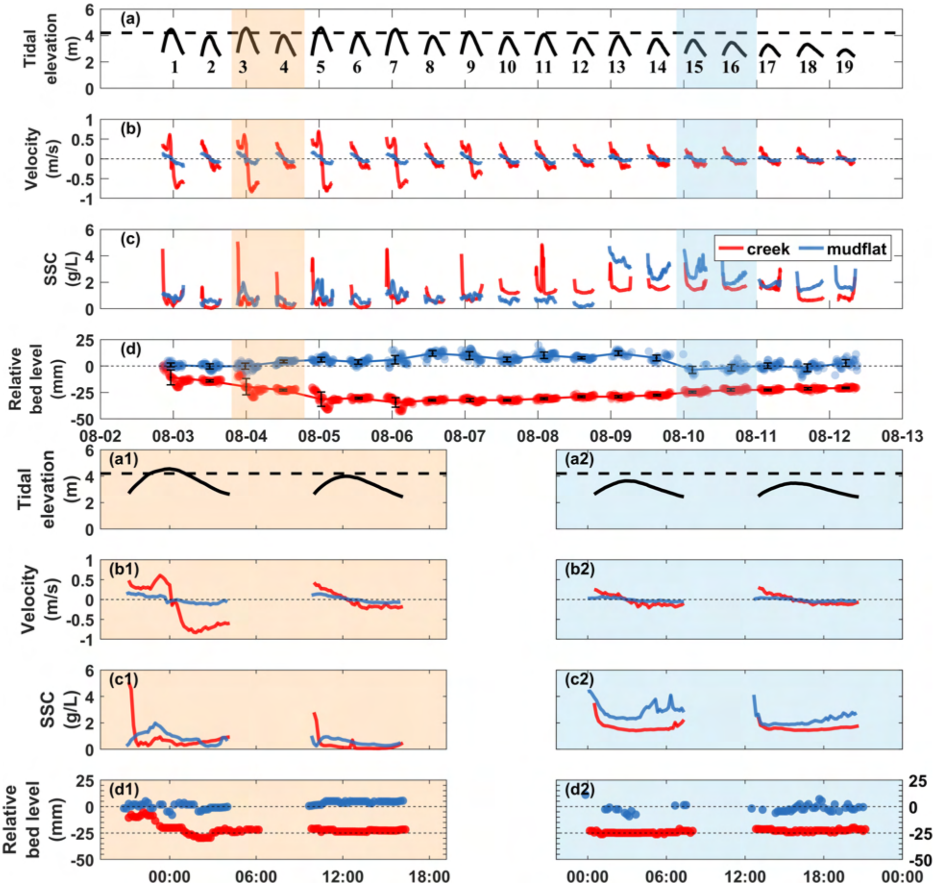

Figure 2.2: Time series of (a) tidal elevation (the dashed line represents the elevation of the creek bank at the measuring location); (b) along-creek velocity in the creek and cross-shore velocity on the mudflat (flood velocity is positive); (c) the suspended sediment concentration observed by OBS-3A; (d) the relative bed level to the initial bed level of measurements in the marsh creek (red) and on the mudflat (blue) in **Chongming**. Negative values indicate erosion and positive values indicate deposition comparing with the initial bed level. The error bar indicates the standard deviation during each tidal cycle. Subfigures below (a1, a2, b1, b2, c1, c2, d1 and d2) are shown to provide more details during highlighted tidal cycles.

observed, but the creek bed remained stable with no evident erosion or deposition (Fig. 2.2c1). Contrarily, the SSC on the mudflat did not always exhibit a large flood peak which was observed in the creek.

During the last few measuring days (T13–T19), a sudden rise of SSC was observed with low velocities at both locations (Fig. 2.2b and c). This increase in SSC was associated with the significant erosion of mudflats (Fig. 2.2d). Abundant sediment from the erosion of mudflats led to an increase in SSC at two locations. The SSC remained high during the entire tidal cycle. During the period from T13 to T19, a slight deposition occurred in the creek (Fig. 2.2d2).

2.3.2. Paulina

In Paulina Saltmarsh, overbank tides were observed during the entire measurement period (Fig. 2.3a), even during neap tidal cycles (e.g., from T20 to T24). This is because the measurements were conducted in the marsh creek at the young lower marsh. Higher velocities exceeding 0.3 m/s were observed in the marsh creek than on the mudflat (Fig. 2.3b). The SSC in Paulina was notably lower compared to the SSC in Chongming. However, a relatively high SSC of 0.23 g/L occurred during the first two days of the measuring period (Fig. 2.3c, from T1 to T4). SSC peaks occurred during flood tides in the marsh creek, accompanied by evident erosion of mudflats, e.g., T3 and T4 (Fig. 2.3c1 and d1). For the remaining measurements, SSC in the marsh creek generally stayed relatively consistent, maintaining a low value of <0.08 g/L. However, the SSC on the mudflat occasionally fluctuated during some tidal cycles, for example, T13, T18 and T21. The measuring point of the mudflat bed remained relatively stable after the erosion during T4, while the creek bed showed considerable variation within tidal cycles (Fig. 2.3d2). In Paulina Saltmarsh, erosion of mudflats contributed to the sediment transport into the marsh creeks, leading to a notable increase in SSC within the marsh creek (e.g., T3 and T4). However, when the sediment supply from the mudflat decreased, the SSC in marsh creeks was affected by the erosion of the creek bed.

2

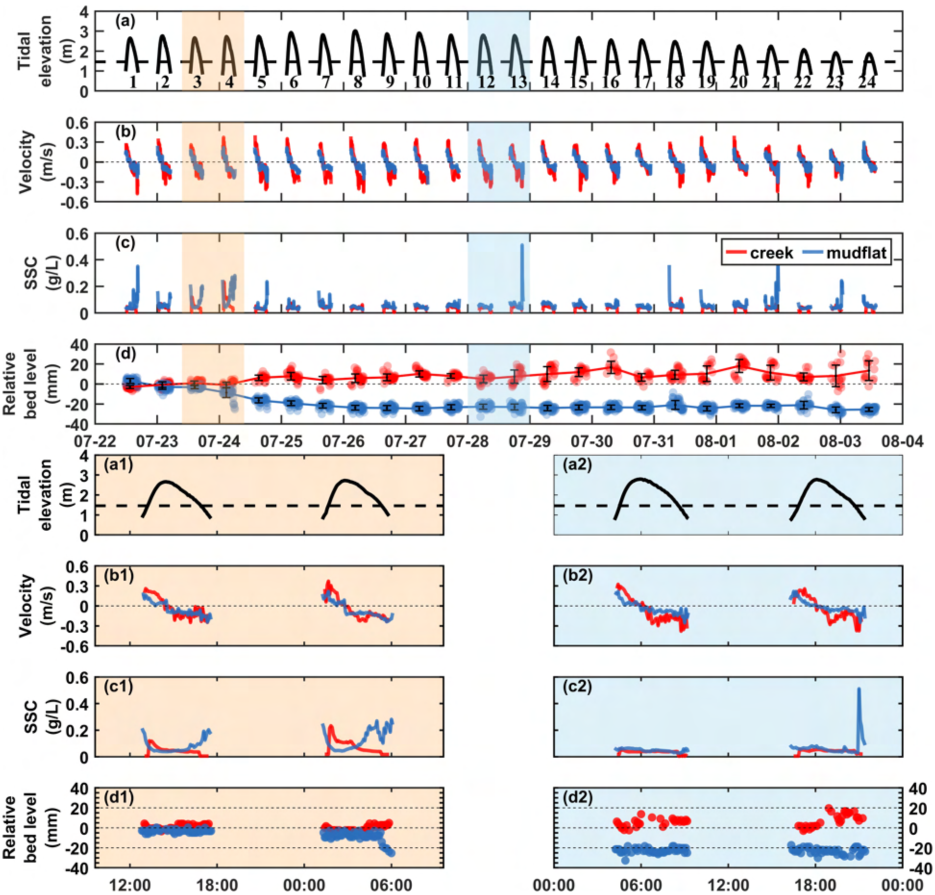

Figure 2.3: Time series of (a) tidal elevation (the dashed line represents the elevation of the creek bank at the measuring location); (b) along-creek velocity in the creek and cross-shore velocity on the mudflat (flood velocity is positive); (c) the suspended sediment concentration observed by OBS-3A; (d) the relative bed level to the initial bed level of measurements in the marsh creek (red) and on the mudflat (blue) in **Paulina Saltmarsh**. Negative values indicate erosion and positive values indicate deposition comparing with the initial bed level. The error bar indicates the standard deviation during each tidal cycle. Subfigures below (a1, a2, b1, b2, c1, c2, d1 and d2) are shown to provide more details during highlighted tidal cycles.

2.4. Discussion

2.4.1. Different sediment sources under varying dynamic regimes

In Chongming, the SSC in the creek showed specific patterns depending on tidal elevations. The average SSC during overbank tides (T1, T3, T5 and T7) was larger than during underbank tides (T2, T4, T6 and T8) (Fig. 2.4a). During overbank tides (during T1, T3, T5, T7), an evident current shear stress larger than 0.6 Pa was observed (Fig. 2.4b). At the same time, the creek experienced considerable erosion during each overbank tide

(Fig. 2.2d). These indicate that tidal currents played an important role in the erosion of Chongming creeks during overbank tides. However, this erosion of the creek induced by current shear stress did not result in the flood peak of SSC. From Fig. 2.2c1 and d1, it is evident that at the beginning of the flood tide with the high SSC, no local erosion but deposition occurred. Later on, significant erosion of the creek was observed with a slight increase of SSC. These observations indicate that local erosion of creek beds did not lead to a substantial SSC peak during flood tides. Therefore, the high SSC is not likely from local erosion but from the advection of the sediment from mudflats or from the creek sections located between the marsh creek entrance and the measurement site.

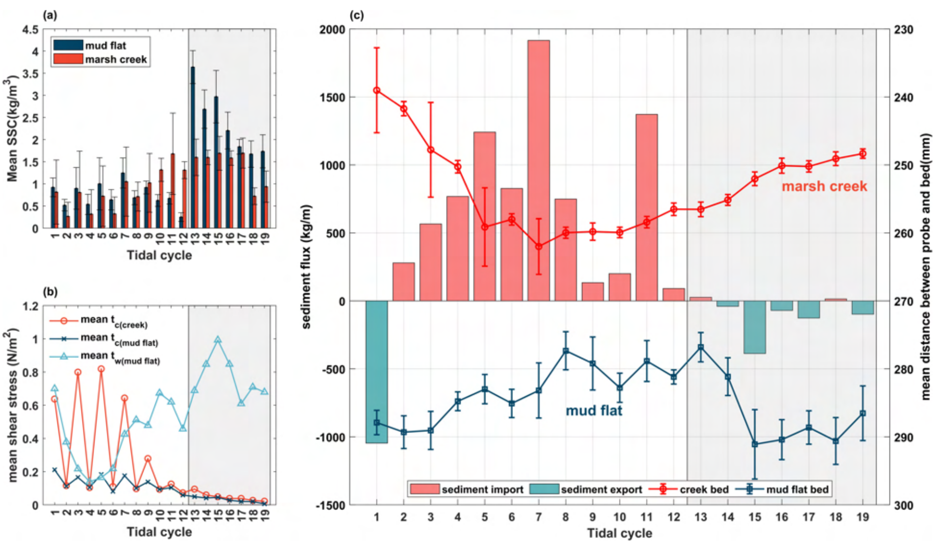

Figure 2.4: (a) Tidal-averaged sediment concentration, (b) tidal-averaged shear stress induced by current and waves, and (c) residual sediment flux in the creek and bed level change of mudflats and creeks in **Chongming** (the error bar represents the standard deviation, and the shadow area indicates the special period when the high SSC occurred).

Considering that the asymmetry in sediment concentration between flood and ebb is key for residual sediment fluxes (Ganju et al., 2015; Nowacki & Ganju, 2019; Sun et al., 2024b), the flood peaks of SSC observed during calm weather result in a flood-dominant asymmetry in SSC. This consequently leads to an influx of sediment into marsh creeks (Fig. 2.4c, from T2 to T12). Therefore, the marsh creek in Chongming generally functions as a conduit for importing sediment during calm weather. During underbank tides, sediment was imported and deposited in the marsh creek system, and during the subsequent overbank tide, the sediment deposited during underbank tides was eroded and was further delivered into the tributaries and also the marsh. The sequence between underbank flow and overbank flow in Chongming leads to a dynamic sediment stock that is eventually delivered to the marsh.

During events when the wave shear stress on the mudflat was high (from T13 to T19), the average SSC increased both in the creek and on the mudflat. Erosion of mudflats and deposition in the creek have been observed during this period (Fig. 2.4c). These observations indicate that waves re-suspended the sediment on the mudflat, leading to the high SSC at both locations. The current shear stress at both locations was low during neap tides (Fig. 2.4b). Therefore, waves played a more dominant role in SSC in the creek than tidal current during this period. Additionally, SSC remained high during entire tidal cycles (Fig. 2.2c, from T13 to T19), and sediment was still suspended even during slack water periods and also ebb tides. It is likely that the coarse sediment with higher settling velocities already deposited earlier (between the mud flat and the measurement location in the creek) with low velocities during neap tides, and fine sediment with lower settling velocities remained in the water column during wave events (Osborne & Greenwood, 1993), leading to a high SSC background value during tidal cycles. This high SSC throughout the tidal cycle resulted in more equal flood and ebb SSC values. Consequently, creeks tended to export sediment during wave events in Chongming (Fig. 2.4c). It is also important to note that, despite the high SSC in the creek induced by waves, significant deposition did not occur when the instruments were submerged during these tidal cycles (Fig. 2.2d2). Sediment settling and deposition mainly occurred during the shallow water periods (water depth < 25 cm) when the water level was below instrument sensors (Zhang et al., 2021). The hydrodynamics during these periods were too weak to suspend sediment, and hence we observed an increase in bed level of the creek during these periods (Fig. 2.4c).

The average SSC in Paulina Saltmarsh, measuring <0.15 kg/m^3, was notably lower than in Chongming (Fig. 2.5a). The SSC in the marsh creek did not show a clear correlation with the current shear stress in the marsh creek (Fig. 2.5a and b). However, during the T3 and T4 periods, relatively high SSC values were observed at both locations, coinciding with relatively large current and wave shear stresses on the mudflat (Fig. 2.5b). Furthermore, the mudflat experienced significant erosion during these tidal cycles (Fig. 2.5c), indicating that the high SSC was caused by the bed erosion of mudflats. The high SSC in the marsh creek in Paulina also responded more significantly to the erosion of mudflats rather than local erosion, which highlights the importance of the advection of sediment transport in the SSC in marsh creeks. The marsh creek played a role in importing sediment when mudflats experienced erosion. During other tidal cycles (from T6 to T24), the average SSC in the creek remained below 0.08 g/L. It seemed that the creek bed reached a dynamic equilibrium (Fig. 2.5c), where erosion in the creek only occurred with the presence of both erodible sediment layers and sufficient shear stress. These variabilities in sediment availability align well with the finding of Choi et al. (2023), where they found the newly deposited sediment exhibits high erodibility, and the critical shear stress for bed erosion decreases with the increase in bed elevation. In contrast with the case in Chongming, the absolute SSC levels in Paulina are limiting the amount of flux through the system. Consequently, the recovery ability of mudflats in Paulina is limited due to the insufficient sediment supply. Thus, no clear recovery of mudflats was observed after the erosion of approximately 20 mm. However, some SSC peaks on the mudflat occurred when the measuring point of the mudflat remained relatively stable (e.g., T13, T18 and

T21 in Fig. 2.3c). These peaks of SSC were likely originated from further offshore or erosion from other locations of mudflats.

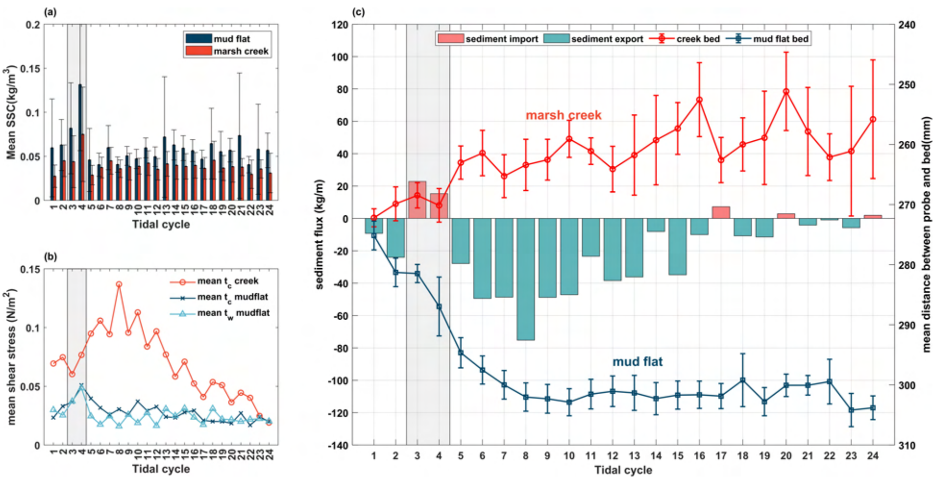

Figure 2.5: (a) Tidal-averaged sediment concentration, (b) tidal-averaged shear stress induced by current and waves, and (c) residual sediment flux in the creek and bed level change of mudflats and creeks flux in **Paulina Saltmarsh** (the error bar represents the standard deviation, and the shadow area indicates the special period when the high SSC occurred).

During tidal cycles when sediment supply from mudflats was limited (e.g., from T5 to T19), the creek in Paulina Saltmarsh tended to export sediment (Fig. 2.5c). This is largely because the residual discharges in Paulina were generally negative due to the presence of overbank tides within the entire measurement period. This asymmetry in flow tended to export water and sediment. Furthermore, the sediment concentration differentials between flood and ebb tides in Paulina were relatively low compared to those in Chongming. The absence of extremely high SSC during flood tides led to the consequence that the sediment concentration differential cannot counteract the exporting trend of the tidal current, resulting in sediment export. However, when erosion of mudflats occurred, leading to an increased sediment supply to the creek, sediment can be imported via the creek (e.g., T3 and T4). This highlights the importance of sediment availability of mudflats in determining the role of marsh creeks in sediment delivery.

It is necessary to note that our measurements only included wave events during neap tides in Chongming and excluded wave events in Paulina Saltmarsh. Seasonality of wave forcings may lead to different mechanisms for sediment transport (Callaghan et al., 2010). For example, in the low-turbidity environment, such as Paulina Saltmarsh, marsh creeks generally function as conduits for sediment export during the calm summer months, while the role of marsh creeks is likely to shift to importing sediment during the storm season in winter. This change is largely due to storm-induced wave events that erode mudflats, subsequently increasing the sediment available for transport towards the salt marsh during flood tides (Pannozzo et al., 2021). However, as observed during neap tides in Chongming, waves may also resuspend sediment and increase the SSC background during the entire tidal cycle. Further research regarding the wave impacts on sediment transport in marsh creeks is required.

Overall, both systems show that the SSC in marsh creeks is more responsive to the erosion of mudflats. Therefore, the high SSC is more likely the consequence of the advection rather than local erosion of the creek bed. The absolute SSC levels outside the intertidal system can influence the recovery of the mudflat after erosion, consequently affecting the sediment availability of mudflats and sediment fluxes in marsh creeks. These findings carry further implications for coastal protection, habitat conservation, and management practices. For example, human activities in coastal areas, such as dredging or land reclamation, can disrupt sediment dynamics. Therefore, understanding the interaction between mudflats and marsh creeks is essential for minimizing negative impacts on salt marsh ecosystems. In addition, recognizing mudflats as crucial sediment reservoirs for marsh creeks offers valuable insights for designing effective conservation and restoration strategies, which can enhance the resilience of salt marshes in the face of future sea-level rise.

2.4.2. Limited erosion in creeks

Current shear stress serves as an indicator of the erosive potential of tides. The critical shear stress is assumed to be the minimum shear stress observed during the erosion phase in creeks (Fig. 2.6a and b). Together with bed level variations, it offers valuable insights into the interaction between tidal conditions and sediment bed dynamics during tidal cycles.

In Chongming, significant erosion occurred twice with different critical shear stresses for erosion. The first erosion event occurred during the late stage of the flood tide with a critical shear stress of 0.35 Pa and a bed level of 2.1 mm above the initial bed of the tidal cycle. After this erosion event, the bed level was 9.4 mm below the initial bed and remained stable until the subsequent erosion during the ebb tide. Yet, the second erosion event of a further 9.7 mm occurred during the early ebb tide and required a larger critical shear stress of 0.77 Pa. This increase in the critical shear stress could be related to consolidation, sediment properties, and benthic effects (Sanford, 2008; Brooks et al., 2021; Choi et al., 2023). After each erosion event, the erosion was then limited even with larger shear stresses, for example, current shear stresses ranging from 0.35 to 1 Pa during the flood tide and shear stresses ranging from 0.77 to 1.78 Pa during the ebb tide did not cause further erosion (Fig. 2.6a and b).

Both erosion events of the creek bed resulted in a slight rise in SSC (Fig. 2.6c), indicating that local bed erosion contributed to the SSC but was not the main sediment source for the initial flood peak of SSC, as only a slight increase of SSC was observed when local erosion occurred. Erosion of other locations, e.g., mudflats or the sections of the creek that lie between the marsh creek entrance and the measurement site, played an important role in flood SSC peaks.

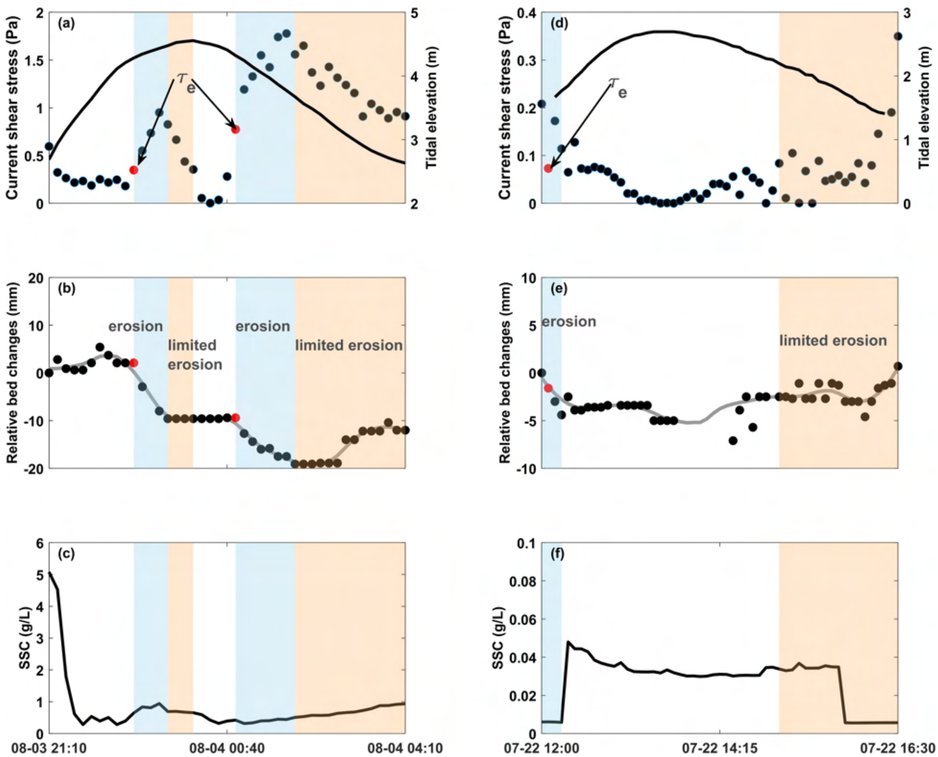

Figure 2.6: Limited erosion in two systems. (a) Current shear stress (dotted line) and tidal elevations (solid line) in Chongming (τ_e represents the critical shear stress for erosion); (b) variations in bed level with respect to the initial bed level at the beginning of the tidal cycle in the creek in Chongming; (c) the measured SSC in Chongming; (d) current shear stress (dotted line) and tidal elevations (solid line) in Paulina Saltmarsh; (e) variations in bed level with respect to the initial bed level at the beginning of the tidal cycle in the creek in Paulina Saltmarsh; (f) the measured SSC in Paulina Saltmarsh. The erosion phases were highlighted in blue, and the limited erosion phases were highlighted in orange.

In Paulina, erosion of 3.9 mm was observed during the beginning of the flood tide, with a potential critical shear stress of 0.07 Pa (Fig. 2.6d and e). This erosion led to a slight increase in SSC (Fig. 2.6f). The creek bed then remained relatively stable until the ebb tide. Subsequently, under shear stress ranging from 0.07 to 0.35 Pa during the ebb tide, deposition occurred instead of erosion, indicating that the creek bed after erosion exhibited less erodibility as the newly deposited sediment.

Because of the heterogeneity of sediment bed erodibility (Zhu et al., 2019; Colosimo et al., 2023), it is crucial to highlight that limited erosion occurs in creeks during tidal cycles. Erosion of a newly-formed fresh sediment bed and a deeper over-consolidated bed require different shear stresses. When considering erosion, especially in numerical models, a constant value of the critical shear stress is normally applied to determine erosion (Dastgheib et al., 2008; Hu et al., 2015; Zhou et al., 2022). However, the critical shear stress varies vertically in reality. Many factors contribute to this vertical variation of erodibility. In addition to the sediment properties (Sanford, 2008; Zhou et al., 2016), consolidation (Quaresma et al., 2004; Williams et al., 2008; Nguyen et al., 2020) and the formation of fluid mud (Maa et al., 1998; Neumeier et al., 2006) may play a role. Take Chongming as an example, a newly-formed bed from the previous underbank tide would be expected due to the moderate flow condition, and hence during the subsequent overbank tide, the erosion requiring a lower current shear stress occurred during the flood tide. During the ebb tide, larger shear stresses were observed due to the convergence of water to the creek, while the bed became more difficult to erode as the erosion progressed in depth. This sheds lights on the timing and conditions where the limited erosion can occur during tidal cycles. In addition, the critical shear stress was lower in Paulina than that in Chongming. We believe that the inundation duration may play an important role in this difference. The tidal regime is different between two systems, where an overbank tide and a successive underbank tide can be observed during spring tides in Chongming. The underbank tide would experience less inundation duration, allowing the sediment layers of marsh creeks to dry for a longer period. This, in turn, leads to a higher critical shear stress for the following overbank tide. On the other hand, there were consistently overbank tides in Paulina, potentially resulting in a lower critical shear stress compared to that in Chongming. Other factors, such as benthic activities (Harris et al., 2016), can also affect the critical shear stress. However, sediment grain size may not play a significant role in this case, as the grain sizes are similar in both systems (Yang et al., 2008; Willemsen et al., 2018).

Limited erosion was found during overbank ebb tides in both systems. This has impacts on the sediment flux in the creek. The limited erosion during ebb tides led to smaller ebb SSC, which indicated that the creek was unable to supply as much suspended sediment to the water column by erosion from waves/currents, as compared to what can be suspended from mudflats. This limited erosion in the creek reduces the amount of sediment transported out of the marsh system during ebb tides, which is beneficial for net sediment import.

2.5. Conclusion

The hydrodynamic and sediment dynamic regimes in marsh creeks vary between Chongming and Paulina Saltmarsh. In Chongming, overbank tides lead to significant erosion of the local creek bed, contributing to a small increase in SSC (<0.7 g/L). However, the flood peak of SSC during the beginning of tidal cycles, which can exceed 4.0 g/L, is not originated from local creek bed erosion but from the erosion of other areas, such as mudflats or the creek sections located between the marsh creek entrance and the measurement site. These high peaks of SSC cause the marsh creek to generally function as a conduit for sediment from the mudflat to be imported on to the marsh surface. In addition, sediment can be slightly deposited in marsh creeks during underbank tides, while it can be eroded during overbank tides in Chongming. The sequence between underbank flow and overbank flow in Chongming leads to a dynamic sediment stock that is eventually delivered to the marsh. Waves during neap tides increase the SSC levels, leading to more equal flood and ebb SSC during tidal cycles.

In Paulina Saltmarsh, overbank tides were observed during the entire measuring period, even during neap tides. In addition, the SSC is notably lower, generally below 0.08 g/L, compared to that in Chongming. Due to the absence of high flood SSC during calm conditions, the marsh creek generally serves as a conduit for sediment export. Only when erosion of mudflats occurred, the SSC in the marsh creek reached 0.23 g/L, and sediment was imported into the system via the creek. The creek bed was active in erosion and deposition among tidal cycles, while mudflats failed to recover after the erosion during our measurements, attributed to the low turbidity outside the intertidal system in Paulina.

By comparing two intertidal systems, sediment availability from mudflats, acting as the key factor for the role of marsh creeks in sediment transport, has been highlighted. In both systems, the SSC in marsh creeks slightly increases due to local erosion of the creek bed but responds more significantly to the erosion of mudflats, indicating that the sources of high suspended sediment in creeks result from the advection of sediment rather than local erosion of the creek bed. Additionally, the erodibility of creek beds varies vertically. Limited erosion of the creek bed occurred during ebb tides, reducing the export of sediment through marsh creeks. This work reveals sediment transport between mudflats and salt marshes through marsh creeks, emphasizing the significance of mudflats in marsh development and offering insights into sediment nourishment strategies for salt marshes.

Photograph of marsh creeks in Chongming Saltmarsh

3

Sediment Fluxes within Salt Marsh Tidal Creek Systems in the Yangtze Estuary

Key Points

- The relative importance of asymmetries in sediment concentration and in flow for residual sediment fluxes was explored.
- The main creek is mainly a conduit for sediment delivery whereas the secondary creek is mainly a drainage conduit.
- Sediment supply limitation can even occur in a turbid system like Chongming.

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Abstract

Creeks are essential for salt marshes by conveying water and sediment through this geomorphic system. In this paper, we investigate the mechanisms that determine the residual sediment flux using measurements conducted in tidal creeks in salt marshes of the Yangtze Estuary. A main creek and a secondary creek were studied to explore whether the mechanisms determining residual sediment fluxes through the main creek differ from those in the secondary creek. Measurements in creeks were carried out over 5 years, spanning different months. Sediment import was found during most tides, both in the main creek and the secondary creek, implying that creeks in Chongming generally function as a conveyor belt of sediment into the marsh. However, sediment export can occur during certain overbank tides. When comparing the role of creeks in drainage and sediment delivery, the main creek functions more in delivering sediment while the secondary creek primarily serves as a drainage conduit. To better understand the mechanisms behind sediment fluxes, the residual sediment flux was compared with the residual discharge and the sediment differential (differences in sediment concentration between flood and ebb). Overbank tides generally lead to a net outward discharge as more water from salt marshes can be concentrated into the marsh creek during ebb tides. This net outward discharge tends to export more sediment during ebb tides. However, due to the sediment abundance during the flood phase in the turbid environment, sediment import can be expected even with the residual export of water. Export of sediment was only found for the few tides with a net outward discharge and a small positive sediment concentration differential. Large negative sediment differentials (larger averaged suspended sediment concentration during ebb tides) have not been observed because the sediment supply during ebb is limited. This paper unravels how the sediment differential and residual discharge contribute to the residual sediment flux, providing a better understanding of sediment dynamics in marsh creek systems.

Keywords

Sediment flux; Marsh creek systems; Sediment availability

3

3.1. Introduction

Salt marshes are multi-functional: they attenuate waves and protect shorelines during storms (Leonardi et al., 2016), provide habitats for a range of species, including migratory birds (Hughes, 2004), and sequester carbon (Lockwood & Drakeford, 2021). Therefore, the preservation of salt marshes is a key component for coastal management. However, one of the issues is whether they can keep pace with accelerating sea-level rise. Sufficient sediment supply is needed, not only at the edge of the salt marsh but also deeper into the marsh. Saltmarsh creeks are perceived as dynamic conduits for transporting sediment. Yet, their role in sediment transport is intricate, as they can either import or export sediment. Consequently, understanding net sediment fluxes in marsh creeks is essential for the preservation of salt marshes.

Net sediment transport is determined by both the tidal asymmetry and the difference in sediment concentration between flood and ebb tides. Boon (1975) found that asymmetry in flow velocity could result in sediment transport towards salt marshes. Tidal asymmetry in salt marshes is caused by the difference in friction and depth between creeks and the vegetated marsh (French & Stoddart, 1992). These mechanisms have been further explored and reviewed in Fagherazzi et al. (2013). They also highlighted the effect of sediment resuspension on the adjacent mud flats, leading to high sediment concentrations during flood stages. Nowacki and Ganju (2019) and Coleman et al. (2020) show that the net sediment flux through creeks depends on the asymmetry in sediment concentration: if the concentration during flood is higher than during ebb, a net inward flux is found, and vice versa. The difference in sediment concentration between flood and ebb could be a consequence of local resuspension, or due to erosion/deposition elsewhere. The quantitative contribution of the asymmetry in flow and in sediment concentration to net sediment fluxes remains unclear.

Various factors can play a role in the net import/export of sediment through salt marsh creeks. For example, large river discharges or strong winds can bring more water and more sediment into creeks (Green & Hancock, 2012; Nowacki et al., 2019; Wang et al., 2020). Seasonal variations in bioturbation (Leonard et al., 1995) and drag by vegetation (Lacy et al., 2020) can influence sediment transport processes within salt marshes. In addition, inundation events are crucial for the net sediment flux towards salt marshes (Fagherazzi et al., 2012). When a salt marsh is not inundated, the flow is confined within the creek, and the velocity is relatively low (Pieterse et al., 2016). When a salt marsh is inundated, overbank tides occur, leading to higher velocities in marsh creeks. High flow velocities in the creek may erode sediment that was deposited in previous tides (Xie et al., 2018a). Sediment transport is influenced by these factors through their impacts on the asymmetries in flow and in sediment concentration.

The interplay between flow and sediment is complex. An often-made assumption is that the sediment concentration scales with the hydrodynamic forcing. For example, Fagherazzi and Priestas (2010) and Fagherazzi et al. (2013) show that the concentration during flood scales with the wave height on the mudflat just in front of the marsh and with the velocity during the ebb stage. Such an assumption is only valid if there is sufficient sediment available. Davidson-Arnott et al. (2002) found that the interaction between flow and sediment is not always scaled, as suspended sediment concentration (SSC) remained consistent with changing hydrodynamics. This possibly indicates that less sediment becomes available for erosion. In that case, erosion is supply-limited. Supply limitation plays a crucial role in sediment concentration and thus affects sediment fluxes. The occurrence of supply limitation in marsh creeks within a turbid system will also be investigated.

The role of marsh creeks in sediment transport may vary under different conditions. In this paper, we explore the mechanisms behind sediment fluxes further to explain how, when, and why sediment is transported towards or out of the salt marsh. We measured flow velocities, depths, and sediment concentrations in creeks in the marsh of Chongming Island, China. We test the statement of Nowacki and Ganju (2019) within the salt marsh tidal creek systems in a turbid estuary: the sediment concentration differential indicates the direction of residual sediment fluxes. Furthermore, we explore the influence of net water discharge on the direction and magnitude of residual sediment fluxes. In this way, we aim to reveal a better understanding of sediment dynamics, especially net sediment fluxes, in marsh creeks.

3.2. Regional setting

Chongming Island is located in the Yangtze Estuary, China (Fig. 3.1a and b). It has been expanding eastwards at rates of 10 m/year over past centuries (Yang et al., 2001). Due to accelerated sea-level rise and the decreasing fluvial sediment supply since 2008the accretion rate of the eastern shoreline has decreased, with a rate of 2.81 km^2/year from 1985 dropping to a rate of 0.15 km^2/year after 2008 (Wang et al., 2022). Chongming Island is regarded a turbid area with an annual averaged tidal range of approximately 2.6 m (Ding & Hu, 2020). In Chongming Island, the wet season is in summer (June–September), while the dry season is in winter (November–February). The main creek is defined as the widest creek close to the mudflat, while the secondary creek is defined as the tributary that is directly connected with the main creek.

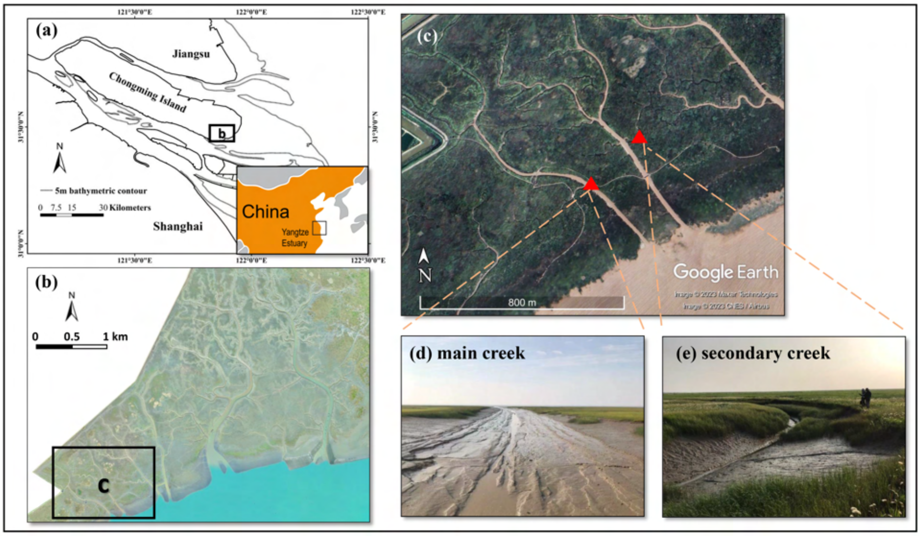

Figure 3.1: (a) Map of the Yangtze Estuary; (b) Drone image of salt marshes in Eastern Chongming Island; (c) Google Earth map of the study area showing locations of measurement sites. Source aerial imagery: Google Earth. (red triangles represent the measuring locations); (d) A photo of the main creek and (e) the secondary creek.

3.3. Method

3.3.1. Experiment set up

Two sites were selected: one in a main creek and one in a secondary creek (Fig.3.1c). To cover this seasonal variation of river discharges and also the state of marshes, we measured the dynamics in different months. Ideally, the measurements would last for a full year to cover all seasonal variations. Due to operational restrictions, the measurements were carried out in the months March, April, May (at the start of the wet season) and in September (at the end of the wet season) in various years. Measurements in the main creek were conducted in April and September (2015). These data sets have been partly presented already in Wang et al. (2020). Here we utilized these data to investigate the mechanisms behind sediment fluxes in the main creek, while Wang et al. (2020) focuses more on local morphological changes in the creek. Measurements in the secondary creek were carried out in late May (2018) and March (2019). Although the measurements of the main creek and the secondary creek were not conducted simultaneously, we believe that we can use these as a comparison because the hydraulic characteristics of the secondary creek are similar for these years. The monthly average discharge for these four months at Datong station was 2.43×10^4 m^3/s, 2.84×10^4 m^3/s, 2.99×10^4 m^3/s and $3.06\times/10^4$ m^3/s, respectively (data source is River Sediment Bulletin of China in http://www.cjh.com.cn/). Effects of local waves were not significant within our measurements. During the measurements of the main creek, the average wave heights were below 0.08 m in April and below 0.04 m in September (Wang et al., 2020). In addition, the impacts of waves were limited due to the vegetation in the secondary creek. The measuring location in the main creek is approximately 500 m upstream of the salt marsh edge. The depth of the main creek is approximately 2 m. The creek is drained during low tide. The bed level of the main creek is fairly uniform over the width of about 30 m (see Fig. 3.1d). The second measurement location is at the thalweg of a vegetated meandering secondary creek (see Fig. 3.1e). The width of the secondary creek is approximately 4 m and the depth is approximately 1.5 m. The distinction between underbank flow and overbank flow is defined at water depths of 1.45 m and 1.4 m for the main creek and the secondary creek, respectively. Morphological changes were not measured in the secondary creek.

Flow velocities and water depths were measured with an ADCP (1.0 MHz or 2.0 MHz Aquadopp Profiler, Nortek AS, Norway) or an ADV (Acoustic Doppler velocimeters, Nortek AS, Norway), see Table 3.1. Turbidity was measured with OBS (OBS-3 A, D&A Instrument Company, Washington, USA). The ADVs were installed 55 cm above the bed in the main creek, facing downwards. The measuring point is thereby approximately 40 cm above the bed. The OBSes in the main creek were deployed 15 cm above the bed. The ADCPs were placed 10 cm above the bed in the secondary creek, facing upwards. The transmitters of the OBSes were positioned 10 cm above the bed as well. The burst intervals and burst periods of ADV or ADCP are indicated in Table 3.1. The OBSes were synced with the ADV/ADCP. More details of the measuring period are provided in Table 3.1.

Table 3.1: An overview of the instruments set up.

Location	Instrument	Measuring period	Burst intervals(s)	Burst period (s)
Main creek	ADV+OBS	01.04.2015-11.04.2015	600	60
Main creek	ADV+OBS	16.09.2015-22.09.2015	300	30
Secondary creek	ADCP+OBS	26.05.2018-02.06.2018	300	60
Secondary creek	ADCP+OBS	18.03.2019-26.03.2019	300	60

3.3.2. Data processing

The velocity data was de-spiked using the approach proposed in Zhu (2017): threshold values of the amplitude and correlation were used to remove invalid data. Velocities were transformed into a coordinate system with a stream-wise (along-creek) and transverse component. ADCP results were averaged over the depth. As ADVs in our measurements only collected data at about 40 cm above the bed, we assumed that the velocities measured by ADVs can represent the depth-averaged velocities. The turbidity data with water levels higher than the velocity sensor and with valid velocity data were taken as reliable data. A few outliers of velocities and turbidity signals were removed manually.

Calibration of the OBSes was carried out in the laboratory, using in-situ sediment samples. Following the procedure described in Hoitink and Hoekstra (2005), the calibration curves are added as supplementary material (Figure B.1).

Translating our measurements into discharges and sediment fluxes requires integration over the cross-section. Flow velocity profiles are averaged over the depth and the sediment concentration is assumed uniform over the depth. Similar to Green and Hancock (2012) and van Weerdenburg et al. (2021), the cumulative discharge (Q_a) and cumulative sediment flux (F_a) per unit width are obtained from the data sets of the instantaneous velocity, water depth, and SSC:

$$Q_a = \sum_0^t v(t) \cdot D(t) \cdot \Delta t \tag{3.1}$$

$$F_a = \sum_0^t v(t) \cdot D(t) \cdot c(t)) \cdot \Delta t \tag{3.2}$$

where v is the velocity in creek direction, D is the water depth and c is the suspended sediment concentration.

The results of the accumulated discharge and sediment flux per unit width are shown, for a better comparison between the main creek and secondary creek. Multiplying with the width would result in too much difference, due to the much larger width of the main creek.

In order to explore the mechanisms of residual sediment fluxes, we use a similar method to obtain the specific residual discharge (ΔQ) and residual sediment flux (ΔF) per unit width:

$$\Delta Q_i = Q_a(t_{i,end}) - Q_a(t_{i,begin}) \tag{3.3}$$

$$\Delta F_i = F_a(t_{i,end}) - F_a(t_{i,begin}) \tag{3.4}$$

where $t_{i,begin}$ is the start time of a tidal cycle i and $t_{i,end}$ is the end of tidal cycle i. The tidal cycles are easily distinguished, as the creeks fall dry. Therefore, residual discharge (ΔQ) and residual sediment flux (ΔF) for each tidal cycle can be determined. Positive values indicate a net import of water or sediment, and negative values indicate a net export of water or sediment.

The sediment differential between flood and ebb (ΔC) is defined as the difference between the mean flood concentration and the mean ebb concentration (Nowacki & Ganju, 2019):

$$\Delta C = \frac{1}{n_{flood}} \sum_{i=1}^{n_{flood}} c_i - \frac{1}{n_{ebb}} \sum_{i=1}^{n_{ebb}} c_i \tag{3.5}$$

where n_{flood} and n_{ebb} represent the number of SSC data points for the flood tide and ebb tide, respectively. A positive value thereby indicates that the averaged flood concentration is higher than the averaged ebb concentration, and vice versa.

3.4. Results

3.4.1. Main creek

A distinct spring-neap tidal cycle can be recognized (Figs. 3.2a and 3.3a). During neap tide, the flow was restricted to the creek (the water depths are <1.45 m). During spring tide, the water level exceeded the marsh level, and overbank flow occurred. The flow velocities were higher during overbank flow (Figs. 3.2b and 3.3b), due to the larger tidal volume when the bank was exceeded. In addition to the spring-neap cycle, daily inequity was found. The ebb velocities during overbank tides were higher in April than in September.

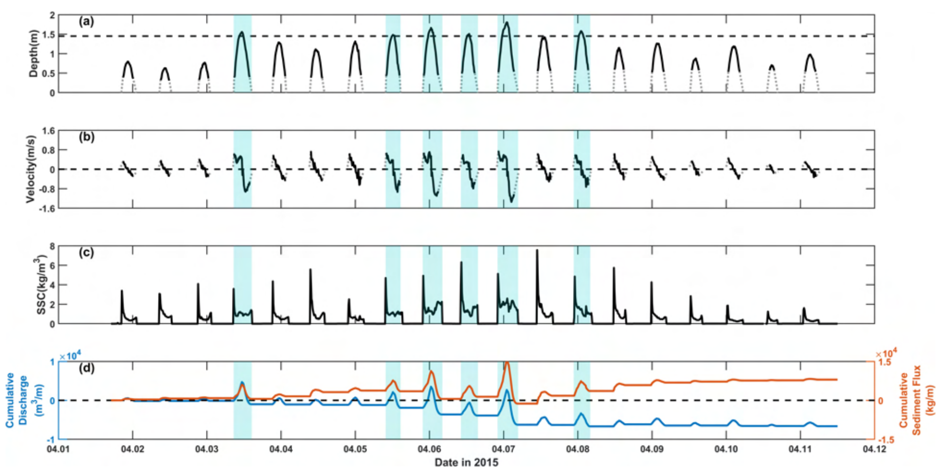

Figure 3.2: Time series of (a) water depth (The dashed line represents the creek depth), (b) velocity (flood velocity is positive), (c) Suspended sediment concentration, and (d) cumulative discharge and sediment flux (into the creek is positive) in the **main creek in April 2015**. The grey dotted data of water depths and velocities are interpolated by linear methods to synchronize them with the SSC data quantities. The overbank tides were highlighted in blue.

An evident peak in SSC appeared at the beginning of each tidal cycle, i.e., when the creek was flooded (Figs. 3.2c and 3.3c). The SSC in the main creek can reach 7.5 kg/m^3 in April and 9.5 kg/m^3 in September. The largest SSC did not occur during the tides with the largest water depths and velocities (e.g., T11 in April and T1 in September). The highest peak in SSC for each tide did not occur at the same time as the peak velocity. For some

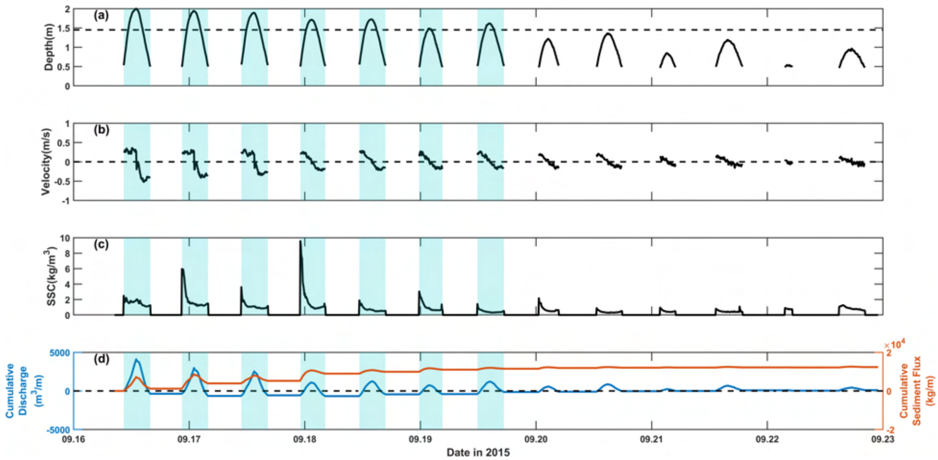

Figure 3.3: Time series of (a) water depth (The dashed line represents the creek depth), (b) velocity (flood velocity is positive), (c) Suspended sediment concentration, and (d) cumulative discharge and sediment flux (into the creek is positive) in the **main creek in September 2015**. The overbank tides were highlighted in blue.

tides, a clear peak in SSC during ebb can be found just before drying. These peaks were however lower than flood peaks.

During underbank tides with shallow water, flow velocities were low, leading to negligible import/export of water. During overbank tides with high water levels, there was a clear export of water as more water from the marsh would be concentrated into the marsh creek during ebb tides. The creeks functioned as a drain. In April, we saw a weak sediment import during underbank tides but sediment export during overbank tides (Fig. 3.2d), whereas in September, an import of sediment was observed with the net export of water during overbank tides (Fig. 3.3d). The net import of sediment depended on the substantial sediment supply during flood tides. Cumulative sediment fluxes over both periods were positive, i.e. sediment import.

3.4.2. Secondary creek

Typical spring and neap tides can also be observed in the secondary creek (Figs. 3.4a and 3.5a). There was a similar pattern of hydrodynamics between March and May in the secondary creek. During underbank tides, similar peaks of velocity can be observed between flood and ebb tides. While a distinct peak of velocity appeared during overbank ebb tides (Figs. 3.4b and 3.5b).

The SSC in the secondary creek showed contrasting patterns between the two months. In March, a recognizable peak can be found at the beginning of each tidal cycle, and for some tides, a smaller peak in SSC during ebb was found (Fig. 3.4c). In late May, the max-

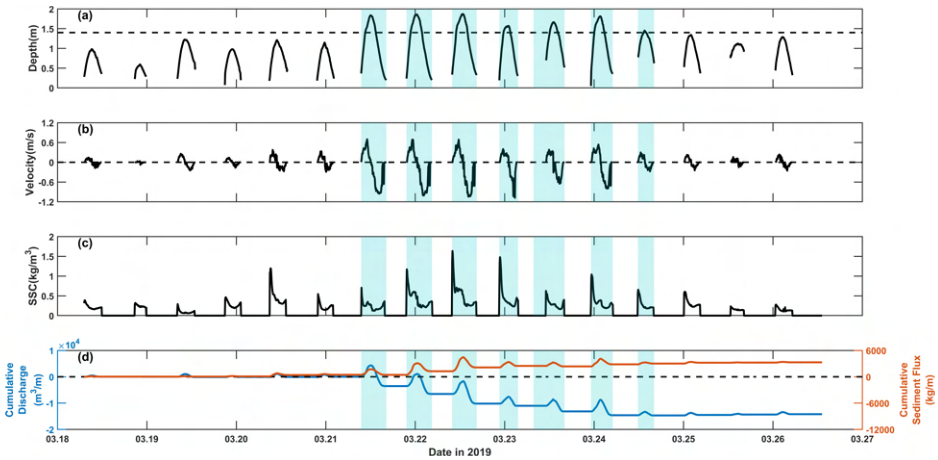

Figure 3.4: Time series of (a) water depth (The dashed line represents the creek depth), (b) velocity (flood velocity is positive), (c) Suspended sediment concentration, and (d) cumulative discharge and sediment flux (into the creek is positive) in the **secondary creek in March 2019**. The overbank tides were highlighted in blue.

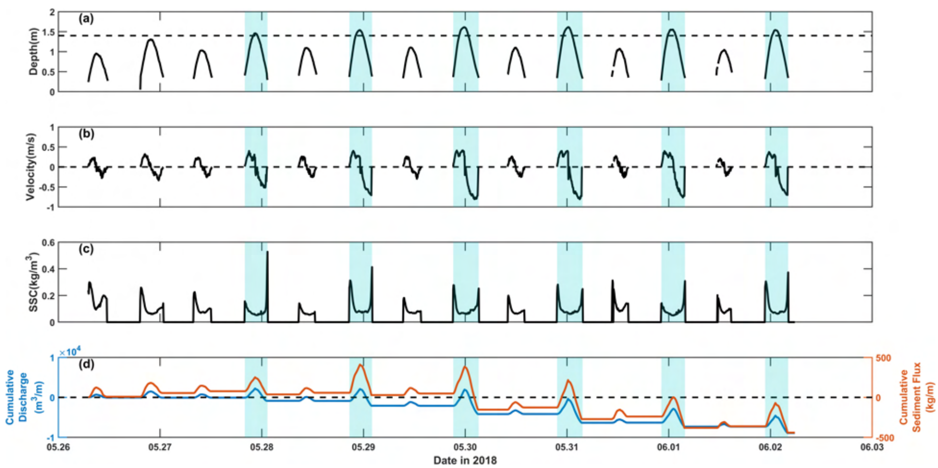

Figure 3.5: Time series of (a) water depth (The dashed line represents the creek depth), (b) velocity (flood velocity is positive), (c) Suspended sediment concentration, and (d) cumulative discharge and sediment flux (into the creek is positive) in the **secondary creek in May 2018**. The overbank tides were highlighted in blue.

imum SSC was higher at the beginning of the flood during underbank tides. However, compared with the peak at the beginning of flood, a much larger peak in SSC during ebb can be seen during overbank tides (Fig. 3.5c). Note that the magnitude of SSC in May was smaller. The maximum SSC reached approximately 1.6 kg/m^3 in March but was <0.6

kg/m^3 in May. Thus, comparing with the SSC in the main creek, the SSC in the secondary creek was much smaller, which results in the weak role of the secondary creek in sediment transport.

The cumulative discharges were negative during both measurement periods, indicating the export of water. This is because more water from the marsh would converge into tributaries during overbank tides. The secondary creek serves more as a conduit for drainage. However, the secondary creek functioned differently between two months. In March, the secondary creek imported more sediment during overbank tides (Fig. 3.4d). In May, sediment was transported out of the secondary creek during overbank tides (Fig. 3.5d). Though a small amount of sediment was transported into the secondary creek during underbank tides, the cumulative sediment flux was still negative in May, indicating that more sediment was exported back to the main creek from the secondary creek. The difference in sediment fluxes between two months is determined by the variation in SSC patterns. In March, a flood SSC peak can be observed during overbank tides. This flood peak in SSC can lead to more sediment import during flood tides. While in May, an ebb SSC peak occurred during overbank tides, leading to more export of sediment during ebb tides.

3.4.3. Residual sediment fluxes

The direction of residual sediment fluxes is determined by the difference of sediment fluxes between flood and ebb tides. When there is more sediment transport during the flood tide than during the ebb tide, it results in sediment import within that tidal cycle, and conversely, sediment export occurs when the sediment transport during the ebb tide surpasses the sediment transport during the flood tide (Fig. 3.6a). The dashed line indicates the conditions for which the sediment flux during flood equals the sediment flux during ebb. The majority of the markers is below this line, indicating larger fluxes during flood than during ebb, implying a net import per tidal cycle. We furthermore see that the import is larger for larger sediment concentration differentials (larger markers), which aligns well with (Nowacki & Ganju, 2019): the direction of net sediment flux can be inferred from the SSC differential. For some tidal cycles, however, we do see an export of sediment for a large tidal range (warm colors) and a small sediment concentration differential (small markers). Those are observed for the secondary creek (triangles) and the main creek (circles).

To gain deeper insights into how the sediment differential and the net discharge influence the residual sediment flux, we plotted the residual sediment flux (ΔF) as a function of the sediment differential (ΔC) and the net discharge (ΔQ). Four quadrants can be identified in Fig. 3.6b, based on the signs of ΔC and ΔQ. No tide is found with ΔQ >0 and ΔC <0 (case 4) during our measurement campaigns.

A closed water balance would imply that ΔQ equals zero. However, based on our data sets, we found that the net discharge is not always zero. Both positive and negative values for ΔQ were found. A positive net discharge indicates that water stays in the creek

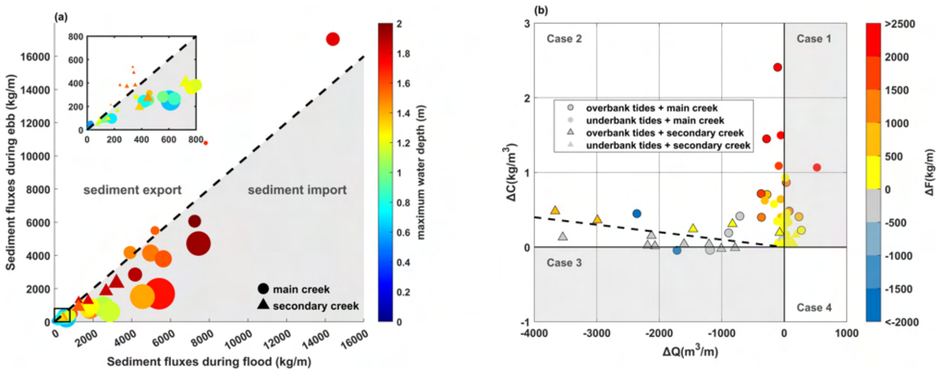

Figure 3.6: (a)Residual sediment fluxes between flood and ebb tides. Circles are the data in the main creek, and triangles are the data in the secondary creek. The size of the circles and triangles represent the absolute value of SSC differential between flood and ebb tides. The colour indicates the maximum water depth during that tidal cycle; (b)Relationship among ΔC (differential of SSC between flood and ebb), ΔQ (residual discharge) and ΔF (residual sediment flux) for each tide cycle. Points with edges represent overbank tides. Positive ΔQ and ΔF indicate onshore net transport of water and sediment, respectively. Positive ΔC indicates larger SSC during the flood tide than during the ebb tide.

system (for both underbank and overbank tides) or in the marsh (for overbank tides). A negative value indicates that water from somewhere else (e.g., from the marsh edge in case of overbank flow) is drained through the creek.

In the first quadrant (case 1), ΔQ and ΔC are both positive, representing the onshore net import of water and higher SSC during flood than during ebb for these tide cycles, respectively. In this case, sediment fluxes are as expected all positive. Only small positive residual discharges can be found in this quadrant. The small positive residual discharge during underbank tides is likely a consequence of groundwater recharge and the substantial drainage basin of creeks, which provides the potential for water to be kept in the tributaries. As for the positive residual discharge during overbank tides, there are some possibilities for explaining smaller amounts of water were transported in the marsh creek during ebb tides than during flood tides: (i) groundwater played a role; (ii) part of the water stayed in the tributaries; (iii) the overflowing water from the creek was exported to other creek systems nearby.

In the second quadrant (case 2), where $\Delta Q < 0$ and $\Delta C > 0$, the water is exported, and the mean SSC during flood is larger than during ebb. In this quadrant, negative residual sediment fluxes are found mainly during overbank tides, and these fluxes are mainly <500 kg per unit width per tide. A line is drawn to indicate a distinction between positive and negative sediment fluxes. This line suggests that negative net sediment fluxes ($\Delta F <$ 0) can be found for situations with higher concentrations during flood than during ebb ($\Delta C > 0$) as long as the net discharge is substantially negative ($\Delta Q < 0$). Four points with large negative sediment flux are found in the main creek, and three of them occur during overbank tides. For other tides, the residual sediment fluxes are positive. The tides with a large value of ΔF have large positive ΔC (> 0.5 kg/m^3).

Two trends are found between ΔQ and ΔC: (i) Substantial export of water (large negative values for ΔQ) is accompanied by small values of ΔC. In those cases, the higher ebb flow can mobilize sufficient sediment to balance the generally higher SSC during flood. (ii) High concentration differentials are found for small values of ΔQ. The ebb flow is not strong enough to generate sufficiently high concentrations. This is likely a characteristic for high-turbid systems like the Yangtze Estuary. A large ΔF is found for large ΔC and low ΔQ.

Only three tides fall in the third quadrant (case 3), with ΔQ <0 and ΔC <0. These three tides all occur during overbank tides. Two are found in the secondary creek and one is found in the main creek. Sediment export can be observed during these three tides, as it could be expected for tides with a net outflow of water and higher concentrations during ebb than during flood.

To sum up, overbank tides can result in negative ΔQ, as a substantial amount of water from the marsh can be concentrated into the marsh creek during the ebb tide. This asymmetry in flow tends to export sediment due to the more dominant ebb flow. However, in a turbid system, such as Chongming, a high flood peak of SSC can be expected, leading to a positive ΔC. This asymmetry in sediment concentration can sometimes counteract the tendency to export sediment caused by the asymmetry in flow during overbank tides, which can lead to a net import of sediment. The dotted line in Fig. 3.6b indicates varying degrees of the asymmetry in SSC required to counteract the asymmetry in flow. A larger net discharge in marsh creeks, a larger sediment differential is required to ensure the role of marsh creeks in importing sediment.

3.5. Discussions

3.5.1. Determination of sediment fluxes from point measurements

Determining the discharge and sediment flux is complicated due to the non-uniformity of the flow velocity and sediment concentration over the depth and width, as well as the variation of the creek width over the depth. Furthermore, sinuosity of the channel leads to non-uniformity in the velocity and concentration distribution over the cross-section. Such non-uniformities can lead to non-linear effects on sediment fluxes. Limited by point measurements, we cannot account for the non-uniformity. Based on point measurements, the instantaneous sediment flux can be estimated by the geometry (water depth D and width W) and the flow velocity u and sediment concentration c in the measurement point: $F = \int_{dA}(uc)dA = \alpha uDWc$. The coefficient α represents the effects of all non-uniformities in the cross-section. In case α = 1, the estimated sediment flux equals the real sediment flux. In case α = constant, the value of the net sediment flux scales linearly with the real net sediment flux. This implies that the sign of the estimated sediment flux is correct for a constant α. In reality, α will vary over time, as the velocity and concentration distribution over the cross-section vary over time. In studies where sediment fluxes were estimated based on point measurements, the (implicit) assumption of $\alpha = 1$ is often made (Andersen & Pejrup, 2001; Green & Hancock, 2012; Colosimo et al., 2020), based on the assumption of close to uniform distributions of the sediment concentration. This is true if the mixing is sufficiently strong. An additional potential limitation of this approach is that high turbidity during extremely shallow water was not captured due to the blanking distance of the field instruments. High SSC may occur during periods of very shallow water (Zhang et al., 2016). However, water depths are also very small during these periods. These shallow water periods are therefore considered to have little effects on our conclusions for the residual sediment fluxes.

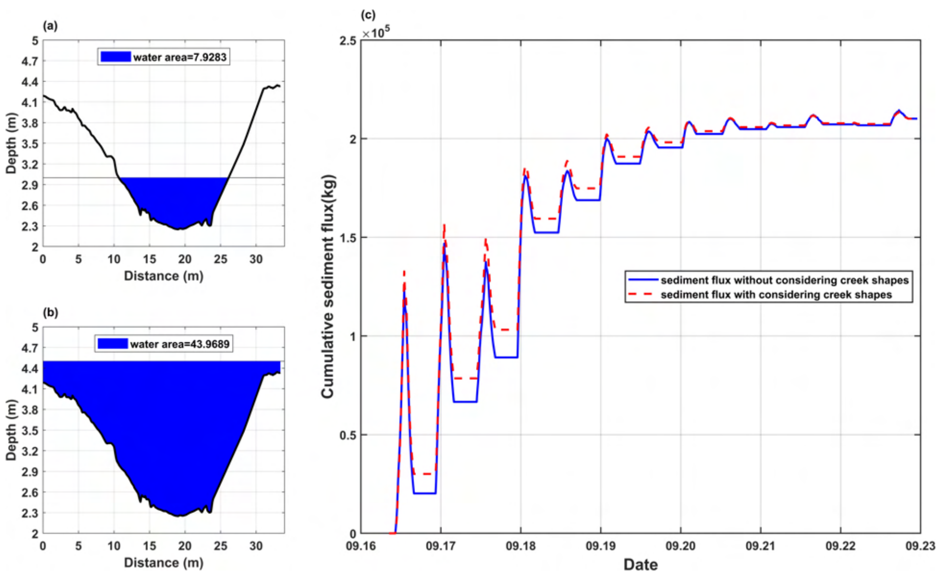

Figure 3.7: The comparison of sediment fluxes between two methods: (a)An example of the water area during underbank tide (tidal elevation = 3 m); (b) An example of the water area during overbank tide (tidal elevation = 4.5 m); (c) cumulative sediment flux based on two methods (the blue solid line represents the result using the method in this work; the red dash line represents the result with considering the real creek shape).

In addition, we also ignore the width variation over the tidal cycle for the sediment flux per unit width, which may lead to additional errors. In order to discuss the errors in the sediment flux due to the variation of width, we compute the fluxes based on the topography data of the main creek in 2016 from Xie et al. (2018a). The maximum depth and width of the main creek are about 2 m and 30 m, respectively. The sediment flux can be affected by the shape of the creek as the width is not uniform over the height (Fig. 3.7a and b). We calculated the sediment fluxes with and without considering the creek shape, see Fig. 3.7c. The sediment flux considering the creek shape is obtained by the cross-section, velocity, and sediment concentration. A width of 17 m turns out to be the representative width. For that width, the accumulated sediment flux based on a constant width is equal to the accumulated sediment flux with a varying creek width. The average difference between two methods is 18 %. Although the values for α might not be constant, the results from Fig. 3.7 indicate that they are sufficiently accurate to draw conclusions about the role of the creeks.

Measurements in the main creek and in the secondary creek were conducted at the relatively straight section of the creek. In addition, we focused on the residual sediment flux at along-creek direction. Therefore, tidal meanders were not considered in our work. However, due to the complex of dynamics in meandering creeks, more sediment can be transported towards the inner/convex bank because of the secondary flow (Finotello et al., 2019; Wang et al., 2020).

3.5.2. Availability of sediment and supply-limitation

The sediment fluxes are affected by the availability of sediment. SSC and velocities are not always correlated. High velocities can sometimes carry only a small amount of sediment due to limited sediment supply. Conversely, high SSC values can sometimes be observed for low velocities when the sediment supply is high. To investigate the sediment carrying capacity, we analyse the relationship between the sediment concentration and the flow velocity.

We first consider the concentration and flow velocity in the main creek (Fig. 3.8a). The concentration is plotted on a logarithmic scale to cover the large range. For visualization, a trend line is included in the plot to highlight different sediment carrying capacity. The trend lines are different for September and April. For the same velocity, higher concentrations are found in September than for April. This would imply that the sediment is easier to erode in September or that the sediment has a smaller settling velocity in September. A difference is also found between flood and ebb. The slopes of the trend lines during flood are higher than during ebb. This implies that more sediment is carried during flood than during ebb, but this sediment did not completely return during ebb again. This would indicate that the settling and scour lag processes (van Straaten & Kuenen, 1958) are potential mechanisms for net sediment transport.

The relation between the concentration and flow velocity in the secondary creek (Fig. 3.8b) is substantially different from the one in the main creek. The concentrations during ebb are hardly influenced by the local flow velocity. They are also low compared to the flood stage and compared to the concentrations in the main creek. These low concentrations indicate that there was limited sediment supply, as the tidal current was capable enough to carry more sediment but less sediment was in the water column. The difference between ebb and flood indicates that during flood much more sediment was available, likely from the main creek or the upstream of the secondary creek. The measurements in March and May show the same pattern, but higher concentrations are found during the March campaign. These differences between months could have two causes. On the one hand, the difference in vegetation between months can have impacts on SSC (Nardin et al., 2020): the density of vegetation is higher in May than in March. The state of vegetation can affect local erosion, deposition, and also the transport of sediment (Brückner et al., 2020). On the other hand, external forces, e.g., strong precipitation or winds, could lead to more sediment import from mud flats to creeks (Green & Coco, 2007; Gomes et al., 2013; Lacy et al., 2018). Both causes can have significant impacts on sediment availability in creeks. The source of the measured high sediment concentrations, however, needs further investigation.

As stated by Ganju et al. (2015), the system is steered by the availability of erodible material. Even in a turbid system like the Yangtze Estuary, we see in the secondary creek, a lack of sediment is limiting the import of sediment. The transport capacity of the flow is not the limiting factor. The key is that sediment beds can develop such a strength that erosion is not possible anymore, even for velocities up to 1 m/s.

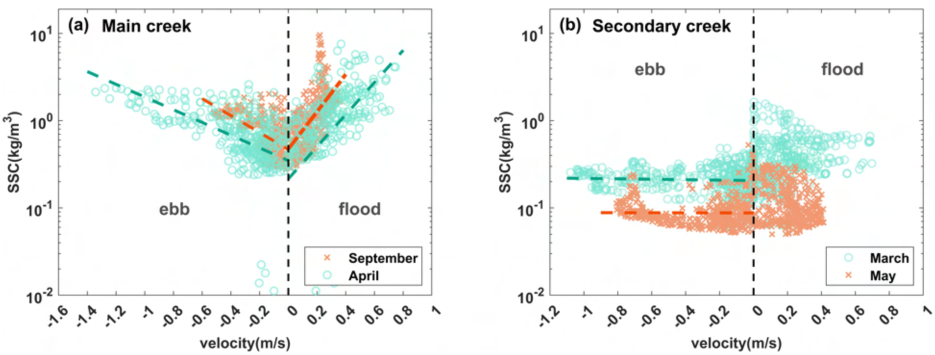

Figure 3.8: Different sediment availability in creek systems in different months: (a)the relationship between velocity and SSC in the main creek in two months; (b)the relationship between velocity and SSC in the secondary creek in two months. Positive velocities represent flood velocities and negative velocities represent ebb velocities.

3.5.3. Role of creeks in sediment flux within the marsh

To classify the role of creeks in Chongming in delivering water and sediment, the residual flux of water and sediment in saltmarsh creeks are conceptualized in Fig. 3.9 for: (i) two types of creeks (a main and a secondary creek); (ii) underbank tides and the overbank tides; (iii) differences in sediment availability.

Overbank tides can lead to negative net discharge in creek systems as more water from the marsh can converge into creeks. This has a positive impact on the survival of marsh vegetation (Morzaria-Luna et al., 2004; Schepers et al., 2017), since creeks result in faster drainage of the marsh as indicated by van Belzen et al. (2017). Whether this net outward discharge also results in a net export of sediment depends tidal asymmetry processes and sediment availability. Tidal asymmetry in combination with sufficient sediment availability on the mudflats generally results in a net import of sediment (Fig. 3.9: case b). In those cases, the sediment concentration during flood is sufficiently high and ebb flow is not strong enough to bring sediment back again. These conditions are, for example, described in Rinaldo et al. (1999). Only if the sediment availability is sufficiently small (to bring sediment inward during flood) and if the outflowing velocities are sufficiently high (due to the extra discharge), sediment can be exported via the creek out of the salt marsh system. We measured such conditions (small concentration differential and relatively high net discharge) for several tides, as indicated in Fig. 3.6b: the tides below the dashed line. Note that the sediment fluxes are small for those tides. These conditions are indicated in Fig. 3.9: case a).

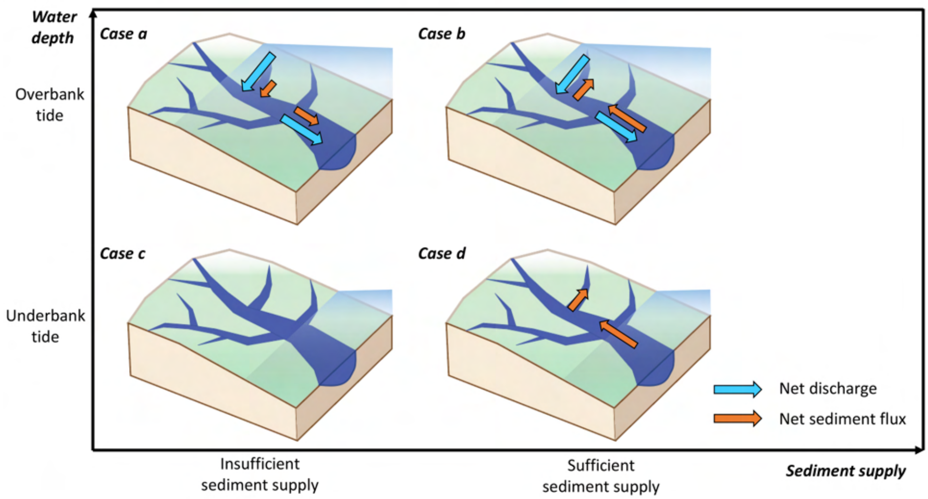

Figure 3.9: Residual discharge and sediment flux in saltmarsh creek systems under different conditions of overbank tides and underbank tides with different availability of sediment supply in Chongming. Arrows indicate the net discharge (blue) and the net sediment flux (orange).

During underbank tides without more water being concentrated from the marsh to the creek during ebb tide, the discharge is approximately zero (Fig. 3.9: case c and case d), indicating a water balance. Without sufficient sediment supply, the role of creeks in sediment delivery can be negligible (Fig. 3.9: case c). However, due to the turbid environment in Chongming, sufficient sediment supply can be expected, even during underbank tides. Consequently, both the main creek and the secondary creek keep importing sediment during underbank tides (Fig. 3.9: case d). The cumulative sediment import during underbank tides can balance or even surpass the sediment export that occurs during overbank tides, e.g., in April (Fig. 3.2d). Therefore, the main creek in Chongming generally imports sediment.

Whether there is a net import/export of sediment to the marsh depends on the occurrence of the conditions as sketched in Fig. 3.9. Waves, which frequently occur in summer in Chongming, can bring more sediment from mudflats to marshes via creeks by increasing the sediment supply (Ladd et al., 2019; Willemsen et al., 2022). Consequently, main creeks in Chongming function more as conduits for importing sediment under wave impacts (Fig. 3.9: case b and d). However, as the vegetation in the secondary creek can grow in summer, which can reduce the sediment supply (Xu et al., 2022), the secondary creeks in Chongming are expected to serve as channels for drainage rather than sediment transport (Fig. 3.9: case a and c). Furthermore, under the condition of sea-level rise and a lack of sediment supply, the creeks are likely to export sediment from the marsh system (as illustrated in Fig. 3.9: case a), which may increase the vulnerability of salt marsh systems to the impacts of climate change.

When comparing the role of creeks in drainage and sediment delivery, we found that the main creek in Chongming primarily serves as a conduit for importing sediment, whereas the secondary creek in Chongming primarily functions as a conduit for drainage. Since the main creek functions more as a conduit for importing sediment to the marsh system in Chongming, we roughly estimate the contribution of the main creek to the vertical accretion of marshes, to give more insights into the role of creeks in delivering sediment. The salt marsh in Chongming has been deposited vertically with an accretion rate of 31 mm/year to 150 mm/year since 2005 (Xie et al., 2018b; Yang et al., 2020). The area of the watershed covering the measuring creek system is around 400 m × 1200 m. Extrapolating the measurement period to a full year, results in a yearly flux of 4.02×10^6 kg. The dry density of sediment is estimated as 1330 kg/m^3 (Yuan et al., 2020). Therefore, the accretion rate via creeks would be 6.3 mm/year, indicating that creeks can contribute potentially 4 % - 20 % to the vertical accretion of the marsh. Considering the sea-level rise rate of 4.0 mm/year in the Yangtze Estuary (Yang et al., 2020), the role of creeks in contributing to the vertical accretion of marshes in the face of accelerated sea-level rise is significant in Chongming. Furthermore, it should be noted that substantial storm events were not captured during our measurement campaigns. Storm events can provide more sediment to the marsh (Turner et al., 2006, 2007), through creeks and marsh edges. The sediment import induced by storms is determined by the duration and magnitude of storm surges (Castagno et al., 2018). Longer measurements in marsh creeks and also at the marsh edge are required for a more accurate and robust quantification of the role of creeks in the development of marshes.

3.6. Conclusions

The direction and magnitude of the residual sediment flux are determined by the relative importance of the asymmetry in flow and in sediment concentration. We confirmed the statement of Nowacki and Ganju (2019) that the sediment differential is key for the sediment flux, especially in a turbid inter-tidal environment, like Chongming Island in the Yangtze Estuary. Substantial net export of water via creeks can mainly be found during overbank tides. This asymmetry in flow tends to export sediment with the net discharge. While due to the turbid environment, a high SSC peak during the flood phase can be normally expected, leading to a net sediment import during most tidal cycles. A weak sediment export can be observed during some overbank tides when the sediment differential is not evident. Therefore, the abundance of sediment during flood tides is essential for the import of sediment. Creeks function more as conduits for sediment import due to this asymmetry in sediment concentration.

Our findings unravel the mechanisms behind sediment fluxes, highlighting the importance of sediment availability in delivering sediment via creeks. However, the source of the measured sediment needs further investigation to advance the understanding of the transport regime in creek systems.

Photograph of Paulina Saltmarsh

4

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

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 on mudflats, waves cause erosion in marsh creeks only during tides with large tidal ranges.

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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, two-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 results 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 the conditions is crucial for better managing salt marshes.

Keywords
marsh creek; marsh edge; sediment transport; tidal and wave impacts; salt marsh

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, two-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.

4.1. 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 (Rountree & Able, 2007; Kelleway et al., 2017; Temmerman et al., 2023). However, salt marshes are challenged by coastal squeeze due to human interventions and accelerating sea-level rise (Kirwan et al., 2010; Crosby et al., 2016; Osland et al., 2017; Alizad et al., 2022). To keep pace with sea-level rise, sufficient sediment supply is needed for the vertical accretion and lateral expansion of salt marshes (Ladd et al., 2019; Fagherazzi et al., 2020).

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 non-linear 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., 2018a).

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 obviously only evident 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 et al., 2024b). 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, supplying sediment to the marsh through marsh creeks (Sun et al., 2024a). 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 (Willemsen et al., 2022; Pannozzo et al., 2023). 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 (Schuerch et al., 2014; Rosencranz et al., 2016). 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 two-month field observations in Paulina Saltmarsh. We aim to explore (i) whether the marsh creek facilitates or impedes sediment import to salt marshes during wave events, (ii) how different conditions of tides and waves may influence the sediment transport via the marsh creek and marsh edge, and (iii) what the optimal conditions are for sediment import into salt marshes. By unravelling the various conditions, we can better understand the impact of future changes, such as human interventions and sea-level rise, on salt marsh development.

4.2. Materials and Methods

4.2.1. Study site

The Western Scheldt is the Dutch part of the Scheldt estuary. It has significant economic value as the 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 4.1a). 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).

Paulina Saltmarsh is a marsh of approximately 0.6 km^2 and located on the southern border of the Western Scheldt(Figure 4.1b). 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 4.1c). 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 suspended sediment concentration (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 et al. (2024a) revealed that the creek generally acts as a conduit for sediment export during this season, especially when there is limited sediment supply from mudflats. Storm mainly occur during autumn/winter (October-March).

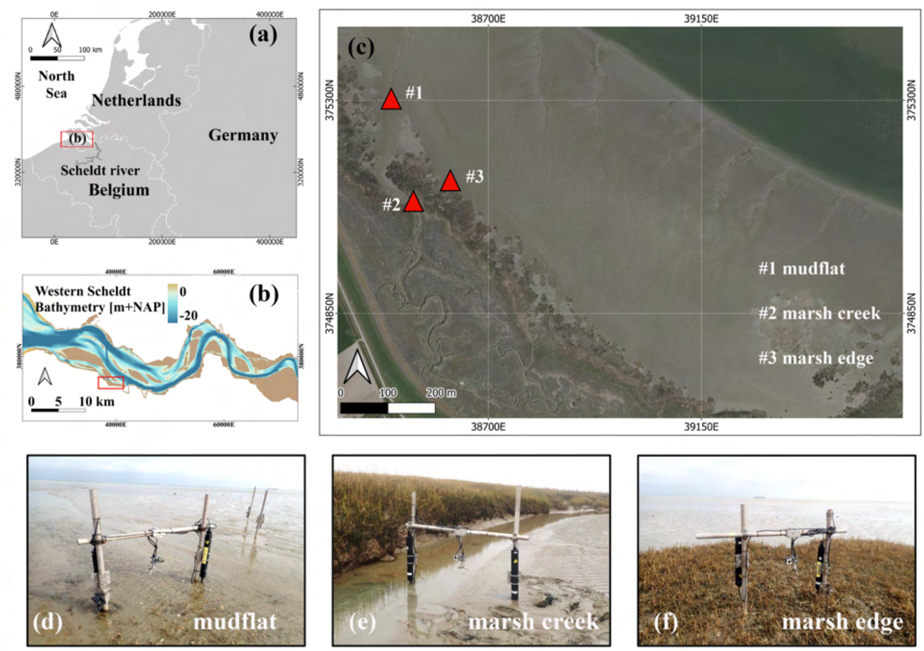

Figure 4.1: Study area and measuring locations. (a) Location of the Netherlands and the red rectangle indicates the Western Scheldt Estuary. (b) The Western Schelde Estuary in the Netherlands and the red rectangle indicates the location of Paulina Saltmarsh. Bathymetry data source: Rijkswaterstaat. (c) The aerial photo showcasing measuring sites in Paulina Saltmarsh (Red triangles indicate measuring locations). Source aerial imagery: Beeldmateriaal Nedeland. Photos of instruments and frames on the mudflat (d), in the marsh creek (e), and at the marsh edge (f).

4.2.2. Data Collection and Processing

To explore the impacts of storms or large wave events, measurements were conducted over a two-month period, from January 26th to March 29th, 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 C.4. To investigate the sediment transport to salt marshes, tides, waves, and sediment concentration were measured simultaneously on the mudflat (Figure 4.1d), in the marsh creek (Figure 4.1e), and at the marsh edge (Figure 4.1f).

We collected time-series data on the water depth, velocity, and bed level change 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 4.1.

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., 2018a). 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 C.3.

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 4.1.

Table 4.1: An overview of the instruments set up

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

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 with the method described in Zhu et al. (2016). Significant wave heights (H_s (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:

$$\tau_w = \frac{1}{4}\rho_w f_w U_\delta^2 \tag{4.1}$$

where ρ_w = 1025 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:

$$A_\delta = \frac{H}{2\sinh(kh)} \tag{4.2}$$

$$U_\delta = \omega A_\delta = \frac{\pi H}{T\sinh(kh)} \tag{4.3}$$

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):

$$f_w = \begin{cases} 2Re_w^{-0.5}, Re_w \leq 10^5 & (laminar) \\ 0.0521Re_w^{-0.187}, Re_w \geq 10^5 & (smooth\ turbulent) \\ 0.237r^{-0.52}, & (rough\ turbulent) \end{cases} \tag{4.4}$$

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 as 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 (Wang et al., 2012; van Weerdenburg et al., 2021). 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 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 et al. (2024b), where the point sediment flux was found sufficiently accurate to indicate the role of marsh creeks in sediment delivery.

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

$$\Delta F = \sum_{i=1}^{n} (v_i h_i c_i) \Delta t \tag{4.5}$$

where Δt=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.

$$\Delta Q = \sum_{i=1}^{n} (v_i h_i) \Delta t \tag{4.6}$$

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 tide (Nowacki & Ganju, 2019).

$$\Delta C = \frac{1}{n_{flood}} \sum_{i=1}^{n_{flood}} c_i - \frac{1}{n_{ebb}} \sum_{i=1}^{n_{ebb}} c_i \tag{4.7}$$

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 Figure C.1 and C.2 in the supporting information.

4.3. 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 (Figure 4.2b and 4.2f). 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 4.2b). When the maximum tidal elevation exceeds 2.74 m, the residual sediment flux is generally negative, indicating sediment export. Conversely, when the maximum tidal elevation is less than 2.74 m, the residual sediment flux is generally positive (Figure 4.2a). The increase in wave shear stress (τ_w>0.06 Pa) leads to an increase in SSC (Figure 4.2c). The SSC in the creek during strong wave events (τ_w>0.06 Pa) is, on average, 4 times larger than during weak wave periods (τ_w<0.06 Pa).

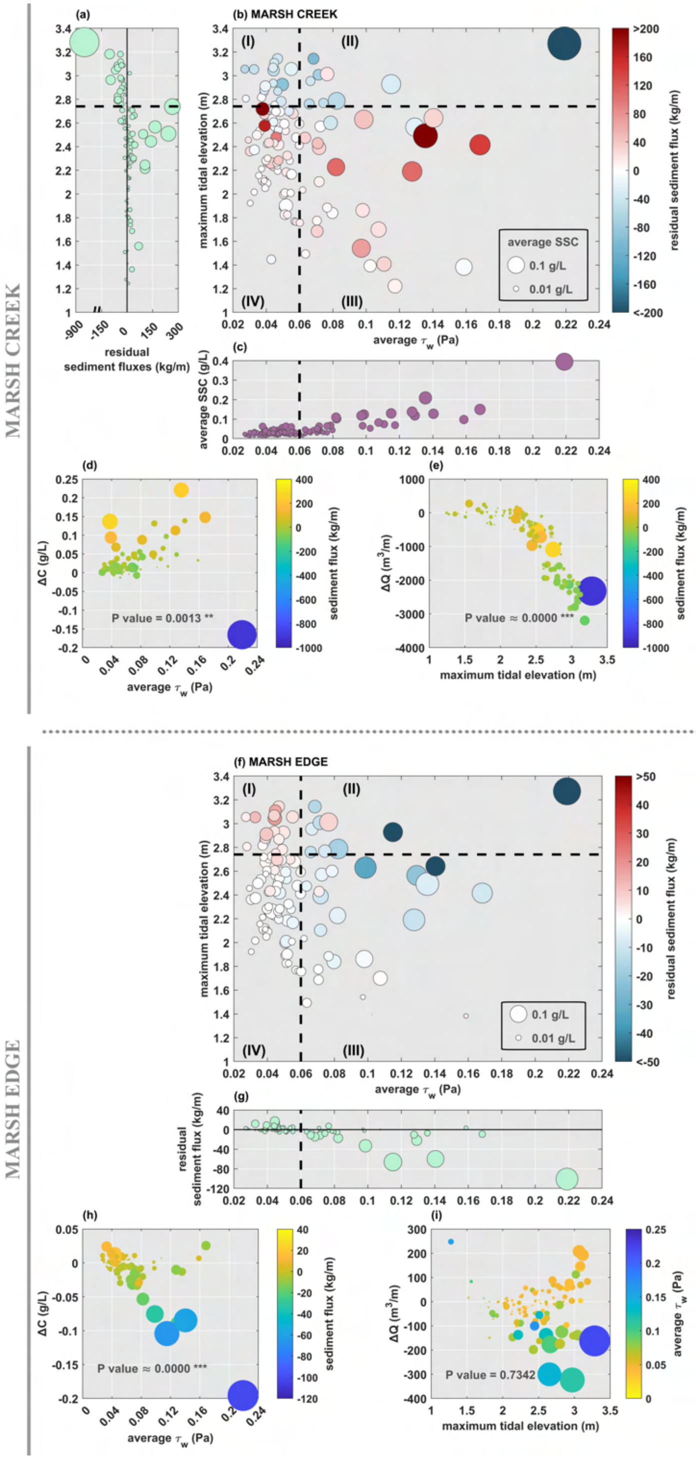

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Figure 4.2: ***(see the caption on the next page)***

Figure 4.2 ***(previous page)*****:** 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 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.

On the contrary, over the marsh edge, waves determine the direction of residual sediment flux, whereas tides influence the magnitude of sediment import (Figure 4.2f). When the wave shear stress becomes relatively strong (τ_w>0.06 Pa), sediment export occurs, regardless of the magnitude of tidal range (Figure 4.2g). However, sediment import is relatively large during large tidal range and weak waves conditions. Sediment exchange at the marsh edge was negligible when both the tidal range and wave intensities are low (Quadrant IV in Figure 4.2f).

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 in 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 4.2d). When waves 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 4.2e), 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 4.2d). 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 4.2h, 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 4.2i). 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.

4.4. Discussions

4.4.1. 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 4.3. These tidal cycles are also highlighted in the overall time-series data in Figure C.1 and C.2.

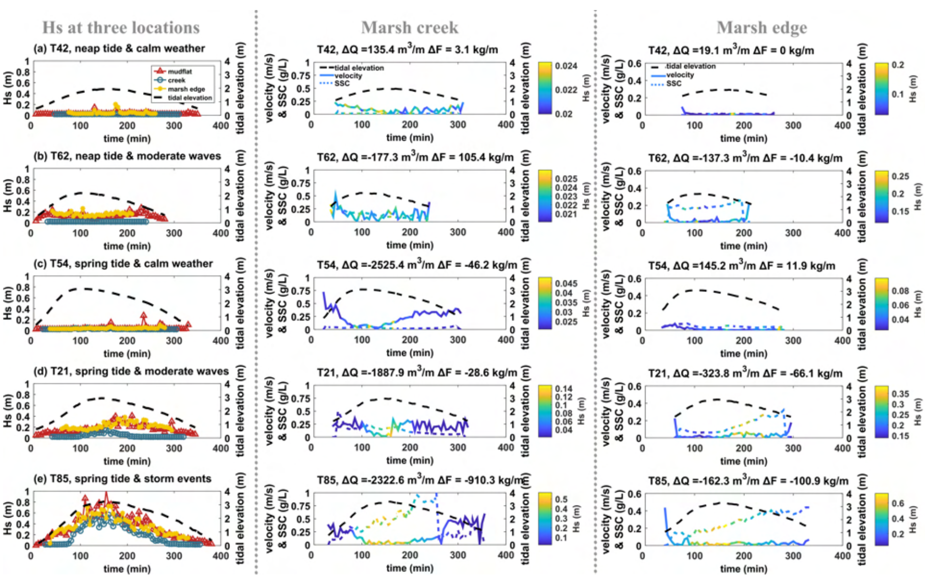

Figure 4.3: Wave impacts on sediment transport regimes in the marsh creek and on the marsh edge under five representative tidal and wave conditions.

There are two different effects of waves on the sediment transport regimes in marsh creeks. Firstly, waves can stir up sediment on mudflats with a consequent increase of 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 4.3b), compared to the sediment import of 3.1 kg/m during neap tides without waves (Figure 4.3a). Secondly, 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 (Figure 4.3d and 4.3e). 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 4.3e). 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 4.2d. Conversely, when the water level was below the marsh canopy, the creek was minimally affected by waves (Figure 4.3b), 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 will 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: (i) 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 (Figure 4.3b, 4.3d, and 4.3e). Consequently, the average SSC during ebb tides was considerably higher than that during flood tides over the marsh edge. (ii) Wave-generated flow caused fluctuations of velocities over the marsh edge, resulting in relatively minor negative net discharge. Due to 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) (Figure 4.3c and 4.3d). 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 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; Shi et al., 2016; Finotello et al., 2020; Choi et al., 2021). 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 (Figure 4.3b, 4.3d, and 4.3e). 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.

4.4.2. 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 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 4.4). 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 2 m), 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.

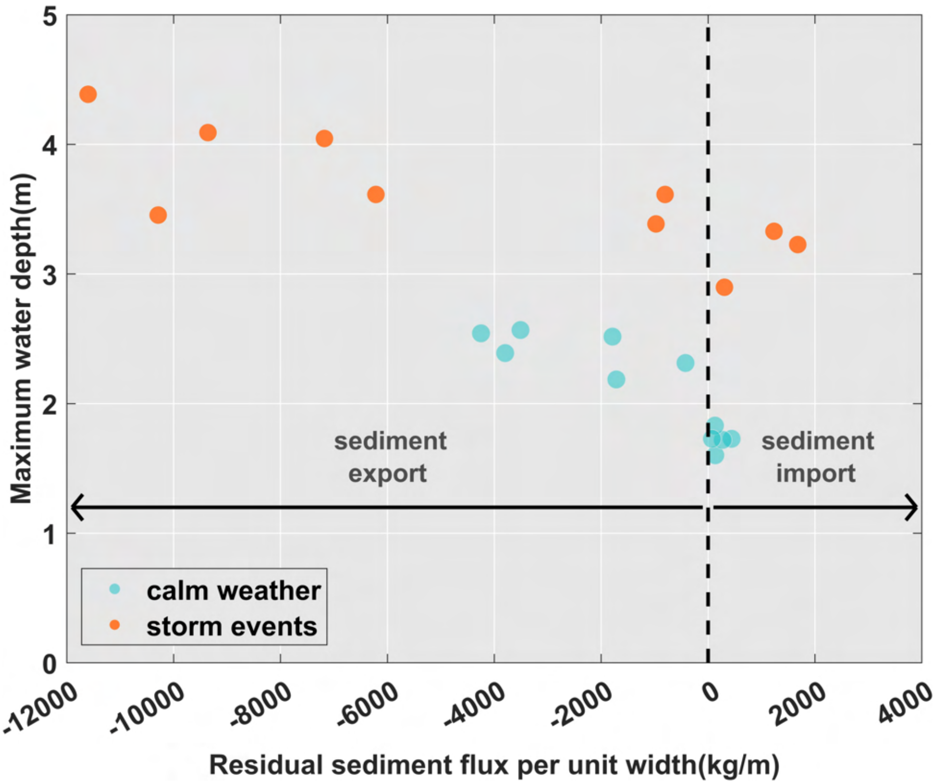

Figure 4.4: Residual sediment flux per unit width under various tidal conditions during calm weather (blue circles) and during storm events (orange circles) in Chongming. Data adapted from the tables and figures of Fan et al. (2019).

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 et al., 2024b). 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 asymmetry in flow tends to export sediment through marsh creeks, especially when there is insufficient sediment supply during flood. 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 (Poirier et al., 2017; Ortals et al., 2021; Zhu & Wiberg, 2022). Future research is essential for further verifying these findings to enrich our knowledge of these complex ecosystems.

4.4.3. 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 et al., 2005a). 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 flood (Figure 4.5a). Waves during neap tides enhance this sediment accumulation in the marsh creek but can cause sediment export over the marsh edge (Figure 4.5c).

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 et al., 2005b). This allows marsh edges to receive an increased supply of water and sediment under calm or weak wave conditions (Figure 4.5b), but leads to a greater sediment export under strong wave conditions (Figure 4.5d). 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 4.5b). Strong waves intensify the erosion of marsh creek beds and may also erode the marsh creek bank (Howes et al., 2010; Mariotti & Fagherazzi, 2013; Ma et al., 2018), enhancing the sediment export in the creek and the sediment exchange between creeks and the marsh platform (Figure 4.5d).

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; Ladd et al., 2019; Fagherazzi et al., 2020). 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 4.5b can occur, resulting in fewer occurrences of small inundation tidal cycles (scenarios depicted in Figure 4.5a). Sediment that would have accumulated in the marsh creek during small inundation tidal cycles cannot be replenished in time, and more erosion of creeks occurs. 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 4.5b), 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 (Kirwan et al., 2010; Alizad et al., 2016; Horton et al., 2018). Storm-induced waves have been identified as a significant contributor to salt marsh erosion (Marani et al., 2011; Leonardi et al., 2016). 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 Figure 4.5c and 4.5d. 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 4.5b, where both creeks and the marsh edge contribute to vertical accretion.

The sediment transport processes through two routes shown in Figure 4.5 were summarized based on the four quadrant-based patterns of sediment transport for the marsh creek and marsh edge in Figure 4.2. 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 4.5 undoubtedly requires further investigation in other systems. It requires measurements of fluxes as well as bed shear stresses by waves. The analysis could also be explored with numerical models.

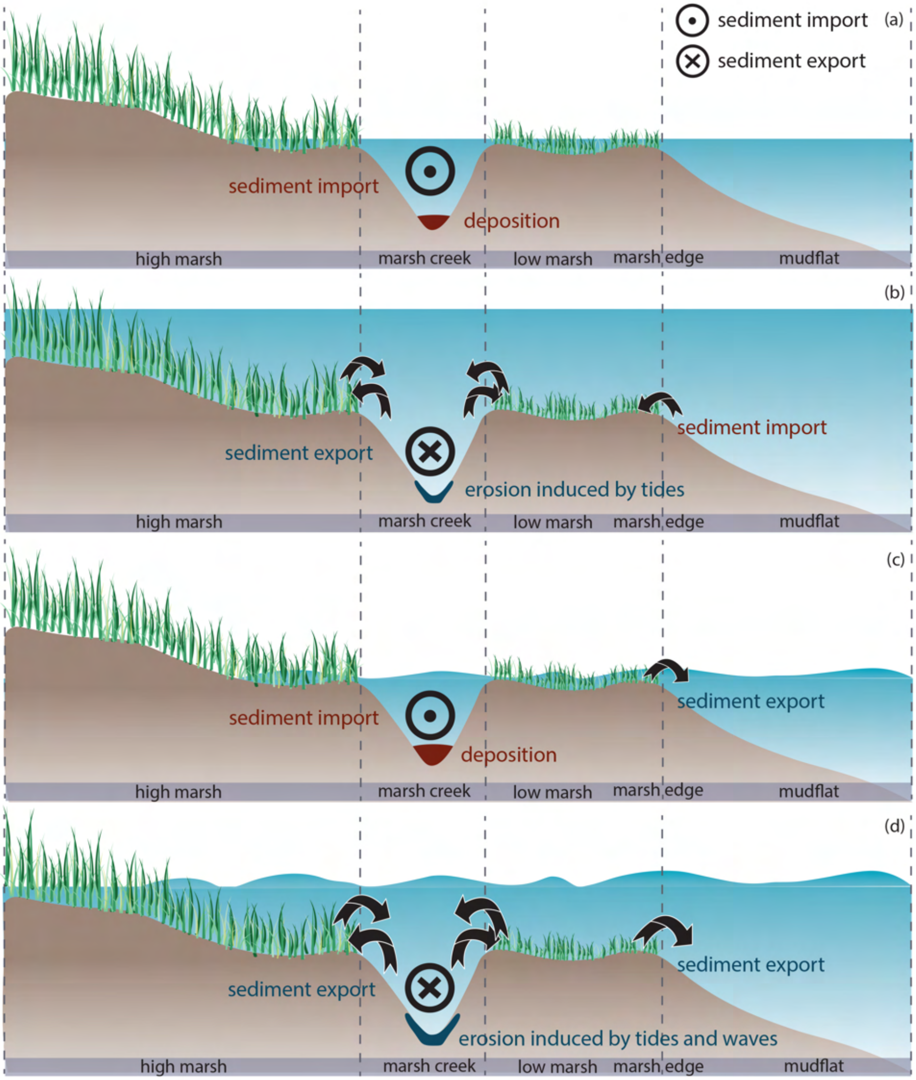

Figure 4.5: Conceptual schemes for the potential residual sediment flux within salt marshes under different tidal and wave conditions: (a) a scenario of small inundation tidal cycles with weak waves; (b) a scenario of large inundation tidal cycles with weak waves; (c) a scenario of small inundation tidal cycles with strong waves; and (d) a scenario of large inundation tidal cycles with strong waves.

4.5. 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 tidal ranges. 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 4.2, were observed in Paulina Saltmarsh, a meso-macrotidal marsh system. Thus, the findings can be applicable 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.

Photograph of the intertidal area of Chongming

5

Synthesis

5.1. Answers to research questions

RQ 1: What are the mechanisms behind sediment transport in marsh creeks?

Residual sediment flux in marsh creeks is determined by the relative importance of the asymmetry in net discharge and in suspended sediment concentration.

The occurrence of the asymmetry in net discharge (ΔQ) in marsh creeks depends on tidal ranges and marsh elevations. Distinct asymmetry in net discharge in marsh creeks exclusively occurs during overbank tides, when water overtops the creek banks. This overbank tide can result in ebb-dominant velocities and net discharge, as some of the water enters via the marsh edge subsequently drains through marsh creeks. This phenomenon aligns well with the findings of Fagherazzi et al. (2013) and Lacy et al. (2018). Conversely, during underbank tides, when water levels remain contained within the creek, water is mainly conveyed through marsh creeks, resulting in net discharge being close to zero. These patterns of net discharge, dependent on overbank and underbank tides, remain consistent in marsh creeks worldwide, despite variations in systems and seasons (Chapter 2, 3 and 4).

5

The asymmetry in suspended sediment concentration is represented by SSC differential between flood and ebb tides (ΔC), which is influenced by sediment availability. Waves are one of the important factors that can induce SSC asymmetry in marsh creeks through two different mechanisms: On the one hand, waves enhance sediment supply to marsh creeks by eroding mudflats. Waves can suspend sediment on mudflats, leading to an increase in SSC during flood tides and thereby causing an flood dominant asymmetry in SSC (Chapter 2 and 4). On the other hand, waves can cause erosion in marsh creeks, resulting in an increase in SSC during ebb and an ebb-dominant asymmetry in SSC (Chapter 4). However, it should be noted that direct wave-induced erosion in marsh creeks likely occurs in the creek section close to the marsh edge, where waves do not have sufficient space to attenuate. Besides, creek orientation, creek shapes, wind direction, and wind intensity also play a role in this. Further into the marsh, waves are likely to be attenuated by the vegetation (Foster-Martinez et al., 2018). Additionally, limited erosion in marsh creek has been observed, especially during ebb tides. Limited erosion indicates that an increase in shear stress and velocity during overbank ebb tides does not lead to an expected rise in SSC (Chapter 2 and 3). This phenomenon may result from factors, such as consolidation, sediment properties, and benthic effects (Sanford, 2008; Brooks et al., 2021; Choi et al., 2023), which contribute to a reduced SSC in marsh creeks during ebb tides. Furthermore, vegetation existing in marsh creeks can reduce sediment supply, thereby altering the asymmetry in SSC (Chapter 3). As a result, seasonal impacts on SSC asymmetry become evident due to the variations in vegetation growth and storm events throughout the year.

During underbank tides, the net discharge is close to zero. Thus, the direction and magnitude of sediment flux in marsh creeks are determined by the asymmetry in SSC. Waves during underbank tides enhance sediment supply to marsh creeks. Consequently, sediment tends to be imported through marsh creeks during neap tides with waves. During overbank tides, the ebb-dominant velocity and net discharge can potentially drive sediment export. In such cases, sediment import depends on the flood-dominant asymmetry in SSC to counteract the export tendency caused by the flow asymmetry. The larger the tidal range, the more sediment supply during flood tides is required for marsh creeks to be able to function as conduits for sediment import.

RQ 2: What are the mechanisms behind sediment transport over the marsh edge?
The mechanisms behind sediment transport over marsh edges differ from those in marsh creeks. Velocities over marsh edges are significantly smaller compare to those in marsh creeks. During neap tides, the tidal prism is too small to result in substantial sediment flux over marsh edges. Only during spring tides, the larger tidal prism allows marsh edges to receive more water and sediment. However, the presence of waves can alter sediment transport patterns over marsh edges. Our measurements in Paulina Saltmarsh showed that waves led to sediment export over the marsh edge (Chapter 4).

Two mechanisms explain this wave-induced sediment export: Firstly, strong waves primarily occurred during late flood and ebb tides, leading to an increase in SSC during ebb tides. However, the source for the increased suspended sediment remains unclear. It could be contributed by marsh surface erosion, marsh edge scouring, or longshore sediment transport on mudflats. For the first two potential sediment sources, wave action is the primary driver for sediment loss in salt marshes. However, if the SSC during ebb tides originates from longshore transport, a negative residual sediment flux does not necessarily indicate marsh loss. Further investigation is needed to identify the source of sediment transported over the marsh edge during ebb tides. Secondly, wave-generated flow caused fluctuations of velocities over the marsh edge, leading to minor negative net discharge. However, the impacts of this minor negative net discharge is less significant compared to the effects of increased SSC during ebb on sediment export over the marsh edge.

Given the broader expanse of marsh edges, the amount of sediment transported over marsh edges could potentially exceed the amount transported through marsh creeks. Even though sediment transport to the inner marsh through marsh edges is hindered by vegetation, the contribution of marsh edges to the accretion/erosion of low marsh should be addressed and requires further quantitative analysis.

RQ 3: How does sediment transport between mudflats and salt marshes differ across different systems?
As previously mentioned in Chapter 1, three factors are crucial for the development of salt marsh systems: (i) sufficient sediment availability outside marsh systems; (ii) an effective mechanism for transporting sediment towards the marsh (i.e. sediment import); and (iii) favorable conditions that guarantee the retention of sediment within the marsh. Here, we aim to identify the differences between marsh systems in Chongming and Paulina by considering these three key factors. Although the salt marshes in Chongming and Paulina may not represent all types of marsh systems globally, these comparisons contribute to a broader understanding of sediment transport in meso-macro tidal systems with varying turbidity.

Sediment availability:
One of the most significant differences between salt marsh systems in Chongming and Paulina is the variation in sediment supply from rivers. The freshwater discharge from the Scheldt River is approximately 3 km^3/yr, constituting 0.1% of the tidal prism (De Vriend et al., 2011). This leads to a well mixed estuary with limited fluvial sediment supply. On the contrary, the Yangtze River has a mean annual discharge of 896 km^3/yr and transports 358 million tons of sediment annually (1953-2013, Datong station) (Zhao et al., 2017). This distinction results in significant differences in SSC levels between the two marsh systems: SSC in Chongming can range from 0.1 g/L to 18 g/L (Wang et al., 2020), whereas the average SSC in Paulina Saltmarsh is approximately 0.05 g/L (Temmerman et al., 2003). Variations in SSC levels outside the marsh systems influence the development and sizes of salt marshes and creeks in these regions. Paulina Saltmarsh is much smaller with an area of approximately 0.6 km^2, and contains an old high marsh and a young low marsh. This marsh is dissected by a branching creek system of 0.3-7 m in width and 0.3-1.5 m in depth (Temmerman et al., 2005b). Conversely, the Chongming Saltmarsh covers an area of approximately 18 km^2 and contains many large creeks, ranging from 20 to 50 m in width and from 0.1 to 3 m in depth (Jing et al., 2007; Ge et al., 2021). Furthermore, the capacity for mudflat recovery after erosion differs, directly influencing the role of marsh creeks in sediment delivery. Mudflats in Chongming recover faster than those in Paulina due to abundant sediment availability. Consequently, a noticeable SSC peak during flood tides generally occurs in the marsh creek in Chongming, allowing it to function as a conduit for sediment import. In contrast, the marsh creek in Paulina Saltmarsh serves as a conduit for sediment export during calm weather, when the sediment supply from mudflats is limited.

Mechanisms for sediment transport:
Tidal current is the primary driver of sediment transport. Tidal inundation frequency varies between systems. Although both systems exhibit the regime of semidiurnal tides, the annual averaged tidal range in Chongming is approximately 2.6 m, with extreme tidal ranges reaching up to 4.6 m (Ding & Hu, 2020). On the other hand, the average tidal range in Paulina Saltmarsh is 3.9 m, with spring tides reaching up to 4.5 m (Oteman et al., 2019). This difference in tidal ranges, along with the relatively low elevation of the young marshes, leads to the young salt marshes in Paulina being more frequently flooded, while Chongming salt marshes experiencing distinct underbank and overbank tides, particularly during spring tides. Underbank tides lead to approximately zero net discharge in creeks, indicating a water balance between flood and ebb tides. As a result, the presence of abundant sediment during flood tides is crucial for the import of sediment. In addition, sediment exchange between creeks and marshes is limited during underbank tides. On the other hand, overbank tides provide an opportunity for sediment exchange between marsh creeks and marshes. The different inundation frequencies lead to distinct sediment transport patterns between two marsh systems. In Chongming, due to the abundance of sediment, sediment is imported and retained in creeks during the underbank tide. During the subsequent overbank tide, sediment retained from the previous tide can be eroded and transported to the marsh. This sequence of underbank and overbank tide in Chongming creates a dynamic mechanism of temporary sediment storage

and efficient sediment transport, ultimately delivering sediment to the marsh. Such phenomena have not been observed in Paulina Saltmarsh, where overbank tides occur nearly every tide. Since overbank tides lead to net export of water in creeks. This asymmetry in flow ultimately results in sediment export when there is insufficient sediment availability from mudflats or outside the intertidal system. Therefore, marsh creeks in Paulina generally serve as a conduit for sediment export during calm weather.

Waves affect sediment transport in marsh creeks in two ways: on the one hand, they contribute to sediment supply in marsh creeks by transporting sediment eroded from mudflats, leading to an increase in SSC within marsh creeks during flood. Therefore, waves partially mitigate the tendency to export water and sediment during overbank tides. They enhance the role of marsh creeks in sediment import by supplying additional sediment from mudflats. On the other hand, waves can enhance sediment export in marsh creeks by eroding sediment in specific creek sections under certain wind and tidal conditions. For example, in Paulina Saltmarsh, measurement locations near the marsh edge experience waves that do not have sufficient space to attenuate, resulting in sediment export during tides with extremely large tidal ranges and strong wave activity. Conversely, further within the marsh, or when the water level is below the marsh canopy, the elevated marshes provide shelter, diminishing the impact of waves on creek beds erosion. In Chongming, the relatively straight main creek with larger dimensions may allow waves to directly suspend sediment in the creek, even during underbank tides. Consequently, waves lead to consistently high SSC in the creek throughout the tidal cycle. This elevated SSC reduces the SSC asymmetry between flood and ebb tides, ultimately resulting in sediment export from the creek.

In Paulina Saltmarsh, sediment import over the marsh edge exclusively occurs under conditions of large tidal ranges and calm weather. During neap tides, the tidal prism is too small to transport sediment over the marsh edges due to the presence of vegetation. In contrast, during spring tides, stronger hydrodynamics lead to increased sediment import over the marsh edge. Strong waves govern the export of sediment over the marsh edge in Paulina Saltmarsh, by causing sediment re-suspension. Although we did not investigate the wave impacts on sediment transport over the marsh edge in Chongming, we believe that severe storms could lead to marsh edge erosion and sediment export; however, significant sediment import over the marsh edge may occur during weak or mild wave events, given the abundant sediment supply during flood tides.

Conditions for sediment retention:
Sediment retention within salt marshes depends on the possibility of erosion, especially during storms. This possibility is closely linked to the properties of plants and storm events.

In Paulina, the lower marsh is predominantly occupied by *Spartina townsendii*, while the high marsh is characterized by a diverse plant community, including *Puccinellia maritima*, *Aster tripolium*, *Atriplex portulacoides*, and *Elytrigia pungens* (Temmerman et al., 2003). In Chongming, the three dominant plant species are *Spartina alterniflora*, *Scir-*

pus mariqueter, and *Phragmites australis* (Yuan et al., 2011). Differences in stem density, height, and flexibility affect sediment dynamics within salt marshes (Rupprecht et al., 2017; Xu et al., 2022). Further measurements on the interaction between sediment dynamics and plants are needed for comprehending sediment retention within salt marshes.

Another factor influencing sediment retention is the timing of storm seasons. In Chongming, storm events typically occur during the summer months (June-September), whereas in Paulina, they occur during the winter months (November-March). Given that the plant growth season aligns with summer, Chongming marshes may experience greater wave attenuation during storm seasons and potentially enhance sediment settling compared to Paulina marshes. Other properties of storm events, such as intensities, wind direction, wind fetch, also play a role in the sediment retention.

5.2. Implications for intertidal system management strategies

Effective management is essential for maintaining the sustainability and resilience of intertidal ecosystems. This section explores the implications of our findings from measurements conducted in intertidal systems in Chongming, China, and Paulina, the Netherlands, for salt marsh management strategies. Key topics include the essentials of Excavating creeks and strategies for dredging disposal.

Excavating marsh creeks: Excavation of marsh creeks can enhance drainage efficiency within salt marshes by increasing connectivity, as marsh creeks play a crucial role in transporting water flow out of the marsh system (Friedrichs & Perry, 2001; Wallace et al., 2005). This enhanced drainage and connectivity prevent plants from experiencing prolonged flooding. Consequently, digging creeks can be beneficial for making drainage more effective and enhancing the survival rate of plants. However, the effectiveness of expanding salt marshes by delivering more sediment through increasing marsh creeks depends on the environment where the salt marsh is located. The effects of excavating marsh creeks on sediment delivery depend on marsh systems. For instance, when digging a marsh creek in a low-turbidity system, such as Paulina Saltmarsh, where the background SSC level outside the marsh system generally stay relatively low, excavation of new creeks may promote erosion rather than accretion of salt marshes. Conversely, in a high-turbidity system, such as Chongming, marsh accretion may occur due to the excavation of marsh creeks. Tidal, wave and biological conditions can alter the role of creeks in sediment delivery, and these factors should be considered as well. Therefore, before conducting the excavation of marsh creeks, it is advised to establish a long-term monitoring measurement to understand physical and biological conditions within intertidal systems.

Dredging disposal for salt marshes: Dredging disposal can be beneficial for salt marshes which face the dual threats of sea-level rise and insufficient sediment supply. Some projects, i.e. thin-layer sediment placement and mud motor, have been conducted to enhance the resilience of salt marshes (Baptist et al., 2019; Raposa et al., 2022). Our analysis of winter field data in Paulina Saltmarsh has revealed that the optimal conditions for sediment import through marsh creeks and marsh edges. These findings give insights into the optimal location and timing for dredging disposal projects. Yet, it is crucial to recognize that these findings from Paulina Saltmarsh cannot be directly applied to dredging disposal projects globally. Sediment transport can vary between systems. In addition, such projects have the potential to substantially modify the local environment conditions, i.e., sediment budget, which can significantly influence a marsh ecosystem. Therefore, instead of directly applying these findings from the specific observations, a comprehensive understanding of the underlying mechanisms behind sediment source and transport is essential.

Management strategies for intertidal systems should always be approached with caution, as they can cause disturbances and influence local environments. Therefore, these strategies should only be implemented after a thorough understanding of the system, to ensure that the benefits outweigh the potential harm to the ecosystem.

5.3. Recommendations for future research

A comparison study across marsh systems: To understand when and where sediment import or export occurs, the residual sediment flux in the marsh creek and over the marsh edge was divided into four quadrants based on the tidal range and wave shear stress in Chapter 4. Clear quadrant-based patterns of sediment transport were observed in Paulina Saltmarsh, a low-turbidity and meso-macrotidal system. However, marsh systems worldwide exhibit significant variability, characterized by different tidal ranges (microtidal, mesotidal, and macrotidal), varying levels of turbidity (low or high), and differing degrees of wave exposure (whether sheltered, such as in lagoons, or exposed along open coasts). Additionally, marshes may experience either erosion or accretion, depending on their environmental conditions. These variations result in different sediment transport in marsh creeks and over marsh edges. Therefore, the general applicability of the findings in Chapter 4 should be addressed in future research. Whether sediment transport in different marsh systems exhibits similar quadrant-related patterns with modified threshold values of the tidal range and wave shear stress requires additional data and further investigation.

Sediment exchange between creeks and marshes: This dissertation has explored along-creek sediment transport within marsh creeks. Direct sediment exchange between marsh creeks and marshes during overbank tides requires further investigation. This sediment process involves the interplay among various factors, including tidal and wave conditions, and vegetation types and states. These factors can vary significantly across different temporal and spatial scales, complicating the sediment exchange between creeks and marshes. In addition, the velocity and SSC profile within marsh creeks may alter after the marsh canopy is inundated (Leonard & Reed, 2002; Temmerman et al., 2005b; Torres & Styles, 2007). High-resolution profile data are required to explore these dynamics.

Sediment source and sink under varying tidal and wave conditions: Single-point residual sediment flux can provide insights into the amount of sediment imported or exported through a measurement location (e.g. the marsh creek or marsh edge) after one tidal cycle. However, such analysis cannot definitively determine whether the marsh is experiencing accretion or erosion. It requires comprehensive understanding of sediment source and sink. For instance, sediment export over the marsh edge during the tide with the storm event (T85) in Chapter 4 does not definitively indicate erosion of the marsh edge. The source of SSC during ebb may originate from longshore transport from mudflats rather than marsh edge or surface erosion. In such cases, net sediment export over the marsh edge does not necessarily imply marsh loss. Additional research is required to better understand sediment transport within intertidal areas.

Sand and mud transport within salt marshes The proportion of sand (coarse sediment, with a grain size larger than 63 μm) and mud (fine sediment, with a grain size less than 63 μm) influences the plant community within salt marshes by altering drainage conditions (Townend et al., 2011). In addition, sediment composition affects sediment erosion rate (Bouma et al., 2016). The distribution of sand and mud can vary significantly due to differences in hydrodynamic conditions, sediment supply and local morphology (de Groot et al., 2011; Pearson et al., 2021). Both sand and mud can be transported towards salt marshes through marsh creeks and over marsh edges. Addressing the variations in sand and mud transport under different tidal and wave conditions can advance our knowledge of how and when sand and mud move and settle within salt marshes. This insight is key to comprehending the spatial distribution of sand and mud within salt marshes, allowing for a better informed salt marsh management decision.

Numerical modeling: Field measurements face limitation in measuring over long timescales or large spatial scales. However, numerical models allow for the simulation of complex hydrodynamic and sediment transport processes that are challenging to measure directly, especially over long timescales or large spatial scales. Therefore, further research should include numerical modeling as an efficient tool for simulating salt marsh development under various scenarios. For instance, a key finding of Chapter 4 is the division of "residual sediment flux" based on "wave shear stress" and "tidal range" into four quadrants for the tidal creeks and the marsh edge. These four quadrant-based patterns of sediment transport were observed in Paulina Saltmarsh, a meso-macrotidal system. The general applicability of sediment transport in other marsh systems, i.e. similar quadrant-related patterns of sediment transport, can be explored with numerical models. Additionally, numerical modeling is useful for identifying the most sustainable and cost-effective approaches for salt marsh restoration facing sea-level rise and impacts of human activity. The data collected from field measurements and insights gained from this study, can contribute to model validation and the analysis of modeling results. Furthermore, numerical models can improve the quantification of the contributions of marsh creeks and marsh edges to sediment import toward salt marshes.

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R

Appendices

A

Supporting Information for Chapter 2

This appendix has been submitted as supporting information for the following article:

Sun, J., van Prooijen, B., Wang, X., Hanssen, J., Xie, W., Lin, J., Xu, Y., He, Q., & Wang, Z.B. (2024). Sources of suspended sediments in salt marsh creeks: Field measurements in China and the Netherlands. *Geomorphology*, 456, 109206, https://doi.org/10.1016/j.margeo.2021.106544.

A

This supporting document includes the results of sediment calibration curves (Figure A.1), and detailed time series data measured on the mudflat and in the marsh creek in Chongming (Figure A.2) and in Paulina (Figure A.3).

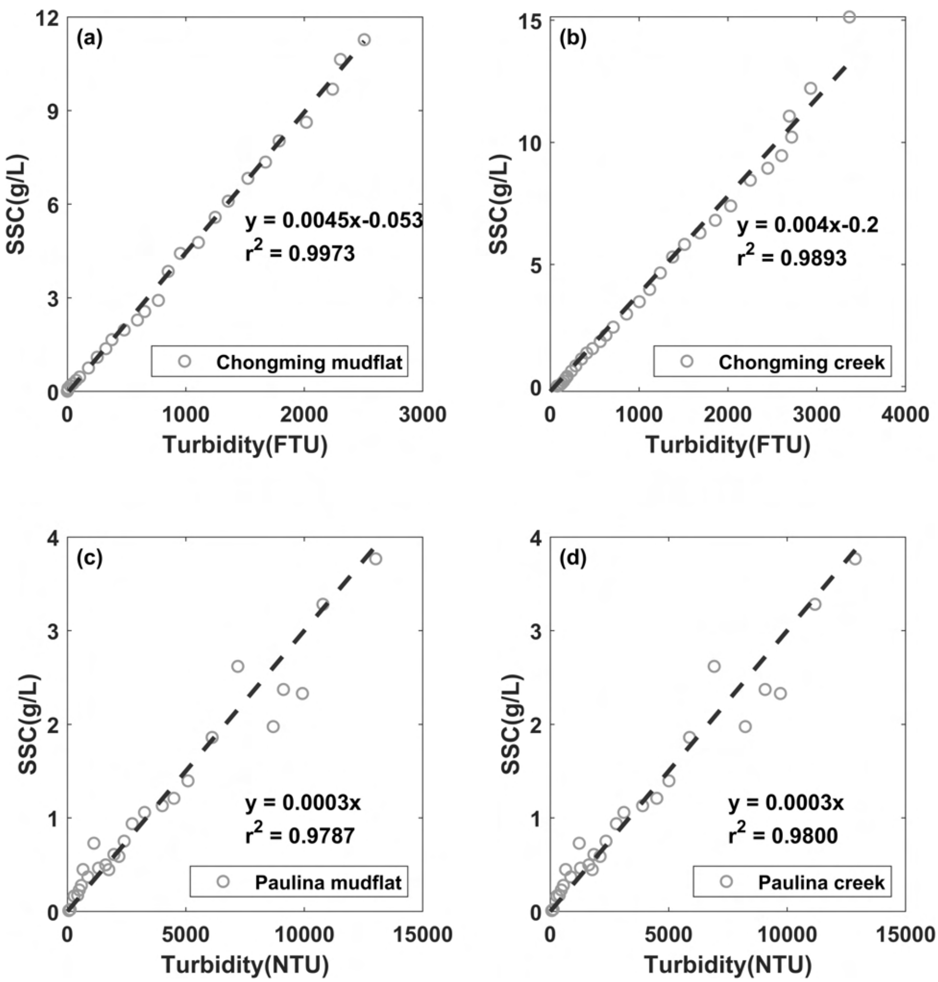

Figure A.1: Sediment calibration curves of the optical backscatter signal with SSC data (a) on the mudflat and (b) in the marsh creek in Chongming, and (c)) on the mudflat and (d) in the marsh creek in Paulina Saltmarsh.

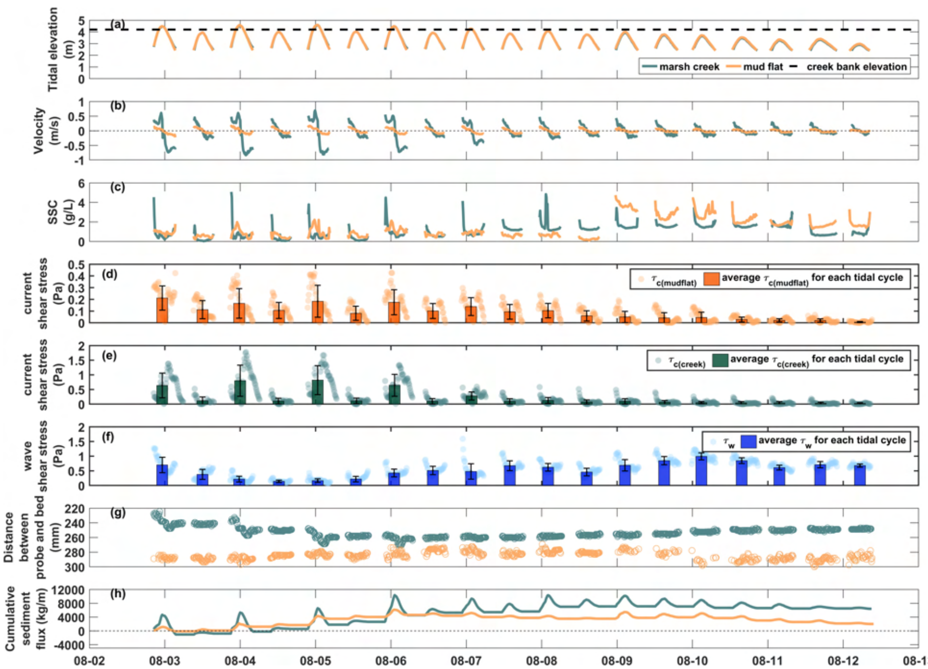

Figure A.2: Time series of (a) water depth (The dashed line represents the elevation of the creek bank at the measuring location), (b) velocity (flood velocity is positive), (c) Suspended sediment concentration, (d) current shear stress on the mudflat, (e) current shear stress in the marsh creek, (f) wave shear stress on the mudflat, (g) bed level change, and (h) cumulative sediment flux (into the creek is positive) on the mudflat (yellow) and in the marsh creek (green) in Chongming.

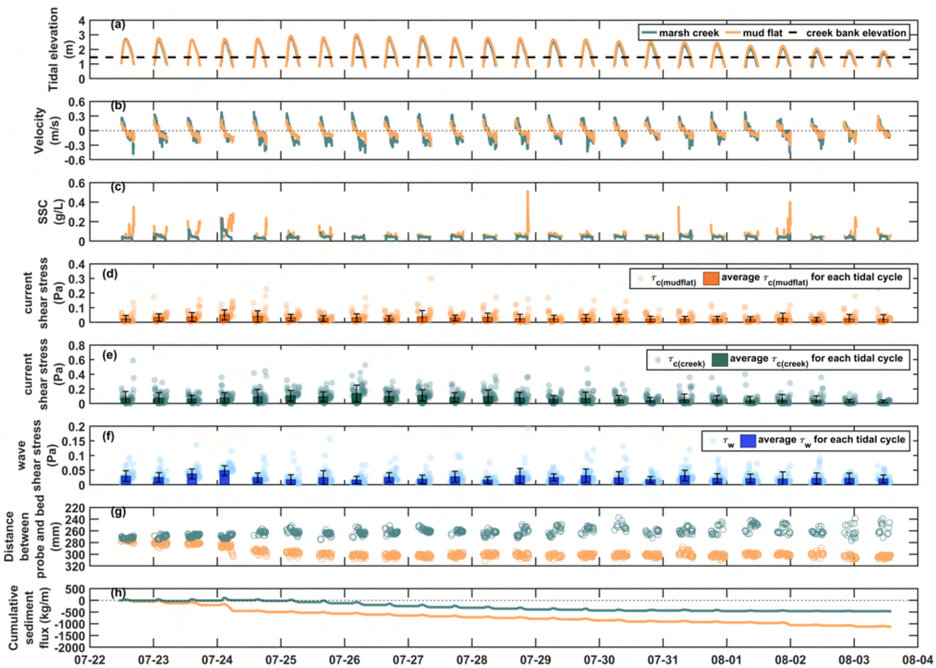

Figure A.3: Time series of (a) water depth (The dashed line represents the elevation of the creek bank at the measuring location), (b) velocity (flood velocity is positive), (c) Suspended sediment concentration, (d) current shear stress on the mudflat, (e) current shear stress in the marsh creek, (f) wave shear stress on the mudflat, (g) bed level change, and (h) cumulative sediment flux (into the creek is positive) on the mudflat (yellow) and in the marsh creek (green) in Paulina Saltmarsh.

B

Supporting Information for Chapter 3

This appendix has been submitted as supporting information for the following article:

Sun, J., van Prooijen, B., Wang, X., Zhao, Z., He, Q., & Wang, Z.B. (2024). Sediment fluxes within salt marsh tidal creek systems in the Yangtze Estuary. *Geomorphology*, 449, 109031, https://doi.org/10.1016/j.geomorph.2023.109031.

This supporting document includes the results of sediment calibration curves (Figure B.1).

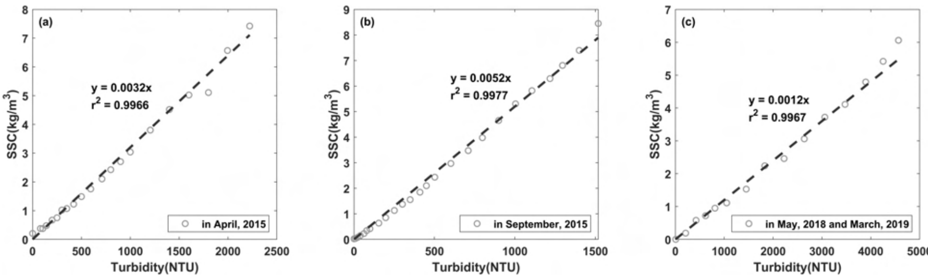

Figure B.1: Sediment calibration curves of the optical backscatter signal with SSC data in (a) the main creek in April, 2015, (b) the main creek in September, 2015, and (c) the secondary creek in May, 2018 and March, 2019.

C
Supporting Information for Chapter 4

This appendix has been submitted as supporting information for the following article:

Sun, J., van Prooijen, B., Wang, X., Xie, W., Xu, F., He, Q., & Wang, Z.B. (2024). Conditional effects of tides and waves on sediment supply to salt marshes. *JGR: Earth Surface*, submitted for publication.

C

This supporting document includes detailed time series data measured on the mudflat, in the marsh creek and at the marsh edge (Figure C.1 and C.2), the results of sediment calibration curves (Figure C.3), and wind & wave data (Figure C.4)

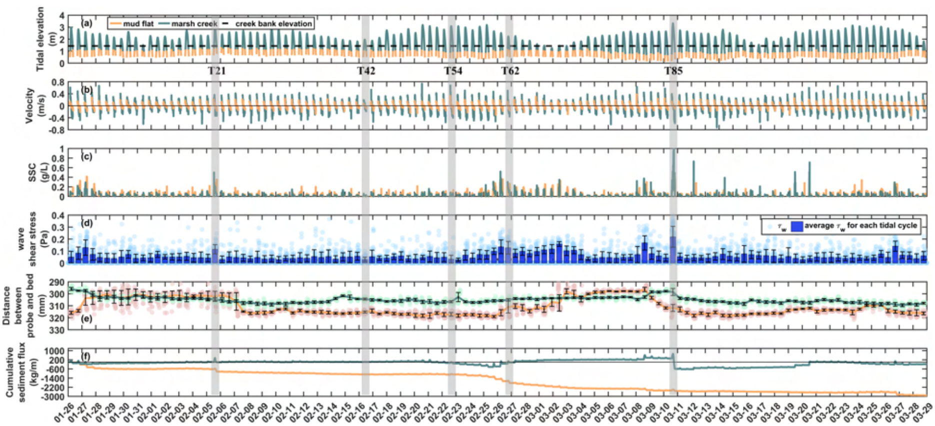

Figure C.1: Time series of (a) tidal elevation (the dashed line represents the elevation of the creek bank at the measuring location); (b) along-creek velocity in the creek and cross-shore velocity on the mud flat (flood velocity is positive); (c) the suspended sediment concentration observed by OBS-3A; (d)wave shear stress on the mudflat; (e) bed level change; (e)cumulative sediment flux in the marsh creek (green) and on the mudflat (yellow) in Paulina Saltmarsh. (Highlighted ones in grey were the representative tidal cycles in Figure 4.3.)

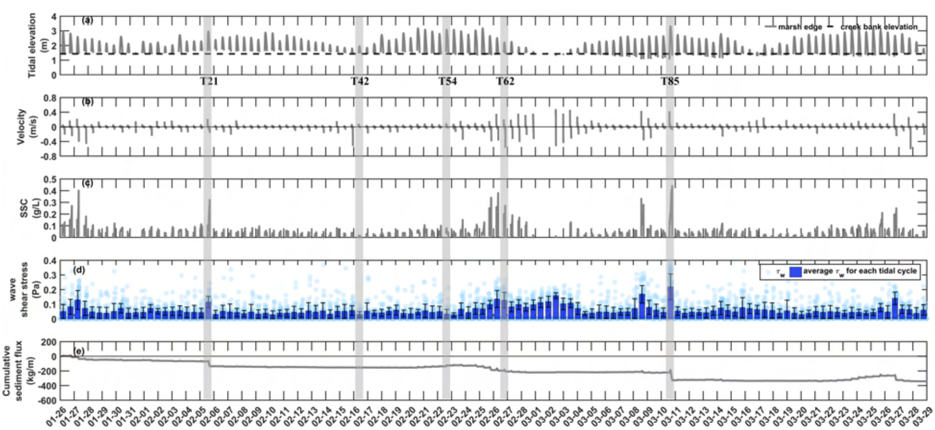

Figure C.2: Time series of (a) tidal elevation (the dashed line represents the elevation of the creek bank at the measuring location); (b) cross-shore velocity (flood velocity is positive); (c) the suspended sediment concentration observed by STM; (d) wave shear stress on the mudflat; (e)cumulative sediment flux at the marsh edge in Paulina Saltmarsh. (Highlighted ones in grey were the representative tidal cycles in Figure 4.3.))

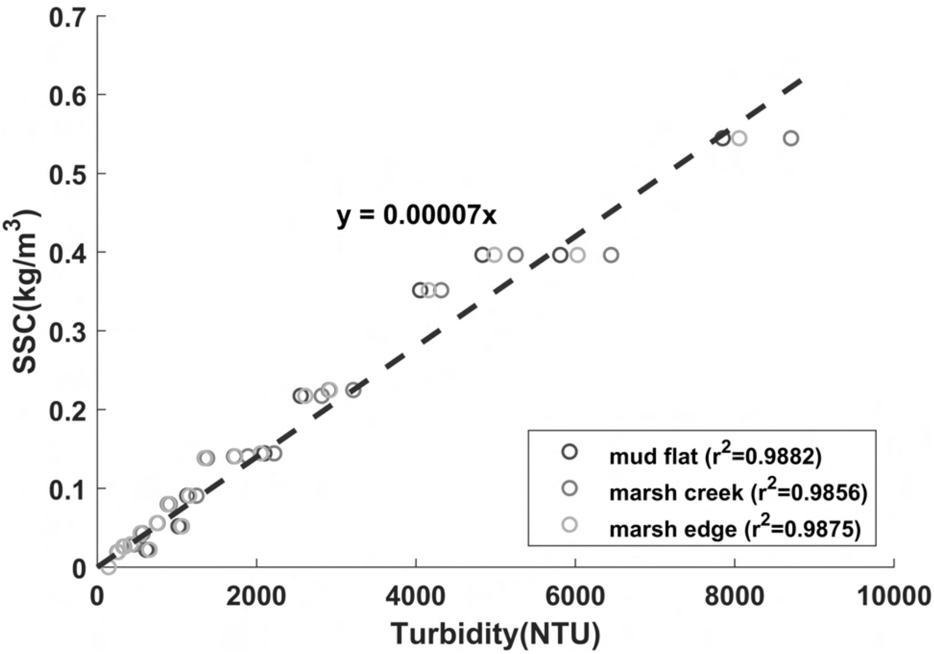

Figure C.3: Sediment calibration curves of the optical backscatter signal with SSC data from STMs on the mudflat, in the marsh creek, and at the marsh edge in Paulina Saltmarsh.

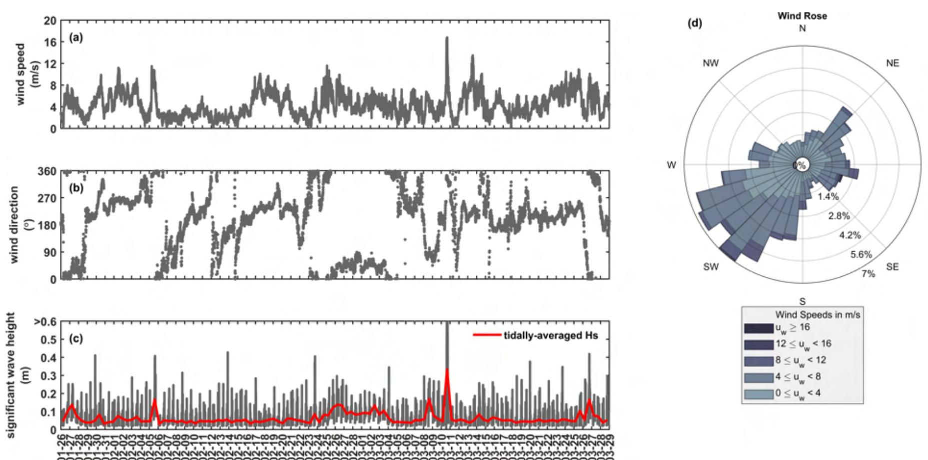

Figure C.4: Wind and significant wave data. (a) Time series of wind speed in Terneuzen. (b) Time series of wind direction in Terneuzen. (c) Time series of significant wave height measured in Paulina Saltmarsh. (d) Wind rose during the measuring period, with colors indicating wind velocities and solid cycles indicating percentage occurrence. Wind data was collected at Terneuzen Westsluis station from Rijkswaterstraat Waterinfo () and wave data was collected on mudflats in Paulina Saltmarsh.

Acknowledgements

I've saved the acknowledgments for last because, honestly, this is the most challenging part to write. When I look back over the past few years, there's just so much to be thankful for. I've been incredibly lucky to meet so many amazing people along the way, each leaving a unique mark on my journey. Where do I even begin?

My PhD journey all began with a conversation. Back when I was in my master's program, one day Prof. Qing He and Dr. Xianye Wang came to me with an exciting, yet intimidating proposal: they asked if I would consider continuing into a PhD program with the opportunity to study abroad. At that time, I was still new to the world of research, and to be honest, I wasn't sure where I was heading. Their offer was both enticing and overwhelming. After a brief moment of hesitation, I said yes. Little did I know, that split-second decision would turn out to be one of the best choices of my life.

During my master's, I went on countless field trips, and it was Dr. Wang who taught me how to conduct field measurements. He took me to the tidal flats at three major estuaries in China, showing me the beauty and complexity of intertidal environments. Thank you, Dr. Wang, for introducing me to the fascinating world of intertidal systems. You sparked my passion for fieldwork, and that has shaped so much of my research. When I transitioned into my PhD, Prof. He became my promotor. Your guidance always pointed me in the right direction. I still remember how much I learned from your presentations —they were clear, compelling, and inspiring. You showed me what it means to deliver a good and impactful talk, and I have carried that lesson with me ever since. Of course, the path to completing a PhD isn't always smooth. There were difficult times, but I'm so grateful to Prof. He for your support when I hit those low points. Your encouragement and belief in me helped me to pull through, and I was able to regain my positive outlook and move forward with renewed energy.

Shortly after I officially became a PhD student at East China Normal University (ECNU), I started reaching out to Prof. Zhengbing Wang to prepare the necessary documents for starting my PhD journey at Delft University of Technology. Thank you, Prof. Wang, for making this journey possible. I'm also deeply grateful for your precise guidance on my three papers and your incredibly prompt feedback. You always had a way of identifying the key issues in my work, and through that, you showed me what it means to be an exceptional researcher. I also cherish the memories of the dinner you and your wife invited us at your home. Not only did we enjoy your homemade chili sauce and delicious Chinese dishes, but you also shared fascinating stories about your time studying in the Netherlands during a very different era. Those stories left a lasting impression on me, and I'm so thankful that you shared them with us.

Before my journey at TU Delft even began, I had the chance to meet Bram in China during a collaborative field campaign between China and the Netherlands. It was my first experience organizing such a large field campaign and working alongside Bram and Jill out on the mudflats. By the way, I was (still am) completely amazed by Jill's speed as she navigated the super muddy area like it was solid ground. Bram, you might think that field campaign was the first time we met, but, in fact, it wasn't. Years earlier, when I was still a MSc student, we briefly crossed paths during a workshop at ECNU. You were a session chair, and I was a presenter nervously giving my first-ever talk in English. During the Q&A, I struggled to understand a question due to a mix of nerves and the speaker's accent. Noticing my struggles, you kindly repeated the question for me. In that moment, I thought, "What a nice person!" I never would have imagined that years later, I'd have the privilege of having you as my PhD supervisor. Prof. He has often remarked on how much more confident and outgoing I've become since coming to the Netherlands. Bram, you are one of the reasons for this transformation. You've helped me grow in ways that extend far beyond research. To me, you've been the ideal supervisor, and I feel so lucky to have worked with someone who shares my enthusiasm for fieldwork. I still laugh when I think about how neither of us felt comfortable standing by and doing nothing while the other worked in the field. I guess we both belong to that group of people who can't help but jump in. You've always been thoughtful and helpful, whether it was double-checking instrument configurations or sharing the workload in the field. Brainstorming with you during our weekly meetings was always an enjoyable experience. And during the more challenging moments, your guidance and support reminded me that I was never tackling this PhD journey alone. Thank you, Bram, for being such an inspiring supervisor and for making these years so rewarding—not just academically, but personally as well.

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Jianwei Sun
Delft
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About The Author

Jianwei Sun was born on the 24^{th} of August, 1993, in Wan'an county, Jiangxi Province, China. Jianwei spent his first 16 years in his hometown, where he attended the primary and middle school. Afterward, he moved to Linchuan county for high school, where he experienced the most challenging and hardworking three years. In 2012, Jianwei moved to Hubei Province to pursue a BSc at the School of Water Resources and Hydropower Engineering, Wuhan University, majoring in Agricultural Water Conservancy Engineering. After obtaining his Bachelor degree in 2016, Jianwei was recommended for direct admission to a MSc at the State Key Laboratory of Eastuarine and Coastal Research (SKLEC), East China Normal University (ECNU) in Shanghai. After two years of researching beautiful saltmarsh creeks during his master's studies, Jianwei had the opportunity to continue his research through a PhD abroad on the same topic by joining the successive master-doctoral program in SKLEC in 2018. As planned, Jianwei started his PhD at Delft University of Technology (TU Delft) in October, 2019, within the PSA project (Coping with Deltas in Transition) and the framework of the dual doctoral degree agreement between ECNU and TU Delft. In his spare time, he enjoys bouldering, swimming, diving, and travelling.

List of Publications

Journal Articles

First Author

3. **Sun, J.**, van Prooijen, B., Wang, X., Xie, W., Xu, F., He, Q., & Wang, Z. B. (2024). ”Conditional effects of tides and waves on sediment supply to salt marshes”. In *JGR: Earth Surface* 129(10). DOI: https://doi.org/10.1029/2024JF007686 [Chapter 4]

2. **Sun, J.**, van Prooijen, B., Wang, X., Zhao, Z., He, Q., & Wang, Z. B. (2024). ”Sediment fluxes within salt marsh tidal creek systems in the Yangtze Estuary”. In *Geomorphology* 449, p. 109031. DOI: https://doi.org/10.1016/j.geomorph.2023.109031 [Chapter 3]

1. **Sun, J.**, van Prooijen, B., Wang, X., Hanssen, J., Xie, W., Lin, J., Xu, Y., He, Q., & Wang, Z. B. (2024). ”Sources of suspended sediments in salt marsh creeks: Field measurements in China and the Netherlands”. In *Geomorphology* 456, p. 109206. DOI: https://doi.org/10.1016/j.geomorph.2024.109206 [Chapter 2]

Co-Author

4. Cornacchia, L., van de Vijsel, R., van der Wal, D., Ysebaert, T., **Sun, J.**, van Prooijen, B., de Vet, P.L.M., Liu, Q., & van de Koppel, J. (2024). ”Vegetation traits and biogeomorphic complexity shape the resilience of salt marshes to sea-level rise”. In *Communications Earth & Environment* 5(1), p. 658. DOI: https://doi.org/10.1038/s43247-024-01829-2

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2. Xie, W., **Sun, J.**, Guo, L., Xu, F., Wang, X., Ji, H., Fan, Y., Wang, Z.B., & He, Q. (2023). ”Distinctive sedimentary processes on two contrasting tidal flats of the Yellow River Delta”. In *Frontiers in Marine Science* 10, p. 1259081. DOI: https://doi.org/10.3389/fmars.2023.1259081

1. Wang, X., **Sun, J.** & Zhao, Z. (2020). ”Effects of river discharge and tidal meandering on morphological changes in a meso tidal creek”. In *Estuarine, Coastal and Shelf Science* 234, p. 106635. DOI: https://doi.org/10.1016/j.ecss.2020.106635

Conference proceedings and talks

5. **Sun, J.**, van Prooijen, B., Wang, X., & He, Q. (2023). Unveiling the role of marsh creeks in delivering sediment: Insights from Paulina saltmarsh. INTERCOH 2023, Incheon, South Korea, September 2023.

4. **Sun, J.**, van Prooijen, B., Wang, X., & He, Q. (2023). The role of marsh creeks in the development of salt marshes during storm events. EGU 2023, Vienna, Austria, April 2023.

3. **Sun, J.**, Wang, X., He, Q., Xie, W., Hanssen, J., & van Prooijen, B., (2022). Sediment routing in saltmarsh creeks –Field measurements in China and the Netherlands. ECSA 59: Using the best scientific knowledge for the sustainable management of estuaries and coastal seas, San Sebastian, Spain, September 2022.

2. **Sun, J.**, Wang, X., He, Q., Xie, W., Hanssen, J., & van Prooijen, B., (2022).The fate of sediment from source to sink in two different tidal flat environments. NCK Days 2022, Enschede, the Netherlands, March 2022.

1. **Sun, J.**, van Prooijen, B., Wang, X., He, Q., & Wang, Z. B. (2021). The sediment flux in salt marsh tidal channel systems. INTERCOH 2021, Delft, the Netherlands, September 2021.